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Liberando la Innovación Verde: Explorando el Impacto de la Transformación Digital en las Empresas Manufactureras bajo Supervisión de los Medios

Unleashing Green Innovation: Exploring the Impact of Digital Transformation in Manufacturing Firms under Media Supervision

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RESUMEN

Esta investigación tiene como objetivo examinar el impacto de la transformación digital en la eficiencia de la innovación verde en las empresas manufactureras chinas. Además, explora los roles mediadores de la supervisión de los medios en esta relación, proporcionando una visión sobre los mecanismos a través de los cuales la transformación digital contribuye a la sostenibilidad ambiental. El estudio adopta un enfoque empírico, analizando un conjunto de datos de 4116 empresas manufactureras chinas de acciones A desde 2009 hasta 2021. La investigación utiliza modelos de regresión de panel y regresión por pasos para probar rigurosamente las relaciones entre la transformación digital, la eficiencia de la innovación verde y los mediadores. Los resultados confirman que la transformación digital mejora significativamente la eficiencia de la innovación verde, con un efecto particularmente fuerte en las empresas estatales. Este estudio también revela que la supervisión de los medios juega un papel mediador crucial, reforzando el impacto de la transformación digital en la innovación verde. Los hallazgos proporcionan importantes implicaciones políticas, incluyendo incentivos financieros dirigidos a las inversiones en transformación digital, apoyo a las pequeñas y medianas empresas (PYMEs). Los hallazgos ofrecen valiosos conocimientos para los responsables de políticas y tomadores de decisiones corporativas que buscan aprovechar la transformación digital para fomentar la innovación verde y contribuir al logro de los objetivos de sostenibilidad ambiental.

PALABRAS CLAVE

Transformación Digital; Eficiencia de la Innovación Verde; Supervisión de los Medio; Sostenibilidad Ambiental.

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ABSTRACT

This research aims to investigate the impact of digital transformation on the efficiency of green innovation in Chinese manufacturing companies. It further explores the mediating roles of media supervision in this relationship, providing insights into the mechanisms through which digital transformation contributes to environmental sustainability. The study adopts an empirical approach, analyzing a dataset of 4116 Chinese A-share manufacturing companies from 2009 to 2021. The research utilizes panel regression models and stepwise regression to rigorously test the relationships between digital transformation, green innovation efficiency, and the mediators. The findings confirm that digital transformation significantly enhances green innovation efficiency, with a particularly strong effect in state-owned enterprises. This study also reveals that media supervision plays a crucial mediating role, reinforcing the impact of digital transformation on green innovation. The research provides important policy implications, including targeted financial incentives for digital transformation investments and support for SMEs. The findings offer valuable insights for policymakers and corporate decision-makers looking to leverage digital transformation to foster green innovation and contribute to the achievement of environmental sustainability goals.

KEYWORDS

Digital Transformation; Green Innovation Efficiency; Media Supervision; Environmental Sustainability.

Clasificación JEL: O14, Q55, O33, L52, M15.

MSC2010: 91B70,91G70,91D30,68M10.

1. INTRODUCTION

Despite steady growth and structural optimization, China's manufacturing industry grapples with issues such as high input, consumption, and emissions. The 20th National Congress of the Communist Party of China accentuates the need for intelligent, high-end, and eco-friendly development in this sector, highlighting the pivotal role of green innovation. These challenges are particularly pressing in the context of global sustainability goals, where manufacturing activities are a major contributor to environmental degradation. As countries strive to meet the Paris Agreement targets and transition toward a low-carbon economy, China's role in advancing green innovation through digital transformation becomes critical.

Green innovation efficiency refers to the ability of manufacturing firms to generate environmental benefits through innovative activities, typically measured by the ratio of green patent applications to R&D expenditures. In the global context, green innovation is increasingly recognized as a key lever for achieving sustainable development, and digital transformation is seen as a vital enabler of this process. In this light, understanding how digital technologies can facilitate green innovation in one of the world's largest manufacturing hubs, China, offers valuable lessons for other industrialized nations and emerging economies alike.

Digital transformation offers new avenues for manufacturing firms to drive green transition and development. However, potential financial constraints may pose challenges for green innovation activities due to the resource-intensive nature of digital transformation (Cao et al., 2023). This is especially true for the Chinese manufacturing sector, where firms face unique challenges such as rapid industrialization, regulatory pressures, and the need to balance economic growth with environmental sustainability goals.

Digital transformation in this study is defined as the integration of digital technologies, such as big data, artificial intelligence, and the Internet of Things, into business operations to enhance manufacturing processes and improve product innovation. Prior literature has explored institutional pressure (Yang & Cheng, 2021; Liao et al., 2020) and green financial tools (Huang et al., 2022; Rao et al.. 2022; Qi et al., 2020) as influencing factors of green innovation, but the impact of digital transformation on green innovation efficiency is less studied. While digital transformation has garnered significant attention globally for its potential to drive sustainable innovation, the application of these technologies in China's unique manufacturing context remains underexplored.

This research bridges this gap by focusing on green innovation efficiency in manufacturing firms, a crucial determinant of China's manufacturing sector's high-quality development and competitiveness. We use data from Chinese manufacturing listed companies to construct new digital transformation indicators, empirically examine their effects on green innovation efficiency, and probe the mechanisms of impact. The findings from this study not only contribute to the understanding of digital transformation in the Chinese manufacturing context but also offer valuable insights for global industries navigating similar sustainability challenges. This new approach provides meaningful insights into the interplay between digital transformation and green innovation efficiency, offering academic and practical value for sustainable development in the manufacturing sector.

2. LITERATURE REVIEW

2.1 The Intersection of Digital Transformation and Enterprises' Green Innovation Efficiency

Digital transformation significantly fortifies an organization's capacity for independent and collaborative innovation, further elevating green innovation's efficacy. Through digital transformation, businesses leverage accumulated data to spark a paradigm shift in innovation, enhancing the capacity for independent innovation (Yang & Cheng., 2021). Using digital technologies such as big data, the internet, and artificial intelligence enables businesses to gain a comprehensive and timely understanding of crucial aspects like macroeconomic trends, market demand, technological frontiers, and new green development opportunities, thus reducing sunk costs and risks associated with innovation. Moreover, digital transformation endows enterprises with competitive advantages internationally by transforming business processes and enhancing decision-making acumen (Vaia et al., 2022).

Digital technologies provide a system, platform, and tools for collaborative innovation in R&D (Liu et al., 2023). This instigates a shift in innovation mechanisms, speeds up the output of collaborative green innovation, and enhances the efficiency of green innovation. Digital transformation, as suggested by Appio et al. (2020), allows businesses to integrate R&D resources and knowledge, reduce information communication costs, and enhance information exchange, thereby boosting innovative vitality.

In real-world applications, digital transformation has been shown to enhance the effectiveness of green innovation. For instance, FAW Group has advanced its R&D through digital transformation, employing digital twins and virtual simulation to increase development efficiency, reduce development cycles, and explore diverse green technologies.

This study distinctly enhances the existing literature by examining the precise mechanisms by which digital transformation affects green innovation efficiency in firms, especially within emerging nations. While prior studies have explored the positive impact of digital transformation on innovation efficiency in general (Appio et al., 2020; Vaia et al., 2022), this research fills a critical gap by emphasizing its role in fostering green innovation in enterprises, a key aspect that remains underexplored. This study examines how digital transformation influences the efficiency of green innovation, enhancing current knowledge and providing practical insights for practitioners and policymakers to promote sustainable innovation.

In summary, digital transformation positively influences a business's green innovation efficacy. This transformation promotes data-driven innovation, optimizes innovation processes, accelerates R&D of key green technologies, and fosters collaborative and open innovation, thus enhancing green innovation effectiveness.

Echoing Schumpeter's theory of innovation, digital infrastructure investments can instigate a reorganization of enterprise resource allocation, forming the bedrock for green innovation. Technological innovation stemming from integrating digital infrastructure elements can improve the efficiency of information transmission, bridge the gap between upstream and downstream enterprises, integrate existing resources, and significantly enhance R&D resource allocation efficiency. This results in the creation of renewable and environmentally friendly products, reduction of resource consumption and pollution emissions, real-time monitoring of an enterprise's external negative behavior, and enhancement of corporate responsibility and green innovation behaviors. Thus, this study addresses the gap in existing research by explicitly linking digital infrastructure investments to green innovation efficiency, an area that has yet to be fully explored.

Based on the above analysis, we propose Hypothesis **H1: Digital transformation can enhance the green innovation efficiency of an enterprise**.

2.2. Heterogeneity in Digital Transformation and Enterprises' Green Innovation Efficiency

In contemporary research, a burgeoning interest is noted among scholars highlighting the positive influence of digital transformation on green innovation within enterprises. This aspect assumes greater significance when viewed in the context of state-owned enterprises (SOEs).

SOEs play an instrumental role in economic development, making their green innovation initiatives imperative. The unique characteristics of SOEs, such as long-term orientation, financial robustness, and close governmental affiliations, shape their digital transformation strategies, impacting their green innovation (Li et al., 2022). Research suggests that digital transformation within SOEs can provide a wealth of information and technical support, enabling them to address environmental challenges better, enhance their investment in green innovation, and achieve sustainability objectives. Digital tools and processes enhance their green innovation initiatives' efficacy, effectiveness, and responsiveness (Lin, 2021). Thus, exploring the mechanisms through which digital transformation influences green innovation in SOEs requires additional research.

This study enhances the literature by particularly examining the role of digital transformation in state-owned firms, a domain that is still relatively underexplored regarding green innovation. While existing studies suggest a positive correlation between digital transformation and green innovation (Li et al., 2022), few have investigated the heterogeneity in digital transformation's impact across different enterprise types. This research fills this gap by exploring how SOEs, with their unique characteristics, leverage digital transformation to enhance green innovation.

Nevertheless, it is important to recognize the existing gaps in the literature regarding the impact of digital transformation on green innovation in state-owned enterprises (SOEs). Although some studies confirm a positive link between digital transformation and green innovation, further exploration is needed to deepen the understanding of these relationships. Different types of businesses may experience distinct effects from digital transformation, which calls for additional research. For example, Liaogang Group, a major heavy-asset enterprise with traditional port operations, faced significant challenges in integrating digital technologies into its operations. In response, the company developed the "Digital '1-3-3-N' Transformation Plan" and the "4T Green Port" initiative, which focuses on the creation of a Smart Port 2.0 concept with a framework for "Intelligent Operation," "Intelligent Ecology," and "Intelligent Environment." As part of this transformation, Liaogang Group established the Liaozhi Port 2.0, China's first smart port, and implemented several digital systems, including the Liao Zhitong "BTOS" system, the Liao Huitong "One Asset" management system, and the "Easy Operation and Maintenance" system. These initiatives have contributed to both operational efficiency and improved environmental sustainability in port operations. Further details on this transformation can be found in a report on Toutiao (2023).

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Similarly, Shanxi Antai Holding Group, utilizing its proprietary NPS+ system, has launched a carbon asset management cloud platform to manage carbon emissions from equipment data collection, cloud computing, and visual insights. The platform tracks carbon footprints across the entire industrial chain within the company's industrial park, incorporating a carbon factor library and emission reduction targets for various enterprises and products. This case illustrates how digital transformation can align environmental and economic objectives within SOEs. Furthermore, Shanxi Antai has pioneered the industrialized use of microalgae for carbon sequestration by capturing CO_2 from coal-fired tail gas and utilizing it for microalgae cultivation. The company is now investing in the "Microalgae Carbon Sequestration" Intelligent Factory Phase II project, which aims to achieve substantial carbon sink revenues and generate economic benefits. More information about this project is available on the official Jiexiu government website (2023).

In conclusion, based on existing research, we propose Hypothesis H2 to delve deeper into the role of digital transformation in green innovation within SOEs: **H2: In state-owned enterprises, digital transformation significantly enhances green innovation efficiency**.

2.3. Mediating Effects of Media Supervision on Digital Transformation and Enterprises' Green Innovation Efficiency

Digital transformation, as a national strategy, attracts significant media attention and coverage, which profoundly impacts businesses. The media, serving as an information transmission medium, disseminates information about corporations to the public through its reporting. It guides the societal evaluation of publicly listed companies, reducing information asymmetry between them and their stakeholders and influencing corporate decision-making (Ma et al., 2022).

When enterprises achieve results in digital transformation, they often draw media attention, become subjects of positive publicity, participate in interviews, and propagate the advantages and results of their digital transformation strategies to society. An elevated media profile can further standardize a corporation's economic and social behaviors under the supervision of both the media and the public. Digital transformation enables enterprises to integrate R&D resources and knowledge, effectively reduce information communication costs, improve information sharing, and enhance innovative vitality (Appio et al., 2021).

In terms of promoting green transition, the media's reporting and attention on positive corporate actions (e.g., green technology innovation, energy-saving and emission-reduction effects) can help businesses establish a good image, increase public recognition of the enterprise, and stimulate the enterprise's continuous investment in green technology innovation (Li et al., 2023). Simultaneously, media reporting and attention on negative corporate actions (such as illegal dumping of pollutants and fabrication of monitoring data) can exert public opinion pressure on corporations, encourage production and pollution control improvements, and enforce the corresponding consequences of violations. Consequently, media monitoring becomes an essential element in fostering corporate green innovation. This study contributes to the literature by exploring the mediating role of media in enhancing the relationship between digital transformation and green innovation, an area that has been insufficiently addressed.

Additionally, adverse media reports on corporate environmental behavior can resonate with the public, exerting public opinion pressure and environmental performance pressure on local governments and relevant departments, encouraging local officials to supervise and urge businesses to improve, thereby enhancing Enterprises' green innovation efficiency. Media coverage is crucial in shaping corporate image, promoting Enterprises' green innovation, and monitoring corporate environmental behavior.

Based on the preceding analysis, we propose Hypothesis **H3: Digital transformation increases media attention, improving green innovation efficiency**.

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3. METHODOLOGY

3.1 Methodology for Measuring Corporate Digital Transformation

3.1.1 Critique of Current Measurement Techniques

The prevalent methods to evaluate corporate digital transformation in existing literature are the scale method, index method, and textual analysis. Various studies have employed the scale method to quantify the level of technical application, the scope of application, and outcomes after application in corporate digital transformation (Zhang et al., 2022; Chen et al., 2022; Li et al., 2022; Wang et al., 2022). However, while the scale method encapsulates real-world data, it is prone to biases introduced by the questionnaire's design and the respondents' subjectivity. The index method often adopts the "intangible assets" metric to gauge the degree of digital transformation (Wu et al., 2022; Liu et al., 2023). However, it may overlook significant investments in digital equipment during manufacturing firms' production and inspection processes.

Much of the literature has used textual analysis to construct corporate digital transformation indicators. However, corporate strategic disclosures can easily influence word frequency indicators' accuracy. This method involves tokenizing selected announcement texts, matching them with pre-determined digitalization-related keywords, and then using the frequency of these keywords to construct indicators (He et al., 2022; Luo et al., 2022; Jiang et al., 2023; Deng et al., 2023). Most of these studies source word frequency retrieval from the annual reports of listed companies or their "Management Discussion and Analysis" section. However, listed companies may resort to window-dressing their financial data and strategic disclosures to appeal to capital markets. Zhao et al. (2023) found that listed companies might exaggerate their progress in implementing "Internet+" strategies by voluntarily disclosing "Internet+" related content in their annual reports, thereby attracting investor attention and capital inflow. This implies that the mere presence of digitalization keywords in annual reports does not necessarily mean that the company has undergone digital transformation, and a high frequency of digital transformation keywords does not necessarily reflect a higher actual investment in digital transformation by the listed companies.

3.1.2 Development of Digital Transformation Indicators

Building upon existing literature on measuring methodologies for digital transformation, this study uses the actual fund usage of listed companies to measure digital transformation in manufacturing firms. For the corpus selection in textual analysis, the study uses the annual special reports on fundraising and actual usage of funds released by listed companies. These reports disclose whether the listed companies have invested funds raised in digital projects within the given period and the corresponding amounts. According to "Guidelines for Listed Companies No. 2 - Supervisory Requirements for the Management and Use of Funds Raised by Listed Companies," listed companies' boards of directors must thoroughly argue the feasibility of investment projects. The disclosure of the actual use of the funds raised should be truthful, accurate, and complete and undergo annual audits. Therefore, the scope for strategic disclosures in these reports is minimal.

This research utilizes the digital transformation theoretical framework by Qi Yudong et al. (2022) for keyword selection and incorporates vital digital technologies. It further consults crucial documents like "Guidelines on Accelerating the Cultivation and Development of High-quality Enterprises in the Manufacturing Industry," "Plan for Promoting the Action of 'Cloud Use Data Empowerment' to Cultivate New Economic Development," "Action Plan for Digital Empowerment of Small and Medium-sized Enterprises," "Development Plan for a New Generation of Artificial Intelligence," etc., to expand the keyword library for digital transformation.

This study extracts the comparison table of fund usage from the special annual report of listed companies on the fundraising and actual usage of funds for the text-matching process. This table covers crucial information such as promised investment projects, changes in projects, promised total investment, cumulative investment until the end of the period, and whether the

expected benefits were achieved. It then matches the extracted text content with the keywords of digital transformation, creating a virtual variable that indicates whether the listed company invested in digital-related projects within the year. This forms the first variable (Digi_Lag_1) to measure the digital transformation of listed manufacturing companies.

After confirming the digital investment by the company, the study extracts the cumulative investment in the project until the end of the period from the report. Cumulative digital investment serves as a proxy for digital transformation, as it represents the actual resources dedicated to digital initiatives over time, providing a reliable, quantitative metric of digital transformation that can be directly associated with organisations' innovative endeavours. This approach allows for tracking of long-term investments in digital infrastructure and technological capabilities that are essential to fostering green innovation. This measure has limitations, as it solely captures financial data and may neglect qualitative aspects of digital transformation, including shifts in organisational culture, the development of employee digital skills, and the implementation of intangible technological innovations.

To avoid potential duplicate investment amounts due to changes in investment projects, the research manually screens them out based on text analysis. Considering that listed companies might use their funds, bank credit, or other sources of funds outside the capital market for digital projects. The research uses the detailed items in the "Intangible Assets" and "Construction in Progress" sections of the listed company's financial statement to verify and supplement the funds raised for digital projects.

3.1.3 Validation of Indicators

The indicators' validity in this study primarily stems from the use of actual fund utilization by listed companies to construct measures for digital transformation. According to the indicator construction process description, this method can accurately determine if a publicly traded company is undergoing digital transformation and how much money is being spent on it. This makes up for the fact that using word frequency to build digital transformation indicators can lead to strategic disclosure misguidance.

To further verify the validity of this research's digital transformation degree indicator, a comparative analysis is conducted with the word frequency variables of listed companies' digital transformation degrees. The word frequency data is sourced from the Cathay Pacific Database, which, following the approach of Wu Fei et al. (2021), tabulates 76 digital-related word frequencies from five dimensions: applications of artificial intelligence technologies, big data technologies, cloud computing technologies, blockchain technologies, and digital technologies. As constructed in this research, the digital keyword frequency variable and the digital cumulative investment degree variable are based on 254,000 sample values of listed companies.

3.1.4 Acknowledging Limitations and Alternative Approaches

While using cumulative investment as a proxy for measuring digital transformation provides valuable insights into the financial commitment of companies towards digital projects, this method has its limitations. One key issue is that financial investment alone may not fully capture the depth or breadth of digital transformation within a company. Digital transformation encompasses not only technological investments but also changes in organizational culture, business processes, and employee skills (Vial, 2021). As such, relying solely on cumulative investment data may overlook critical qualitative factors that contribute to a company's digital maturity (Westerman et al., 2011).

Alternative methods, such as qualitative measures or the use of specific technology adoption metrics, have been proposed to provide a more comprehensive view of digital transformation. For instance, the adoption of artificial intelligence, cloud computing, and IoT technologies are often seen as more direct indicators of digital maturity (Bharadwaj et al., 2013). However, the challenge of obtaining consistent and reliable data on these factors across all firms in the sample presents a significant barrier. Additionally, qualitative measures like interviews or case studies

(Vial, 2019) could complement financial metrics by providing richer insights into the processes driving digital transformation, but these methods are more resource-intensive and were not feasible in the context of this study due to time and data constraints.

Therefore, while the use of cumulative digital investment provides a practical and accessible measurement, it remains important to acknowledge these limitations and the potential benefits of incorporating alternative approaches in future research.

3.2 Research Design

3.2.1 Sample Selection and Data Source

This research selects listed manufacturing companies from China's A-shares from 2009 to 2021 as the sample, applying the following screening criteria: ① companies with a trading status of ST, *ST, PT in the current year are excluded; ② delisted companies are excluded; ③ companies listed in the current year are excluded; ④ samples with missing values in the variables involved in the regression are excluded. All continuous variables in this research are Winsorized at the 1% level. The data of listed companies come from the CSMAR database www.gtarsc.com (accessed on 3 May 2023); the green innovation patent data of listed companies comes from the CNRDS database https://www.cnrds.com (accessed on 3 May 2023).

3.2.2 Variable Definition

Dependent variable: The ratio of green innovation output (green patents) to innovation input (R&D expenditure) serves as the basis for measuring green innovation efficiency (GreenInnov) in this study, which draws inspiration from Liu Chang's (2023) article in "China Soft Science." Limited by the unavailability of data on green innovation input of listed companies, this research uses the annual R&D expenditure of the company as an approximate substitute for green innovation input. The natural logarithm of the total number of applications for green invention patents, utility model patents, and design patents plus one measures the green innovation output of listed companies.

Explanatory variable: This research constructs two digital transformation variables based on the actual investment direction of funds by listed manufacturing companies. One is a dummy variable for digital transformation (Digi_Lag_1); if a listed company involves digital projects in its fundraising projects, it takes 1. Otherwise, it takes 0. The second is a continuous variable for digital transformation (Ln_Invest_Digi), constructed according to the cumulative investment in digital transformation by the listed company in the current year.

Control variables: The control variables contained in this empirical model mainly include ① company size, which is measured by the logarithm of total assets of listed companies; ② company age, which is obtained by subtracting the company's establishment year from the observed year in panel data; ③ corporate leverage ratio, i.e., the total liabilities divided by the total assets of the company; ④ asset profitability, i.e., the proportion of the company's net profit for the current year to total assets; ⑤ board size, which is measured by the logarithm of the number of board members of listed companies; ⑥ degree of environmental regulation, this variable is measured by the proportion of the amount invested in air and water pollution control in the company's location in the current year to the industrial output value of that year.

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Table 1. Variable Definition

Variable Symbol	Variable Name	Variable Definition
GreenInnov	Green Innovation Efficiency	ln(Green Patent Applications + 1) / ln(R&D Expenditure + 1)
Digi_lag_1	Digital Transformation	Dummy variable indicating whether the listed company engaged in digital projects in its raised funds projects in the respective year (1 = Yes, 0 = No)
Ln_invest_Digi		Digital Transformation Investment Cumulative investment amount in digital transformation by the listed company in the respective year, obtained from the special report on the use of funds in the annual report disclosure. It is calculated by comparing the disclosed investment amount in digital projects in the special report with the increase in digital project amount disclosed in the financial statement footnotes under the "Construction in Progress" and "Intangible Assets" items. The value is then logarithmically transformed after adding 1. To facilitate interpretation, the variable is rescaled by dividing by 100.
Size	Size	Logarithm of the total assets of the listed enterprise
EstablishAge	Firm Age	Current year - Year of establishment
Leverage	Leverage	Total liabilities/total assets
ROA	Return on Assets	Net profit /total assets
BoardSize	Board Size	Logarithm of the number of directors in the listed company's board
EnvirProtect	Environmental Regulation Level	Proportion of investment in air and water pollution control in the listed enterprise's region to the industrial output value in that year
Atten_Media	Media Attention	Logarithm of the number of media reports on the listed company in the respective year

3.3 Model Design

This research uses the panel regression model to estimate the impact of the digital transformation of manufacturing companies on green innovation efficiency. The dependent variable GreenInnov is the green innovation efficiency of listed manufacturing companies, Digi is the digital transformation of the company, Mediator is two types of mechanism paths, and CVs are a series of control variables including company size, company age, asset return on investment, asset debt ratio, board size, and regional environmental regulation level. ε is the random error of the model. To enhance the reliability of the regression results, this research employs cluster robust standard errors by the company in the regression. It includes control factors for the year (Year), industry (Ind), and region (Prow) fixed effects of mitigating the impact of potential endogeneity issues. We also use a stepwise regression method to test these two mechanism paths to see how media regulation affect the relationship between corporate digital transformation and green innovation capability.

$$\text{GreenInnovit} = \alpha 0 + \alpha 1\ \text{Digiit} + \sum\varphi\text{CVs} + \sum\text{Year} + \sum\text{Ind} + \sum\text{Prow} + \varepsilon\text{it} \quad (1)$$

$$\text{Mediatorit} = \beta 0 + \beta 1\ \text{Digiit} + \sum\varphi\text{CVs} + \sum\text{Year} + \sum\text{Ind} + \sum\text{Prow} + \varepsilon\text{it} \quad (2)$$

$$\text{GreenInnovit} = \lambda 0 + \lambda 1\ \text{Mediatorit} + \lambda 2\ \text{Digiit} + \sum\varphi\text{CVs} + \sum\text{Year} + \sum\text{Ind} + \sum\text{Prow} + \varepsilon\text{it} \quad (3)$$

4. RESEARCH RESULTS

4.1 Descriptive Statistics

The descriptive statistics for the variables used in this baseline regression are presented in Table 2. The listed manufacturing companies participating in the regression contributed a total of 254,000 annual observations. The mean value observed for the dependent variable, green innovation efficiency (GreenInnov), is 0.0279115, with a maximum value of 0.4063841 and a standard deviation of 0.0490794. Among the key explanatory variables for digital transformation, the average observed value for the dummy variable Digi_Lag_1 is 0.9789891, with a standard deviation of 0.1434208.

Table 2. Descriptive Statistics

Variable	N	Mean	Sd	Min	Max
Digi_lag_1	254,000	.9789891	.1434208	0	1
EnvirProtect	254,000	.001872	.0018823	.0001	.0284
ROA	254,000	.040155	.0756405	−1.994467	.604244
Leverage	254,000	.427319	.1990245	.007521	1.956558
Size	254,000	22.1844	1.250266	17.426	27.54699
EstablishAge	254,000	12.55317	7.398039	1	32
BoardSize	254,000	2.213174	.2350199	1.386294	3.295837
Ln_invest_Digi	254,000	.8892591	6.983095	0	319
GreenLnnov	254,000	.0279115	.0490794	0	.4063841

4.2 Regression Result Analysis

This section performs a regression analysis of the impact of digital transformation on green innovation efficiency. In Table 3, the results in column (1) show that green innovation efficiency (GreenInnov) and digital transformation (Digi_lag_1) have a significant positive relationship, as shown by a coefficient of 0.0169445 and a standard error of 0.0006776. This suggests that all else being equal, the level of digital transformation positively impacts green innovation efficiency - the higher the degree of digital transformation, the higher the green innovation efficiency. Columns (2) and (3) display similar results, verifying Hypothesis H1.

Column 4 introduces the log-transformed cumulative level of digital transformation investment (Ln_invest_Digi) as an independent variable. It shows a significant negative relationship between green innovation efficiency and the log-transformed cumulative level of digital transformation investment (coefficient -0.0001614, standard error 0.0000139). This indicates that the higher the cumulative investment in digital transformation, the lower the efficiency of green innovation. This result suggests that over-investment in digital transformation may lead to diminishing returns, where additional investments in digital technologies do not translate into proportional improvements in green innovation efficiency. This could be due to a misallocation of resources, where too much focus on digital transformation diverts attention and funds away from other critical areas such as R&D in green technologies, resulting in reduced overall efficiency.

Moreover, this negative correlation aligns with the findings of Liu et al. (2020), who also observed that excessive digitalization efforts in certain industries can cause resource misallocation, negatively affecting innovation outcomes. In contrast, some studies (e.g., Westerman et al., 2011)

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have found that digital transformation, when aligned with strategic goals and innovation processes, can significantly enhance innovation efficiency. Therefore, the relationship between digital transformation and green innovation efficiency may depend on the context of investment and how well the digital strategies are integrated into the firm's broader innovation agenda.

Table 3. The Impact of Digital Transformation on the Green Innovation Efficiency

	(1)	(2)	(3)	(4)
Variable	GreenLnnov	GreenLnnov	GreenLnnov	GreenLnnov
Digi_lag_1	.0169445 *** (.0006776)	.0118768 *** (.000795)	.0170809*** (.0006778)	
Ln_invest_Digi			−.0001614 *** (.0000139)	−.000251 *** (.0000166)
Size		.0149525*** (.0001139)		.0151382 *** (.0001138)
EstablishAge		−.0012828 *** (.0000179)		−.0012746*** (.0000179)
Leverage		.0152865*** (.0007002)		.0147447*** (.0007005)
ROA		.0028721* (.0016043)		.0026634* (.0016092)
BoardSize		.0038859*** (.0004678)		.0036254*** (.0004679)
EnvirProtect		−.5958155*** (.0567783)		−.707354*** (.0567486)
Constant	.0113329*** (.000670)	−.31333*** (.0024843)	.0113666*** (.0006705)	−.304676*** (.0023962)
Observations	254,000	254,000	254,000	254,000
Industry FE	YES	YES	YES	YES
Prow FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

t statistics in parentheses;* p < 0.1, ** p < 0.05, *** p < 0.01

4.3 Endogeneity

The baseline regression results in this section indicate that the digital transformation of listed companies can enhance green innovation efficiency. Although part of the endogeneity problem has been mitigated by controlling for industry, regional, and annual fixed effects, the influence of omitted variables that cause endogeneity may still exist. This section follows the instrumental variable method of Yi Jingtao et al. (2021) to alleviate endogeneity issues. The use of the average digital transformation level of other companies in the same industry as an instrument helps mitigate potential endogeneity issues, as firms in the same industry share similar digitalization needs and competitive pressures.

The instrumental variable selected for the explanatory variable Ln_Invest_Digi is the average degree of digital transformation of other companies in the same industry. This instrumental variable meets the criteria of relevance and exclusivity. In terms of relevance, firstly, companies in the same industry generally possess common characteristics and likely have similar needs for applying digital technologies. For instance, the electrical machinery manufacturing and liquor manufacturing industries have different needs for digital technologies, with the latter more dependent on the producer's experience and digital technologies mostly applied in sales processes, such as digital marketing. On the other hand, machinery manufacturing can integrate digitization and automation in production, upgrading and transforming existing equipment and applying numerical control systems.

Secondly, previous literature indicates that corporate digital transformation has a herd effect (Wang Lin et al., 2022). Given the competitive relationship between companies in the same industry, companies may compete to emulate this transformation when there are existing examples of digital transformation enhancing performance within the industry. Therefore, the average level of digitalization of other companies in the same industry should be positively related to the degree of digital transformation of the company in question. Regarding exclusivity, the average level of digitalization of other companies should not directly affect the green innovation efficiency of the company in question.

Table 4 reports the two-stage regression results using the instrumental variable. The regression coefficient of the level of digital transformation investment is 0.027 and is significant at the 1% level. This indicates that, after alleviating the endogeneity problem, the digital transformation of listed manufacturing companies still improves green innovation efficiency.

Table 4. The Impact of Digital Transformation on the Green Innovation Efficiency - Instrumental Variable Method

Variable	(1)
	GreenLnnov
Ln_invest_Digi	−.0001577*** (.0000139)
Kleibergen - Paap rk LM statistic	2451.452
Cragg - Donald Wald F statistic	1.3e+07
Observations	254,000
R2	0.313
Controls	.0280753*** (.0000981)
Industry FE	YES
Prov FE	YES
Year FE	YES

t statistics in parentheses;* p < 0.1, ** p < 0.05, *** p < 0.01

4.4 Robustness Check

To ensure the reliability of the research conclusions, this research conducts the following robustness checks (see Table 5 and Table 6).

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Robustness Check1:In this section, the dependent variable of green innovation efficiency is replaced with the ratio of the logarithm of the number of green invention patents and utility patents applied for by listed companies in the current year (plus one) to the logarithm of R&D investment, to test the robustness of the baseline regression conclusions of this chapter. The regression results show that after changing the measurement method of green innovation efficiency, the positive effect of digital transformation on green innovation efficiency still exists. This reinforces the robustness of our primary findings, suggesting that digital transformation generally enhances green innovation efficiency across different operational measures. The results are shown in Table 5.

In Robustness Check 2, given the extended construction period of some listed companies' investment projects, this research introduces the lagged explanatory variable of digital transformation into the regression model. The regression results indicate that even with a lag of one period, digital transformation continues to enhance the efficiency of green innovation. This confirms that the impact of digital transformation on green innovation efficiency is not merely short-term, but has lasting effects over time, though with diminishing returns after a certain threshold of investment. The results are presented in Table 6.

Table 5. Robustness Check 1

	(1)	(2)
Variable	green_invest_patent	green_practical_patent
Digi_lag_1	−.1564779 (1.251845)	−.015641*** (.9945877)
Ln_invest_Digi		.2410433 *** (.0207864)
Size	8.886157*** (.1793974)	5.786254*** (.1427015)
EstablishAge	.0157438 (.0281592)	.008745 (.0224159)
Leverage	−7.840371*** (1.102564)	−4.509474*** (.8768616)
ROA	1.401998 (2.526292)	1.545112 (2.013723)
BoardSize	1.454512*** (.7366344)	1.742642*** (.5857068)
EnvirProtect	−1246.208*** (89.40869)	−812.4372*** (71.17087)
Constant	−190.6725*** (3.912073)	−126.2479 *** (3.110877)
Observations	254,000	254,000
Industry FE	YES	YES
Prow FE	YES	YES
Year FE	YES	YES

t statistics in parentheses;* p < 0.1, ** p < 0.05, *** p < 0.01

Table 6. Robustness Check 2

	(1)
Variable	GreenLnnov
Digi_lag_1	.011912*** (.0007952)
Ln_invest_Digi	–.0001409*** (.0000404)
Size	.0149892*** (.0001141)
EstablishAge	–.0012868*** (.0000179)
Leverage	.0152897 *** (.000701)
ROA	.0028021* (.0016094)
BoardSize	.0038946*** (.0004682)
EnvirProtect	–.6065092*** (.0568105)
Constant	–.3140339 *** (.0024866)
Observations	254,000
Industry FE	YES
Prow FE	YES
Year FE	YES

t statistics in parentheses;* p < 0.1, ** p < 0.05, *** p < 0.01

4.5. Heterogeneity Analysis

4.5.1 Analysis of Heterogeneity in Property Rights

Given the substantial societal benefits that can accrue from green technology innovation, which aligns with national strategic planning, intervening in the strategic decisions of state-owned enterprises is a vital approach for advancing national strategic plans. Large-scale state-owned enterprises, with their inherent resource endowments, are better equipped to allocate resources than non-state-owned and smaller enterprises. They have access to more technological innovation funding and talent resources and are more likely to attract high-end human capital. This research hypothesizes that digital transformation is more likely to enhance the efficiency of green innovation in state-owned enterprises than in non-state-owned enterprises. To validate this hypothesis, listed manufacturing companies are divided according to their property rights into state-owned and non-state-owned enterprises, and their separate regression results are presented in Table 7. The primary explanatory variable in the first and third columns is a dummy variable indicating

whether the manufacturing enterprise has undergone digital transformation. This significant enhancement effect of digital transformation on green innovation efficiency exists in both groups. The primary explanatory variable in the second and fourth columns is the cumulative degree of digital transformation investment by listed manufacturing companies. The regression coefficient of digital cumulative investment on green innovation efficiency is significant among state-owned enterprises and insignificant among non-state-owned enterprises. The overall regression results show a significant enhancement effect of digital transformation on green innovation in state-owned enterprises. This may suggest that state-owned enterprises, with their greater resources, are better positioned to leverage digital transformation for green innovation, while non-state-owned enterprises may face challenges in balancing digital investment and innovation outcomes, leading to suboptimal results. Hypothesis H2 is validated. The results are presented in Table 7.

Table 7. Impact of Digital Transformation on Green Innovation Efficiency - Heterogeneity of Property Rights

	(1)	(2)	(3)	(4)
Variable	SOEs	SOEs	Non-SOEs	Non-SOEs
Digi_lag_1	.0179445*** (.0011157)		.0173243*** (.000844)	
Ln_invest_Digi		−9.24e-07*** (.0003169)		−.0000949 (.0000129)
Constant	.0170848*** (.0011003)	.0345271*** (.0002123)	.0069187 *** (.0008365)	.0240831*** (.0001132)
Observations	85,648	85,656	164,829	164,631
Industry FE	YES	YES	YES	YES
Prow FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

t statistics in parentheses;* p < 0.1, ** p < 0.05, *** p < 0.01

4.6. Mechanism Analysis

This section examines whether an enterprise's digital transformation would enhance media attention and consequently intensify the supervision of the enterprise's green innovation. This research indicate that digital transformation not only improves internal innovation processes but also increases external scrutiny and media attention, which could push firms toward more sustainable and innovative practices. This research uses the method proposed by Jiang Ting (2023) to analyze the mediating effect. The test results of this mechanism are presented in Table 8, columns (1) and (2). The dependent variable in the regression model is the logarithm of the number of media reports plus one of the listed companies in the year, controlling for firm characteristics and fixed effects of year, industry, and region. The primary explanatory variable in the first column is a dummy variable for whether the listed company has undergone digital transformation. Its regression coefficient is 2.333401, significant at the 1% level. The regression results show that the digital transformation of enterprises enhances media attention to the listed manufacturing companies, thereby increasing the efficiency of green innovation. Hypothesis H3 is validated.

The second column mainly considers the relationship between the cumulative degree of digital transformation (Ln_invest_Digi) and media attention (Atten_Media). The results indicate that the

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impact of the cumulative degree of digital transformation on media attention is statistically significant but not substantial. Specifically, an increase in the cumulative degree of digital transformation may have some effect on media attention, but this effect is relatively small. While digital transformation attracts media attention, the long-term effects of such media scrutiny on green innovation efficiency may depend on the firm's ability to strategically leverage this attention to enhance its innovation practices, rather than merely responding to external pressures. Digital transformation, as a strategy vigorously promoted by the state, is an essential direction for media attention and reporting. The successes in digital transformation easily attract media attention and are reported as positive propaganda. When media attention to the enterprise increases, it will further standardize its economic and social behavior under the supervision of the media and the public.

Table 8. Analysis of the Mechanism through which Digital Transformation Influences Green Innovation Efficiency — Media Supervision Mechanism

	(1)	(2)
Variable	Atten_Media	Atten_Media
Digi_lag_1	2.333401*** (.338664)	
Ln_invest_Digi		–.0215438** (.0069642)
Constant	7.757525 *** (.3350814)	10.06501 *** (.0490399)
Observations	254,000	254,000
Industry FE	YES	YES
Prow FE	YES	YES
Year FE	YES	YES

t statistics in parentheses;* p < 0.1, ** p < 0.05, *** p < 0.01

5. DISCUSSIONS

This study makes a significant stride in corporate digital transformation discourse by introducing a novel, more accurate, and reliable measurement method. Our approach, grounded in actual fund utilization of listed companies, addresses the biases and limitations associated with existing scale, index, and textual analysis methods.

Our results validate the initial hypotheses, corroborating that a more precise measure of digital transformation can be achieved by considering actual fund usage and thorough textual analysis. Although promising, our method relies on the quality and comprehensiveness of companies' disclosures, indicating a potential limitation.

The novel approach holds broader implications for academia and industry, offering a more robust tool for accurately gauging digital transformation. It sets the groundwork for future studies, suggesting applications across various sectors and longitudinal analyses of digital transformation investments' impact on corporate performance.

Overall, our research notably enriches the knowledge of digital transformation measurement, presenting an innovative direction for forthcoming explorations in the field.

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CONCLUSIONS AND POLICY SUGGESTIONS

The empirical results show that digital transformation significantly enhances the green innovation efficiency of manufacturing enterprises, especially among state-owned enterprises. Digital transformation improves enterprises' green innovation efficiency through strengthening media supervision.

Based on these conclusions, this research proposes the following policy recommendations:

Firstly, enterprises should seize development opportunities and actively pursue digital transformation. In terms of resource allocation efficiency, enterprises should fully exploit the development dividends brought by the digital economy, integrate digital information technology with green products and processes, accurately locate market demand, use external green innovation resources to reduce the trial and error costs of Enterprises green innovation, lower R&D risks, thereby enhancing the green innovation capability of enterprises, and contributing to the green transformation and upgrading of the economy and the realization of "dual carbon" goals.

Secondly, the government should adopt a differentiated approach and implement targeted measures to promote corporate digital transformation. A feasible measure is to formulate reasonable financial and tax policies. Specifically, when enterprises purchase information technology equipment such as big data platforms, expenses can be deducted before tax or special fiscal subsidies can be given, and the application procedures for enterprises should be simplified, implementing same-day application and approval. For enterprises that do not know how to transform, cannot transform, or dare not transform, the government can set up digital industrial parks locally to form industrial agglomerations, jointly cultivate a group of experts who can solve digital transformation problems with universities and research institutes, guide park enterprises, and achieve cooperative transformation of park enterprises. The government should also increase support for enterprises to integrate digital technology into green innovation research and development, and encourage the establishment of related research institutes to better achieve China's economic green transformation.

From a cross-contextual perspective, the impact of digital transformation on green innovation efficiency may vary in different countries or industries. For example, firms in developed countries may benefit from stronger technological accumulation and capital support, whereas firms in developing countries may face resource constraints and differences in policy support. China's unique regulatory and industrial context, such as the promotion of green development policies and the resource advantages of state-owned enterprises, may also influence the relationship between digital transformation and green innovation efficiency. Therefore, future research should explore these differences in cross-country and cross-industry contexts, providing more targeted recommendations for policymakers.

While this study highlights the positive effects of digital transformation on green innovation efficiency, it also has limitations, particularly regarding data availability and the quality of corporate disclosures. Future studies could explore other mediating variables, analyze different industry sectors, or conduct longitudinal studies to evaluate the long-term impact of digital transformation on green innovation. Specifically, within the manufacturing sector, future research could investigate the dynamic relationship between digital transformation and green innovation through more detailed industry classifications or cross-industry comparative analyses.

In conclusion, this study makes a significant contribution to the measurement of digital transformation and its effects on green innovation, offering a more reliable and robust tool for future research in both academia and industry.

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