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How Enterprise Digitalization Drives Green Innovation—From the Perspectives of R&D Expenditure, Agency Conflict and Analyst Coverage

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Abstract. With the in-depth implementation of the carbon peaking and carbon neutrality strategy, exploring how enterprise digitalization drives green innovation is of great value for promoting high-quality economic development. Taking China's A-share listed enterprises from 2010 to 2022 as samples, this study examines the influence path of enterprise digital transformation on their green innovation performance. The study finds that the degree of digitalization has a significant enhancement effect on green innovation output. Mechanism analysis shows that digital transformation internally relies on increasing corporate R&D investment and reducing agency costs, and externally attracts the attention of securities analysts through external channels, thereby improving enterprises' green innovation capability. The results of heterogeneity grouping analysis show that this driving effect is more prominent in eastern and western regions of China, non-heavy-pollution enterprises and high-tech industries.

Keywords: enterprise digitalization, R&D investment, green innovation, agency cost, analyst coverage

1. Introduction

The global climate and environmental crisis is increasingly becoming a core bottleneck hindering sustainable development. Firmly following the development path of green innovation and leading the economic and social system to undergo in-depth transformation toward ecologicalization and low-carbonization is not only the core essence of achieving high-quality development, but also injects strong impetus into the construction of a "Digital China", thus effectively boosting the long-term development of enterprises. Meanwhile, the State Council emphasizes that strengthening scientific and technological support and improving the innovation system are regarded as key grips for accelerating the low-carbon technological revolution, which highlights the core position of enterprises as key implementers of green innovation. However, restricted by the long cycle, high sunk cost and dual externality characteristics of green technology itself, enterprises under the traditional model often encounter problems such as resource constraints, information asymmetry and insufficient innovation incentives. They often face the trade-off dilemma of balancing "economic benefits" and "environmental responsibility", resulting in insufficient internal driving force.

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At the same time, with the iterative development of cutting-edge tools such as blockchain and big data, as a key strategic decision for modern enterprise management, digital transformation plays a crucial role in driving green development [1]. The in-depth application of digital technology not only breaks internal and external information barriers, but also changes enterprise production, management and innovation modes as a new management concept and technology application [2], providing a key technological engine for solving the resource and governance constraints faced by green transformation. Therefore, identifying the driving effect and internal logic of digitalization degree in the process of promoting green innovation can not only enrich theoretical literature in related fields, but also have certain application value. This study deeply discusses the internal connection and action path between the two, provides micro evidence for enterprises to formulate scientific transformation strategies, and ultimately effectively serves the national "dual carbon" goals and green development strategy.

2. Theoretical analysis and research hypotheses

2.1. Enterprise digital transformation and green innovation

Enterprise digital transformation significantly weakens the physical space barriers formed by geographical and temporal factors on enterprise innovation activities. With the help of digital networks, enterprises can obtain massive cutting-edge technical information from the upstream and downstream of the industrial chain at lower search costs, and timely grasp changes in market demand to realize data-driven operation [3], thereby accurately locking in potential green technology opportunities and broadening innovation horizons. Meanwhile, digital R&D platforms and networks accelerate the convergence and integration of various technologies among enterprises [4], reduce the R&D cost of multi-party joint innovation, enable enterprises to carry out multiple green technology research projects at the same time, and effectively expand the output scale of green patents.

At the same time, digital transformation can effectively improve the overall planning and allocation efficiency of enterprise resources, and improve the input-output efficiency of R&D [5]. Under the traditional model, R&D investment often faces risks due to information asymmetry. Digital technology effectively reduces ineffective resource input and improves the output efficiency of per unit R&D expenditure through full-process tracking and feedback of the R&D process. In addition, digital transformation improves enterprise business decision-making [6], enabling enterprises to adjust R&D directions in a timely manner, focus limited resources on green projects with high potential, and maximize the accuracy of green R&D.

Finally, digital transformation is promoting the green innovation mode of enterprises to gradually shift from "strategic" behavior that focuses on formal response to "substantive" behavior driven by technological core. Strategic innovation refers to green activities carried out by enterprises to cater to external policies and supervision, while substantive innovation emphasizes technological breakthroughs oriented to solving real environmental problems. By building a full-process and traceable environmental data system, digital technology enables full disclosure of enterprises' environmental performance and greatly reduces the probability of "greenwashing" behavior. When the cost and risk of disguise increase, rational enterprises will actively adjust their innovation modes to ensure that the investment in green innovation can achieve substantive results [7].

H_1: The improvement of enterprise digitalization level helps to enhance its green innovation capability.

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2.2. Mechanism analysis at the internal level of enterprises

Green innovation activities generally present the attributes of large capital investment, long R&D cycle and significant uncertainty [8], and are highly dependent on stable R&D investment. However, traditional enterprises often face dilemmas such as insufficient R&D funds, vague R&D directions and low R&D efficiency. Digital transformation strengthens the financial guarantee foundation of enterprise R&D investment from multiple dimensions and enhances the sustainability of R&D resource base. First, digital transformation can assist enterprises in data mining and application [9], enabling them to accurately portray the frontier of green technology and market demand, reduce the uncertainty caused by unclear technical routes in the early stage of innovation, and thus strengthen the confidence of decision-makers in expanding green R&D investment. Meanwhile, relying on data-driven governance tools, the matching efficiency of R&D resources is significantly optimized. The application of R&D project management platforms and collaborative design tools makes the R&D process more transparent and controllable, reduces enterprises' working capital and reduces resource mismatch [10], indirectly releasing more R&D funds.

Under the contemporary corporate governance framework, principal-agent conflict is one of the core cruxes that restrict enterprises from making long-term investments. Rising agency fees will significantly inhibit the internal motivation of enterprises to engage in green innovation activities. Management tends to choose projects with short return cycles and low risks, while avoiding green innovation projects with long cycles and high risks, forming a "short-termism" tendency. Digital transformation can effectively restrain agency costs by virtue of high information transparency. First of all, the application of digital management systems enables the board of directors and shareholders to obtain operational data in real time, so as to have more sufficient ability to supervise the behavior of management. R&D activities that were difficult to quantify in the past can now be tracked throughout the process through digital platforms, thereby compressing the space for management's opportunistic speculation. At the same time, the circulation and sharing of data and information within the enterprise promote the optimization of resource allocation pattern and production operation mode, thus setting procedural control standards for green innovation activities and effectively reducing the cost dissipation in the supervision link. In addition, the digital environment also helps to build a more scientific compensation mechanism, linking green innovation performance with executive compensation to form an effective institutional arrangement. When short-sighted behavior is restrained, enterprises will be more willing to invest in green innovation projects with high sustainability, improve their organizational and environmental performance, and help companies gain competitive advantages.

H_2a: Digital transformation improves green innovation level by increasing enterprise R&D investment.

H_2b: Digital transformation improves green innovation level by reducing enterprise agency costs.

2.3. Mechanism analysis at the external market level

Green innovation projects are difficult to generate cash flow in the short term, and their long-term benefits are highly uncertain, making banks and investors tend to evaluate cautiously or even avoid such investments. Companies that implement digital transformation usually have more cutting-edge governance structures and strategic patterns. Such upgrading actions can release positive signals, thus winning widespread attention from securities analyst teams, news media and the general public. High analyst coverage means that enterprises are under the spotlight of the market, and substantive green technology breakthroughs can be quickly converted into market premiums and improve

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market expectations; on the contrary, under the high-density research of multiple institutions, it is much more difficult for enterprise management to whitewash green performance externally, and "greenwashing" behavior may trigger severe market reputation penalties. The financial environment with both external constraints and positive reinforcement promotes enterprises to shift more investment to substantive green technology R&D, so as to respond to the market's value demands.

H_2c: Digital transformation promotes green innovation by increasing analyst coverage.

3. Model construction

3.1. Benchmark regression model

Based on the theoretical deduction and research hypotheses mentioned above, this paper constructs a two-way fixed effect model that controls both individual effect and year effect to empirically analyze the driving mechanism of enterprise digital transformation on green innovation output. The specific form of the benchmark regression equation is set as follows:

$$GI_{i,t} = \beta_0 + \beta_1 \times lnDT_{i,t} + \sum \beta_j \times Controls_{i,t} + \lambda_t + \mu_i + \varepsilon_{i,t} \tag{1}$$

Where GI_{it} represents the green innovation level of enterprise i in year t ; DT_{it} corresponds to the digital transformation of enterprise i in year t ; $Control_i$ represents the control variables affecting green innovation indicators; α_0 is the intercept term; λ_t is the time fixed effect; μ_i represents the individual fixed effect; ε_{it} represents the unobservable random disturbance term.

3.2. Sample selection and data sources

This paper takes the data of Shanghai and Shenzhen A-share listed enterprises from 2010 to 2022 as research samples, and the data are processed as follows: ① Eliminate enterprise samples that are ST, *ST and belong to the financial industry; ② Delete observation samples with serious missing core variable data; ③ To reduce the bias caused by extreme observations in the data, winsorize treatment at the upper and lower 1% quantiles is performed on all continuous variables. Relevant required data are basically obtained from CSMAR database, Wind database and annual reports of listed enterprises.

3.3. Variable definition

(1) Green innovation (GI) is the explained variable of this paper. The total number of green patents is defined as the sum of the number of applications for green invention patents and green utility model patents, which is used to describe the green innovation level of enterprises. Meanwhile, add 1 to the above sum and take the natural logarithm to alleviate the right-skewed distribution characteristic of the data.

(2) The explanatory variable is enterprise digital transformation (lnDT). Based on literature themed on digital transformation, annual reports of listed enterprises and policy documents, a feature lexicon is constructed. After constructing the feature lexicon, text extraction is performed on the company's annual reports, and then word frequency statistics are performed on the feature lexicon according to keywords in modules such as blockchain and cloud computing technology, and the results are aggregated. To alleviate the interference of extreme values, the study performs logarithmic smoothing on the initially counted word frequency scale, and introduces it as a proxy

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variable for the degree of digital penetration into the model. As the value of this variable increases, the digital coverage of enterprise operations becomes wider.

(3) Mediating variables: R&D investment, agency cost and analyst coverage. R&D investment (lnRD): Measured by the natural logarithm of the total R&D expenditure of the enterprise, which directly reflects the resource investment intensity of the enterprise in technological innovation.

Agency cost (AC): Drawing on the common practice in mainstream literature, this paper takes the management expense ratio as the proxy indicator, that is, calculated by dividing the enterprise's current year management expenses by operating income.

Analyst coverage (Analyst): This paper selects the total number of analyst teams that follow and research the company in the current year as the proxy variable of analyst coverage. If multiple analysts belong to the same team, they are counted once without repetition. This indicator reflects the degree of external information intermediary attention received by enterprises.

(4) Control variables: Referring to literature in related fields, this paper introduces the following control variables about enterprise nature characteristics into the regression model, as shown in Table 1.

Table 1. Variable definition

Variable Type	Variable Name	Variable Symbol	Variable Description
Explained Variable	Green Innovation Scale	GI	Ln (Number of independently applied green inventions in the current year + Number of independently applied green utility models in the current year + 1)
Explanatory Variable	Digital Transformation	lnDT	See definition above
Mediating Variable	R&D Investment	lnRD	Natural logarithm of total enterprise R&D expenditure
	Agency Cost	AC	Management expenses / Operating income
	Analyst Coverage	Analyst	Number of analyst teams following the company in the current year
Control Variable	Enterprise Size	Size	Natural logarithm of total enterprise assets
	Asset-Liability Ratio	Lev	Total liabilities / Total assets
	Return on Total Assets	ROA	Return on total assets
	Cash Flow Ratio	Cashflow	Net cash flow from operating activities / Total assets
	Firm Establishment Age	FirmAge	Ln (Current year - Year of company establishment + 1)
	Shareholding Ratio of the Largest Shareholder	Top1	Number of shares held by the largest shareholder / Total number of shares
	Management Shareholding Ratio	Mshare	Number of shares held by management / Total share capital

4. Analysis of empirical results

4.1. Descriptive statistics

According to Table 2, the mean value of enterprise green innovation (GI) is 0.3582, with a standard deviation of 0.7645, indicating that there are large individual differences in the green innovation

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level of Chinese enterprises. The mean value of enterprise digital transformation (lnDT) is 1.4248, with a standard deviation of 1.4149, indicating that many enterprises are actively promoting digital transformation, but the promotion levels vary among different enterprises. In addition, the mean value of R&D investment (lnRD) is 15.1113, the mean value of agency cost (AC) is 0.0873, and the mean value of analyst coverage (Analyst) is 9.7987, all within a reasonable range. The statistical characteristics of each control variable are basically consistent with existing literature.

Table 2. Descriptive statistics

Variable	Sample Size	Mean	Standard Deviation	Minimum	Maximum
GI	36236	0.3582	0.7645	0.0000	3.5264
lnDT	38418	1.4248	1.4149	0.0000	5.0752
lnRD	36090	15.1113	6.6508	0	21.6579
AC	38450	0.0873	0.0712	0	0.4668
Analyst	26539	9.7987	9.8797	1	44
Size	38510	22.1652	1.3007	19.5850	26.4297
Lev	38510	0.4146	0.2082	0.0274	0.9246
ROA	38509	0.0427	0.0672	-0.3750	0.2539
Cashflow	38510	0.0458	0.0697	-0.2244	0.2656
FirmAge	38497	2.8983	0.3514	1.0986	3.6109
Top1	38456	0.3423	0.1485	0.0806	0.7584
Mshare	37396	14.7201	20.2531	0.0000	70.5964

4.2. Benchmark regression analysis

Table 3 shows the estimation results of the impact of digitalization on enterprise green innovation output in the benchmark regression. Column (1) is the preliminary estimation that only controls time and individual fixed effects and has not introduced other control variables. The results initially show that the process of enterprise digitalization has a positive driving effect on green innovation. Column (2) introduces enterprise-level control variables. The regression results show that lnDT has a significant positive driving effect on green innovation, and this effect is statistically significant at the 1% level, thus confirming that the theoretical hypothesis H1 of this paper holds.

Table 3. Benchmark regression results

Variable	(1)GI	(2)GI
lnDT	0.0240*** (0.0037)	0.0191*** (0.0038)
Size		0.0453*** (0.0069)
Lev		0.0186 (0.0283)
ROA		0.0596 (0.0560)

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Table 3. (continued)

Cashflow		-0.0393 (0.0470)
FirmAge		0.0389 (0.0393)
Top1		-0.0208 (0.0455)
Mshare		0.0003 (0.0003)
_cons	0.3232*** (0.0058)	-0.7886*** (0.1854)
Time Fixed Effect	Controlled	Controlled
Individual Fixed Effect	Controlled	Controlled
N	35775	34752
Adjusted R2	0.6593	0.6619

Note: Robust standard errors are in parentheses; ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively; the same below.

4.3. Robustness checks

(1) Replace the core explanatory variable. Use text analysis to construct a word segmentation lexicon, then count the word frequency of keywords in the company's annual reports, and finally form the final DIGI_text index after standardization and other processing. Columns (1) and (2) of Table 4 report the test results. After replacing the measurement method of the core variable, the regression coefficient of DIGI_text is still positive at the 1% significance level, verifying the robustness of the core conclusion.

(2) Replace the explained variable. The previous benchmark regression mainly focuses on the output scale of innovation. The proportion of green patents submitted by enterprises is used to measure the intensity of enterprise green innovation activities. Secondly, focusing on invention patents with higher technical content, the development quality of enterprise green technology is measured according to the proportion of enterprise green invention applications in total invention applications. Green innovation intensity (GII) and quality (GIQ) are introduced as alternative explained variables. Columns (3) and (4) of Table 4 show that the estimated coefficients of enterprise digital transformation on green innovation intensity and quality are significantly positive at the 1% and 5% significance levels respectively, and multiple robustness tests confirm that this driving effect has reliable robustness in multiple evaluation dimensions.

(3) Lag the explanatory variable by one period. Given that digitalization enabling innovation may have a time-lag effect, and to a certain extent weaken the endogenous interference caused by reverse causality, the enterprise digital transformation (lnDT) is lagged by one period and recorded as lnDT-1. The empirical results in columns (5) and (6) of Table 4 show that the core explanatory variable

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lagged by one period still maintains a significant positive promotion effect on green innovation output, which again proves the robustness and reliability of the conclusions of this paper.

Table 4. Robustness checks

Variable	Replace Explanatory Variable		Replace Explained Variable		Lagged Explanatory Variable	
	(1)	(2)	(3)	(4)	(5)	(6)
	GI	GI	GII	GIQ	GI	GI
lnDT			0.0021 (0.0009)	0.0022 (0.0011)		
DIGI_text	2.1205*** (0.2734)	1.7758*** (0.2835)				
$lnDT_{-1}$					0.0230*** (0.0053)	0.0198*** (0.0054)
Control Variables	No	Yes	Yes	Yes	No	Yes
_cons	0.3311*** (0.0041)	-0.7017*** (0.1867)	0.0144 (0.0420)	0.0181 (0.0523)	0.3355*** (0.0071)	-0.5404 (0.3885)
Time Fixed Effect	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Individual Fixed Effect	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
N	35775	34752	34752	34752	30184	29304
Adjusted R2	0.6595	0.6620	0.4475	0.3778	0.6724	0.6753

4.4. Mediating effect test

To test the mechanism paths proposed above, this paper constructs the following stepwise regression model to systematically examine the intermediate conduction role of R&D investment, agency cost and analyst coverage (collectively referred to as mediating variable $Med_{i,t}$) in the process of digital transformation enabling enterprise green innovation. The model is set as follows:

$$Med_{i,t} = \alpha_0 + \alpha_1 \times lnDT_{i,t} + \sum \alpha_j \times Control_{i,t} + \lambda_t + \mu_i + \varepsilon_{it} \tag{2}$$

$$GI_{i,t} = \gamma_0 + \gamma_1 \times lnDT_{i,t} + \gamma_2 \times M_{i,t} + \sum \gamma_j \times Controls_{i,t} + \lambda_t + \mu_i + \varepsilon_{i,t} \tag{3}$$

According to the benchmark regression results above, the regression coefficient is significant and the total effect has been verified, so follow-up tests can be carried out. On this basis, the direction and intensity of the effect of digital transformation on mechanism variables are further tested. The

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results in columns (1), (3) and (5) of Table 5 show that enterprise digital transformation significantly increases R&D investment and analyst coverage, and significantly reduces agency costs.

Finally, both the explanatory variable $lnDT_{i,t}$ and the mediating variable $Med_{i,t}$ are included in the regression model for green innovation, and the results are shown in columns (2), (4) and (6) of Table 5. The regression results show that the estimated coefficients of the three mechanism variables all reach significant levels, and at the same time, the coefficient of lnDT is still significantly positive at the 1% confidence level. Thus, hypotheses H2a, H2b and H_2c are verified.

Table 5. Mechanism test results

Variable	Increase R&D Investment		Reduce Agency Cost		Improve Analyst Coverage	
	(1)lnRD	(2)GI	(3)AC	(4)GI	(5)Analyst	(6)GI
lnDT	0.0824*** (0.0313)	0.0191*** (0.0038)	-0.0010*** (0.0003)	0.0191*** (0.0038)	0.1938*** (0.0634)	0.0218*** (0.0049)
lnRD		0.0012* (0.0007)				
AC				-0.2048*** (0.0675)		
Analyst						0.0021*** (0.0005)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
_cons	0.3056 (1.5183)	-0.7892*** (0.1864)	0.5993*** (0.0160)	-0.6719*** (0.1893)	-93.5517*** (3.2602)	0.0174 (0.2596)
Time/Individual Fixed Effect	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
N	34591	34581	36902	34752	25205	24048
Adjusted R2	0.6971	0.6618	0.6815	0.6620	0.6108	0.6733

4.5. Heterogeneity analysis

(1) Regional heterogeneity. The research samples are divided into three groups: eastern, central and western regions according to geographical location, and group regression tests are carried out respectively. It can be seen from columns (1), (2) and (3) of Table 6 that the driving effect of digital transformation on green innovation is more significant in western and eastern regions, with regression coefficients of 0.0391 and 0.0194 respectively, but not significant in the central region. This feature may stem from the fact that the eastern region, benefiting from mature digital infrastructure networks and abundant professional and technical talents, can more smoothly convert digital potential energy into innovation dividends; while the western region has benefited from policy inclinations of national strategic digital infrastructure projects such as the "Western Development" and "East Data West Computing" in recent years. Due to the more considerable marginal returns generated by latecomer catch-up, digital upgrading has become a key engine leading its green leapfrog development.

(2) Whether the enterprise belongs to heavy-pollution industries. According to the industry classification catalogue issued by the Ministry of Ecology and Environment, the research samples are divided into two categories: heavy-pollution and non-heavy-pollution according to pollution attributes, and group regression tests are carried out respectively. Columns (4) and (5) of Table 6 show that the enabling effect of digitalization on green innovation is only significant in the group of

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non-heavy-pollution enterprises, but does not reach statistical significance in the sample of heavy-pollution industries, which reveals that this effect has distinct industry asymmetric characteristics. This indicates that non-heavy-pollution enterprises often have higher strategic flexibility and are easier to use digital technology to capture market opportunities in green and low-carbon transformation; while traditional heavy-pollution enterprises have strong asset specificity and high transformation sunk costs, and often adopt passive compliance strategies such as end-of-pipe treatment in the face of rigid environmental regulations, so digital means can play a relatively limited role in promoting innovation in their core green production processes.

(3) According to enterprise technical attributes. The research samples are divided into high-tech industry group and non-high-tech industry group for comparison. The regression results in columns (6) and (7) of Table 6 show that the promotion effect of digital transformation on green innovation is statistically significant in both sub-samples. Further inter-group coefficient difference test confirms that the estimated coefficient of the high-tech industry group is significantly higher than that of the non-high-tech industry group (empirical p-value = 0.010). High-tech enterprises themselves have strong digital genes and R&D heritage, and digital technology has a higher degree of integration with their R&D chains, so they can show a stronger "multiplier effect" when carrying out difficult green technology research.

Table 6. Heterogeneity test results

Variable	Regional Heterogeneity			Industry Pollution Degree Heterogeneity		High-Tech Industry Heterogeneity	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Western	Central	Eastern	Heavy Pollution	Non-Heavy Pollution	High-Tech	Non-High-Tech
lnDT	0.0391*** (0.0109)	0.0041 (0.0101)	0.0194*** (0.0045)	0.0073 (0.0114)	0.0189*** (0.0041)	0.0261*** (0.0056)	0.0068** (0.0049)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	1.7423*** (0.576)	-0.3399 (0.4930)	-1.1619*** (0.2212)	-0.8241 (0.5874)	-0.9571*** (0.2007)	-0.7746*** (0.2738)	-1.3156*** (0.2456)
Time/Individual Fixed Effect	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
N	4267	5382	24924	3895	30842	20969	13748
Adjusted R2	0.6026	0.6535	0.6721	0.4567	0.6736	0.6552	0.6457
Empirical p-value						0.010**	

5. Research conclusions and suggestions

On the basis of revealing the internal mechanism of enterprise digitalization level promoting green innovation, this study further tests the differentiated performance of this promotion effect in different regions and industries, and summarizes the following main findings: (1) The empirical results show that the digitalization process has significantly improved the level of enterprise green innovation, and the relevant estimation results remain highly consistent under different robustness frameworks, indicating that the main conclusion is not caused by sample specificity or setting sensitivity, and the conclusion has high credibility. (2) Enterprise digital transformation enables

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green innovation through three differentiated paths: strengthening R&D investment, reducing agency costs and improving analyst coverage. (3) The grouping test results confirm that the driving effect of digitalization on green innovation is not evenly distributed, but presents obvious asymmetric characteristics: from the geographical dimension, the driving effect of digitalization on enterprises in eastern and western regions is stronger; the digital dividend has structural imbalance at the industry level, and its boosting effect on environment-friendly innovation has obvious comparative advantages in high-tech industries and non-heavy-pollution sectors. Based on the above research conclusions, this study puts forward the following countermeasures and suggestions:

Deepen digital infrastructure and improve the guarantee system. Government departments should take digital technology as a key focus to promote the green and low-carbon upgrading of the economic system, and guide enterprises to accelerate digital transformation by formulating supporting and incentive policies. On the one hand, continue to deploy infrastructure such as cloud computing platforms and 5G base stations, reduce the threshold for enterprises to promote digital transformation, and consolidate the technical support for green innovation. On the other hand, when formulating industrial policies, we should strengthen the concept of "digital-green synergy", and introduce incentive measures such as special subsidies, tax reductions or accelerated depreciation, so as to guide enterprises to deeply embed digital technology into the green R&D system, thus fully releasing their internal momentum for substantive green innovation.

Deepen digital transformation and improve the internal control structure of the company. It is necessary for enterprises to elevate digital capability to the height of an overall strategy for overall planning. At the same time, we should actively build digital management platforms, optimize the allocation of R&D resources, use big data to accurately analyze technological evolution and market demand, reduce the losses caused by random exploration and ineffective experiments in innovation activities, and thus optimize the investment accuracy of green R&D funds. In terms of internal governance, enterprises should give full play to the inherent transparency advantage of digital technology and establish a sound internal monitoring and restraint system. With the help of digital management tools such as ERP systems and blockchain auditing, improve the transparency of enterprise operations, thereby reducing agency costs and realizing the implementation of substantive green innovation strategies.

Improve information disclosure and strengthen external supervision. Capital and information asymmetry are the core constraints of green innovation. Regulatory authorities should accelerate the improvement of digital information disclosure norms for enterprises' ESG performance, and guide enterprises to send positive signals of "digital empowerment for green" to the outside world. This can not only provide more reliable information for financial institutions to grant credit, but also guide analysts and investors to evaluate enterprises more accurately, realizing the overall drive of "information transparency - external supervision - resource injection".

Given that the driving effect of enterprise digital transformation shows significant structural differences, relevant policies should be formulated according to local conditions, and differentiated support strategies should be implemented to effectively bridge the technological gap in digital application. The selection of policy tools should not be limited to a single standard. For traditional heavy-pollution enterprises, the government should strengthen guidance rather than simply end-of-pipe punishment. A technical transformation reward and subsidy mechanism for low-carbon transformation can be constructed, and special fund injection can alleviate enterprises' financing constraints, effectively relieve the financing constraints and liquidity pressure faced by enterprises in the process of technological transition, and help them break through the practical constraints caused by weak transformation willingness and risk aversion mentality. For the central and western regions,

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we should continue to deepen the construction of computing power networks such as "East Data West Computing" to amplify their latecomer policy dividends; for high-tech enterprises and enterprises in developed eastern regions, we should encourage them to play a leading role, strive for international advanced levels in the digital integration R&D of key low-carbon technologies and cutting-edge zero-carbon technologies, and form a demonstration-leading industrial cluster effect.

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