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Transmission Channels of Digital Empowerment on Listed Firms' Green Innovation Performance

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Abstract: As the digital economy continues to advance, the ways in which corporate green innovation is shaped by digital transformation are still poorly understood. Adopting a green technological innovation perspective, the degree of corporate digital transformation is measured in this paper via a textual analysis method and constructs a sample of Shanghai and Shenzhen's A-share listed enterprises over the period 2011–2022, methodically investigating the underlying logic and transmission pathways through which corporate green innovation is influenced by digital transformation. The results indicate that corporate green innovation is significantly and favorably impacted by digital transformation, this conclusion is supported by several robustness checks. Mechanism tests reveal that corporate green innovation is driven by digital transformation through three distinct channels: enhancing organizational resilience, improving the quality of carbon information disclosure, and easing financial restrictions. Furthermore, the above promotional impacts are most particularly noticeable among high-tech companies, firms in non-heavily-polluting industries, and companies that located in eastern and western China.

Keywords: digital transformation; the quality of carbon information disclosure; corporate green innovation; financing constraints; organizational resilience

1. Introduction

The global economy is going through a significant change right now from an industrial paradigm to a digital one. Big data, cloud computing, and artificial intelligence are examples of emerging digital technology reshape the configuration of global value chains and function as core boosters for firms' green innovation and strategic transition [1,2]. As documented in the Digital China Development Report (2023), the market-oriented reform of data elements in China is accelerating in both scale and scope. The ongoing growth of the digital economy and the deepening of application scenarios are generating significant low-carbon technology spillover effects. With the in-depth development of China's digital economy, digital transformation has transcended the scope of mere technical empowerment, evolving into a systemic transformation deeply integrated with corporate production and operations. Such transformation constitutes not merely the strategic alternative enabling businesses to pursue digital dividends and leapfrog growth [3–5], but also an intrinsic driver for achieving goals for sustainable development and green innovation under resource and environmental constraints. The practical application of digital technology can significantly reduce information asymmetry and optimize the efficiency of resource distribution, thereby providing strategic opportunities for enterprises to realize industrial structural transformation, breakthroughs in green technology, and the reconstruction of core competitive advantages [6]. During the 11th Collective Study Session of the Political Bureau of the CPC Central Committee, General Secretary Xi Jinping

underlined the necessity of "accelerate the development of new quality productive forces and solidly promote high-quality development". Green productive forces are fundamentally a type of new quality productive forces. Their core logic lies in moving away from traditional high-input, high-energy-consumption growth models through the comprehensive innovation of technologies, models, and pathways. In the contemporary era where the digital economy and green transition are intertwined, can corporate green innovation be "catalyzed" by digital transformation? What are its underlying mechanisms and boundary conditions? Exploring these questions bears significant theoretical value and practical relevance for utilizing digital technology in boosting the enterprises' green and low-carbon transition and promote China's high-quality economic growth.

Currently, the academic community has engaged in extensive discussions regarding how digital transformation empowers corporate innovation. Studies by Zhou [7] and Wang [8] have validated the positive impact of digital transformation on innovation efficiency across various industrial contexts. As research deepens, the empowering function of digital transformation is extending from general innovation to the field of green innovation. Studies by Jin et al. [9] and Di [10] consistently find that digital transformation significantly drives green and low-carbon technological innovation in enterprises through technology spillovers and process optimization. Shi [11] further points out that digitalization is not merely an update of technical means but a strategic pillar for enterprises to attain a low-carbon and green transition. As for the inner mechanisms whereby digital transformation fuels green innovation, extant research mainly centers on optimizing resource allocation [12]. Notably, information transparency plays an irreplaceable mediating role in this process. Deployment of digital technology supports real-time data gathering and transparent transmission of production data, effectively reducing information asymmetry between enterprises and stakeholders by tightening internal controls and outside supervision. This enhancement in transparency, on the one hand, suppresses "greenwashing" behavior and forces enterprises to participate in substantive green R&D; on the other hand, a highly transparent information ecosystem improves the level of environmental information disclosure, drawing precise support from green financial resources [13]. However,in the volatile, uncertain, complex and ambiguous (VUCA) era, can mere technological transformation and transparency improvement sustain continuous innovation output? Organizational resilience-defined as the core capability of an enterprise to reorganize resources, achieve recovery, and renew itself amidst crises [14]—is increasingly becoming a key variable connecting digital transformation with innovation opportunities [15]. From the standpoint of dynamic capacities, some academics have endorsed the effectiveness of digital transformation in fostering organizational resilience [16,17], Systematic empirical evidence remains insufficient on how to integrate digital transformation, information transparency, organizational resilience, financing constraints, and corporate green innovation into a integrated theoretical framework to explore their interactive effects and pathways.

To address above questions, this study adopts panel data from Shanghai and Shenzhen A-share listed companies from 2011 to 2022 to objectively examine how corporate green innovation is affected by digital transformation. We introduce organizational resilience (Score), carbon information disclosure quality (CID), and financing constraints (FC) as mediating indicators to identify and test their mechanisms. By further exploring the effects among these variables, we aim to provide evidence for digital transformation practices and policy formulation.

Three major marginal contributions are presented in this research: First, it integrates digital transformation, organizational resilience, carbon information disclosure, and financing constraints into a unified framework, systematically revealing the transmission pathways of digital empowerment for green innovation and expanding the scope of study in the domains of green advances and the digital economy. Second, it evaluates the level of corporate digital upgrading based on the textual analysis approach and employs multiple mediation models for empirical tests, so as to further clarify the black box mechanism through which digitalization affects green innovation. Third, it conducts heterogeneity analysis across industry, pollution attributes, and regional levels to identify differentiated driving effects, providing more granular empirical evidence for micro-firm transition and macro-policy formulation.

2. Theoretical Analysis and Hypotheses

2.1. Corporate Digital Transformation and Green Innovation

Scholars conducting studies concerning the nexus between green innovation and digital transformation mostly pay attention to their incentive impacts, segmented dimensional indicators and intrinsic transmission mechanisms. Firstly, the output performance of corporate green innovation is markedly boosted via digital transformation. Via conducting empirical analysis covering China's listed corporations, Li et al. [18] conclude that the advancement of green innovation capabilities is greatly aided by digital transformation. This effect is reflected not only in the quantity of innovation but also in the optimization of innovation quality. Guo et al. [19] confirm

that digital transformation achieves a positive trend of "improving both quantity and quality" in green technology innovation by maximizing the structure of human capital and boosting R&D collaboration. Furthermore, digital transformation exhibits significant synergistic effects; Yang and Wang [20] point out that digitalization effectively promotes green collaborative innovation by cutting operational expenses and streamlining human resources, especially in technology-leading and supply-chain-concentrated firms.

Secondly, digital transformation systematically strengthens the green R&D logic through technical empowerment at different stages. The theoretical framework constructed by Yang et al. [21] reveals that digital transformation strengthens knowledge absorption capacity, innovation output capacity, and environmental adaptability at different stages. Using data empowerment, data operation, and data analysis, this process comprehensively fuels the evolution of low-carbon technology innovation. Some studies also emphasize that accelerating digitalization - including the coordinated development of digital infrastructure, investment, literacy, and application - holds significant strategic value for resource-based corporates' innovation in environmental technologies [22].

Finally, digital transformation empowers corporate green transition through multiple transmission channels. Mechanistically, digital transformation helps the green process by strengthening internal capability building, deepening responses to the external environment, and obtaining government subsidies. As a core engine for green productivity, it induces environment-friendly technology innovation and industrial structure upgrades, further consolidating green innovation results. Simultaneously, the green technology innovation triggered by digital transformation is a key indirect way to achieving pollution reduction and carbon neutrality goals. In summary, digital transformation has become a core trigger for green innovation, providing essential technical support and power through resource integration, process reengineering, and capability reconstruction. Consequently, the following hypothesis is proposed by this study:

H1: *Digital transformation exerts a positive influence on the progress of corporate green innovation*.

2.2. Digital Transformation, Organizational Adaptive Capacity, and Corporate Innovation

Digital transformation is a complex and rapidly changing process involving changes in organizational structure, culture, and processes. The digital economy raises the requirement for high-quality workforce and alleviates market distortions in talent elements [23], which further strengthens firms' capacity to cope with risks dynamically [24]. The enhancement of organizational resilience is an inevitable result of digital transformation, which is a process of comprehensive and multi-dimensional transformation and upgrading of the organization [25]. Digital transformation systematically enhances organizational resilience. In the anticipation dimension, digitalization improves information transparency and risk early warning capabilities, strengthens enterprises' ability to predict and respond to crises and trends, and constructs an agile response mechanism [26–28]. In the adaptation dimension, digital technologies optimize resource allocation and the reorganization of production factors, helping enterprises quickly allocate resources, restart production, and enhance dynamic adaptation and learning capabilities [29–31]. In the scenario dimension, digitalization promotes organizational network transformation and business model innovation, expands resource networks and social capital, and forms systematic resilience to resist uncertainty [32,33].

As enterprises undergo digital restructuring, organizational resilience is indispensable for enterprises' green innovation. Green innovation is marked by a high degree of uncertainty, strong external dependence, and a long cycle, and the fixed resources formed solely by digitalization are difficult to provide sustained support. The anticipation capability of organizational resilience can accurately guide resources to the key areas of green innovation; the adaptation capability can integrate new knowledge, talents, and existing resources to improve the success rate of innovation; the scenario capability can restructure business processes and organizational structures to adapt to technological iteration and optimize green products and services [25]. Digital transformation enhances organizational resilience by strengthening internal and external coordination and resource integration, thereby reducing the uncertainty of green innovation and breaking through resource bottlenecks [34,35]. In summary, digital transformation strengthens organizational resilience through efficient resource integration and collaborative linkage, and organizational resilience further converts the advantages of digitalization into the predictive power, integration capability, and adaptability required for green innovation, thereby reducing innovation risks, breaking through resource constraints, and ultimately bolstering the sophisticated and sustainable development of firm green innovation. Drawing on the aforementioned theoretical context, the following hypothesis is proposed by this study:

H2: *Digital transformation promotes corporate green innovation by enhancing organizational resilience*.

2.3. Digital Transformation, Carbon Disclosure Quality, and Corporate Green Innovation

Corporate digital transformation uses digital technology as its core to achieve data integration, process reconstruction, and governance optimization, significantly improving the quality of disclosure of carbon and environmental information. Carbon information disclosure is a core component of environmental information disclosure; the two are highly consistent in disclosure objectives, governance logic, and supervision mechanisms, forming a complete system of corporate environmental responsibility disclosure. High-quality carbon information disclosure upgrades the holistic level of enterprise environmental information transparency [36].

Regarding disclosure willingness, digitalization breaks information barriers, reduces the cost of publishing environmental and carbon information, and brings enterprises closer to stakeholders. Positive environmental and carbon information can increase market attention and share, while negative information forces enterprises to regulate environmental behavior and carbon emissions [37,38]. Regarding disclosure quality, digital technology can efficiently process massive unstructured environmental and carbon data, outputting standardized and structured information, improving information usability; simultaneously, digital platforms enable real-time monitoring of pollutant emissions and carbon emission status, reducing management friction and managerial irrational behavior, promoting more standardized and transparent disclosure of environmental and carbon information [39,40].

Green technology innovation faces double externality and path dependence, leading to stronger financing constraints and insufficient innovation motivation [41]. The improvement of environmental and carbon information disclosure constitutes a core intermediate mechanism for alleviating information asymmetry and driving green innovation. At the external level, high-quality environmental and carbon information disclosure attracts environmentally friendly and low-carbon investors through signal transmission, alleviating financing constraints for green innovation; simultaneously, using reputation mechanisms, it forces enterprises to repair their image and obtain long-term environmental and low-carbon benefits through green technology innovation to attract innovation resource inflows [42,43]. At the internal level, digitalization optimizes internal information governance, integrates production resources based on high-quality environmental and carbon information, clarifies environmental and low-carbon responsibilities, and guides enterprises to formulate green and low-carbon innovation strategies, ultimately driving green technology innovation [44,45]. Drawing on the aforementioned theoretical context, this study proposes the following hypothesis:

H3: *Corporate digital transformation boosts corporate green innovation* via *carbon information disclosure*.

2.4. Digital Transformation, Financing Constraints, and Corporate Green Innovation

Corporate green innovation features long R&D cycles, high investment costs, and significant risk uncertainty, making financing constraints a core bottleneck restricting innovation activities [46]. On one hand, cumbersome financing procedures and severe information asymmetry weaken the willingness of financial institutions to lend, causing enterprises to miss optimal R&D periods or lose core talents due to lack of funds [47,48]; on the other hand, under funding pressure, enterprises tend to abandon high-risk green projects and turn to low-risk non-green projects, producing a "compliance cost effect" that hinders the evolution of green technology. Digital transformation effectively alleviates corporate financing constraints through multiple mechanisms. First, by actively responding to national strategic directions, digital transformation enables firms to secure governmental resource preferences and policy backing, thereby broadening financing channels [22]. Second, digital technology breaks "information silos" between enterprises, significantly improving information transparency through the sharing advantages of digital information, reducing investor information screening costs and financing premiums, and alleviating funding difficulties caused by information asymmetry [49–51].

By relieving financing constraints, enterprises can obtain end-to-end resource guarantees for green innovation. In the development and application stage, sufficient funding allows enterprises to bear the R&D costs of cutting-edge technologies and strengthen intellectual property protection; in the production implementation stage, well-capitalized enterprises are more socially responsible, and they are more willing to build a sound environmental image by adopting green production modes [52]; in the pollution control stage, reduced financing pressure ensures resources are invested in end-of-pipe treatment equipment. In summary, digital transformation weakens the detrimental effects of financial limitations through the dual logic of responding to policy orientation and alleviating information asymmetry, thereby driving corporate low-carbon technological innovation comprehensively. Drawing on the aforementioned theoretical context, this study proposes the following hypothesis:

H4: *Digital transformation facilitates corporate green innovation by easing financing constraints*.

3. Research Design

3.1. Sample Selection and Data Origins

The research sample for this study is A-share listed companies in Shanghai and Shenzhen from 2011 to 2022. The digital transformation indicator construction is derived from Shanghai Stock Exchange and Shenzhen Stock Exchange annual reports, while remaining research data are sourced from the CSMAR database. The following treatments were applied: (1) Excluding financial companies; (2) Excluding enterprises labeled as ST and *ST throughout the sample period; (3) Excluding companies with severe data missing; (4) Applying 1% level winsorization to all variables. Ultimately, 37,944 sample observations were obtained. Stata 18.0 was used for data processing.

3.2. Variable Definition and Measurement

3.2.1. Dependent Variable

Green Technology Innovation (EnvrPat). This study refers to the patent indicator construction methods of proposed by existing literature [53]. The green patent application count indicator uses the overall green patent (EnvrPat), given abundant zero observations and obvious right skewness in the data, raw data would cause biased estimates in regression. Thus, we conduct a log-plus-one transformation for EnvrPat, constructed based on listed enterprises' annual green patent filings. In robustness checks, this paper adopts the ratio of green patent share indicator (RatioEnvrPat), defined as each enterprise' yearly green patent count divided by all its annual patent submissions, to validate the reliability of benchmark empirical results

3.2.2. Independent Variable

Digital Transformation (Dig). Digital transformation is a process of vision, strategy, organizational structure, process, capability, and cultural reconstruction using digital technology [54]. As a major corporate strategy, digital transformation is often reflected in comprehensive annual reports. Referring to the research of Wu [1], this paper constructs a database based on corporate annual reports, and measures the level of enterprise digital transformation through keyword frequency statistics pertaining to "corporate digital transformation" from annual disclosure reports of listed enterprises. The digital transformation index indicator is constructed by taking the natural log of the sum of matched keyword word frequencies plus one.

3.2.3. Mediating Variables

Organizational Resilience (Score)

Defined as the capability to predict, prepare, respond, and adjust to growing shifts and sudden destructive disturbances for survival and sustainable development [55]. Referring to LV [56] and Wu et al. [57], this study measures organizational resilience from two angles: long-term sustained growth and Variations in finances. Growth is quantified by the cumulative sales revenue growth over 3 years (unit: 100 million RMB); fluctuations is calculated by the daily stock return standard deviation over one-year period. Finally, the entropy approach is adopted to construct the composite organizational resilience indicator.

Carbon Information Disclosure Quality (CID)

Currently, academia mainly uses textual analysis to measure carbon information disclosure quality [58,59]. Referring to mainstream paradigms and considering data objectivity and comparability, this paper adopts the "Carbon Information Disclosure Index" from the CSMAR database as an indicator. This index comprehensively evaluates carbon-related information in corporate CSR disclosure reports, sustainability reports, and annual reports across five dimensions: governance, risk management, opportunity management, strategy, and indicators, measuring the disclosure level regarding carbon reduction management, carbon emission performance, carbon trading, carbon assets, and carbon neutrality goals.

Financing Constraints (FC)

Financing limitations are measured using the SA index, which is based on Hadlock and Pierce [60]. For ease of interpretation, a larger FC indicates more financial limitations when utilizing the absolute value of the SA index. The SA index calculation is simple and unaffected by endogeneity. It considers firm age and size, calculated using Formula (1):

$$SA\_index = -0.737 \times Size + 0.043 \times Sizex^2 - 0.04 \times Age \quad (1)$$

In Formula (1), Age represents the operating duration of a listed firm in years, and Size represents the logarithm of total assets.

3.2.4. Control Variables

Fundamental information and financial data of listed enterprises were selected. Referring to previous literature [61,62], This study incorporates firm characteristic control variables including firm size (Size), leverage ratio (Lev), return on assets (ROA), asset turnover ratio (ATO), and revenue growth rate (Growth), as well as board size (Board) and the shareholding ratio of the top ten shareholders (Top10) as corporate governance variables.

3.3. Model Specification

Model (1) is constructed to examine how corporate innovation levels are affected by digital transformation:

$$\mathrm{EnvrPat_{it}} = \alpha_0 + \alpha_1 \mathrm{Dig_{it}} + \alpha_2 \mathrm{Controls_{it}} + \sum \mathrm{Year} + \sum \mathrm{Firm} + \varepsilon_{it} \quad (2)$$

To verify mediating effects, referring to Jiang [63], a two-step method is adopted. Models (3), (4), and (5) test the mediating mechanism of organizational resilience, carbon information disclosure quality, and financing constraints:

$$\mathrm{Score_{it}} = \beta_0 + \beta_1 \mathrm{Dig_{it}} + \beta_2 \mathrm{Controls_{it}} + \sum \mathrm{Year} + \sum \mathrm{Firm} + \varepsilon_{it} \quad (3)$$

$$\mathrm{CID_{it}} = \beta_0 + \beta_1 \mathrm{Dig_{it}} + \beta_2 \mathrm{Controls_{it}} + \sum \mathrm{Year} + \sum \mathrm{Firm} + \varepsilon_{it} \quad (4)$$

$$\mathrm{FC_{it}} = \beta_0 + \beta_1 \mathrm{Dig_{it}} + \beta_2 \mathrm{Controls_{it}} + \sum \mathrm{Year} + \sum \mathrm{Firm} + \varepsilon_{it} \quad (5)$$

where $\mathrm{EnvrPat_{it}}$ is corporate green technology innovation; $\mathrm{Dig_{it}}$ is the digital transformation index; $\mathrm{Score_{it}}$ represents organizational resilience, $\mathrm{CID_{it}}$ denotes the quality of publication of carbon information disclosure; $\mathrm{FC_{it}}$ stands for financing constraints; $\mathrm{Controls_{it}}$ is the battery of control variables; α and β represent parameters for estimation; ε_{it} indicates the stochastic disturbance term. Firm and year fixed effects are taken into account by the models.

4. Empirical Verification and Results Analysis

4.1. Statistical Description of Variables

Descriptive statistics for the primary variables are shown in Table 1. The mean of Digitalization (Dig) is 1.474, with a median close to the mean and a standard deviation of 1.432, a minimum value of 0 and a maximum value of 6.380, indicating significant differentiation in digital levels among sample firms. Green Patents (EnvrPat) average 0.338 with a SD of 0.770, showing high dispersion and significant differences in enterprises' green innovation performance. The mean value for Firm Size (Size) stands at 22.174, the average level of Leverage (Lev) reaches 0.414. ROA averages 0.042, and ATO averages 0.638. Growth (Growth) averages 0.162, indicating dispersed distributions in operational efficiency and growth capabilities. The logarithmic board size (Board) and the top ten shareholders' shareholding ratio (Top10) average 2.116 and 0.589 respectively, with relatively gentle overall fluctuations. On the whole, sample firms present obvious individual differences in digitalization, green innovation, financial characteristics and corporate governance, conforming to the typical cross-sectional features of listed enterprises.

Table 1. Descriptive statistical analysis.

Variable	Count	Mean	p50	sd	min	max
Dig	37,944	1.4737	1.0986	1.4317	0	6.3801
EnvrPat	37,944	0.3381	0	0.7695	0	6.8480
Size	37,944	22.1742	21.9804	1.2999	19.8307	26.2203
Lev	37,944	0.4142	0.4045	0.2066	0.0514	0.8882
ROA	37,944	0.0416	0.0404	0.0660	−0.2315	0.2238
ATO	37,944	0.6379	0.5437	0.4320	0.0677	2.5723
Growth	37,944	0.16229	0.1029	0.3949	−0.5755	2.4025
Board	37,944	2.1159	2.1972	0.1970	1.6094	2.6391
Top10	37,944	0.5894	0.6004	0.1537	0.2293	0.9045

4.2. Variable Correlation and Co-Linearity Diagnosis

Table 2 displays pairwise correlation coefficients of all key variables in the research. Digital transformation (Dig) and green patents (EnvrPat) yield a Pearson correlation coefficient of 0.133, which reaches the 1% significance level, suggesting that digital transformation is positively and significantly associated with firms' green innovation output. The Pearson correlation coefficients of Dig with Score, CID and FC are 0.031, −0.010 and −0.017 correspondingly, all passing the corresponding significance tests.

Meanwhile, the Variance Inflation Factor (VIF) for each of the primary variables is determined in this study. The findings indicate that the average VIF is 1.830 and the maximum VIF is 4.340, both far below the critical value of 10. This suggests no severe multicollinearity exists among the main variables, which lays a reliable data foundation for subsequent empirical analysis.

Table 2. Correlation coefficient matrix.

	Dig	**EnvrPat**	**Score**	**CID**	**FC**
Dig	1	0.133 ***	0.031 ***	−0.010 *	−0.017 ***
EnvrPat	0.134 ***	1	0.007	0.176 ***	−0.073 ***
Score	0.020 ***	0.018 ***	1	−0.012 **	−0.132 ***
CID	0.002	0.197 ***	0.033 ***	1	−0.271 ***
FC	−0.008	−0.117 ***	−0.159 ***	−0.303 ***	1

Note: (1) ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. This convention applies to all tables hereafter. (2) Due to space limitations, only correlation results of major variables are reported.

4.3. Benchmark Effect Test

According to Table 3, the baseline regression results confirm that corporate digital transformation exerts a positive promotional effect on green innovation. Columns (1) and (2) only include the Independent Variable. Column (1) is estimated without controlling for firm and year fixed effects, while Column (2) includes dual firm-level and year fixed effects. Column (3) further incorporates a set of firm characteristic controls, and Column (4) further incorporates corporate governance variables. The empirical outcomes reveal that the coefficient of digital transformation (Dig) is positively significant at the 1% level (0.072 in Column 1, 0.022 in Column 2, and 0.019 in Columns 3 and 4), and the results further validate the significant positive impact of digital transformation on corporate green innovation output, indicating that the research conclusion is highly robust.

In terms of model goodness of fit, R^2 rises from 0.018 to 0.708, suggesting a greatly improved fitting effect. The sample size is sufficient (37,486–37,944), so the regression outcomes are credible. From an economic perspective, increasing digital transformation by one standard deviation (1.432) boosts green innovation output by 0.0272 (≈0.019 × 1.432), which represents an approximately 8% increase relative to its mean (≈0.0272/0.3380 × 100%), reflecting strong economic significance. Preliminarily, as the estimates demonstrate, digital transformation, involving utilizing digital technologies, can improve corporate green innovation capacity through channels such as technological progress.

Table 3. Benchmark regression.

	(1)	**(2)**	**(3)**	**(4)**
	EnvrPat	**EnvrPat**	**EnvrPat**	**EnvrPat**
Dig	0.072 ***	0.022 ***	0.019 ***	0.019 ***
	(0.007)	(0.005)	(0.005)	(0.005)
Size			0.035 ***	0.039 ***
			(0.010)	(0.011)
Lev			0.010	−0.006
			(0.032)	(0.032)
ROA			0.107 *	0.123 **
			(0.057)	(0.057)
ATO			0.010	0.008
			(0.016)	(0.016)
Growth			−0.022 ***	−0.020 ***
			(0.006)	(0.006)
Board				−0.023
				(0.032)

Table 3. *Cont.*

	(1)	(2)	(3)	(4)
	EnvrPat	**EnvrPat**	**EnvrPat**	**EnvrPat**
Top10				−0.110 **
				(0.044)
Firm FE	No	Yes	Yes	Yes
Year FE	No	Yes	Yes	Yes
_cons	0.232 ***	0.309 ***	−0.483 **	−0.436 *
	(0.012)	(0.007)	(0.226)	(0.229)
N	37,944	37,486	37,486	37,486
R^2	0.018	0.707	0.708	0.708

Note: (1) ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. This convention applies to all tables hereafter. (2) Parentheses report firm-level clustered standard errors.

4.4. Tests for Endogeneity and Robustness Verification

4.4.1. Robustness Checks

A series of robustness tests are implemented to validate how digital transformation affects Climate Transition Risk, and the detailed results are presented in Table 4. These robustness checks include: (1) Substituting the independent variable: drawing on Zhao et al. [64] and based on listed firms' annual reports provided by the CNRDS database, an alternative proxy for digital transformation is adopted for re-estimation. (2) Substituting the dependent variable: following Xu and Cui [65], we use the year-end ratio of green patent applications to total patent applications for alternative measurement. (3) Adding control variables: a control variable for ownership type is added to the model. (4) Changing the model specification: industry-level fixed effects are employed instead. (5) Adjusting the sample timeframe: to eliminate the potential confounding effects of the 2015 domestic stock market crash and the 2020–2022 COVID-19 pandemic on corporate green innovation, following Zhang [15], observations from these periods are excluded and the regression is re-estimated. All of the above robustness checks produce results consistent with the baseline conclusions.

Table 4. Robustness checks.

	(1)	(2)	(3)	(4)	(5)
	EnvrPat	**RatioEnvrPat**	**EnvrPat**	**EnvrPat**	**EnvrPat**
Dig		0.002 **	0.019 ***	0.061 ***	0.012 **
		(0.001)	(0.005)	(0.007)	(0.005)
DIGI_text	1.124 ***				
	(0.413)				
Year FE	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	No	Yes
Industry FE	No	No	No	Yes	No
SOE			−0.074 **		
			(0.029)		
_cons	−0.393 *	0.024	−0.419 *	−2.740 ***	−0.303
	(0.227)	(0.044)	(0.229)	(0.302)	(0.264)
N	37,486	37,486	37,486	37,944	22,137
R^2	0.708	0.478	0.708	0.142	0.723

Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. This convention applies to all tables hereafter.

4.4.2. Endogeneity Handling

Instrumental Variable Approach

On the one hand, potential reverse causality concerns persist between the two variables: firms endowed with greater green innovation potential tend to actively pursue digital transformation due to their more abundant resource endowments and stronger strategic motivations. On the other hand, although this paper controls for multi-dimensional firm characteristic indicates and fixed effects, unobservable omitted variables may still exist (e.g., corporate culture) that simultaneously affect both digital transformation and green innovation. To address these endogeneity problems, following the approaches of Lewbel [66] and Yang et al. [62], to alleviate endogeneity

bias, this study develops IV_Dig as the cubic difference between digital transformation at the firm level and its industry-province mean. This variable is computed through centering on the degree of digital transformation for each company, thereby reflecting the firm's relative degree of digital deviation and competitive position within the same industry and region. On one hand, the instrumental variable is derived from a transformation of the firm's own digital transformation level and is therefore correlated with the firm's digital transformation level; on the other hand, with firm-year fixed effects and all relevant control variables controlled for, this relative deviation indicator is unlikely to directly affect green innovation through other channels, thus satisfying the pertinence and exogeneity requirements of an instrumental variable.

Column (1) of Table 5 displays the corresponding regression outcomes. As shown by the first-stage results, the coefficient on IV_Dig is positive and predominant at the 1% confidence level, confirming that the instrument meets the relevance requirement. The phase 2 estimation in Column (2) shows that, at the 1% level, the coefficient of digital transformation on green innovation remains substantially favorable. Consequently, after correcting for endogeneity, digital transformation still exerts a significant positive effect on green innovation. In addition, the underidentification test and weak instrument test are conducted. Further analysis validates that the model passes the underidentification test. And the Kleibergen-Paap rk Wald F statistic stands at 775.77, which surpasses the Stock-Yogo critical value of 16.38 at the 10% significance level, confirming that there is no weak instrument problem in this model.

Table 5. Endogeneity handling.

	(1)	(2)	(3)	(4)	(5)	(6)
	IV Estimation		**Lagged Effects**		**Long-Run Effects**	
	First Stage	**Second Stage**	**First Stage**	**Second Stage**	**First Stage**	**Second Stage**
	Dig	**EnvrPat**	**Dig**	**EnvrPat**	**Dig**	**Forward_EnvrPat**
IV_Dig	0.088 ***					
	(0.003)					
Dig		0.033 ***		0.042 ***		0.049 ***
		(0.011)		(0.011)		(0.013)
L.Dig			0.449 ***		0.427 ***	
			(0.008)		(0.009)	
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Kleibergen-Paap rk LM	498.92 ***		807.74 ***		673.86 ***	
Kleibergen-Paap rk Wald F	775.77		3116.441		2283.128	
N	37486	37486	31896	31896	27172	27172
R^2		0.002		0.0005		0.0003

Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. This convention applies to all tables hereafter.

For the sake of excluding potential reverse causality and omitted variable biases, following relevant literature [67,68], this paper also uses the lagged values of the independent variable as instruments and conducts IV-2SLS regressions. The rationale is that, under certain conditions, the independent variable in historical periods is uncorrelated with the contemporaneous period error term, thereby satisfying the requirements for a valid instrument.

Considering that the build-out of digital infrastructure and its integration with production modes and technology during the digital transformation process requires time, a pronounced time lag exists in the effect of digital transformation on green innovation-i.e., earlier investments in technology R&D take time to be converted into output. Accordingly, this paper introduces the one-period lagged value of digital transformation (L.Dig) as an instrument and employs the 2SLS method. The first-stage regression result in Column (3) and (4) of Table 5 shows that the instrument is significantly and positively correlated with the explanatory variable, ruling out weak instrument concerns. The second-stage result in Column (4) demonstrates that, after controlling for dynamic effects, the coefficient of digital transformation (Dig) remains significantly positive at the 1% level, further confirming that digital transformation promotes corporate green innovation.

Long-Run Effects

For a deeper investigation into green innovation' s long-run effects-theoretically, digital transformation not only optimizes resource allocation in the short run but may also generate sustained long-run promotion of innovation activities through knowledge accumulation, technological path dependence, and improvements in organizational capabilities [69]—this study advances the dependent variable by one period (Forward_EnvrPat) to capture the predictive effect of digital transformation on future green innovation. Estimation outcomes from

Column (6) of Table 5 reveal a persistently positive and significant coefficient, indicating that digital transformation produces a significant intertemporal effect on corporate innovation.

Furthermore, when benchmarked against the baseline regression, the coefficients show a notable increase, revealing a significant incremental and cumulative long-term effect of digital transformation on green innovation. A possible explanation is twofold: in the initial phase of digital transformation, investment is primarily directed toward infrastructure, organizational adjustment, and technology integration, so this leads to a time lag between digital input and innovation output; subsequently, as data factor accumulation deepens, technology integration intensifies, and organizational learning effects strengthen, digital capabilities are progressively converted into more efficient green knowledge production, generating more pronounced innovation output in later periods. Consequently, digital transformation's facilitating effect on corporate green innovation exhibits a cumulative increasing trend-its promoting effect strengthens continuously over time-indicating increasing returns to scale for digital capabilities and further supporting the baseline conclusions from a dynamic perspective.

4.5. Mechanism Tests

The preceding section conducted the main effect analysis. To further investigate the underlying mechanisms and identify transmission channels, this paper selects three variables-organizational resilience, carbon information disclosure quality, and financing constraints-for mechanism testing based on the foregoing theoretical analysis.

4.5.1. Organizational Resilience

Digital technology itself possesses the characteristics of universality and non-excludability, which determine that it cannot directly confer sustained competitive advantage on firms [70]. This implies that new resources acquired through digital transformation do not necessarily translate into actual value. If digital transformation is regarded as a value 'input' and green innovation as the ultimate value 'output', there is most likely not a direct linear relationship between the two; rather, an intermediate transmission process exists. Dynamic capabilities theory provides theoretical support for exploring this mediating process, indicating that the external environment is dynamic and complex, and that firms must possess the capacity to quickly adjust to changes in the environment and integrate and utilize resources to gain competitive advantage in intense market competition. Especially in the current VUCA era featuring high volatility, uncertainty, and complexity, environmental uncertainty is further intensified, and organizational resilience-as the core capability of firms to respond to risks and maintain stable development-becomes increasingly important.

Specifically, firms with high organizational resilience typically demonstrate higher degrees of risk-taking ability, proactiveness, and innovativeness, empowering firms to rapidly adjust development strategies in complex environments. Empirical studies have confirmed that organizational resilience serves as a crucial mediating mechanism between technological innovation and performance [71]. Regarding the linkage between corporate digital transformation and green innovation, firms acquire vast external resources in the course of corporate digital transformation, and corporate organizational resilience can help firms to effectively absorb and integrate these resources, internalizing digital operational capabilities into higher-level operational resilience, which in turn stimulates firms' intrinsic motivation to pursue green innovation.

Following Jiang [63], this paper adopts a two-step procedure to test this mechanism using Models (2) and (3). The coefficient of the independent variable digital transformation (Dig) on organizational resilience (Score) is significantly positive at the 1% level is displayed in Column (1) of Table 6, representing that an improvement in firms' digital transformation level can yields significant improvements in organizational resilience, thereby driving corporate green innovation.

Table 6. Mechanism tests.

	(1)	(2)	(3)
	Score	**CID**	**FC**
Dig	0.003 ***	0.115 **	−0.003 ***
	(0.001)	(0.053)	(0.001)
Controls	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
_cons	0.685 ***	−33.547 ***	3.733 ***
	(0.028)	(2.928)	(0.080)
N	36,676	37,207	36,869
R^2	0.372	0.724	0.887

Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. This convention applies to all tables hereafter.

4.5.2. Carbon Information Disclosure Quality

Firms pursuing green technology innovation generally face pronounced financing constraints. The quality of carbon information disclosure, as a crucial mechanism for alleviating information asymmetry in capital markets, directly affects firms' financing environment for green innovation. Digital transformation, as a major force behind high-quality corporate development, can provide strong support for carbon information disclosure, thereby advancing firms' green innovation.

From one angle, firms engaged in digital transformation and green innovation practices can release positive signals for carbon information disclosure [61], enhancing firms' willingness to proactively disclose carbon information and improving information transparency, enabling market participants to promptly grasp the transformation outcomes of traditional assets driven by digitalization and green innovation. According to reputation mechanism theory, media exposure of corporate environmental violations or disclosure of poor environmental information rankings can easily trigger public trust crises. To maintain their green image or respond to external public pressure, listed companies typically take immediate measures to compensate for reputational damage [72]. However, short-term environmental governance cannot fundamentally resolve environmental problems; in this context, firms in this setting demonstrate a greater propensity to enhance long-term environmental performance through green technological innovation, signaling to the outside world their proactive fulfillment of environmental responsibilities to repair corporate reputation [42]. This positive 'exposure effect' helps firms build a highly responsible social image, enhance market reputation, and attract more social capital and innovative talent, thereby further promoting green technology innovation [73].

Following Jiang [63], this paper adopts a two-step procedure to test this mechanism using Models (2) and (3). Estimates from Column (2) of Table 6 indicate that the coefficient of the independent variable digital transformation on carbon information disclosure quality (CID) is significantly positive at the 5% level, lending support to the view that an improvement in firms' digital transformation level can significantly enhance carbon information disclosure quality and thereby promote corporate green innovation.

4.5.3. Financing Constraints

Compared with conventional technological innovation, green and low-carbon technological innovation typically involves longer R&D cycles, greater capital investment, and higher risk levels. Insufficient capital supply is a critical factor constraining corporate innovation activities [45]. Firms facing financing constraints can effectively mitigate such pressures through digital transformation.

On one hand, by actively responding to national policy orientations, digital transformation helps firms broaden diversified financing channels; on the other hand, digital means reduce information asymmetry, lower financing costs, and further improve firms' financing conditions [74]. During the green technology R&D and patent application stage, mitigating financing constraints can offer more abundant financial backing for enterprises. Firms with stronger financial capacity are better positioned to explore new green and low-carbon technologies and to file timely patent applications and seek intellectual property protection. Financing constraints exacerbate the 'compliance cost effect' of green innovation, while digital transformation-by alleviating financing constraints-weakens this effect, thereby encouraging firms to more actively pursue green technology innovation [52].

Following Jiang [63], this paper adopts a two-step procedure to test this mechanism using Models (2) and (4). The coefficient of the independent variable digital transformation (Dig) on financing constraints (FC) is significantly positive at the 1% level, as shown in Column (3) of Table 6. This suggests that a firm's level of digital transformation can greatly reduce financing constraints, which in turn promotes corporate green innovation.

4.6. Heterogeneity Analysis

The preceding analysis demonstrates that digital transformation introduces new production factors and modes of production for firms, enhancing their green innovation capabilities. However, further analysis is needed to examine how the positive effects of digital transformation may vary across different industries, pollution attributes, and regional locations.

4.6.1. Heterogeneity by High-Tech Industry Status

The very nature of high-tech industries requires them to remain at the frontier of science and innovation. In comparison to enterprise in non-high-tech industries, high-tech enterprises possess more sophisticated information and communication technologies, richer technical resources and expertise, more sophisticated R&D capabilities, and broader pools of technical talent; consequently, the innovation-enhancing effects of digital transformation are

more pronounced. Following Peng and Mao [75], For the purpose of this analysis, according to the 2012 CSRC industry classification rules, companies having company classification codes "C25-C29, C31-C32, C34-C41, I63-I65, and M73" are classified as high-tech industry enterprises. A high-tech industry dummy indicator is constructed (firms belonging to high-tech industries are assigned a value of 1; otherwise, the value is 0). As shown in Columns (1) and (2) of Table 7, digital transformation significantly improves green innovation in high-tech industries, confirming the foregoing conjecture.

Table 7. Heterogeneity analysis.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	High-Tech	**Non-High-Tech**	**Heavy Polluters**	**Non-Heavy Polluters**	**Eastern**	**Central**	**Western**
Dig	0.026 ***	0.007	0.012	0.019 ***	0.022 ***	−0.003	0.037 **
	(0.007)	(0.005)	(0.008)	(0.006)	(0.005)	(0.013)	(0.015)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	−0.916 **	−0.551 **	0.018	−0.782 ***	−0.497 *	−0.718	−0.007
	(0.383)	(0.272)	(0.408)	(0.296)	(0.274)	(0.629)	(0.720)
N	22,212	15,197	10,610	26,811	26,042	6009	4091
R^2	0.711	0.677	0.640	0.723	0.724	0.682	0.633

Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. This convention applies to all tables hereafter.

4.6.2. Heterogeneity by Heavy-Pollution Industry Status

Firms with varying pollution intensities face distinct environmental compliance pressures, resource endowments, and transformation pathways, which could result in how digital transformation affects green innovation to display pronounced industry heterogeneity. Non-heavily-polluting company face relatively moderate environmental regulations and possess greater transformation space; these enterprises can leverage digitalization to improve information transparency, optimize resource allocation, and-through organizational resilience-effectively absorb and integrate digital resources, converting digital capabilities into green innovation momentum.

By contrast, heavily-polluting enterprises typically face stronger environmental regulations, higher pollution control costs, and technological transformation pressures; long subject to high compliance costs and risk constraints, their digital investment is more directed toward end-of-pipe treatment, emission monitoring, and other compliance-related needs, hindering the effective transformation of digital resources into green technological innovation capabilities. To test these conjectures, firms are categorized into non-heavily polluting groups and heavily polluting. The outcomes in Columns (3) and (4) of Table 7 indicate that in the non-heavily-polluting group, the independent variable digital transformation significantly improves firms' performance in green innovation, while in the heavily-polluting group the result is not significant. A possible explanation is that heavily-polluting enterprises are characterized by high asset specificity and high adjustment costs, which limits the empowerment space for organizational resilience, thereby dampening digitalization' s promotional impact on green innovation and resulting in an insignificant regression outcome.

4.6.3. Spatial Heterogeneity Analysis

Spanning a vast geographic area, China exhibits obvious differences in local development conditions, innovation environments, and other dimensions across regions. The eastern region is economically developed, possesses abundant innovation resources and talent, and has a well-established policy support system, enabling firms to draw on sufficient resources for green innovation activities. The central region has a relatively traditional industrial structure, slower demand for and responsiveness to green innovation, and certain gaps in green innovation input and output. The western region, although relatively less developed, has made certain progress in infrastructure construction, green innovation, and other areas with the continuous increase in national support.

To test these conjectures, the sample is divided into central, eastern and western regional subgroups for regional heterogeneity analysis. The results in Columns (5) and (7) of Table 7 indicate that in the eastern and western regional subgroups, the independent variable digital transformation significantly enhances firms' green innovation level. In Column (6), however, the main effect is not significant for the central region subsample. This result is in line with expectations.

5. Conclusions

Using data on Chinese listed companies, the present paper systematically investigates the effects of corporate digital transformation on the performance of green innovation and clarifies the relevant internal mechanisms. The research results show: First, can markedly improve enterprises' green innovation performance; following a series of robustness tests including two-stage least squares instrumental variable estimation, and substitution of the independent and dependent variables. Second, corporations can stimulate green innovation by enhancing organizational resilience and the quality of publication of carbon information through digital technologies, reduce financing constraints they face, and thereby positively influence their green innovation; organizational resilience, carbon information disclosure quality, and financing constraints play mediating roles in explaining how digital transformation promotes green innovation. Third, the examination of subgroup differences is carried out across three dimensions. From the perspective of industry attributes, this improvement effect is more pronounced in high-tech sectors. In terms of pollution characteristics, compared with heavily polluting firms, non-heavily polluting ones show a stronger response. At the regional level, significant regional differentiation exists, with the western region showing a more prominent effect than other regions.

Against the backdrop of previous scholarly work, the academic significance of this paper is primarily embodied in two key respects. First, by introducing organizational resilience, carbon information disclosure, and financing constraints as mediating variables, it offers fresh study angles for examining the connection between green innovation performance and digital transformation. extends the application of dynamic capabilities theory, signaling theory, reputation mechanism theory, and financing constraint theory in the domain of green innovation, and contributes to a deeper understanding of corporate digital transformation.

Notwithstanding its findings, this research inevitably contains certain deficiencies. On one hand, because digital transformation is multidimensional and complex, related influencing factors and transmission mechanisms require further research. On the other hand, this paper's analysis is primarily focused at the firm level; future research may consider adopting broader perspectives encompassing industry, regional, and national levels. Second, the research conclusions contribute to encouraging firms to leverage digitalization to enhance organizational resilience and information disclosure quality, alleviate financing constraints, and thereby achieve green innovation upgrades. They also provide reference for government formulation of differentiated digital economy policies and green transition incentive programs, assisting firms in coordinating high-quality development with the dual-carbon goals.

Considering the empirical findings and the aforementioned conclusions in this paper, the following suggestions for policy are put forth to provide references for the formulation and implementation of corporate strategies. First, firms should place great emphasis on digital transformation. In the current wave of the Fourth Industrial Revolution centered on artificial intelligence, digitalization has become a compelling necessity for enterprises pursuing high-quality development. To this end, firms need to formulate clear digital transformation strategies, invest in digital technologies and infrastructure, cultivate and attract digital talent, establish data-driven decision-making mechanisms, explore and apply new technologies and business models, strengthen data security and privacy protection, develop and improve data security policies and procedures, and enhance cooperation with digital technology providers and innovative enterprises to obtain technical support and resources. Second, firms should emphasize the cultivation of organizational resilience and proactively disclose relevant environmental information. Firms need to cultivate a positive organizational culture, build flexible organizational structures, and advocate for employee teamwork, knowledge sharing, continuous learning, and ongoing innovation, so as to better adapt to the wave of digital economic development. Enhancing openness in environmental reporting helps raise investor trust and enables regulatory authorities and markets more accurately assess firms' ability to respond to climate risks. Third, in the course of development, firms should fully anticipate environmental information uncertainty and proactively respond to it. Firms should build dynamic adaptability to the environment, maintain flexibility and agility, rapidly reallocate resources and organizational structures, remain undeterred by risks, and not miss opportunities. They should establish flexible strategic planning, decompose objectives and action plans into adjustable steps, and build a solid supply chain system, deepen high-quality partnerships, ensure better anticipation and response to environmental changes, maintain competitive advantages, and drive enterprises to achieve steady and long-term growth. Fourth, it is advisable for the government to enhance the green innovation incentive mechanism. The costs of green innovation should be reduced through tax incentives and subsidies to stimulate firms' vitality for green innovation. Given that environmental information disclosure by Chinese firms currently remains primarily voluntary, it is recommended that regulatory authorities gradually implement mandatory disclosure requirements and develop industry-specific disclosure standards.

Author Contributions

Z.L.: conceptualization, methodology, software, writing—original draft, visualization, investigation; N.X.: supervision, writing—review and editing; G.L.: data curation, validation; J.H.: visualization, investigation, writing—review and editing; W.X.: writing—original draft. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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