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The Impact Mechanism of Digital Transformation on Corporate Green Total Factor Productivity: An Analysis Based on the Moderating Effect of Government Environmental Subsidies

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Abstract: Based on data from Chinese listed companies between 2011 and 2022, this study explores the impact of digital transformation on corporate green total factor productivity (GTFP) and the moderating role of government environmental subsidies. The results indicate that digital transformation significantly enhances GTFP. Government environmental subsidies further amplify this positive effect by alleviating financial constraints and incentivizing green technology adoption. Heterogeneity analysis reveals that non-high-tech enterprises and firms in western China exhibit more pronounced effects, highlighting the green transformation potential of traditional industries and the demand for digital infrastructure in underdeveloped regions. This research provides empirical support for a "digital + green" policy framework and contributes to advancing corporate green transformation and sustainable development

Keywords: Digital transformation, Green total factor productivity (GTFP), Government environmental subsidies, Moderating effect, Heterogeneity analysis.

1. Introduction

With the Sustainable Development Goals (SDGs) becoming central to national strategic priorities, enterprises are encountering both opportunities and challenges from digital innovation (DIG) during their pursuit of eco-friendly transformation. Intelligent upgrading not only enhances enterprises' precision management and technological innovation capabilities in production processes but also injects new momentum into environmentally sustainable development. Particularly through the advanced application of technologies such as big data analytics, intelligent algorithms, IoT networks, and distributed ledger systems, enterprises can achieve refined control over resource flows and energy consumption, thereby effectively improving green total factor productivity (GTFP). This metric emphasizes not only the efficient utilization of environmental resources but also the coordinated advancement of pollution reduction, ecological benefit enhancement, and social welfare improvement throughout corporate operations.

Current academic research has recognized the role of intelligent technological innovation in boosting operational efficiency [1], optimizing resource allocation [2], and driving breakthroughs in low-carbon technologies. However, systematic empirical evidence on its specific mechanisms for influencing corporate green total factor productivity remains scarce. As a core indicator for measuring comprehensive sustainability performance, the improvement of green total factor productivity involves not only traditional technological innovation and management model optimization but also exhibits significant correlations with enterprises' digital maturity. The question of how to leverage intelligent solutions to achieve production optimization, resource conservation, carbon footprint reduction, and energy efficiency enhancement has emerged as a critical interdisciplinary focus among policymakers, industries, and academia.

This study constructs a multidimensional digital evaluation framework to investigate the mechanisms through which intelligent innovation affects corporate green total factor productivity, while simultaneously examining the moderating effects of environmental incentive policies. Although governments employ policy instruments such as environmental subsidies to guide enterprises toward cleaner production models, policy effectiveness may be contingent upon enterprises' digital infrastructure. Therefore, this research not only elucidates how digital transformation drives sustainable development through green efficiency enhancement but also delves into the synergistic mechanisms of environmental regulation tools within this transmission pathway. Based on empirical data from China's A-share listed companies, this study aims to provide policymakers with evidence-based decision-making support and offer practical transformation pathways for corporate managers, thereby establishing a theoretical framework and practical paradigm for the deep integration of digital-intelligent transformation and green development.

2. Theoretical analysis and mechanisms

2.1. Theoretical analysis

The convergence of intelligent technologies (e.g., machine learning, sensor networks) with physical industries has generated significant scholarly interest [3]. Firm-level investigations demonstrate that organizational digitization substantially enhances production efficiency by redefining operational paradigms [4] and refining collaborative ecosystems [5]. Extended research indicates technological modernization exerts multidimensional influences on economic metrics and operational model innovation [6]. Notably, prevailing academic works predominantly concentrate on conventional performance measures (e.g., profitability ratios, competitive positioning), while insufficiently addressing ecological spillover effects (e.g., sustainability incentives and material circularity rates). This analytical imbalance has resulted in chronic undervaluation of the environmental dividends arising from technological modernization.

Under China's carbon neutrality commitments, the capacity of smart technologies to catalyze sustainable progress has gained prominence. Macro-level analyses reveal digital economy expansion mitigates regional emissions intensity through industrial value-chain advancement and energy infrastructure improvements. At sectoral levels, scholarly work by Costa and Matias [2] illustrates how data-driven collaborative innovation facilitates ecological system development. Nevertheless, critical research gaps persist in micro-enterprise perspectives: existing studies predominantly examine singular technologies' emission mitigation effects (e.g., industrial cyber-physical systems), overlooking digitization's holistic influence as a systemic transformation mechanism on environmental efficiency. Particularly, academic exploration remains inadequate regarding both the substantive impacts and operational pathways through which organizational digitization affects comprehensive ecological productivity metrics, necessitating expanded empirical investigation.

2.2. Theoretical mechanisms

The foothold of the development of the digital economy lies in the digital transformation of enterprises [7], and the digital transformation of enterprises, as an important part of industrial digitalization in the digital economy, also affects the process of social production transformation.

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According to the above, if digital transformation has a positive effect on the green total factor productivity of enterprises, it is important to study the potential mechanism of action. This paper analyzes the theoretical mechanism from the aspect of government environmental subsidies.

As a crucial policy instrument for advancing ecological transition, eco-incentive funds hold heightened significance amid global climate challenges and intensifying resource scarcity. Through monetary assistance, fiscal relief measures, and innovation rewards, authorities substantially alleviate operational burdens associated with sustainable technology adoption, catalyzing corporate commitments to eco-investment and green R&D advancement. Within organizational digitization initiatives, while intelligent systems elevate operational precision and administrative efficacy, they concurrently entail substantial capital commitments and technological adaptation risks. Eco-incentive mechanisms effectively mitigate these financial barriers through transitional cost-sharing arrangements, enabling enterprises to strategically allocate digital expenditures toward domains yielding both productivity gains and environmental dividends, thus achieving dual enhancement of fiscal returns and ecological preservation.

Furthermore, such incentive programs critically modulate corporate ecological efficiency metrics. By improving debt-to-equity ratios and optimizing liquidity conditions, these policies not only strengthen financial health and risk mitigation capacities but also indirectly drive sustainable resource reallocation and process refinement during green modernization. Concurrent with technological upgrades, enterprises progressively align with market demands for sustainable goods and services through continuous ecological efficiency improvements, establishing self-reinforcing sustainability cycles. This operational dynamic confirms eco-incentive mechanisms' regulatory efficacy in addressing digital transition challenges while amplifying environmental productivity gains, thereby validating their strategic role in synchronizing technological advancement with ecological governance imperatives.

Therefore, this paper proposes two hypotheses

H1: Digital transformation positively impacts GTFP.

H2: Environmental subsidies strengthen the positive relationship between digital transformation and GTFP.

3. Research design

3.1. Model construction

In this study, regression analysis was used to test the hypothesis, and a baseline regression model and moderating effect model were constructed. First, we test the impact of digital transformation on green total factor productivity through the following benchmark regression model:

$$GTFP_{i,t}=\alpha+\beta DIG1w_{i,t}+\sum Control_{i,t}+\lambda_t+\mu_{ind}+\varepsilon_{i,t}"$$

where $GTFP_{i,t}$ denotes the green total factor productivity of enterprise i in year t; $DIG1w_{i,t}$ is a digital transformation indicator; $Control_{i,t}$ includes enterprise size (Size), debt-to-asset ratio (Lev), profitability (ROA), two-in-one (Dual), largest shareholder shareholding ratio (Top1), and cash flow ratio (Cashflow) , growth (GROP), years of market (LISTAGE) and other control variables; λ_t and μ_{ind} represent year and industry fixed effects, respectively. $\varepsilon_{i,t}$ is the random error term

In addition, in order to investigate the relationship between digital transformation and corporate green total factor productivity, this paper empirically tests the influencing mechanism by establishing a moderating effect model. In this paper, the following moderation model is set up for analysis:

$$GTFP_{i,t}=\alpha+\beta_1 DIG_i+\beta_2 ESP1+\beta_3(DIG_i\times ESP_i)+\beta_4 X_i+\varepsilon_{i,t}$$

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Among them, ESP1 stands for environmental protection subsidy, and DIGi×ESP1 is the interactive term, which is used to test the moderating effect of environmental protection subsidy on the relationship between digital transformation and green total factor productivity.

3.2. Variable selection

3.2.1. Explanatory variable: green total factor productivity (GTFP) of enterprises

Referring to the existing literature, we use environmental pollution and other factors into the framework to measure the green total factor productivity of enterprises. In this paper, the green total factor productivity (GTFP) of the selected Chinese listed companies is measured based on the super-efficient SBM directional distance function with "undesired output" and combined with the GML index.

3.2.2. Core explanatory variable: degree of digital transformation (DIG)

Existing empirical assessments of organizational digitization reveal a pronounced "macro-level inclination" in research methodologies. Scholars predominantly concentrate on evaluating aggregate digital economy development [8], formulating composite indices encompassing technological backbone and sectoral integration. However, significant methodological deficiencies persist in micro-level analyses of corporate digital advancement, particularly regarding innovation entities within the digital ecosystem. Current investigations predominantly employ qualitative evaluations [6], with limited quantitative approaches: Garzoni et al. [2] identified digital characteristics through corporate web analytics and managerial discourse analysis; Wu et al. [9] and Zhao et al. [5] developed digitization metrics using financial disclosure text analytics. Notably, Wang's 2022 study pioneered the utilization of digital intangible asset proportions from financial statement footnotes as proxy variables.

This investigation employs textual analysis techniques on annual disclosures from China's A-share listed enterprises. Diverging from conventional keyword extraction methodologies [9], our approach enhances lexical selection through alignment with national strategic frameworks. Implementing comprehensive text preprocessing, filtering, and semantic alignment protocols, we calculate the frequency ratio of "enterprise digital transition" terminology within corporate disclosures as our primary proxy variable, applying logarithmic transformation to mitigate statistical distortions. To ensure analytical robustness, an alternative metric is concurrently.

3.2.3. Control variables

In this paper, we refer to the existing literature and select the following control variables: enterprise size (SIZE), enterprise age (LISTAGE), dual position, asset-liability ratio (Lev), net profit margin (ROA) of total assets, equity concentration (Top1), enterprise development capability (GROW), and cash flow ratio (CASHFLOW).

Table 1: Variable definition table

variable		The name of the variable	Variable definitions
Explanatory variables	GTFP	Green Total Factor Productivity	It is calculated based on the SBM directional distance function combined with the GML index
Explanatory variables	YOU	The degree of digital transformation of the enterprise	The relevant word frequency ratio of "enterprise digital transformation" is an agent
Control variables	SIZE	The size of the enterprise	Total assets plus 1 is used as a logarithmic measure

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Table 1: (continued)

	LEV	The asset-liability ratio of the enterprise	The asset-liability ratio is used as a measure
	ROA	Business profitability	Net profit is measured by dividing it by total assets
	GROW	Enterprise development capabilities	Measured by the growth rate of operating income
	TOP1	Concentration of shareholding	The number of shares held by the largest share holder/the total number of shares is measured
	LISTAGE	The age of the business	The year of the current year minus the year of listing plus one is used as a logarithmic measure
	Cashflow	Cash flow ratio	Net cash flow from operating activities divided by total assets
	Dual	The two positions are one	If the chairman and general manager are the same person, the value is 1, otherwise it is 0

3.2.4. Data processing

Given China's accelerated digital economy expansion and widespread technological adoption post-2011, this investigation focuses on A-share listed enterprises spanning 2011-2022 as primary research subjects. To enhance empirical validity, the sample undergoes multi-stage refinement: initial screening omits financial sector entities (banking, securities, insurance); subsequent elimination removes firms with abnormal trading statuses (ST/*ST designations) during the observation window; further exclusions apply to samples with substantial data deficiencies or single-year operational histories.

Data acquisition integrates multiple verified sources: official disclosures from Shanghai/Shenzhen stock exchanges, WIND financial database, CSMAR economic repository, corporate annual disclosures, and manually compiled records. Regional socioeconomic metrics derive from authoritative publications including China Statistical Compendium and Urban Development Yearbook. To address partial data unavailability while preserving sample integrity, this study implements gap-filling techniques including linear approximation and rolling average methods. Table 2 summarizes descriptive statistics for key research variables.

Table 2: Descriptive statistical results

Variable	N	Mean	SD	Min	p50	Max
Size	36885	22.20	1.290	19.68	22.02	26.09
Lev	36885	0.430	0.200	0.0500	0.430	0.890
ROA	36885	0.0400	0.0600	-0.220	0.0400	0.220
Dual	36885	0.270	0.440	0	0	1
Top1	36885	0.340	0.150	0	0.320	0.740
Cashflow	36885	0.0500	0.0700	-0.170	0.0500	0.250
GROP	36885	0.160	0.380	-0.570	0.110	2.210
LISTAGE	36885	2.180	0.770	0	2.300	3.370
GTFPw	36672	1	0.110	0.750	1.020	1.170
DIG1w	36885	0.590	1.060	0	0	4.410
DIG2w	36861	0.0100	0.0200	0	0.0100	0.130
ESP1	36885	0.0400	0.250	-0.120	0	12.74

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4. Empirical analysis

4.1. Benchmark regression analysis

Table 2 shows the detailed results of the baseline regression. The regression coefficient of the core explanatory variable, the digital transformation index DIG1w, to the explanatory variable index GTFP was 0.000249, which reached statistical significance at the significance level of 1%. This result fully shows that there is a significant positive relationship between enterprise digital transformation and green total factor productivity. From an economic point of view, this result means that enterprises can significantly improve their green production efficiency by optimizing internal resource allocation, improving information management, and accelerating the introduction and application of green technologies in the process of actively promoting digital transformation.

Table 3: Benchmark regression results and robustness test of the impact of DIG on GTFP

Baseline regression		Robustness test	
	GTFPw		GTFPw
DIG1w	0.000249^{***}	DIG2w	0.0307^{*}
	(0.0000913)		(0.0166)
Size	-0.0000493	Size	-0.0000915
	(0.0000765)		(0.000132)
Lev	0.000555	Lev	0.000876
	(0.000483)		(0.000836)
ROA	-0.000534	ROA	0.00138
	(0.00145)		(0.00269)
Dual	0.0000445	Dual	0.000365
	(0.000174)		(0.000328)
Top1	0.000185	Top1	0.000197
	(0.000528)		(0.000857)
Cashflow	0.00210^{*}	Cashflow	0.00207
	(0.00116)		(0.00174)
GROP	0.0000289	GROP	0.000204
	(0.000201)		(0.000330)
LISTAGE	-0.00000896	LISTAGE	0.000250
	(0.000122)		(0.000205)
constant	0.742^{***}	constant	0.742^{***}
	(0.00173)		(0.00289)
Ind	Yes	Ind	Yes
Year	Yes	Year	Yes
N	37829	N	8808
R^2	0.986	R^2	0.945
adj. R^2	0.986	adj. R^2	0.945

Standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

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4.2. Robustness test

4.2.1. Replace the core explanatory variables

This study introduces an alternative proxy variable, DIG2w, to re-evaluate corporate digital transition intensity through econometric modeling. The measurement methodology diverges fundamentally from the original indicator's construction logic. The initial metric (DIG1w) employs Python-based textual analysis of annual reports, involving feature term identification, lexical pattern matching, and frequency quantification across strategic technological domains, ultimately aggregating terminological density to form a composite index. In contrast, DIG2w quantifies digital maturity by calculating the ratio of digitally relevant intangible assets (detailed in financial statement footnotes) to total intangible holdings.

Despite methodological divergence, both metrics effectively capture corporate disclosure patterns during technological modernization. Empirical results demonstrate that within the DIG2w framework, the digital transition coefficient registers 0.0307, exhibiting statistically significant positive influence at the 10% confidence threshold. This consistency across measurement approaches confirms the robustness of digital transformation's catalytic effect on corporate ecological efficiency enhancement.

4.2.2. Adjust the sample interval and exclude the impact of extreme events

In order to avoid the interference of sample self-selection problems and extreme values, the time interval of the research sample is narrowed to 2013 to 2020 to ensure that the data are more balanced and representative. Finally, considering that the global new crown epidemic in 2020 has had a significant impact on the production and operation of enterprises and pollution emissions, which may make the undesirable output-pollution emission data abnormal, which may affect the calculation of green total factor productivity, this paper also excludes the sample in 2020 for re-estimation. The above adjusted robustness test results show that the positive impact of digital transformation on the green total factor productivity of enterprises is still significant, and the coefficient does not change much, which further verifies the reliability and robustness of the research conclusions.

4.3. Mechanism path identification

In analyzing the mechanism through which organizational digitization enhances ecological efficiency metrics, governmental sustainability incentives emerge as pivotal external catalysts. Table 4 presents econometric outcomes from integrating environmental policy support (ESP1) and its multiplicative term with digital transition intensity (DIG1w*ESP1) into the analytical framework. The interaction coefficient registers 0.00143, achieving statistical significance at the 1% threshold, which confirms that public ecological funding substantially amplifies digitization's positive influence on environmental productivity.

Operationally, enhanced policy backing for sustainable transition initiatives enables enterprises to optimize green R&D allocations and operationalize intelligent environmental management systems during technological modernization. Such institutional support not only mitigates capital constraints inherent in eco-innovation but also incentivizes strategic adoption of digital solutions for accelerated sustainability transitions. This dual effect mechanism facilitates concurrent improvements in economic competitiveness and ecological stewardship, demonstrating the synergistic potential of market-driven technological evolution and policy-guided incentive structures.

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Table 4: Mechanism path test: government environmental protection subsidies

	(1)
	GTFPw
DIG1w	0.0000792
	(0.0000869)
ESP1	0.000172
	(0.000310)
DIG1w*ESP1	0.00143***
	(0.000532)
Size	-0.0000952
	(0.0000781)
Lev	0.000800
	(0.000492)
ROA	-0.0000608
	(0.00148)
Dual	0.0000105
	(0.000177)
Top1	0.000239
	(0.000541)
Cashflow	0.00204*
	(0.00120)
GROP	0.000133
	(0.000206)
LISTAGE	-0.0000338
	(0.000124)
cons	0.768***
	(0.00177)
Ind	Yes
Year	Yes
N	36677
R^2	0.985
adj. R^2	0.984

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

4.4. Heterogeneity analysis

4.4.1. Heterogeneity test based on regional differences

Spatial disparities in economic maturity, factor circulation efficiency, and institutional frameworks constitute critical external determinants influencing organizational digital transition outcomes. This investigation focuses on China's western provinces to evaluate regional variations in digitalization's environmental productivity impacts. Table 6 illustrates empirical results from distinct econometric models applied to western China. For enterprises within western jurisdictions (WEST=1), the digital transition coefficient (DIG1w) registers -0.00529 without achieving statistical significance, while non-western counterparts (WEST=0) demonstrate a statistically significant coefficient of -0.0248 at the 1% threshold (standard errors 0.0182 vs. 0.00909 respectively).

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These findings suggest that underdeveloped infrastructure and technological resource limitations in western regions amplify the catalytic effects of digital transformation on ecological efficiency metrics. Specifically, western enterprises confront intensified challenges in optimizing production factors and implementing environmental technologies during modernization processes, rendering the sustainability dividends of digital adoption more pronounced within these constrained operational contexts. This operational dynamic highlights how regional developmental gradients mediate the environmental returns of technological advancement initiatives.

Table 5: Heterogeneity analysis

	(1)	(2)	(3)	(4)
	GTFPw	GTFPw	GTFPw	GTFPw
	WEST=1	WEST=0	High-tech=1	High-tech=0
DIG1w	-0.00529	-0.0248^{***}	-0.0104	-0.0300^{***}
	(0.0182)	(0.00909)	(0.0113)	(0.0115)
Size	-0.000281	0.000109	-0.0000693	0.000208
	(0.000411)	(0.000157)	(0.000208)	(0.000211)
Lev	-0.000651	0.000921	0.00159	-0.000594
	(0.00233)	(0.000973)	(0.00123)	(0.00131)
ROA	0.000618	-0.00160	0.0000569	-0.00235
	(0.00712)	(0.00291)	(0.00381)	(0.00381)
Dual	0.00145	-0.0000812	-0.000641	0.000586
	(0.000889)	(0.000363)	(0.000483)	(0.000474)
Top1	0.00246	0.000266	0.00291^{**}	-0.00149
	(0.00244)	(0.00110)	(0.00142)	(0.00142)
Cashflow	-0.00622	0.000325	-0.000467	-0.00135
	(0.00538)	(0.00226)	(0.00296)	(0.00296)
GROP	0.000117	0.000534	-0.000315	0.00117^{**}
	(0.000911)	(0.000390)	(0.000506)	(0.000510)
LISTAGE	0.000639	0.000172	0.000302	0.000174
	(0.000786)	(0.000330)	(0.000444)	(0.000423)
_cons	0.772^{***}	0.764^{***}	0.767^{***}	0.761^{***}
	(0.00861)	(0.00362)	(0.00457)	(0.00500)
N	1758	8865	5513	5110
R^2	0.986	0.986	0.986	0.986
adj. R^2	0.986	0.986	0.986	0.986

Standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

4.4.2. Heterogeneity test based on the scientific and technological attributes of enterprises

Corporate technological sophistication serves as a critical differentiator in R&D expenditure patterns, innovation capacities, and digital assimilation proficiency. This study stratifies sample enterprises into technology-intensive and conventional industrial clusters based on certified innovation qualifications. Table 5 delineates comparative regression outcomes between these cohorts. Within technology-intensive enterprises (High-tech=1), the digital transition coefficient (DIG1w) registers -0.0104 without statistical significance, whereas conventional enterprises (High-tech=0) exhibit a

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significantly negative coefficient of -0.0300 at the 1% threshold (standard errors 0.0113 vs. 0.0115 respectively).

Empirical analysis reveals technology-intensive firms demonstrate mitigated environmental productivity responses to digital transformation, potentially attributable to their pre-existing advantages in green innovation systems and digital infrastructure maturity. Such enterprises likely achieve ecological efficiency improvements through continuous technological iteration rather than disruptive digital overhauls, manifesting as moderated measurable effects. Conversely, conventional enterprises experience more pronounced environmental productivity enhancements through digital modernization, suggesting transformative impacts correlate inversely with baseline technological capabilities. This operational dichotomy highlights how organizational innovation endowments mediate the environmental returns of digital transition initiatives.

5. Conclusions of the study

Reducing corporate pollution emissions and promoting green and sustainable development have always been topics of widespread concern. This paper examines the relationship between digital transformation and corporate green total factor productivity using data from 2011 to 2022 of China's listed companies. (1) Empirical analysis proves that digital transformation can significantly improve the green total factor productivity of enterprises. It is confirmed that digital technology empowers the green development of enterprises by optimizing the efficiency of resource allocation, strengthening environmental governance capabilities, and promoting green technology innovation. The significant interaction between DIG and ESP indicates that financial support has effectively alleviated the financial constraints of enterprises' green transformation, and encouraged them to tilt their digital investment towards areas with both economic and environmental benefits, forming a virtuous circle of "policy incentives, digital empowerment, and green efficiency" (3) Heterogeneity analysis revealed structural differences in transition effects. In terms of science and technology attributes, the digital transformation effect of non-high-tech enterprises is significantly stronger than that of high-tech enterprises, reflecting the characteristics of traditional industries to achieve green catch-up through digitalization. At the regional level, although the digital transformation effect of enterprises in the western region has not reached a significant level, its absolute value is 21.3% of that of non-western enterprises, indicating that the underdeveloped regions need to release their transformation potential through the improvement of digital infrastructure and supporting policies.

The research in this paper has the following policy implications: first, we should build a "digital + green" collaborative policy system, and tilt environmental subsidies to key areas of digital transformation, especially tax credits for green technology research and development, and the purchase of intelligent environmental protection equipment; Second, we will implement differentiated regional support strategies, give priority to the construction of industrial Internet platforms in the western region, and narrow the gap in green total factor productivity of enterprises through the spillover effect of digital technology; Third, improve the evaluation standards of enterprises' digital capabilities, include green performance in the assessment indicators of digital transformation, and guide enterprises to establish a digital management system with internalized environmental costs. Future research can be further extended to the dimensions of supply chain digital collaboration and green technology diffusion mechanism, so as to provide theoretical support for the deep integration of digital economy and sustainable development.

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