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A Study of the Impact of Digital Transformation on Corporate Environmental Performance: A Green Innovation-based Perspective

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Abstract: Amidst the escalating global climate crisis and mounting environmental protection consciousness, digital transformation and green innovation have emerged as pivotal strategies for enterprises to pursue sustainable development. Both businesses and governments are increasingly recognizing the importance of environmental stewardship, not only by enacting policies at the governmental level but also by integrating green principles into their operational practices. Simultaneously, through embracing digital transformation, companies are not only enhancing operational efficiency but also achieving resource optimization and recycling, thereby fueling sustainable growth. This highlights the synergy between technology and environmental protection as a key driver of healthy and green socio-economic development worldwide.Digital transformation is catalyzing green innovation through the integration of advanced digital technologies, not only by injecting new vitality into the process but also by optimizing internal business processes, significantly boosting operational efficiency, and strengthening green supply chain management mechanisms. This comprehensive approach enables companies to achieve higher environmental performance goals.This study meticulously analyzes empirical data from Chinese A-share listed companies, elucidating how digital transformation and green innovation specifically contribute to environmental performance improvement. It further validates the mediating role of green innovation as a crucial mechanism linking digital transformation to enhanced environmental performance.The findings reveal that the digital transformation of enterprises significantly boosts their environmental performance, positively impacting their sustainable development by accelerating the pace of green innovation. This study enriches the theoretical framework in the domain of digital transformation and green innovation, offering a novel perspective through empirical analysis, thus propelling the advancement of theory in this field.

Keywords: Digital transformation, green innovation, corporate environmental performance, mediating role.

1. Introduction

In recent years, in pursuit of the "dual-carbon" goal, China's government has enacted a series of energy-saving and emission-reduction policies, compelling enterprises to assume their

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responsibilities for energy conservation, emission reduction, and green development, thereby accelerating the pace of green transformation and technological innovation. Amidst this backdrop, digital transformation has emerged as a pivotal avenue for enterprises to revamp and upgrade their operations. Enterprises have injected new impetus into green innovation by integrating advanced technologies such as big data, cloud computing, and artificial intelligence. This digital shift not only streamlines business processes and boosts operational efficiency but also catalyzes green innovation through data-driven decision-making, intelligent production and operation, and green supply chain management. These endeavors effectively reduce resource consumption and waste emissions, enhance energy efficiency, strengthen environmental management capabilities, and foster the development of a green innovation culture. Consequently, it holds significant theoretical and practical importance to explore how digital transformation empowers enterprises' green innovation development and impacts their environmental performance.

According to existing research, green innovation can significantly improve the environmental performance of enterprises by optimizing resource allocation and reducing environmental load. However, enterprises also face challenges such as high risk and high cost in the process of implementing green innovation. With the continuous advancement of digital technology, digital transformation provides a new impetus and path for enterprises' green innovation, which can improve innovation efficiency and environmental performance while reducing costs [1].

This research aims to elucidate the mediating effect of green innovation in the relationship between digital transformation and environmental performance, exploring whether and how digital transformation significantly enhances firms' environmental performance through fostering green technological innovation. This investigation will shed light on the role of green innovation as a bridge between digital transformation and environmental improvement, thereby enriching and deepening our understanding of the connection between digital transformation and green development. By dissecting the complex interplay among corporate digital transformation, green innovation, and environmental performance using empirical data, this study seeks to uncover the influential dynamics that underpin these relationships.

This research not only enriches the existing theoretical frameworks, but also significantly deepens our understanding of the multifaceted and intricate factors impacting corporate environmental performance. It innovatively explores how digital transformation accelerates green innovation processes, thereby expanding the horizons of green innovation theory. The paper unveils the emergent power of green innovation within the digital context, elucidating its realization pathways. Moreover, it advances our comprehension of green innovation's evolutionary laws in the digital era. As a pivotal force driving modern enterprise development, the interplay between digital transformation and green innovation has received limited scholarly attention thus far. Through the establishment of a theoretical model and empirical analysis, this study contributes robust empirical evidence to the discourse on digital transformation and green innovation. It fosters enhancements and deeper insights into the theoretical framework of this domain.

2. Theoretical Analysis and Hypothesis Formulation

2.1. Digital Transformation and Corporate Environmental Performance

Digital transformation transcends merely altering business processes, organizational structures, and business models; it significantly elevates the competitive edge and operational efficiency of enterprises. In the environmental management domain, digital transformation's impact is particularly pronounced. It notably enhances corporate environmental performance across various dimensions including, but not limited to, boosting resource efficiency, facilitating real-time monitoring and

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feedback mechanisms, optimizing supply chain management, and strengthening environmental governance capacities[2].

The application of digital technology promotes the enterprise's fine control of resource utilisation, significantly reduces resource wastage and effectively curbs the growth of pollution emissions. The application of the Internet of Things (IoT) and big data analytics enables enterprises to monitor and optimise energy consumption and raw material use in real time, ensuring efficient use of resources [3]. Secondly, digital transformation empowers companies with powerful real-time monitoring and feedback capabilities. By dynamically monitoring environmental parameters and responding quickly, companies are able to better comply with environmental regulations and adjust their operational strategies in a timely manner in order to improve environmental performance [4]. Furthermore, optimising supply chain management is also one of the significant results of digital transformation in environmental management. By choosing environmentally friendly suppliers and optimising logistics routes, enterprises have achieved significant reductions in carbon footprints in their production processes. Finally, digital transformation also significantly enhances the enterprise's environmental governance capability [5] by identifying environmental risks, implementing preventive measures, and promoting the continuous improvement of environmental management processes through data analysis tools.

Accordingly, the following is proposed: Hypothesis 1: Digital transformation of enterprises can significantly improve their environmental performance.

2.2. The Mediating Role of Green Innovation

Green innovation, as an innovative activity carried out by enterprises in the field of environmental protection, optimisation of production processes or innovative management practices, and is an important way to achieve environmental performance improvement. Digital transformation, as an important driving force for the transformation of modern enterprises, and green innovation are closely linked and mutually reinforcing.

Digital transformation provides strong technical support for enterprises to innovate green products [6]. Through the use of artificial intelligence, big data analysis and other advanced technologies, enterprises can more accurately grasp the market demand trend for environmental products, accelerating the research and development of green products and the speed to market. At the same time, digital design and simulation technology also provides enterprises with the possibility of environmental assessment and optimisation at the product development stage, effectively reducing material waste and environmental pollution [7]. With the integration of the Internet of Things and automation technology, enterprises have achieved a high degree of intelligence and fine control of the production process, which not only greatly improves production efficiency, but also effectively reduces energy consumption and pollutant emissions. In addition, digital transformation also promotes the promotion of the circular economy model, through the reuse and recycling of resources to further enhance the environmental protection of the production process. The environmental management information system constructed by the enterprise makes it possible to track environmental data in real time and facilitates in-depth data profiling, thus enhancing the transparency of environmental management and ensuring a clear traceability path for management activities. This management innovation not only helps enterprises to better fulfil their environmental responsibilities, but also helps them to identify potential environmental risks and take timely countermeasures [8].

Accordingly, it is proposed that: Hypothesis 2: Green innovation mediates the relationship between digital transformation and corporate environmental performance.

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3. Research Design

3.1. Data Sources

The sources of the data utilized in this paper are comprised of three segments: the initial segment pertains to digital transformation data, which encompasses research into[9], This approach aims to precisely capture and compare the inputs and outcomes of an enterprise's digitalization process, thereby objectively assessing the scale of its transformation value. It leverages cutting-edge technologies such as artificial intelligence, blockchain, cloud computing, big data, and digital technology, analyzing their usage in annual reports from sample companies. By quantifying the transformation value through these technological indicators, a method is established where the natural logarithm of the sum of the frequency of digital terms plus one acts as a key metric. This metric demonstrates a significant positive correlation with the depth and breadth of a company's digital transformation. The second part of the research delves into green innovation, serving as another pivotal data indicator. This aspect is extensively explored within the paper, highlighting its importance in the context of sustainable business practices and environmental responsibility.[10], The third segment comprises corporate environmental performance metrics sourced from the China Research Data Service Platform, the Cathay Pacific Database (CSMAR), and the RESSET Database (RESSET).

Concurrently, to ensure robustness and mitigate the influence of outliers on regression outcomes, this paper implements a 1 percent trimming technique on pertinent continuous variables.

3.2. Explanation of Variables

1. Explanatory variables. In this paper, the enterprise digital transformation index is taken as th e core explanatory variable. Drawing on [9], The exploration involves the utilization of Big Da ta Technology and Digital Technology Application, alongside Python and other analytical tools, to perform text mining on the annual reports of various enterprises. This process entails quant ifying the frequency of occurrence for specific keywords -"BigDataTechnology","DigitalTechno logyApplication", Python, and others - within these annual reports. The significance that an ent erprise attributes to content related to digital transformation is directly proportional to the statis tical word frequency value obtained. By aggregating the total frequency of each aforementione d technique, a comprehensive index (LDIGITAL) is formulated, which encapsulates the overall emphasis of enterprises on digital transformation as depicted in their annual reports.

2. Explained variables. This paper takes corporate environmental performance as an explanatory variable, which is measured by the CR ESG index.

3. The present study employs the quantity of green patent applications as a fundamental explanatory variable. This approach is chosen over indicators like R&D investment because the number of green patent filings directly mirrors the tangible outcomes of enterprises in the realm of green innovation, showcasing superior quantifiability and practical significance [11]. Consequently, this research utilizes the logarithm of the aggregate number of green invention patents and green utility model applications plus one (EnvrPat) to gauge the level of green innovation within organizations.

4. Based on the analyses presented in [12], [13], and [14], we have selected seven key enterprise-level control variables for our investigation. The precise metrics employed to evaluate these variables are delineated in Table 1, while the descriptive statistics for each variable are provided in Table 2.

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Table 1: Selection and description of control variables.

Variable	Short name	Description
Firm size	SIZE	Natural logarithm of total assets
Return on assets	ROA	Net profit/average total assets
Gearing ratio	LEV	Total liabilities/total assets
Firm growth capacity	GROW	Growth rate of operating income, growth rate of operating income/total operating income of the previous year
Years of listing	AGE	Statistical date minus listing date rounded to the nearest whole number plus 1
Shareholding Concentration	FIRST	Proportion of shares held by the first largest shareholder
DUAL	DUAL	The chairman of the board of directors and the general manager of the board of directors is 1, otherwise it is 0.
Board Size	BOARD	The natural logarithm of the number of board members

Table 2: Descriptive statistics for key variables.

Variable	Short name	Description
Firm size	SIZE	Natural logarithm of total assets
Return on assets	ROA	Net profit/average total assets
Gearing ratio	LEV	Total liabilities/total assets
Firm growth capacity	GROW	Growth rate of operating income, growth rate of operating income/total operating income of the previous year
Years of listing	AGE	Statistical date minus listing date rounded to the nearest whole number plus 1
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4. Analysis of Empirical Results

4.1. Benchmark regression results

However, the specific realization pathway of digital transformation remains largely unexplored. This paper introduces a regression analysis model to conduct a comprehensive empirical investigation and analysis on this subject. The findings reveal that digital transformation significantly enhances enterprise Environmental, Social, and Governance (ESG) performance. This might be attributed to digitalization's ability to optimize resource allocation and boost operational efficiency, thereby unlocking the sustainable development potential of enterprises

Moreover, the control variables of our regression analysis underscore the positive relationship between firm size (SIZE) and ESG performance, indicating that larger firms benefit from greater resources and capabilities. Conversely, higher leverage(LEV) is found to negatively affect ESG performance, suggesting that high financial debt may constrain firms' investments in ESG initiatives. Similarly, the negative impact of firm age(AGE) on ESG performance is confirmed, implying that older firms might be less inclined towards green innovation.

Interestingly, we observe a positive effect of leadership structure (DUAL) on ESG performance, highlighting the importance of dual leadership in driving sustainability efforts. However, the effect of board size (BOARD) and other variables on ESG performance does not show statistical significance. These insights offer valuable guidance for firms aiming to integrate digital transformation strategies into their ESG practices effectively.

4.2. Mediating effect results

To put it simply, digital transformation indirectly boosts corporate Environmental, Social, and Governance(ESG) performance by enabling green technology innovation. To substantiate this mechanism, the study constructs a mediation effect model, gauging the level of green tech innovation through the number of environmental patents filed. As evident from model(2)'s results, with high statistical significance at the 1% level, digital transformation demonstrably enhances ESG performance of firms. Model(1) reveals that the coefficient of digital transformation on environmental patent applications is 0.0678, showing statistical significance at the 1% level, indicating digital transformation's significant impact on enhancing enterprises' environmental technology innovation capabilities.

When integrating both digital transformation and the number of environmental patents into model(2), it becomes apparent that the coefficient for environmental patents is 0.328, significant at the 1% level. This suggests that as environmental technological innovation improves, there is a substantial improvement in the ESG performance of enterprises. Moreover, the coefficient of the digital transformation's impact on ESG performance decreases when the mediator variable isn't considered, further confirming that the number of environmental patents plays a partial mediating role in the process of digital transformation enhancing firms' ESG performance.

The findings of this analysis underscore not only the direct contribution of environmental technology innovation to the sustainability of businesses but also its pivotal mediating role in the impact of digital transformation on ESG performance.

4.3. Endogeneity Test

Analyzing the data in the table, both models(1) and(2) unequivocally demonstrate that digital transformation(LDIGITAL) has a substantial positive impact on Environmental, Social, and Governance (ESG) performance, achieving statistical significance at the 1% level. Furthermore, firm size(SIZE) and return on assets (ROA) also exhibit significant positive contributions to ESG

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performance across these models. Conversely, leverage(LEV) and the age of the firm(AGE) are found to have notable negative effects. Despite concerns about potential endogeneity, the beneficial influence of digital transformation on ESG performance remains robust in the regression analysis, passing the robustness test. The R-squared and adjusted R-squared values suggest that the models offer some explanatory power for the dependent variables. Hence, the benchmark regression outcomes presented herein remain robust and valid after accounting for potential endogeneity issues, reinforcing the conclusion that digital transformation significantly and positively drives corporate ESG performance.

4.4. Robustness Test

The robustness test not only validates the findings from the preceding regression analysis, but also strengthens the evidence for the substantial positive effects of digital transformation and firm size on Environmental, Social, and Governance (ESG) performance. Moreover, it illuminates the positive influence of leverage and the benefits of a dual leadership role on ESG outcomes. Additionally, the test underscores the significance of year-specific and industry-related factors in shaping ESG performance, necessitating their consideration in future analyses.

Table 3: Empirical Results.

	Benchmark regression	Mediating effect		Endogenous processing		Robustness test
	(1)	(1)	(2)	(1)	(2)	(1)
	ESG	EnvrPat	ESG	ESG	ESG	E
LDIGITAL	0.139***	0.068***	0.116***	0.256***	0.237***	0.282***
	(0.024)	(0.005)	(0.024)	(13.520)	(10.290)	(0.035)
SIZE	1.225***	0.381***	1.101***	1.094***	1.236***	1.629***
	(0.026)	(0.005)	(0.028)	(44.150)	(39.620)	(0.038)
ROA	5.645***	0.054	5.628***	6.348***	8.484***	0.636
	(0.358)	(0.067)	(0.357)	(17.630)	(19.470)	(0.519)
LEV	-1.837***	0.103***	-1.871***	-1.582***	-3.607***	0.278
	(0.136)	(0.026)	(0.136)	(-11.790)	(-18.340)	(0.197)
GROW	0.000	0.000	0.000	-0.114***	-0.098***	0.000
	(0.000)	(0.000)	(0.000)	(-29.610)	(-20.380)	(0.001)
AGE	-0.115***	-0.001*	-0.114***	0.012***	0.011***	-0.071***
	(0.004)	(0.001)	(0.004)	(6.740)	(4.650)	(0.006)
FIRST	0.014***	-0.002***	0.015***	-0.000	-0.002	-0.007**
	(0.002)	(0.000)	(0.002)	(-0.230)	(-1.390)	(0.003)
DUAL	0.144**	0.004	0.142**	0.115	0.167*	0.508***
	(0.059)	(0.011)	(0.059)	(1.910)	(2.320)	(0.086)
BOARD	-0.022	0.009***	-0.025	-0.036*	-0.037	0.078***
	(0.017)	(0.003)	(0.017)	(-2.180)	(-1.830)	(0.024)
EnvrPat	-	-	0.328***	-	-	-
	-	-	(0.028)	-	-	-
year	yes	yes	yes	yes	yes	yes
indcode	yes	yes	yes	yes	yes	yes
_cons	44.160***	-8.355***	46.900***	50.090***	47.590***	23.420***
	(0.609)	(0.114)	(0.651)	(102.480)	(78.030)	(0.882)
N	35582	35582	35582	35582	23267	35582
R^2	0.148	0.340	0.151	-	-	0.168
adj. R^2	0.146	0.338	0.149	-	-	0.165

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5. Further Research

5.1. Heterogeneity Test

Contrary to the diverse impacts of digital transformation across companies due to varying pollution levels, China's industrial landscape exposes significant disparities between heavily and less heavily polluted firms. Analysis through regression models reveals that for the former, the coefficient of digital transformation on Environmental, Social, and Governance (ESG) performance stands at 0.049. However, this finding does not achieve statistical significance. This suggests that while digital transformation may contribute to enhancing ESG performance in heavily polluted firms, its impact is statistically insignificant. These firms typically necessitate substantial investment and time to realize the benefits of digital transformation on their ESG metrics, given their heightened environmental pressures and stringent regulations.

Conversely, digital transformation has a pronounced positive effect on the ESG performance of less heavily polluted firms, with a coefficient of 0.162 at a 1% significance level. This implies that less heavily polluted firms can more effectively utilize digitalization to enhance their ESG performance. These firms, under relatively lesser regulatory pressure, see quicker improvements in operational efficiency and environmental performance as a result of digital transformation.

However, due to varying resource endowments and technological bases across industries where enterprises operate, the "enabling" role of digital transformation manifests significantly differently among diverse enterprises. In China, this disparity in digital transformation is notably pronounced between high-tech and non-high-tech firms. High-tech firms often boast a stronger technological foundation and higher digital acumen, facilitating their more effective utilization of digital transformation to enhance green innovation capabilities. Conversely, non-high-tech firms might struggle to fully harness the green innovation benefits from digital transformation, primarily due to their weaker technological base, inadequate investment, and deficiencies in technology access and application skills. Additionally, these firms may face further challenges in integrating advanced digital technologies into their existing operations, which can impede their ability to achieve significant improvements in environmental performance and sustainability.

Regression analysis reveals that digital transformation has a substantial positive influence on the Environmental, Social, and Governance (ESG) performance of high-tech firms, with a coefficient of 0.319 (at a significance level of 1%). This suggests that high-tech enterprises often possess a stronger technological base and higher digital awareness, allowing them to more effectively utilize digital transformation to enhance their green innovation capacities. High-tech firms can better integrate internal and external innovation resources and improve green innovation efficiency through the deep integration of digital technologies.

On the other hand, the impact of digital transformation on the ESG performance of non-high-tech firms appears negligible, with a coefficient of -0.017. Given the relative inadequacy of these firms in terms of technological base, capital investment, and digitalization capability, they find it challenging to achieve the anticipated green innovation outcomes during the process of digital transformation.

However, due to the differing resource endowment and technological foundations among enterprises, the "enabling" role of digital transformation manifests in heterogeneous characteristics across industries. This disparity is notably pronounced between manufacturing and non-manufacturing firms. Manufacturing enterprises often encounter more environmental pressures and resource constraints during production. Regression analysis reveals that digital transformation significantly boosts the Environmental, Social, and Governance (ESG) performance of manufacturing companies, with a coefficient of 0.137 (at a significance level of 1%). The enhanced efficiency from digital transformation aids these firms in optimizing their production processes, reducing resource consumption, and emissions, thereby enhancing their ESG performance.

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Digital transformation also positively impacts the ESG performance of non-manufacturing firms, with a coefficient of 0.177 (at a significance level of 1%). Despite being less resource-dependent and environmentally sensitive in their operations, non-manufacturing firms can leverage digital transformation for green innovation and environmental improvement by optimizing their operations and management efficiency. Both types of firms benefit from digital transformation in improving their ESG performance, albeit through distinct pathways. Manufacturing firms primarily achieve greener transformations by refining their production processes and emission reductions, whereas non-manufacturing firms often rely on streamlining overall management and business processes to enhance environmental performance.

In summary, digital transformation has a significant impact on firms' ESG performance, but its effects are heterogeneous across different types of firms. This heterogeneity underscores that policymakers and business managers should formulate appropriate strategies and policies based on the industry attributes, pollution level and technology level of enterprises when promoting digital transformation and green innovation to maximise the green effect of digital transformation.

Table 4: Heterogeneity test.

	(1)	(2)	(3)	(4)	(5)	(6)
	Heavy Pollution	Non-Heavy Pollution	High-Tech	Non-High-Tech	Manufacturing	Non-Manufacturing
LDIGITAL	0.049	0.162***	0.319***	-0.017	0.137***	0.177***
	(0.054)	(0.027)	(0.036)	(0.033)	(0.028)	(0.046)
SIZE	1.446***	1.178***	1.079***	1.467***	1.353***	1.312***
	(0.053)	(0.030)	(0.041)	(0.035)	(0.034)	(0.042)
ROA	7.313***	5.576***	6.111***	6.898***	7.478***	3.827***
	(0.747)	(0.405)	(0.538)	(0.481)	(0.423)	(0.671)
LEV	-5.080***	-1.171***	-0.320*	-4.869***	-4.588***	-0.459**
	(0.316)	(0.150)	(0.187)	(0.214)	(0.196)	(0.216)
GROW	-0.008	0.000	-0.003***	0.001	-0.003***	0.001**
	(0.005)	(0.000)	(0.001)	(0.000)	(0.001)	(0.001)
AGE	-0.103***	-0.115***	-0.139***	-0.087***	-0.112***	-0.074***
	(0.008)	(0.005)	(0.006)	(0.005)	(0.005)	(0.008)
FIRST	0.014***	0.012***	0.019***	0.008***	0.018***	0.002
	(0.004)	(0.002)	(0.003)	(0.002)	(0.002)	(0.003)
DUAL	-0.050	0.232***	0.179**	0.115	0.181***	0.186
	(0.117)	(0.068)	(0.086)	(0.082)	(0.068)	(0.118)
BOARD	0.137***	-0.101***	0.050*	-0.076***	0.013	-0.088***
	(0.031)	(0.020)	(0.026)	(0.022)	(0.021)	(0.0276)
year	yes	yes	yes	yes	yes	yes
indcode	yes	yes	yes	yes	yes	yes
cons	40.130***	45.590***	47.300***	40.710***	44.690***	42.250***
	(1.179)	(0.678)	(0.895)	(0.754)	(0.718)	(0.908)
N	10474	25108	15442	20140	24738	10844
R^2	0.155	0.155	0.132	0.183	0.144	0.201
adj. R^2	0.152	0.152	0.130	0.179	0.142	0.196

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6. Conclusions and Implications

Digital transformation notably amplifies enterprises' capacity for innovation and operational efficiency. It concurrently facilitates substantial enhancements in environmental performance by advancing both areas simultaneously. This transformation specifically assists businesses in innovating labor structures, increasing investments in environmental protection, and strengthening their financing capabilities. Moreover, it empowers enterprises to green their innovations effectively through the optimization of production efficiency and enhancement of operational performance, thereby fostering sustainable development.

For instance, clean and high-tech firms often excel in realizing green innovation during their digital transformation journey. This is largely attributed to their pronounced advantages in terms of capital resources, technological prowess, and supportive policies. Specifically, the integration of green innovation as a pivotal driver in digital transformation significantly boosts the environmental performance outcomes of these processes. Consequently, it underscores the pivotal role of green innovation in propelling the sustainable development of enterprises.

Primarily, digital transformation acts as a potent mechanism to enhance business environmental performance. Subsequently, within the realm of digital transformation, green innovation has surfaced as an indispensable driving force. Enterprises must significantly increase their investment in green technologies and expedite the development and practical implementation of green innovations to fortify their environmental competitiveness and secure the foundation of their sustainable growth. Furthermore, acknowledging that digital transformation's impact varies across different types of enterprises, companies should tailor their digital transformation strategies according to their industry-specific characteristics and resource conditions to maximize the benefits of transformation. Lastly, policymakers should recognize the pivotal role of digital transformation and green innovation in promoting green enterprise development and sustainable economic growth. They should provide robust support for these endeavors through the formulation and implementation of relevant policies and measures, particularly in manufacturing and high-tech sectors.

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