

Transformation in Growth: The Moderating Effect of Sustainable Growth Rates on Digital-Driven Green Innovation

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Abstract. In today's society characterized by the rapid expansion of the digital economy, enterprises are under pressure to use digital innovation for green development, which is mainly reflected in China's current "dual carbon" challenges. Using a sample of 1678 firm-year observations of China's A-share listed companies between 2007-2023, this paper explores the impact mechanism of digital transformation on green innovation, and the moderating role of corporate sustainable growth. The empirical results found strong evidence that digital transformation has a direct and significantly positive impact on green innovation. The sustainable growth rate interacts positively with digital transformation, leading to larger improvements in green innovation performance. To accurately measure the digital transformation of firms in this paper, both the proportion of digital-related intangible assets and entropy-method composite index are used. Several robustness tests support the reliability of our main findings. The analysis of heterogeneity shows that larger firms and publicly-owned enterprises play more significant roles than others. This paper contributes to the understanding of how enterprises achieve low-carbon transitions by clarifying the mechanistic linkage of digital transformation and green innovation, thus providing a micro-level foundation for relevant policy support.

Keywords: Digital transformation, green innovation, enterprise sustainable growth rate, entropy method

1. Introduction

The path to transformation for "digital efficiency enhancement and green quality improvement" of the enterprise was clearly defined in the strategic deployment of the 20th National Congress of the Communist Party of China. In the global trend of digital economy, digitalization gives enterprises transformation and development a new mind-set. Digital transformation of the organization is broadly defined as the use of a structured approach via the selective application of modern technologies, including but not limited to big data, artificial intelligence and cloud computing, to fundamentally rewire the business core architecture of a business, notification and jobs to be done, entity and operational procedures, management framework and what have you. Such deep penetration of digitalization into the daily production and operation process will manifest itself by

enhancing the effectiveness of enterprises in the short term and subsequently resulting in a uplift in the long-term competitiveness and effectiveness of management model [1], reduce financial risks [2], boost the resilience of development [3], and promote an affluence of high quality development. Under the context of twin carbon, green development is essential for these enterprises. With respect to income, the size of China's green economy accounts for 16%. Unless estimate based on a green industry catalog indicate that the output value of national-level green factories (those identified nationally and recorded with the Ministry of Industry and Information Technology) accounts for nearly 20% of China's large-scale manufacturing total output value. Green innovation refers to innovative activities that comprehensively blends environmental concepts with technologies, models, and management. While green innovation does mean a corporate development capability improvement, it has a long research cycle, high costs, high uncertainty of return and return on investment is relatively high. The relationship between enterprise digital transformation and green innovation is not simple, while some research found significant positive "dual effect" can stimulate quality and efficiency two to gain in green innovation [4], others for strategic emerging industries found a U-shaped pattern affected by the digital economy [5]. In the high-quality development of the context of twin carbon, how to clarify the relationship is the most important, we thus study set of Chinese A shares listed companies (2007 - 2023) for empirical inspection, the articles for three contributions, to provide theoretical reference for corporate practice. Systematically analyze in the context of the dual carbon policy digital transformation effect on green innovation. Exploring the sustainable growth rate as conditional boundary confirms its moderating role of optimizing resource support and the necessary reference; Factor heterogeneity enterprise size and property right explained the more substantial impact large scale and private enterprises, so as to refine".

2. Theoretical analysis and research hypotheses

2.1. The digital transformation-green innovation nexus

The digital transformation of enterprises and green innovation goals form a powerful synergy, significantly speeding up and deepening the process of green innovation in a number of ways. First of all, digitalization provides crucial resource supports for green innovation. As early as the advent of the digital transformation of enterprises, the online data stream and massive computing power are basic resources needed for the development of new green innovations. In traditional innovation systems, production relies on physical forms of material. But in the digital era, data has become a vital new form of production [5]. By placing IoT sensors within the production stream to collect real-time information about energy use, pollution, and delivery, businesses amass extremely rich stores of data needed to identify green changes and optimisation [6]. Meanwhile, digital tools such as cloud computing, AI, etc. provide technical support analysis. Such as, by simulating complex systems, speeding up new materials R&D, and intelligently scheduling resource deployments, these digital technologies tremendously shorten the cycle of green innovation and save trial-and-error costs [7]. The application of data and intelligent resources is the basis for empowering green innovation [8]. Secondly, digital operations improve the corporate management model, making green innovation more efficient. Unlike most traditional corporate families, enterprises adopting a plethora of different digital technologies often have flat, platform-based businesses [9]. These flat organisations with their less hierarchical model break many traditional management levels and shorten the chain of decision-making and execution, making it much cheaper to disseminate and communicate information. In this case, employees can directly contact suppliers here, and break through many organizational boundaries. Only by building shared and open platforms with digital

technologies can we attract internal and external resources, value co-creation, reduce energy and material consumption in transactions, and finally build a green supply chain to create a necessary external green innovation environment for the enterprise [10]. Having discussed the preceding, the study propose Hypothesis 1.

H1: Digital transformation contributes significantly to the advancement of green innovation.

2.2. Moderating effects of corporate sustainable growth rate

The degree to which digital transformation effectively manifests into enhanced green innovation gains, however, is not the same for every firm; it depends on critical internal contingencies, among which a firm's capacity for sustainable growth is posited as an important moderating variable. Digital transformation "empowers" enterprises with unprecedented abilities to perceive and optimize environmental data and processes and to deliver decision support, through technologies like big data, artificial intelligence, and IoT, so that such empowerment can drive innovations in green product development and manufacturing technologies [11]. However, the process of transforming such technological empowerment to actual green innovation is by no means guaranteed. Rather, it is conjectured ingrained in the nature of enterprise whether it possesses a strong sustainable growth capability. Beyond financial notions of capabilities, such Availability indicates a dynamic capability of the firm to integrally, constructively and reconstructively apply internal and external resource bases to environmental challenges so as to extract a sustainable long-term competitive advantage [12]. More specifically, such companies are generally found to have richer financial resources, more mature management systems, and strategies the horizon of which are more developed to embody their developmental cycles. Such a sustainable growth capability means that in their digital transformation efforts, they will have sufficient base in terms of resource capital to support a high-risk long-term R&D exploration of emerging and existing green technologies, when other enterprises may be too risk averse to effectively utilize technology, and mitigate uncertainties around them digitally transforming an enterprise. Meanwhile, their more developed foresight around their vision ensures the bulk of digital conforms to "what" problem the enterprise is trying to solve as part of their development rather than a time-consuming efficiency enhancement, to seize green capability breakthroughs more positively. Enterprises that lack such sustainable growth strengths on the other hands are unable to release their full technology potential even adopting advanced digital technologies, simply because they lack both resource strength to support such deployment, but have not derived mature enough strategic models to direct the deployment, and therefore risks remain in stringent regulatory or marginal transformations rather than the capture of the full green transformation. As pointed out in extant research, the process of converting digital innovation capability to competitive advantage depends too heavily on an organization's dynamic capabilities, which are the heart of sustainable growth capacity and thus play an important mediating role in the pursuit of green development through digital transformation to seize the green transformation from the opportunities the transformation opens of digital. Based on this line of thought, we propose Hypothesis 2.

H2: The mediating effect of enterprise sustainable growth rate enhancement in green innovation driven by digital transformation

3. Research design

3.1. Sample construction and data sources

The sample of this study includes A-share listed companies in the mainland of China from 2007 to 2023, and after performing data screening, as explained below. (1) Excluding samples that are ST. (2) Excluding samples that are in the financial industry, such as monetary finance, financial trust, and insurance, due to the high sensitivity of the data. (3) Excluding samples with less than one year observation years. (4) Excluding samples with much fewer complete data. (5) Lastly, 1% trimmed in tails, which further decrease the data outliers. After selecting, we were left with something like 14,883 observations.

3.2. Variable definitions

1. Dependent Variable: Corporate Green Innovation (LnInva). Firm's green innovation capability is evaluated as the logarithmic value of firms' green patent application count. As the green patents number may be proposed to be pinned down by external shocks including government policies and economic environment, while these factors might distort the actual green patent number, patent applications have better representativeness of firm's innovation intention and potential, so our research attaches more importance to it.

2. Explanatory Variables: Corporate Digital Transformation (DIG). Drawing inspiration from research findings reported in [15], we leverage data from listed companies' annual reports to statistically aggregate artificial intelligence, big data, cloud computing, and blockchain technologies into a digital transformation scorecard. These geographic points are left-skewed, thus following our research we resort to natural logarithmism based on 'add 1' mathematically.

3. Moderating Variable: Corporate Sustainable Growth Rate (SGR). Following research hypothesis. Select the SGR as the moderating variable.

4. In addition to our main variables of interest, we include a set of control variables, selected in line with established literature in the field of corporate digital transformation and green innovation, to enhance the reliability and robustness of our analysis. These variables are: Firm Age (Age), measured as the natural logarithm of the number of years since establishment; Firm Size (Size), indicated by the natural logarithm of the number of employees; Investment Opportunity (Tobin's Q), measured by the Tobin's Q index; Leverage (Lev), the ratio of total liabilities to total assets; Cashflow, calculated as net operating cash flow relative to total assets; and Management Share in Capital (Mshare), calculated as the ratio of shares held by management to total shares outstanding. The overall variable description and measurement stated are presented in Table 1.

Table 1. Variable definition

Type of variable	Variable name	Variable symbol	Variable-definition
Explained variable	Enterprise green innovation capability	LnInva	The number of green patent applications filed by an enterprise each year.
Core explanatory variables	Enterprise digital transformation	DIG	$\ln(1 + \text{Total number of digital word frequencies obtained from corporate annual reports})$
Moderator variable	Enterprise Sustainable Growth Rate	SGR	$(\text{Net profit/Total owner's equity balance at the end of the period}) * [1 - \text{Earnings before tax per share/}(\text{Net Profit Periodic Value/Paid-up capital at the end of the period})] / (1 - \text{Numerator}); \text{Return on Equity} * \text{Retention Ratio} / (1 - \text{Return on Equity} * \text{Retention Ratio})$
Control variable	Enterprise Age	Age	$\ln(\text{enterprise age})$
	Enterprise Scale	Size	$\ln(\text{Total number of homo sapiens in the enterprise})$
	Debt-to-Asset Ratio	Lev	Total liabilities/Total assets
	Management shareholding	Mshare	Number of shares held by management/Total capital
	Cash Flow Ratio	Cashflow	Cash Flow/Total Assets
	Enterprise Value	Tobin Q	$(\text{Floating market capitalization} + \text{Number of non-tradable shares} * \text{Net Assets per Share} + \text{Book value of liabilities}) / \text{Total assets}$

3.3. Model construction

This study examines the impact of digital transformation on green innovation using a bivariate fixed-effects model control for time-invariant heterogeneity across sectors and time.

$$LnInva_{ij} = \beta_0 + \beta_1 DIG_{ij} + \beta_2 con_{ij} + ind_i + year_j + \varepsilon_{ij} \quad (1)$$

In the model, *i* indicates industry and *j* indicates year. LnInva is green innovation capability; DIG is digital transformation. It also contains a series of controls (*con*), fixed effects for industry and year (*ind* and *year*), an intercept (β_0) and a disturbance term (ε). The theoretical model relies on the premise that digital transformation influences green innovation via sustainable growth capability. To illustrate the mechanism, we construct the following theoretical model

$$LnInva_{ij} = \beta_0 + \beta_1 DIG_{ij} + \beta_3 SGR + \beta_4 DIG * SGR + \beta_2 con_{ij} + ind_i + year_j + \varepsilon_{ij} \quad (2)$$

SGR is denoted as the moderator of corporate sustainable growth capability. DIG*SGR is the product term of corporate digital transformation level (DIG) and the sustainable growth rate (SGR),

testing the moderation effect. β_4 is the moderation effect coefficient. Other settings are as in Equation (1).

4. Empirical analysis

4.1. Descriptive statistics

The descriptive statistics of the main variables are presented as a tabulated summary (Table 2). The results show that there is substantial variation in green innovation among Chinese firms, as the number of green patents ranges from zero to thirty-three. The value of the digital transformation indicator is 18.96 with a standard deviation of 33.66 indicating large disparities in digitalization. The sustainable growth rate ranges between -0.04444 and 0.0102 .

Table 2. Descriptive statistics

	(1)	(2)	(3)	(4)	(5)
Variable	Sample size	Mean	Standard	Minimum	Maximum
Lev	14,882	0.354	0.179	0.0408	0.789
Age	14,882	1.930	0.577	1.099	3.258
Size	14,882	22.00	1.001	20.17	25.11
TobinQ	14,882	2.137	1.220	0.911	7.892
ROA	14,882	0.0110	0.0136	-0.0235	0.0605
Mshare	14,882	23.31	20.18	0.00140	69.60
Cashflow	14,882	0.0622	0.0759	-0.143	0.304
LnInva	14,878	1.483	4.571	0	33
DIG	14,882	18.96	33.66	1	196
SGR	14,882	0.0178	0.0225	-0.0444	0.102

4.2. Regression to zero

The descriptive statistics of the key variables are also presented in Table 2. There are considerable differences between the innovative capacity of Chinese firms, with green innovation ranging from $[0 - 33]$ across the sample. These differences are illustrated further in the form of standard deviation scores (33.66) from a mean score of 18.96 which measures the level of means digital transformation adoption and indicating that its adoption levels differ greatly between enterprises. The sustainable growth rate ranges from -0.04444 to 0.0102 .

4.3. Moderation effect analysis

The moderating role of sustainable growth is examined in Column (2) of Table 3 using an interaction term (DIGSGR) that captures the joint effect of digital transformation and sustainable growth rate. Column (2) of Table 3 shows the inclusion of the interaction term. The significantly positive coefficient on this term (2.286 , $p < 0.05$) provides strong empirical support for Hypothesis H2 as it indicates that a high sustainable growth rate enhances the positive effect of digital transformation on green innovation, confirming the importance of financial steadiness and future

potential and therefore H2. The higher the sustainable growth rate the stronger effect of digital transformation on green innovation.

Table 3. Baseline regression and moderating effect analysis and robustness test

	(1)	(2)	(3)	(4)
	LnInva	LnInva	LnInva	LnInva
DIG	0.00853*** (0.00139)	0.00778*** (0.00143)	0.00859*** (0.00139)	1.145* (0.666)
SGR	20.18*** (5.224)	16.35*** (5.526)		
DIGSGR		2.286** (1.080)		
Controls/year/ind	YES	YES	YES	YES
N	14878	14878	14878	14878
R^2	0.146	0.147	0.145	0.079
adj. R^2	0.135	0.135	0.134	0.067

4.4. Robustness test

Here we conduct a further sensitivity analysis by using a composite digital transformation index (allotting each element according to the entropy method) to checking the robustness of the main results. Regression results are presented in Column (4). The correlation coefficient through the entropy approach of the composite index value is 1.145, which passes the 10% significance level. That is to say, if we change the measurement of digital transformation from single-dimensional to composite index, its positive impact on green innovation is still holding firm, but its significance drops relative to the benchmark regression result. This may be because the information difference of the underlying index has a slight influence on the integration of the entropy method, resulting in a slight influence on the composite index. But it can still be shown that the conclusions of this study's benchmark regression is sufficiently robust.

5. Heterogeneity analysis

5.1. Heterogeneity analysis of enterprise size

Digital transformation may have a different influence on green innovation under different enterprise scales. A dummy variable is generated to classify companies as large enterprises or small enterprises, taking their number of employees as a cutoff point. A noticeable difference is that it can be observed from the subgroup analysis in Table 4, the promoting effect of digital transformation is larger in large enterprises (coefficient=0.0111) than in small enterprises (0.00762), the two are significant at the same time. It implies that the scalability of digital initiatives and the benefits for green innovation are more easily obtained in larger firms than in smaller ones, likely attributable to their superior resource endowment and organizational slack. The following factors can be explained according to the empirical results: first, large enterprises have more extensive financing channels,

they can not only get the funds they need to rely on traditional bottom-up approaches, but also use brand influence and industry status to attract strategic investment and diversified capital, Some multinational corporations can even use the world capital market integration of green financing resources in different regions, large enterprises have more abundant financial resources to support and tolerate the long-term and uncertain green transformation digital transformation investments, second, large enterprises use a more mature management model. In the context of the deep integration of global green transformation and digitalization, the established management model of large enterprises provides important underlying support for digital transformation to accurately empower green innovation.

5.2. Analysis of enterprise heterogeneity

Due to the heterogeneity in the impacts of digital transformation on green innovation among firms, we utilize an ownership classification framework to divide our sample into publicly owned and private-sector firms. The corresponding correlation coefficients for private-sector is 0.00424 while the value for publicly-owned enterprises is 0.00808, significant at the 1% level, which indicates that digital transformation has a stronger promoting effect on green development in publicly-owned enterprises, which may be related to to the following factors. First, publicly-owned enterprises receive relatively more policy support, and are more directly affected by government policies. For both types that are subsidized-based for digital transformation infrastructure, government policies are more inclined to favor publicly-owned enterprises, giving them greater subsidy intensity while posing lower financing difficulties. As important carriers for national strategies, publicly-owned enterprises can more quickly respond to policy orientations like "dual carbon" and green development. Only then can digital transformation be integrated with green innovation to a greater degree, making it easier to gain the support of resource policy. Second, publicly-owned enterprises have a stronger risk tolerance. Both green innovation and digital transformation require a long cycle, and have their risks concentrated through the entire process. Less affected by short-term game fluctuations in the market, publicly-owned enterprises can also provide long-term investment to groundbreaking throughout the whole R&D stage, prototyping, and finally commercialization, rather than meeting the expectations of projects with a higher short-term return.

Table 4. Heterogeneity test

	(1) Small scale	(2) Large scale	(3) Private-sector	(4) Publicly-owned
DIG	0.00762*** (0.00222)	0.0111*** (0.00142)	0.00424 (0.00643)	0.00808*** (0.00150)
_cons	-32.38*** (4.879)	-14.94*** (2.700)	-10.99*** (2.803)	-28.13*** (2.639)
Controls/year/ind	YES	YES	YES	YES
N	8604	6274	2909	11969
R^2	0.158	0.136	0.115	0.149
adj. R^2	0.144	0.111	0.093	0.138

6. Conclusions and implications

6.1. Research findings

This study uses data drawn from China's A-share market (2007-2023), to develop baseline and moderated models to examine how digital transformation influences green innovation, and how sustainable growth capability as a moderator plays a contingent role. We find that: (1) a critical mechanism through which digital transformation facilitates greener technologies is via the company level; (2) the sustainable growth rate was found to be important in framing the digital transformation and green innovation relationship, through mechanism analysis; (3) tests for heterogeneity found that the relationship is significantly stronger in large, and Publicly traded enterprises relative to their more marginally sized counterparts".

6.2. Implications for policy and practice

Firms need to up their investments in digital transformation, bolster infrastructural drives and spur internal technical conversion relying upon prioritization of digital resources and increasing funding. Speeding up the top-level design of the digital covers including cloud computing systems, enterprise-sector big data centers and an industrial internet will push fundamental works for further data deep utilization and deep-seated value conversion. Systematic planning will make digital concepts the groundwork of organizational restructuring, commercial process and management model reengineering. Total digital ingression on internal capital planning will enhance the sustainable development rates. Internal capital planning is the key for the firms to appropriate the kind of capital flow constituting their more fragile basis so essential for putting the kind of hammer blows on the sustainable development rates. Companies should hold a rigid constraint on capital budget management and adjust the direction of financing to adapt to Forward Industry cycles and the firms overall development phase, funding those operations that generate high-value additions and on core technologies R&D. Meanwhile they should widen the force of digital tools to build dynamic feedback and monitoring mechanisms on capital utilization, opening a portal for frontierless data flow from capital to information and business process flows so that internal capital can be tracked, monitored and controlled in real time to achieve internal tracing and automatically regulate itself, making cost and Liquidity efficiency through refined controls.

Digital technology enhances whole-process green innovation capability. At the same time, enterprises have fully integrated digital technology with the whole-process green innovation chain to construct a digitalized green innovation ecosystem, making use of "Internet Plus" and big data technology to accurately grip green innovation pain points and optimization directions; establishing a green R&D simulation platform, shortening the product development cycle, reducing trial and error costs and improving the accuracy and foresight of technological innovation; and realizing the effective integration of green innovation resources of industrial chains and promoting cross-entity technology, talent, data collaboration in accelerating green technology iteration and application. Through real-time adjustments, green innovation strategies sufficiently use recovery, completely maximize the empowerment efficiency of digital technology.

Policy support should be strengthened to provide enterprises with financial funds for combining digital transformation and green innovation, and to improve the supporting legal and regulatory system. The deep integration between the enterprise digital transformation and green innovation faces realistic difficulties such as project scale, technological barriers and risk uncertainty, which urgently needs the government to play macro-regulation and institutional protection roles in order to

provide strong backing towards the enterprise transformation practice. From the perspective of capital, governments should make good fiscal funds allocation, increase special support funds, expand green digital credit scale, and give special financial subsidies, so that a continuous and rich funding source mechanism can be integrated into the practice of enterprise innovation. From the perspective of law, the government should speed up the improvement of the two-in-one institutional system framework of digital transformation and green innovation, including the acceleration of standard formulation of digitalization and green innovation, while introducing supporting incentive and regulatory policy mechanisms. Enterprises that achieve huge success in green innovation can enjoy rewards such as tax reduction and credit score rise while enterprises that have high energy consumption, high emissions, and refuse to "go green" can also have a strengthened regulatory stick, which will provide a solid boost to the realization of "dual carbon" goals and the highquality development of digital economy in China.

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