A study of the impact of digital transformation on corporate green innovation——Based on the Financing Constraints Perspective

Ji-wen Zhang

Shandong University of Finance and Economics, Jinan, Shandong 250014 China

Abstract. Against the backdrop of a booming digital economy and green and low-carbon becoming the main theme of the times, this paper empirically explores how digital transformation affects and enhances the green innovation capability of enterprises based on the data of A-share listed companies in Shanghai and Shenzhen from 2018 to 2022. The possible mediating role of financing constraints in this process is deeply analyzed. The findings show that digital transformation significantly promotes the development of green innovation in enterprises, and this positive effect is more prominent in non-state-owned enterprises and mature enterprises. Further exploration shows that financing constraints play a partial mediating role between digital transformation and green innovation. Combining the findings, this paper makes recommendations at the enterprise and government levels, respectively: first, enterprises should actively participate in digital transformation and strive to enhance green innovation by alleviating financing constraints. Second, the government should continue to optimize the subsidy policy to provide stronger support for enterprises' green innovation, and then promote the sustainable enhancement of green innovation in the whole society.

Keywords: digital transformation; green innovation; financing constraints.

1. Introduction

Since the reform and opening up, China's traditional industrial development has been rapid, in bringing great material wealth, but also caused serious environmental pollution, so the state gradually pay attention to the environmental pollution situation. 2020 put forward the "dual-carbon target", which has become the leader of China's green and low-carbon development; in 2021, the national "14th Five-Year Plan" clearly states that we should vigorously develop green technological innovation and promote the green transformation and upgrading of key industries and important areas. Fourteenth Five-Year Plan" clearly points out that we should vigorously develop green technological innovation, and promote the green transformation and upgrading of key industries and important fields. Green innovation is a key path to solving environmental pollution and realizing sustainable development, and it is one of the links to realize high-quality development. However, green innovation is high-risk and faces serious financing constraints compared with general innovation. The national "14th Five-Year Plan" proposes "accelerating digital development and building a digital China". Driven by the wave of informationization, various industries have carried out digital transformation, expecting to apply information technology such as artificial intelligence, blockchain, and big data to production and operation. Digital transformation has pushed the economy from the pursuit of high speed to the pursuit of high-quality development. Under the background of "new infrastructure" and "dual-carbon", most enterprises hope to promote green technology innovation through digital transformation to meet the new requirements of economic development. However, enterprise digital transformation is characterized by a long cycle, high cost and insufficient resource investment, therefore, exploring whether enterprise digital transformation can promote green technological innovation is an urgent issue to be solved nowadays.

Existing studies on the subject mainly focus on the economic effects of digital transformation. It is found that digital transformation can improve enterprise capital market performance (Wu Fei, 2021), enterprise economic growth (Shen Kunrong and Qiao Gang, 2022), enterprise labor productivity (Tang Xuan et al., 2022), enterprise innovation performance (Zhang Jichang and Long Jing, 2022) and other aspects. With regard to corporate innovation, previous literature has mainly

studied the impact of digital transformation on corporate innovation performance, with less reference to the content of "greening". Existing research on the drivers of corporate green innovation mainly focuses on external factors such as market pressure (Rui Xue, 2022) and environmental systems (Sun Mingwei et al., 2023), and internal factors such as the characteristics of corporate executives (Wo Lifen et al., 2024), and corporate environmental awareness (Dai Wanliang and Lu Wenling, 2020), ignoring the possible impacts of corporate digital transformation. In addition, it is still controversial among some scholars as to whether digital transformation can promote green innovation (Wang Xu et al., 2022). Therefore, in the context of the era of digital economy and green low-carbon development, enterprise green innovation has a new development direction driven by digital transformation, and this paper enriches the related research on green innovation driving and financing, so that the existing theory of the environmental effects of digital transformation can be further enriched and expanded.

This paper has the following innovations: first, starting from the micro level, it links the digital transformation of enterprises with green innovation, enriches the related research on the driving factors of green innovation of enterprises, and further enriches and expands the existing theory of the environmental effect of digital transformation. Second, from the perspective of financing constraints, we study its mediating effect in the process of digital transformation affecting green innovation, providing theoretical support for the study of the impact mechanism of digital transformation on green innovation. Third, the heterogeneous characteristics of the impact of digital transformation on green innovation in different contexts are explored in terms of the nature of enterprise property rights and enterprise life cycle, which enriches the relevant literature.

2. Theoretical analysis and research hypothesis

2.1 The direct impact of digital transformation on green innovation in business

Digital transformation means that in order to achieve the goal of improving quality and efficiency, enterprises accelerate the digitization of their production materials and processes through the use of digital resources such as digital technology, digital techniques and hardware systems. (Wu Fei et al., 2021) Green innovation is committed to the implementation of innovations in green products, processes and technologies, in order to achieve the purpose of improving the efficiency of enterprise resource allocation and reducing the environmental impact of the entire value chain process (Demirel P and Kesidou E, 2011). At the same time, enterprise green innovation can be divided into "green" and "innovation" levels (Fang Xianming and Na Jinling, 2020), so the shaping of enterprise green innovation capability should have both environmental protection and innovation attributes. Nowadays, digital economy and green innovation are both necessary to promote high-quality development, and this paper analyzes the impact of digital transformation on enterprise green innovation as follows:

First, digital transformation can improve the efficiency of resource allocation (Fang, Wenlong et al., 2023), thus energizing the green innovation of enterprises. First, human capital. Digital transformation can break through the limitations of time and space, enabling enterprises to more widely identify and attract potential professional and innovative talents from all over the world, improving the efficiency and accuracy of recruitment and the flexible allocation of labor resources (Cong Yi et al., 2020). At the same time, digital transformation promotes the intelligent upgrading of employee technical training, promotes the accumulation of human capital, and provides strong talent support for green innovation projects (Xiao Jinghua, 2020). Secondly, in terms of innovation resource allocation, the green innovation process requires efficient integration of knowledge, technology, innovation resources, internal and external funds in multiple fields, while digital transformation can promote the integration of R&D resources and knowledge, help enterprises understand and master the latest development trend and mainstream technology of green innovation, and ultimately stimulate enterprises to continuously carry out green technological innovation to realize the efficient matching of innovation factors and improve green innovation efficiency of green innovation.

Secondly, digital transformation can improve the level of information sharing, so as to improve the green innovation of enterprises (Zhu Deyong et al., 2022). Digital transformation can strengthen the enterprise internal and external information sharing. For internal information sharing, the main thing is that digital transformation enables enterprises to build a unified information technology platform to achieve information sharing between departments, and this information sharing helps enterprises break departmental barriers (BRIEL F V et al., 2018). For external information sharing, the main point is that enterprises can analyze and process the data of upstream and downstream companies related to them at any time on the cloud platform, accurately predict market demand and trends, avoid blind investment, and reduce innovation costs. It also promotes the establishment of closer cooperation with other enterprises, research institutions, etc., which ultimately broadens the innovation channels and accelerates the innovation process. Based on the above analysis this paper proposes the following hypotheses:

H1 Digital transformation has a significant positive impact on corporate green innovation.

2.2 Mediating role of financial constraints

Enterprises' green technology innovation activities are characterized by high capital investment, high technological risk, secrecy and uncertainty. Higher financing constraints will increase the cost of financing for enterprises, at which time enterprises often choose to actively limit their investment in green innovation activities, making green innovation squeezed out (Yang Guozhong and Xi Yuting, 2019). The digital economy can help enterprises solve the problem of financing constraints in several ways. First, when the digital development level of enterprises reaches a new height, their ability and willingness to disclose information are significantly improved, which in turn enhances the transparency of information and effectively alleviates the plague of information asymmetry (Li Sanshi et al., 2021), and ultimately promotes the broadening of financing channels and the reduction of financing costs. Second, through the effective use of digital technology, enterprises are able to reduce financial risks and more accurately match resources with the risk characteristics of innovative projects in order to achieve the optimal allocation of resources (Wang Xiaoyan et al., 2019). Thirdly, enterprises carrying out digital transformation are actually conveying a positive and aggressive posture to the outside world, which can significantly enhance the positive evaluation of the enterprise by stakeholders, thus attracting more investors to be interested in the enterprise and put money into the enterprise, realizing the steady growth of external investment, and effectively alleviating the financing constraints of the enterprise. The digital transformation of enterprises is a reflection of positive response to the national development strategy and the policy orientation of government departments, and this initiative sends a signal to the government that the enterprise is actively acting, which helps to enhance the government's goodwill and trust in the enterprise, and then prompts the enterprise to obtain more resources from the government to invest and policy support. (Hua Junguo et al., 2022). In general and enterprise digital transformation can reduce financing constraints by alleviating information asymmetry and financial risk problems, playing the role of signaling, and then stimulate enterprise green innovation. Based on the above analysis this paper proposes the following hypotheses:

H2 Financing constraints have a mediating effect in the process of digital transformation affecting firms' green innovation.

3. Study design

3.1 Sample Selection and Data Sources

This paper selects the data of all Shanghai and Shenzhen A-share listed companies from 2018 to 2022 as the research sample. On this basis, in order to ensure the completeness of the sample data and the reliability of the research conclusions, this paper screened the sample enterprises as follows: ① excluding ST and ST* enterprises; ② excluding enterprises with missing key data; ③

excluding financial enterprises; ④ in order to avoid the errors caused by the extreme values on the research results, this paper carried out the Winsorize shrinkage of the upper and lower 1% on all continuous variables. After the above screening and processing, the total number of valid sample data is 17667. Among them, green patent application data comes from China Research Data Service Platform (CNRDS), digital transformation data comes from annual reports of listed companies, and the rest of the data comes from Cathay Pacific Database (CSMAR). This paper uses Stata 17.0 statistical software for data statistics and analysis.

3.2 Definition of variables

3.2.1 Explained variables

Corporate Green Innovation (GPat). There are two main ways for academics to measure corporate green technology innovation: (1) R&D input aspect. (2) R&D output aspect: the number of green patent applications or authorizations. The R&D input indicator has a certain disadvantage because the R&D input cannot be broken down into green technology categories. Green innovation is a reflection of the utilization rate of resources and inputs, and only the number of green patent applications can reflect the original innovation activities of enterprises in green development. Therefore, considering the accuracy of data response, this paper chooses the number of green patent applications of enterprises to measure the green innovation of enterprises. And make considerations as follows: first, green patent authorization often needs to go through a long cycle with high uncertainty, so the number of patent applications can better reflect the innovation achievements of enterprises in the current period (Zhou Jingmiao et al., 2018). Second, considering that the number of green patent applications has the characteristic of "right skewness", this paper takes the logarithm of the total number of green patent applications after adding one to the total number of green patent applications in data processing, and the larger the indicator is, the stronger the green innovation ability of the enterprise is.

In the later study, this paper will also replace the explanatory variables with the number of green invention patent applications (GreInvia) and the number of green utility model patent applications (GreUmia) of enterprises for robustness testing, and each data indicator is processed by adding one to take the logarithm.

3.2.2 Explanatory variables

Digital Transformation (DT). In this paper, following Wu Fei et al. (2021), the total number of word frequencies related to "enterprise digital transformation" in the annual reports of listed companies is used as an indicator to measure the degree of enterprise digital transformation, specifically, from the five categories of "artificial intelligence technology", "big data technology", "cloud computing technology", "blockchain technology", and "digital technology application", Specifically, the five dimensions of "artificial intelligence technology", "big data technology", "cloud computing technology", "blockchain technology" and "application of digital technology" are identified. The digital transformation lexicon was identified in five dimensions: "big data technology", "cloud computing technology", "blockchain technology" and "use of digital technology", and the frequency of 76 digitization-related words was counted. Finally, the total number of occurrences of the above words in the annual report is added to the logarithm to indicate the degree of digital transformation of enterprises.

3.2.3 Intermediate variables

Financing constraints (SA). Regarding the measurement of corporate financing constraints, existing studies have mainly constructed relevant indices by synthesizing various indicators of enterprises, and comprehensive indices can comprehensively reflect the degree of corporate financing constraints, such as WW index, KZ index, SA index and FC index, etc. The WW index and KZ index have endogeneity problems to a certain extent, so this paper chooses the SA index, which is more exogenous, to measure the degree of corporate financing constraints, and the larger the index, the

smaller the enterprise faces (Kang et al., 2022). The larger the index, the smaller the financing constraints faced by enterprises (Kang Weiguo et al., 2022).

3.2.4 Control variables

Considering that there are more factors affecting this study, so in order to control the influence of other variables, this paper refers to the practice of previous scholars' empirical research on green technology innovation, and selects enterprise size (Size), return on net assets (Roe), gearing ratio (Lev), equity concentration (Top1), board of directors' size (Bsize), innovation investment strength (RD), and enterprise age (Age) as control variables. Also, year (Year) and industry (Indcode) are used as dummy variables.

Each variable is defined, as shown in Table 1:

Table 1 Variable Definition Table

variant	variable name	variable symbol	Variable Definition
explanatory variable	Green Patent Applications by Enterprises	GPat	ln (green patent applications +1)
	Number of patent applications for green inventions by enterprises	GreInvia	ln (patent applications for green inventions +1)
	Green Utility Model Patent Applications by Enterprises	GreUmia	ln (green utility patent applications +1)
explanatory variable	Digital Transformation	DT	ln (total frequency of digital transformation feature words + 1)
intermediate variable	Financing constraints	SA	SA index
control variable	Enterprise size	Size	ln (total business assets)
	return on net assets	Roe	Net profit/net assets
	gearing	Lev	Total liabilities/total assets
	shareholding concentration	Top1	Shareholding ratio of the largest shareholder
	Board size	Bsize	ln (number of board members)
	Innovation investment efforts	RD	Net profit/shareholders' equity balance
	Age of business	Age	Number of years of business establishment
	sector	Year	virtual variable
	vintages	Indcode	virtual variable

3.3 Modeling

3.3.1 Benchmark estimation model

In order to verify the role of digital transformation on the influence of green innovation of enterprises, this paper constructs a model based on hypothesis 1, the specific formula is shown in equation (1).

$$\text{Pat}_{i,t} = \alpha_0 + \alpha_1 \text{DT}_{i,t} + \alpha_j \text{Controls}_{j,i,t} + \sum \text{Year} + \sum \text{Indcode} + \varepsilon_{i,t} \quad (1)$$

where.$\text{Pat}_{i,t}$ is the explanatory variable, i.e. the degree of green innovation of firm i in year t;$\text{DT}_{i,t}$ is the explanatory variable, denoting digital transformation;$\text{Controls}_{j,i,t}$ is a set of control variables listed above that affect green innovation;$\varepsilon_{i,t}$ is the random error term. Industry fixed effects Incode and time fixed effects Year are also introduced. if the regression coefficients in model (1) are α_1 is significantly positive, it indicates that digital transformation plays a positive role in promoting green innovation of enterprises.

3.3.2 Mediated effects model

In order to verify the mediating effect of financing constraints in the impact of enterprise digital transformation on enterprise green innovation, this paper constructs model(2) and model(3) according to hypothesis 2, and the specific formulas are shown below.

$$SA_{i,t} = \beta_0 + \beta_1 DT_{i,t} + \beta_j Controls_{j,i,t} + \sum Year + \sum Indcode + \varepsilon_{i,t} \quad (2)$$

$$Pat_{i,t} = \theta_0 + \theta_1 DT_{i,t} + \theta_2 SA_{i,t} + \theta_j Controls_{j,i,t} + \sum Year + \sum Indcode + \varepsilon_{i,t} \quad (3)$$

where$SA_{i,t}$ is the measured variable of financing constraints. Models (1) (2) (3) form a complete mediation effect model, if model (1) in the α_1 , in model (2) β_1 in model (2), and in model (3) θ_2 are significant, and $\beta_1 * \theta_2$ in model (3), then the mediation effect is significant. θ_1 have the same sign, then it means that the mediation effect is significant, i.e., digital transformation will affect corporate green innovation by affecting financing constraints, and the degree of its effect is $\beta_1 * \theta_2$, also called the indirect effect of digital transformation affecting green innovation. In addition, the direct effect is θ_1, and the total effect is α_1.

4. Empirical analysis

The empirical results of this paper include the following five parts: first, the baseline regression results, which yield the regression results of the impact of digital transformation on corporate green innovation as a whole; second, the mediation effect test, which tests the financing constraints pathway proposed in this paper to promote corporate green innovation; third, the robustness test, which uses the method of replacing the explanatory variables to test the robustness of the regression results of the main variables; fourth, the endogeneity test that The endogeneity problem is mitigated by lagged data and PSM method; and fifth, the heterogeneity test of the sample, which examines the heterogeneity at the firm ownership level and the firm cycle level of the impact of digital transformation on firms' green innovation.

4.1 Descriptive statistical analysis

According to the results in Table 2, the mean value of the explanatory variable of this paper - green innovation of enterprises (GPat) is 0.406, the standard deviation is 0.805, the maximum value is 3.714, and the minimum value is 0, which shows that there is a great difference in the ability and degree of green innovation among different enterprises, and also shows that the green innovation output of enterprises is generally is relatively small, and green innovation is still in the primary stage. The reason may be that the operation and R&D are different between different industries, which leads to different degrees of emphasis on green development, so the paper fixes the industry gap. The explanatory variable in this paper, the digital transformation (DT) indicator, has a variation range of 0 to 5.352, with a mean of 1.876 and a standard deviation of 1.438, which is a large degree of dispersion, and the results also indicate that most enterprises have begun to carry out digital transformation, but there are differences in the digitization intensity between enterprises, and the overall digitization level of the enterprises is also not high. The mean value of the mediating variable, financing constraints (SA), is -3.891, the maximum value is -3.297, the minimum value is -4.498, and the standard deviation is only 0.240, which indicates that most of the enterprises suffer from the problem of financing constraints. The results also show that there are large differences in the values of each statistic for the same statistic for each control variable, indicating that different firms face different situations and prospects.

Table 2 Descriptive Statistics for the Overall Sample

variant	sample size	average value	(statistics) standard deviation	minimum value	p50	maximum values
GPatw	17667	0.406	0.805	0	0	3.714
DTw	17667	1.876	1.438	0	1.792	5.352
SAw	17667	-3.891	0.240	-4.498	-3.890	-3.297

Sizew	17667	22.240	1.245	20.070	22.030	26.090
Roew	17667	0.048	0.167	-0.985	0.071	0.346
Levw	17667	0.401	0.196	0.057	0.393	0.895
Top1w	17667	32.640	14.350	8.376	30.250	71.990
Bsizew	17666	2.093	0.193	1.609	2.197	2.565
RDw	17667	5.612	5.651	0.032	4.100	32.620
Age	17667	20.020	5.827	3	20	64

4.2 Benchmark regression

In order to verify that digital transformation has a positive promotion effect on green innovation as proposed in hypothesis 1, this paper controls the time effect and industry effect can make the regression results more reliable. The regression results made based on equation (1) are shown in Table 3.

Table 3 Benchmark regression results for the impact of digital transformation on firms' green innovation

	(1)	(2)
	GPat	GPat
DT	0.086***	0.056***
	(16.49)	(10.77)
Size		0.125***
		(21.04)
Roe		0.316***
		(8.67)
Lev		0.311***
		(8.36)
Top1		0.001***
		(2.60)
Bsize		0.093***
		(3.07)
RD		0.013***
		(9.96)
Age		-0.006***
		(-6.21)
Year	Yes	Yes
Indcode	Yes	Yes
_cons	-0.021	-3.012***
	(-0.23)	(-19.90)
N	17667	17666
R^2	0.132	0.181
adj. R^2	0.128	0.177

The superscripts ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; t-values are in parentheses. The following tables are identical

Column (1) in Table 3 only adds core explanatory variables and two dummy variables, and the adjusted R2 is 0.128, and column (2) adds control variables on this basis, and the adjusted R2 is 0.177, which indicates that the addition of control variables strengthens the model's explanation of green innovation. At the same time, the coefficient of digital transformation is 0.086 and 0.056 respectively, both significant at both 1% level, indicating that the greater the digital transformation is the more favorable to the green innovation of the enterprise, and the two are positively correlated, and Hypothesis 1 can be verified. Among the control variables, the coefficient of enterprise age is -0.006 negative and significant, which may be due to the fact that as the age increases, along with the

accumulation of technology and knowledge precipitation, the enterprise forms a more fixed mode of operation and production, which will lead to the enterprise's lack of acceptance and investment in innovation.

4.3 Analysis of mediating effects

In order to verify that the financing constraints proposed in Hypothesis 2 play a mediating role in the process of digital transformation for green innovation, this paper conducts regressions according to model (2) (3) sequentially, and the results are shown in Table 4.

Table 4 Intermediation Effects (Financing Constraints)

	(1) SA	(2) GPat
DT	0.002**	0.055***
	(2.35)	(10.65)
SA		0.438***
		(7.37)
Size	0.022***	0.115***
	(29.98)	(18.93)
Roe	-0.007	0.319***
	(-1.48)	(8.76)
Lev	-0.030***	0.324***
	(-6.44)	(8.72)
Top1	0.001***	0.001**
	(11.42)	(1.96)
Bsize	-0.012***	0.098***
	(-3.01)	(3.24)
RD	0.000	0.013***
	(1.37)	(9.89)
Age	-0.038***	0.011***
	(-299.68)	(4.22)
Year	Yes	Yes
Indcode	Yes	Yes
_cons	-3.627***	-1.423***
	(-189.13)	(-5.40)
N	17666	17666
R^2	0.852	0.183
adj. R^2	0.852	0.179

This paper analyzes the mediating effect of financing constraints in the impact of digital transformation on corporate green innovation according to the mediating effect test process (Zhonglin Wen and Baojuan Ye, 2014) and with the regression results in Table 4: The regression coefficient of digital transformation in column (1) is 0.002, which is positively significant at the 1% level, suggesting that the digital development can alleviate the financing constraints of enterprises. The coefficient of financing constraints in column (2) is 0.438 and the coefficient of digital transformation is 0.055, both positively significant at 1% level, and 0.438*0.002 has the same sign as 0.438. It shows that financing constraints do play a mediating utility between digital transformation and corporate green innovation, and Hypothesis 2 is verified.

4.4 Robustness Tests

To ensure the robustness of the model, this paper distinguishes between types of green innovation patents, with green invention patents having higher requirements for innovativeness, while green utility model patents emphasize practical use value. Song Deyong et al. (2022) pointed out that the degree of innovation embedded in the two types of green patents makes the depth of impact of digital

transformation on different types of patents may be different. Therefore, this paper refers to Yang Lihong and Jia Ruyun et al. (2024), replacing the total number of green patent applications (GreInvia) and the number of green utility model patent applications (GreUmia) as the explanatory variables, respectively, and re-utilizing model (1) for regression.

Table 5 Robustness Tests (Replacement Variables)

	(1) GreInvia	(2) GreUmia
DT	0.051***	0.015***
	(12.25)	(3.97)
Size	0.108***	0.068***
	(22.48)	(16.09)
Roe	0.243***	0.153***
	(8.22)	(5.89)
Lev	0.216***	0.186***
	(7.16)	(7.03)
Top1	0.001*	0.001**
	(1.95)	(2.16)
Bsize	0.053**	0.068***
	(2.17)	(3.15)
RD	0.012***	0.004***
	(11.69)	(4.65)
Age	-0.004***	-0.006***
	(-4.49)	(-7.95)
Year	Yes	Yes
Indcode	Yes	Yes
_cons	-2.549***	-1.647***
	(-20.78)	(-15.30)
N	17666	17666
R^2	0.164	0.150
adj. R^2	0.160	0.146

In Table 5, the regression coefficients of digital transformation in Columns (1) (2) are 0.051 and 0.015 respectively, which are both significant at 1% level, and the adjusted R2 are 0.160 and 0.146 respectively. this indicates that digital transformation has a facilitating effect on the enhancement of the level of green invention patents and utility model patents respectively, and the model (1) passes the robustness test. The results also show that the improvement of digital transformation on the total level of green innovation patents is accomplished by promoting green invention patents. The reason may be that the technical depth and complexity of green invention patents are higher, and digitalization can provide more information support, which makes the promotion effect greater.

4.5 Endogeneity test

4.5.1 Lagged variable approach

Some scholars have pointed out that enterprises with high levels of green innovation may accelerate digitalization. In order to avoid the endogeneity problem arising from reverse causation, this paper adopts the lagged variable method to solve the problem, based on which the data of the explanatory variables lagged by two periods are chosen to be brought into the model (1) for regression to alleviate the problem of enterprises' green innovation forcing digital transformation. The specific results are shown in Tables 6.

Table 6 Endogeneity Tests (Lagged Explanatory Variables)

	(1) one period behind GPat	(2) Phase II lag GPat

L. DT	0.057***	
	(9.41)	
L2.DT		0.053***
		(7.40)
Size	0.127***	0.135***
	(18.20)	(16.38)
Roe	0.330***	0.331***
	(7.74)	(6.46)
Lev	0.294***	0.309***
	(6.71)	(5.91)
Top1	0.001**	0.001
	(2.21)	(1.18)
Bsize	0.081**	0.065
	(2.25)	(1.53)
RD	0.013***	0.012***
	(8.67)	(6.99)
Age	-0.007***	-0.008***
	(-5.88)	(-5.21)
Year	Yes	Yes
Indcode	Yes	Yes
_cons	-2.993***	-3.068***
	(-16.91)	(-14.60)
N	13037	9066
R^2	0.183	0.187
adj. R^2	0.177	0.179

In Tables 6, column (1) is a lagged one-period regression and column (2) is a lagged two-period regression, and the digital transformation coefficients are both significant at the 1% level, 0.057 and 0.053, respectively, which are not much different, indicating that the lagged data alleviate the endogeneity problem of digital transformation and corporate green innovation.

4.5.2 Propensity score matching (PSM)

Table 7 Endogeneity Test (PSM Balance Test)

variant	brochure	Treatment group mean	Control group mean	%bias	|bias|	t-value	p>|t|	V(C)
Size	U	22.326	22.062	21.7		3.91	0.000	1.40*
	M	22.326	22.251	6.2	71.7	-9.35	0.000	1.25*
Roe	U	.053	.058	-3.5		-10.06	0.000	1.14*
	M	.053	.048	3.1	12.2	-14.21	0.000	0.85*
Lev	U	.415	.384	15.8		-0.31	0.755	1.01
	M	.415	.406	4.9	69.4	-13.02	0.000	0.95
Top1	U	33.459	33.556	-0.7		-15.56	0.000	1.05
	M	33.459	33.46	-0.0	99.5	-30.37	0.000	1.02
Bsize	U	2.101	2.095	3.4		-5.72	0.000	1.09*
	M	2.101	2.096	2.4	29.3	-10.65	0.000	1.07*
RD	U	4.699	4.500	4.5		41.50	0.000	1.22*
	M	4.699	4.982	-6.3	-41.5	62.58	0.000	0.91*
Age	U	20.223	20.266	-0.8		-7.52	0.000	1.09*
	M	20.223	20.118	1.9	-138.7	-11.38	0.000	1.10*

* if variance ratio outside [0.94; 1.06] for U and [0.94; 1.06] for M

Existing studies have found that regional characteristics, industry characteristics, property rights characteristics, and the degree of marketization of enterprises all affect the effect of digital transformation to promote green innovation, in order to test the possible endogeneity problem due to sample selection, so this paper adopts a 1:1 nearest neighbor matching method, first calculates the median green innovation (GPat), and then divides the entire sample into a high GPat group and a low GPat group in accordance with the median The remaining variables are used as covariates for estimating the propensity score. The matching results are shown in Tables 7, most of the covariates have a relatively large reduction in standard deviation , and the overall matching effect is better and passes the balance test.

4.6 Heterogeneity test

4.6.1 Nature of property rights

To further explore the effect of digital transformation on corporate green innovation in enterprises with different ownership, this study refines the sample data into two categories: state-owned enterprises and non-state-owned enterprises, and performs regressions in order.

Table 8 Heterogeneity test (distinguishing nature of property rights)

	(1)	(2)
	nationalized business	non-state enterprise
	GPat	GPat
DT	0.045***	0.057***
	(3.90)	(10.04)
Size	0.163***	0.111***
	(13.47)	(15.68)
Roe	0.178**	0.379***
	(2.32)	(9.31)
Lev	0.138*	0.347***
	(1.75)	(8.24)
Top1	0.000	0.001*
	(0.55)	(1.83)
Bsize	0.162**	0.031
	(2.36)	(0.92)
RD	0.017***	0.012***
	(4.50)	(9.35)
Age	-0.005**	-0.008***
	(-2.18)	(-7.17)
Year	Yes	Yes
Indcode	Yes	Yes
_cons	-4.020***	-2.429***
	(-13.76)	(-12.20)
N	4794	12872
R^2	0.232	0.185
adj. R^2	0.219	0.180

Note: Component coefficients passed the Chow test P-Value = 0.000

Column (1) represents the regression of state-owned enterprises, and column (2) represents the regression of non-state-owned enterprises. From the regression coefficients of digital transformation, it can be seen that the digital transformation of non-state-owned enterprises has a greater effect on the enhancement of green innovation than that of state-owned enterprises, and this difference passes the Chow test of coefficient difference at the 1% significance level. The reasons for this may be: first, non-state-owned enterprises usually have higher flexibility and can quickly respond to market changes and technology trends. In the process of digital transformation, NSOEs are able to adjust their business model and strategic direction faster to adapt to the needs of green innovation. Second,

non-state-owned enterprises are under high market pressure, and they will attract and retain talent by offering higher incentives for innovation, so digital transformation and green innovation have become one of the key means for enterprises to improve their competitiveness. Fourth, the financing environment. Non-state-owned enterprises face greater financing constraints than state-owned enterprises, and digital transformation can improve the financial environment so as to vigorously solve the financing problem of innovation for non-state-owned enterprises.

4.6.2 Life cycle

Enterprises in different life cycle stages have different innovation characteristics, investment strategies and financing situations, so the progress of R&D innovation needs to consider the life cycle of enterprises (Liu Shiyuan et al., 2020). In this paper, we adopt the cash flow modeling method, using three kinds of cash flows of enterprise operation, investment, and financing to represent the operation, profitability, and financing characteristics, and divide the sample into three types of life cycle stages, namely, growth, maturity, and decline, and regress them sequentially according to the model (1), as shown in Table 9.

Table 9 Heterogeneity Test (Life Cycle)

	(1)	(2)	(3)
	formative years	maturity	recession (in economics)
	GPat	GPat	GPat
DT	0.055***	0.061***	0.053***
	(6.74)	(7.00)	(4.95)
Size	0.114***	0.134***	0.124***
	(11.97)	(14.04)	(9.42)
Roe	0.275***	0.321***	0.349***
	(4.11)	(5.07)	(5.69)
Lev	0.440***	0.224***	0.308***
	(7.07)	(3.61)	(4.20)
Top1	-0.000	0.001	0.004***
	(-0.44)	(1.37)	(4.34)
Bsize	0.076	0.070	0.174***
	(1.57)	(1.42)	(2.66)
RD	0.014***	0.012***	0.012***
	(7.17)	(5.03)	(5.13)
Age	-0.005***	-0.006***	-0.012***
	(-3.21)	(-3.68)	(-5.24)
Year	Yes	Yes	Yes
Indcode	Yes	Yes	Yes
_cons	-2.823***	-3.130***	-3.138***
	(-11.03)	(-12.47)	(-10.18)
N	7490	6488	3688
R^2	0.182	0.204	0.185
adj. R^2	0.172	0.193	0.166

Note: Component coefficients passed Chow test P-Value = 0.006

Columns (1)-(3) of Table 9 represent the regressions of the three life cycle stages of enterprises, which passed the Chow test for the difference of component coefficients at 1% significance level, while the positive moderating effect of digital transformation on green innovation passed the test at 1% significance level. However, the influence of digital transformation shows the characteristic of "maturity > growth > decline", which indicates that the effect of promoting green innovation through digital transformation is most obvious in the maturity period. This may be due to the following reasons: First, in the maturity period, enterprises have already established stable market positions and

sources of funding, and they begin to pay attention to the overall strategy and sustainable development strategy, and prefer green innovation projects with high uncertainty and long payback cycles, while digitalization can effectively help enterprises to put data elements into production, and improve green supply chain management and green innovation. Second, the growth period, enterprises are mainly concerned about the development of the market and product promotion, and do not pay enough attention to green development, and digital transformation mainly improves the production efficiency of enterprises. Third, the recession period, enterprises enter the conservative operation, digital transformation application more performance in enterprise transformation and upgrading.

5. Conclusions and recommendations

Taking 2018-2022 Shanghai and Shenzhen A-share listed companies as research samples, this paper theoretically analyzes and empirically tests the impact of digital transformation on corporate green innovation and the impact mechanism, and draws the following conclusions: first, through the two-way fixed effect test, digital transformation has a significant positive impact on corporate green innovation. The conclusion still holds after robustness and endogeneity tests. Meanwhile, under the differentiation of green innovation types, it is found that digital transformation has a stronger role in promoting green invention patents. Second, digital transformation can promote corporate green innovation, which is mainly accomplished through the way of alleviating corporate financing constraints. Third, the results of heterogeneity analysis show that under property rights heterogeneity, the effect of digital transformation to enhance green innovation is more obvious in non-state-owned enterprises. Under life cycle differences, digital transformation significantly promotes green innovation in mature enterprises, and the role of promoting green innovation in growing and declining enterprises is less obvious in comparison.

Based on the study, the following recommendations are made: first, enterprises should actively promote digital transformation, especially non-state-owned enterprises and mature enterprises should make full use of advanced information technology and data analysis tools, improve the level of information disclosure, and enhance the operational efficiency and innovation ability of enterprises, so as to provide digital guarantee for the enhancement of green innovation. Secondly, enterprises should raise their awareness of environmental protection and take green innovation as an important strategy for enterprise development under the background of "dual-carbon". Through green innovation, enterprises can not only improve their competitiveness, but also contribute to the sustainable development of society. Third, financial institutions should also strengthen their support for enterprises in digital transformation by providing low-threshold and low-cost financing services, thereby providing more financing opportunities for enterprises. Fourth, the government should increase its support for digital transformation, improve its subsidy policy, and use the policy to attract more enterprises to realize digital transformation. At the same time, when formulating digital development strategies and related policies, factors such as the nature of enterprise property rights and life cycle characteristics should be taken into account, so as to improve the effectiveness and precision of the incentive role of digital transformation innovation.

References

[1] Wu, F., Hu, H. Z., Lin, H. Y., et al: "Corporate digital transformation and capital market performance: empirical evidence from stock liquidity," Management World, Vol. 7, No. 7, 2021.

[2] Shen Kunrong, Qiao Gang. Research on the mechanism of digital economy promoting economic growth[J]. East China Economic Management, 2022, 36(10):1-8.

[3] Tang Xuan, Gao Xing, Lai Xiaobing. Research on the impact of digital transformation on enterprise labor productivity[J]. Economy Vertical, 2022(9):104-112.

[4] ZHANG Jichang, LONG Jing. Digital Transformation, Dynamic Capabilities and Firm Innovation Performance - Empirical Evidence from High-Tech Listed Firms[J]. Economy and Management, 2022, 36 (03): 74-83.

[5] Rui Xue. An overview of the influencing factors of green technology innovation in manufacturing enterprises[J]. Business Economy, 2022(04):121-123.

[6] SUN Mingwei,XU Xiumei,JING Ruolan. Environmental regulation, social responsibility disclosure and corporate green innovation[J]. Qilu Jutan, 2023,(05):6-11.

[7] He Lifen,Shi Yahui,Wang Qiaoyi.ESG responsibility fulfillment,executive compensation incentives and corporate green innovation sustainability[J]. Friends of Accounting,2024,(03):58-65.

[8] Dai Wanliang, Lu Wenling. Impact of environmental public opinion pressure on green innovation capability of manufacturing enterprises - Chain mediation effect of leadership environmental awareness and organizational green learning[J]. Science and Technology Progress and Countermeasures, 2020, 37(09):131-137.

[9] WANG Xu, ZHANG Xiaoning, NIU Yuewei. "Data-driven" and "capability curse": the strategic paradox of enterprise digital transformation under the orientation of green innovation strategy upgrading[J]. Research and Development Management,2022,34(04):51-65.

[10] Demirel P, Kesidou E. Stimulating different types of eco-innovation in the UK: government

[11] policies and firm motivations[J]. Ecological Economics, 2011, 70(8): 1546-1557.

[12] Fang Xianming, Na Jinling. Study on Green Innovation Premium of GEM Listed Companies[J]. Economic Research, 2020, 55 (10): 106-123.

[13] FANG Wen-Long,NIE Wan-Ni,Lai Dan. Enterprise digital transformation, resource allocation and green innovation capability[J]. Finance and Accounting Monthly,2023,44(13):139-145.

[14] Cong Yi,Yu Boyang. The impact of digital economy on the allocation efficiency of labor resources in China[J]. Finance and Economics Theory and Practice,2020,41(02):108-114.

[15] Xiao Jinghua. Enterprise cross-system digital transformation and management adaptive change[J]. Reform,2020,(04):37-49.

[16] Song, D. Y., Zhu, W. B., Ding, H.. Can corporate digitalization promote green technology innovation? -- An Examination Based on Listed Companies in Heavily Polluting Industries[J]. Financial Research, 2022, 48 (04): 34-48.

[17] BRIEL F V, DAVIDSSON P, RECKER J. Digital technologies as external enablers of new venture creation in the IT hardware sector [J]. Entrepreneurship Theory and Practice, 2018, 42(1): 47-69.

[18] YANG Guozhong,XI Yuting. Empirical research on the financing constraints of enterprises' green technology innovation activities[J]. Industrial Technology Economy,2019,38(11):70-76.

[19] Li San-Xi, Wang Tai-Ming, and Wu I hope I can help you. Information friction in the digital economy: an analysis from the perspective of information economics[J]. Journal of Beijing Jiaotong University (Social Science Edition),2021,20(04):12-22.

[20] WANG Xiaoyan,ZHANG Junying,WANG Shengnan. Fintech, Firm Life Cycle and Technological Innovation - Heterogeneous Characteristics, Mechanism Tests and Government Regulatory Performance Assessment[J]. Research in Financial Economics,2019,34(05):93-108.

[21] Hua Junguo, Liu Chang, Zhu Di. Digital Transformation, Financing Constraints and Corporate Total Factor Productivity[J]. Southern Finance, 2022(7):54-65.

[22] ZHOU Jingmiao, ZHAO Yuzhe, WU Chunyou, et al. Research on guided technological innovation choice under green growth[J]. Journal of Management Science, 2018, 21(10):61-73.

[23] KANG Weiguo,LI Zijun. Digital financial inclusion and technological innovation--a new perspective from the life cycle of enterprises[J]. Macroeconomic Research,2022,(12):21-42.

[24] WEN Zhonglin, YE Baojuan. Mediation effects analysis: methodology and model development[J]. Advances in Psychological Science, 2014, 22(5):731-745.

[25] LIU Shiyuan,LIN Zhifan,Leng Zhipeng. Do tax incentives improve the level of corporate innovation? -- A test based on firm life cycle theory[J]. Economic Research,2020,55(06):105-121.