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Original Research

Enterprise Digital Transformation and Green Technology Innovation: Evidence from Innovation Sub-Dimension and Time Lag Effect

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Abstract

With the development of digital and green economies, enterprise digital transformation inventively promotes green technological innovation. Using data from listed companies in Shanghai and Shenzhen from 2008 to 2021 with text analysis, we construct a multidimensional fixed-effect model to study the impact of enterprise digital transformation on green technology innovation. We find that enterprise digital transformation promotes green technology innovation, holding after a series of robustness tests and endogeneity treatments, by reducing financing constraints and easing enterprise risks. Further analysis shows that among the two sub-dimensions of enterprise green technology innovation, the promotion effect on independent innovation of green technology is more prominent. There is also a time lag effect in the promotion effect on both green technology innovation and its sub-dimensions, showing a tendency to enhance and then weaken. Moreover, the positive effect of enterprise digital transformation is more significant in heavy pollution industries, alongside non-state-owned and small-scale enterprises, with different performances in sub-dimension.

Keywords: digital transformation, green technology innovation, sub-dimension, time lag effect

Introduction

As the key support for green transformation of economic development, green technological innovation is conducive to realize a "win-win" between economic benefits and environmental protection [1], with many policies strengthening the important role of green technological innovation. However, compared with traditional technological innovation, externality from green technological innovation makes enterprises less interested in carrying out green innovation activities [2]. As the main force behind innovation and entrepreneurship, the accelerated release of innovative energy has become a hot topic. At the same time, with the rapid development of information technology, various policies aim for a digital economy. Therefore, enterprises grasp these opportunities and actively promote digital transformation, since digital technologies deeply benefit enterprises in various aspects. In conclusion, widely exploring the relationship between enterprise digital transformation and green technological

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innovation has great significance. However, due to the complexity and long cycle of green innovation, the impact of digital transformation on firm-independent and joint green innovation, as well as the impact on green innovation over time, is of significant research interest. Therefore, we attempt to fill the gap regarding the effect of enterprise digital transformation on green innovation sub-dimension, namely green independent and joint innovation, and the time-lag effect.

Numerous studies have focused on the positive effect of digital transformation on corporate green technology innovation. EI-Kassar and Singh (2019) [3] indicate that big data and predictive analytics positively influence green innovation practices. Li et al. (2023) [4], Yin (2023) [5], and Sui and Yao (2023) [6] confirm the promotion effect of digital transformation on enterprise green innovation. Further, existing research finds that digital transformation can promote green technology innovation in various aspects, including enhancing absorptive capability[7], improving human capital level [8], increasing innovation resource investment [9], improving internal control [10], reducing internal and external costs [11].

Using data from enterprises listed on the Shanghai and Shenzhen stock exchanges in China from 2008 to 2021, we explore the impact of enterprise digital transformation on green technological innovation, measured by the number of green invention patent authorizations. Our results can be summarized as follows. First, enterprise digital transformation promotes green technology innovation. And this result holds after a series of endogeneity and robustness tests, including high-dimensional fixed effects, replacing explanatory variables, changing clustered error, and winsorizing the sample at 1% level, with instrument variable (IV) using the interaction term between the spherical distance from the prefecture-level city where the enterprise is located to Hangzhou and the average level of enterprise digital transformation in prefecture-level city [12]. This positive effect functions by alleviating financing constraints and mitigating enterprise risks. Moreover, further analysis shows that enterprise digital transformation promotes both sub-dimensions of green technology innovation, with a more obvious effect on enterprise green independent innovation. Besides, there is a time lag effect on both green technology innovation and its sub-dimensions, with promotion effect first enhancing and then weakening. Lastly, the promotion effect of enterprise digital transformation on green technology innovation is more significant among enterprises in the heavy pollution industry, as well as non-state-owned and small-scale enterprises, with different performances in sub-dimension.

Our paper makes contributions in several aspects. First, we construct a multi-dimensional fixed effects model confirming the positive impact of enterprise digital transformation on green technology innovation, especially the two sub-dimensions of green technological innovation, namely green independent and joint innovation. Second, we examine the time-lag effect of digital transformation on green technology innovation, because of the long cycle of innovation. Specifically, we find the same trend variation with time in both green innovation and its sub-dimensions. Third, we further explore the difference in the relationship between different enterprise characteristics, including industry, ownership, and size, and study the different influences of enterprise digital transformation on independent and joint innovation.

Our paper is organized as follows. Section 2 develops hypotheses, and Section 3 presents data and model construction. Moreover, Section 4 presents empirical results, with Section 5 carrying out further analysis. Lastly, Section 6 concludes our paper.

Hypothesis Development

Enterprise Digital Transformation and Green Technology Innovation

With information technologies rising, the integration of digital technology and real economy has accelerated, and enterprises digital transformation has been expedited. The new generation of digital technology is widely used in all aspects of enterprise production, operation, and management [13, 14], accelerating the delivery and feedback of information in organizations, promoting internal and external knowledge sharing [15, 16]. Internally strengthening the communication between various departments in enterprise and externally promoting innovation cooperation between enterprises, digital transformation makes enterprises function as the main body of technological innovation in regional radiation [17], and encourages enterprises toward innovation. In addition, digital transformation can enhance enterprise resource integration capability and trigger synergistic effects through better integration of internal and external green innovation elements, with stronger green innovation capabilities [18]. Enterprise digital transformation also expands innovation resource allocation scope [19, 20], creating a more favorable environments for green innovation activities and enterprise development [21].

And the typical application of digital technology on green innovation is the Zero Carbon Pioneer Program of Siemens in 2021, integrating digital twin technology, energy management, edge computing, and underlying blockchain trusted technology, dedicating to building a zero-carbon industrial chain in China with more green innovation activities carried out.

Compared with traditional technological innovation, the R&D cycle of green and low-carbon technologies is long, complex, and risky [22, 23]. Therefore, sustained and sufficient financial resources should be supported to solve the environmental externalities and technology spillover effects of green technological innovation [24]. The digital transformation can improve enterprise financing situations and provide sufficient financial support for green innovation activities. On the one hand, digital transformation enables enterprises to efficiently process massive, non-standardized and unstructured data,

improving information availability [25], and helping financial institutions obtain more internal information of enterprise [26]. Thus, an information docking channel between banks and enterprises will be constructed, effectively alleviating asymmetric information, which helps enterprises reduce thresholds and financing costs, which are beneficial for green technology innovation. On the other hand, based on signaling channels, enterprise digital transformation becomes prominent in this new era [27]. As a complex project, enterprise digital transformation reflects enterprise strength, releasing positive signals to market participants [28], thus making it likely to be trusted by banks and pursued by investors. Therefore, enterprises in digital transformation will face fewer financing constraints, with more investments in green technological innovation.

Additionally, digital transformation provides tools and methods for enterprises to carry out risk assessment, helping enterprises screen out high-risk innovation projects and match better green innovation projects with less risk [29]. Digital transformation can also improve enterprise internal information transparency and governance capacity [27], then select suitable green innovation projects with risk avoidance. Also, digital transformation provides enterprises with more funds for green technological innovation, reducing financial risk and improving financial stability [30]. Therefore, digital transformation will make enterprises avoid more risk, and we propose our first hypothesis:

H1: Enterprise digital transformation promotes green technology innovation by easing financing constraints and reducing enterprise risk.

Enterprise Digital Transformation and Sub-Dimensions of Green Technology Innovation

Digital technologies have widened enterprise boundaries, offering more possibilities for comprehensive open innovation [31], functioning with information sharing, and strengthening communication and innovation cooperation between enterprises [32]. However, due to the complexity and dynamics of green technology innovation, the opportunistic behavior of enterprises under cooperative innovation, which leads to short-term and unstable cooperation [33], is still an important factor hindering enterprises from cooperating in green innovation activities. Therefore, in digital transformation, enterprises prefer to take advantage of information technology to enhance independent innovation capacity; promoting green innovation and achieving high-quality development. In conclusion, our second hypothesis is proposed as follows:

Table 1. Variable definition and Descriptive statistics

Variable	Definition	N	Mean	Std. Dev	Min	Max
GrePat	Enterprise green technology innovation, the number of green invention patent authorization plus 1 and take natural logarithm	23718	0.143	0.484	0.000	6.753
DigTra	Digital transformation level of enterprises, the number of digital keywords to total number of words in annual reports	23718	0.001	0.001	0.000	0.025
Age	Age of the enterprise, the number of years since establishment plus 1 and take natural logarithm	23718	2.799	0.365	0.693	4.796
Size	Enterprise size, total assets plus 1 and take natural logarithm	23718	22.056	1.318	15.577	29.755
Growth	Operating income growth rate, current year's operating income / prior year's operating income - 1	23718	0.009	0.966	-0.013	148.831
Lev	Asset-liability ratio, total liabilities at year-end / total assets at year-end	23718	0.436	0.211	0.007	1.968
Roa	Return on total assets, net profit/total assets	23718	0.040	0.073	-1.859	0.880
Property	Ownership, if company is a state-owned enterprise, the value takes 1 and 0 otherwise	23718	0.396	0.489	0.000	1.00
Equity	Shareholding balance, 2nd - 5th largest shareholder shareholding / 1st largest shareholder shareholding	23718	0.698	0.609	0.000	3.921
Inst	Institutional shareholding ratio, total number of shares held by institutional investors / total outstanding share number	23718	44.223	23.752	0.000	98.584
Merge	Duality, if the chairman and general manager is the same person, value takes 1 and 0 otherwise	23718	0.253	0.435	0.000	1.000
Share	Management shareholding ratio, number of management shares/ total share number	23718	11.681	18.967	0.000	89.725
Board	Board size, the number of board members and take the natural logarithm	23718	8.699	1.794	0.000	19.000
Ind	Independent director percentage, number of independent directors/total number of directors	23718	37.263	5.535	0.000	100.000

Table 2. Enterprise digital transformation on green technology innovation

	(1)	(2)	(3)
DigTra	5.354**	5.523**	5.115**
	(2.26)	(2.35)	(2.18)
Age	0.081***	-0.009	-0.025
	(2.87)	(-0.22)	(-0.58)
Size	0.040***	0.036***	0.042***
	(3.36)	(3.49)	(3.67)
Growth	0.000***	0.001***	0.001***
	(3.15)	(3.73)	(3.90)
Lev	-0.044**	-0.022	-0.025
	(-2.03)	(-0.97)	(-1.13)
Roa	-0.086*	-0.104**	-0.104**
	(-1.88)	(-2.40)	(-2.41)
Property	0.008	0.017	0.020
	(0.52)	(1.02)	(1.17)
Equity	-0.018*	-0.013	-0.014
	(-1.66)	(-1.21)	(-1.21)
Inst	-0.001***	-0.001***	-0.001**
	(-2.66)	(-2.87)	(-2.42)
Merge	-0.005	-0.008	-0.008
	(-0.56)	(-0.96)	(-0.95)
Share	0.001	0.000	0.000
	(1.28)	(0.07)	(0.30)
Board	0.000	0.001	0.001
	(0.03)	(0.23)	(0.22)
Ind	0.001	0.001	0.001
	(1.08)	(1.01)	(1.00)
Constant	-0.926***	-0.594***	-0.685***
	(-3.27)	(-2.71)	(-2.91)
Firm FE	YES	YES	YES
Year FE	NO	YES	YES
Industry FE	NO	NO	YES
N	23720	23720	23718
R^2	0.652	0.655	0.657
adj. R^2	0.609	0.613	0.613

Note: t-values in parentheses, ***, **, and * represent 1%, 5%, and 10% significance levels, respectively. All the following tables are the same.

Table 3. Endogeneity test

	Stage 1	Stage 2
IV	0.001***	
	(7.37)	
DigTra		22.566**
		(2.01)
Control variables	YES	YES
Firm FE	YES	YES
Year FE	YES	YES
Industry FE	YES	YES
N	22541	22541
K-P rk LM statistic P-val	0	
C-D wald F	1441.739	
R^2	0.478	0.003

H2: Enterprise digital transformation promotes the sub-dimensions of green technology innovation, with a more prominent effect on enterprise-independent innovation for green technology.

Time Lag Effect of Enterprise Digital Transformation on Green Technology Innovation

Enterprise digital transformation can't play roles immediately, as a continued process. At the same time, a green invention patent is characterized by a long cycle [34]. Therefore, the impact of enterprise digital transformation on green technology innovation has a time-lag effect. For enterprises in the early stages of transformation, with the deepening application of high tech, enterprises can fully mobilize internal and external innovation resources and optimize green innovation resource allocation, playing a strong incentive role in green technology innovation in the short term. However, when the enterprise digitalization process enhances greatly, the marginal effect on green innovation will reduce [11]. In the later stages of transformation, the positive impact of enterprise digital transformation on green technology innovation will diminish. Thus, we propose our three hypotheses:

H3: There is a time lag effect on the impact of enterprise digital transformation on green technology innovation and its sub-dimensions, with trends first enhancing and then weakening.

Data and Model Construction

Data

We draw data from the China Stock Market Accounting Research Database, with innovation data from the Chinese Research Data Services database. Further, we remove the sample companies from financial industry and those with unavailable variables, and finally, the data from 23,718 firm-year observations is obtained.

Variable Definition

Dependent Variables

Following Yi et al. (2022) [35], we use the number of green invention patent authorizations plus one, and use logarithm to measure corporate green technology innovation (GrePat). Specifically, green invention patent authorization consists of green invention patents authorized by enterprises independently (GrePat-In) and jointly (GrePat-Un).

Independent Variables

Enterprise digital transformation (DigTra) is based on textual analysis. We use the number of key words related to digital transformation from CNRDS as the total number in the annual reports of listed companies.

Mechanism Variables

Financing constraints and firm risk are mechanism variables. We select two proxy variables, the WW index and bank lending size, to measure the financing constraints of enterprises. Following Whited and Wu (2006) [36], WW index is constructed as follows:

$$WW = -0.091 \times CF - 0.062 \times DivPos + 0.021 \times Lev - 0.044 \times Size + 0.102 \times ISG - 0.035 \times SG$$

Bank credit is an important source for enterprise external financing[37, 38], so the size of bank lending to enterprises can reflect the enterprise financing constraints. We use the sum of short-term borrowings, long-term borrowings, and non-current liabilities due within one year plus 1 and take the logarithm to measure bank lending size (Loan). With a low WW index and large bank lending size, enterprises will face fewer financing constraints.

Moreover, we use the volatility of stock returns to measure corporate risk. With greater volatility of stock returns, corporate will face higher risk. Following Su Kun (2015) and Zhang et al. (2015) [39, 40], we use the annualized standard deviation of monthly stock returns (Risk1), and the standard deviation of industry-adjusted stock returns over a five-year period (Risk2), respectively.

Control Variables

Referring to He et al.(2023) [34], Peng and Tao (2022) [20] and Liu et al. (2023) [9], we control 12 variables, including financial, governance, and ownership structure, as defined in Table 1.

Model Construction

To test the impact of enterprise digital transformation on green technology innovation, our multidimensional fixed effects model is constructed as follows:

$$GrePat_{i,t+1} = \alpha + \beta \times DigTra_{i,t} + \rho X_{i,t} + \gamma_{i,t} + \mu_{j,t} + \sigma_t + \varepsilon_{i,j,t} \quad (1)$$

Where i, j, and t denote firm, industry, and year, respectively. The dependent variable $GrePat_{i,t+1}$ is enterprise green technology innovation, and the independent variable $DigTra_{i,t}$ denotes the firm's digital transformation level. To alleviate endogeneity, we use the independent variables at $t+1$ year. $X_{i,t}$ is a vector of control variables described in Table 1. And $\gamma_{i,t}$, $\mu_{j,t}$, and σ_t is firm, industry, and year fixed effect, and $\varepsilon_{i,j,t}$ is standard error clustered at industry level.

Descriptive Statistics

Table 1 reports descriptive statistics. As shown in Table 1, the minimum and maximum of GrePat are 0 and 6.753, with a standard deviation of 0.484, confirming the large difference in green technology innovation among companies. While those from DigTra indicate that enterprise digitalization levels are relatively low, with need to be improved.

Empirical Results

Baseline Results

Table 2 reports baseline results of digital transformation on green technology innovation. In column (1), this paper only controls firm-fixed effects. And in column (2), we further control year-fixed effects, and coefficients are significantly positive at the 5% level. To control the unobservability of changes in industry, after controlling industry-fixed effect, the coefficient in column (3) is significantly positive, indicating that enterprise digital transformation promotes green technology innovation.

Endogeneity Test

We adopt an instrumental variable (IV) approach to further address endogeneity concerns. Following Feng et al. (2022) [12], we use the interaction term between the spherical distance from prefecture-level cities where enterprise is located to Hangzhou and the average level of digital transformation of all enterprises (except the enterprise itself) in the prefecture-level city as IV.

On one hand, Hangzhou, as the first city of China's digital economy, has the highest level of comprehensive digital development. The high connectivity and permeability of the network brought by the digital economy makes the connection between regions closer and the dissemination of knowledge and information more convenient [41]. So the distance between the prefectural city enterprise is located and Hangzhou will have an impact on enterprise digital transformation. At the same time, there are significant peer effects in enterprise digital transformation [42], and the level of enterprise digital development is often influenced by other enterprises within the same region. Therefore, we use the interaction between the spherical distance from prefectural city enterprise located to Hangzhou and the average level of digital transformation as the IV. What's more, both the spherical distance from prefectural city enterprise located to Hangzhou and the average level of digital transformation of other enterprises in the city can't influence corporate green technology innovation directly; therefore, the instrumental variable is exogeneous. As shown in Table 3, the test statistics show that the instrumental variable is appropriate. After addressing endogeneity concerns, the promotion effect of enterprise digital transformation on green technology innovation remains significant.

Robustness Test

High-Dimensional Fixed Effect

To control unobservable influence factors at province level, we add a province-fixed effect. The result in column (1) of Table 4 is consistent with baseline regression. Further, we use a high-dimensional fixed effects model controlling firm, industry, and year × province fixed

effect as well as firm, province, and year × industry fixed effect. From columns (2) and (3) of Table 4, the positive influence of enterprise digital transformation on green technology innovation remains.

Replacing Explanatory Variables

The explanatory variable of baseline regression is measured by the frequency of all digitization-related keywords in annual reports. Further, all keywords related to digitization in the table are removed to construct ReDigTra. The result in column (4) of Table 4 shows that the coefficient of ReDigTra is still significantly positive.

Changing Cluster Level

We change clustered standard errors from industry level to firm level. As shown in column (5) of Table 4, the estimated coefficient stays significantly positive.

Variable Winsorizing

Considering the effect of extreme values on our results, the result in column (6) of Table 4, where all continuous variables are winsorized at the 1% level, indicates that enterprise digital transformation still contributes to green technology innovation.

Mechanism Analysis

Our result shows that the improvement of enterprise digitalization can significantly promote green technology innovation. We further explore the mechanism of enterprise digital transformation affecting enterprise green technology innovation through financing constraints and enterprise risk.

Financing Constraints

We chose two indicators, the WW-Index and bank lending size, to measure enterprise financing constraints. The results in column (1) of Table 5 show that the coefficient of DigTra is significantly negative, while the coefficient of DigTra reported in column (2) is significantly positive, indicating that enterprise digital transformation can significantly alleviate enterprise financing constraints while promoting enterprise green technology innovation. Through digital transformation, enterprises can use digital technology to collect and analyze massive user data, with the ability to accurately understand the needs and preferences of users [43], before adjusting business strategies, enhancing operational efficiency, and improving business performance, with the result of alleviating enterprise finance constraints [44], benefiting corporate green innovation activities. Besides, digital technology can significantly reduce the degree of information asymmetry between banks and enterprises, helping enterprises obtain credit support in a timely manner and helping enterprise solve the problem of "difficult and expensive financing", with more green technological innovation activities [28].

Enterprise Risk

Using Risk1 and Risk2 as dependent variables, the coefficients of DigTra in columns (3) and (4) in Table 5 are significantly negative, indicating that the improvement of enterprise digitalization has a significant mitigating effect on enterprise risk, then promoting enterprise green technology innovation. Digital transformation can improve the efficiency and effectiveness of risk assessment [45]. With the help of digital technology, enterprises can quickly and efficiently identify risk factors in innovation and assess the possibility of risk occurrence, with risk management capabilities improvement and corresponding risk avoidance, benefiting green innovation with higher successful possibility [29]. And through digital transformation, internal information sharing can be realized efficiently, with improved communication and collaboration between organizational departments improvement [25, 26], promoting the decision-making of management, especially in innovation activities.

Table 4 Robustness test

	(1)	(2)	(3)	(4)	(5)	(6)
DigTra	5.257**	4.983**	4.032*	5.895*	5.115*	4.670**
	(2.26)	(2.12)	(1.79)	(1.79)	(1.72)	(2.09)
Constant	-0.715***	-0.645***	-0.473**	-0.683***	-0.685***	-0.625***
	(-2.94)	(-3.01)	(-2.04)	(-2.91)	(-3.36)	(-2.89)
Control variables	YES	YES	YES	YES	YES	YES
FE	Firm, year, industry, province	Firm, industry, year×province	Firm, province, year×industry	Firm, year, industry	Firm, year, industry	Firm, year, industry
N	23718	23718	23620	23718	23718	23718
R^2	0.659	0.665	0.672	0.657	0.657	0.615
adj. R^2	0.615	0.614	0.614	0.613	0.613	0.565

Table 5 Test of the mechanisms by which the enterprise digital transformation affects green technology innovation

	Financing constraint		Enterprise risk	
	(1)	(2)	(3)	(4)
	WW-Index	Loan	Risk1	Risk2
DigTra	-2.893**	13.377*	-11.893*	-12.579**
	(-2.04)	(1.80)	(-1.93)	(-2.05)
Constant	0.211***	-6.179***	-2.500***	-1.724***
	(3.87)	(-8.06)	(-5.99)	(-6.95)
Control Variable	YES	YES	YES	YES
Firm FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES
N	22928	17167	18424	23704
R^2	0.998	0.910	0.469	0.423
adj. R^2	0.998	0.896	0.385	0.349

Moreover, with the enhancement of internal control with the help of digital technologies, risk caused by principal-agent problems can be reduced, thus promoting green innovation with strategy improvement [30].

Further Analysis

Analysis of Green Technology Innovation Sub-Dimensions With Time-Lag Effects

Enterprise invention patents consist of inventions cooperating with other enterprises or made independently. Therefore, we separate enterprise green technology innovation into green technology independent innovation and cooperative innovation. The dependent variable of model (1) is replaced with the number of green invention patent authorization by corporate independently (GrePat-In) and the number of green invention patent authorizations by corporate jointly (GrePat-Un), respectively, to explore the impact of digital transformation on the two sub-dimensions of green technology innovation. The results in columns (4) and (7) of Table 6 show that digital transformation promotes both independent innovation in green technology and collaborative innovation in green technology.

This paper lags enterprise digital transformation by two and three years to study the time lag effect of promotion on green technology innovation, and the regression results are shown in Table 6. The results in columns (1) to (3) show that the regression coefficient of DigTrat-2 is significantly positive and greater than the regression coefficient of DigTrat-1, and the regression coefficient of DigTrat-3 is positive but not significant. It indicates that the impact of enterprise digital transformation on green technology innovation has a time-lag effect, and the effect shows a tendency to enhance first and then weaken as time goes by. The improvement of digital transformation provides the greatest green innovation benefits after two years, but the positive effect on green technology innovation decreases after the development of enterprise digitalization. In addition, the time lag effect also significantly presents in two sub-dimensions of green technology innovation, and the promotion effect of enterprise digital transformation on enterprise green technology independent and collaborative innovation similarly tends to enhance first and then weaken over time.

Table 6 Analysis of green technology innovation sub-dimensions with time lag effects

	GrePat			GrePat-In			GrePat-Un		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$DigTra_{t-1}$	5.115**			2.799*			2.685**		
	(2.18)			(1.71)			(2.00)		
$DigTra_{t-2}$		7.345**			4.996**			3.109*	
		(2.52)			(2.52)			(1.95)	
$DigTra_{t-3}$			2.299			1.552			2.060
			(0.91)			(0.76)			(1.30)
Constant	0.685***	0.570**	0.320	0.459**	-0.372*	0.171	0.354**	0.250*	0.165
	(-2.91)	(-2.26)	(-1.23)	(-2.30)	(-1.79)	(-0.75)	(-2.26)	(-1.74)	(-1.27)
Control variable	YES	YES	YES	YES	YES	YES	YES	YES	YES
Firm FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	23718	22850	20265	23718	22850	20265	23718	22850	20265
R^2	0.657	0.674	0.695	0.616	0.633	0.655	0.661	0.676	0.694
adj. R^2	0.613	0.630	0.652	0.567	0.584	0.606	0.618	0.634	0.652

Further, by comparing the coefficients of enterprise digital transformation on the two sub-dimensions of green technology innovation, the results in columns (4)-(5) and (7)-(8) show that the impact of digital transformation on green technology independent innovation is significantly higher than that of green technology cooperative innovation in both lagged one period and lagged two periods, indicating that digital improvement has a more prominent effect on enterprise green technology independent innovation within 2 years.

Heterogeneity Analysis

Heavy Pollution Industry

In the process of green transformation, enterprises in heavy pollution industries need a huge amount of external financial support for green innovation. However, such enterprises face higher financing thresholds and costs. The digital development of enterprises can reduce information asymmetry between enterprises and banks, help heavy polluters solve financing problems, and ease financing constraints; with more funds to carry out green technology innovation. So, the contribution of corporate digital transformation to green technology innovation may vary significantly with company industry.

Following Ma et al. (2021) [46], we select companies with industry codes of B06, B07, B08, B09, B10, B11, B12, C17, C18, C19, C22, C25, C26, C27, C28, C29, C31, C32, and D44 as heavy polluting groups with value takes of 1, with 0 for non-polluting industry contributors. The result in column (1) of Table 7 shows that the coefficient of interaction is significantly positive at the 5% level, indicating that digital transformation is a stronger driver of green technological innovation for companies in heavy pollution industries. By comparing the results in columns (2) and (3), it can be found that the positive effect of digital transformation in heavy polluting industries only exists in green technology-independent innovation.

Enterprise Size

In traditional financial markets, small enterprises are affected by information asymmetry and other factors, facing more financing constraints, and lacking sufficient financial support for enterprise development. Due to a weak risk management foundation, small enterprises are less risk-resistant. Digital transformation allows enterprises to rely on digital technology to effectively identify risks in the green innovation process, strengthening risk management and control capabilities. At the same time, it can also help enterprises identify the optimal innovation path in decision-making, minimizing the probability of failure [47]. Thus, enterprise digital transformation may contribute differently to green technology innovation when considering enterprises of different sizes. From columns (4)-(6) of Table 7, digital transformation has a greater impact on green technology innovation in small-scale firms, which is mainly realized through the promotion of collaborative innovation in small-scale firms.

Ownership

Financing availability is different in enterprises with different ownership. State-owned enterprises benefit from government support and policy, with stronger external financing abilities, and face fewer financing constraints than non-state-owned enterprises. Therefore, enterprises are divided according to ownership, with value tasking 1 for state-owned enterprises and 0 otherwise. The coefficient in column (7) of Table 7 is significantly

Table 7 Results of heterogeneity analysis

	Industry			Size			Ownership		
	GrePat	GrePat-In	GrePat-Un	GrePat	GrePat-In	GrePat-Un	GrePat	GrePat-In	GrePat-Un
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
DigTra	1.536	0.288	1.687	7.720***	4.317**	4.426***	8.294**	4.971*	4.930***
	(0.69)	(0.16)	(1.15)	(2.79)	(2.17)	(2.86)	(2.64)	(1.84)	(3.05)
Interact	14.144**	9.924**	3.943	-7.938*	-4.626	-5.305*	-8.027*	-5.483	-5.668**
	(2.39)	(2.43)	(1.37)	(-1.84)	(-1.05)	(-1.86)	(-1.69)	(-1.02)	(-2.19)
Constant	-0.687***	-0.460**	-0.355**	-0.702***	-0.469**	-0.366**	-0.690***	-0.463**	-0.358**
	(-2.93)	(-2.32)	(-2.27)	(-2.95)	(-2.35)	(-2.32)	(-2.92)	(-2.31)	(-2.27)
Control variable	YES	YES	YES	YES	YES	YES	YES	YES	YES
Firm FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	23718	23718	23718	23718	23718	23718	23718	23718	23718
R^2	0.657	0.616	0.661	0.657	0.616	0.661	0.657	0.616	0.661
adj. R^2	0.613	0.567	0.618	0.613	0.567	0.618	0.613	0.567	0.618

negative, which indicates that the promotion of digital development has a significant propulsive effect on green technological innovation of non-state-owned enterprises. The results in columns (8) and (9) indicate that the impact of digital transformation on non-state-owned firms is more prominent in green technology collaborative innovation.

Conclusions

Using listed companies on the Shanghai and Shenzhen Stock Exchanges from 2008-2021, we explore the impact of enterprise digital transformation on green technological innovation, measured by the number of green invention patent authorizations. First, enterprise digital transformation promotes green technology innovation, holding after a series of endogeneity and robustness tests, including high-dimensional fixed effects, replacing explanatory variables, changing clustered error, winsorizing sample at 1% level, and an instrument variable (IV) approach. Enterprise digital transformation also steps in by alleviating financing constraints and mitigating enterprise risks. Moreover, further analysis shows that enterprise digital transformation promotes both sub-dimensions of green technology innovation, with a more obvious effect on enterprise green independent innovation. Besides, there is a time-lag effect on both green technology innovation and its sub-dimensions, with the promotion effect first enhancing and then weakening. Lastly, the promotion effect of enterprise digital transformation on green technology innovation is more significant among enterprises in heavy pollution industry, and non-state-owned and small-scale enterprises, with different performance in sub-dimension. The main implications of the findings of this paper are as follows:

First, enterprises should actively promote digital transformation and fully release the positive incentive effect on green technology innovation. By improving the efficiency of information transfer within enterprise and making full use of technological innovation resources, enterprises should explore a suitable green innovation path.

Second, the government should fully consider the differences in enterprise characteristics when formulating policies. At the same time, it is also necessary to take advantage of the spillover and sharing characteristics of digital technology, actively promoting cooperation among enterprises, especially in innovation.

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Conflict of Interest

The authors declare no conflict of interest.

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