

Article

Not peer-reviewed version

How Digital Transformation Affects Corporate Environmental Governance – Evidence from Listed Manufacturing Companies in China

[Hong Zhou](#), [Junguo Qiao](#)^{*}, [Xianxiang Fei](#)^{*}, [Yinyan Shi](#)

Posted Date: 28 January 2026

doi: 10.20944/preprints202601.2215.v1

Keywords: digital transformation; enterprise digitization; environmental governance



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a [Creative Commons CC BY 4.0 license](#), which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Article

How Digital Transformation Affects Corporate Environmental Governance—Evidence from Listed Manufacturing Companies in China

Hong Zhou ¹, Junguo Qiao ^{1,2,*}, Xianxiang Fei ^{3,*} and Yinyan Shi ¹

¹ School of Management, Guangdong Ocean University, Zhanjiang 524088, China

² Shenzhen Institute of Guangdong Ocean University, Shenzhen 518120, China

³ School of Electronic and Information Engineering, Guangdong Ocean University, Zhanjiang 524088, China

* Correspondence: zjqjg@163.com (J.Q.), feixx@gdou.edu.cn (X.F.)

Abstract

How to promote enterprises to actively engage in environmental governance is a hot topic of common concern in both academia and practice. Against the backdrop of the booming digital economy, the digital transformation of enterprises is driving traditional technological innovation and reshaping corporate resources and capabilities, but its impact on corporate environmental governance behaviors remains to be verified. Based on panel data of China A-share listed manufacturing companies from 2014 to 2023, this study empirically tests the influence of corporate digital transformation on environmental governance using a two-way fixed effects model. The findings indicate that the higher the degree of digital transformation, the higher the level of environmental protection investment, suggesting that digital transformation has a positive driving effect on corporate environmental governance behaviors. Further mechanism analysis shows that digital transformation primarily promotes corporate environmental protection investment by improving internal control quality and alleviating exogenous financing constraints. Heterogeneity analysis reveals that the driving effect of digital transformation on corporate environmental governance behaviors is more pronounced in less competitive markets and large-scale enterprises. The conclusions of this study provide policy and management insights for fully leveraging the environmental governance effects of corporate digital transformation, thereby promoting the green transition of manufacturing enterprises.

Keywords: digital transformation; enterprise digitization; environmental governance

1. Introduction

Resource and environmental issues are common challenges faced by humanity. With the global consensus on the concept of sustainable development, promoting green growth and implementing the Green New Deal have become the common choice of major global economies[1]. In the past, during the process of embedding in the global value chain, China mainly accelerated its industrialization process by undertaking labor-intensive industries at the lower end of the industrial chain transferred from developed countries to strengthen its economic power. However, since most of the transferred industries were high-consumption and high-pollution segments of the value chain, and pollution control capabilities were relatively weak during the initial stage of economic construction, China also faced issues such as industrial structure imbalance and severe environmental pollution during the rapid expansion of its manufacturing sector [2,3]. The green transformation of manufacturing has thus become an inevitable choice [4]. At the micro-enterprise level, the green transformation of manufacturing is reflected in enterprises actively engaging in environmental governance through technological innovation [5], management optimization, and strategic reshaping, ultimately achieving the unification of environmental and economic benefits [6].

Under the current situation where green development has been elevated to a national strategy, many enterprises have begun to prioritize environmental governance and adopt forward-looking environmental protection strategies to proactively invest in environmental protection [7,8].

In recent years, digital technologies such as artificial intelligence [9], blockchain [10], cloud computing, and big data [11] have been continuously developing, and the digital economy has become an important driving force for China to optimize its economic structure and develop new productive forces. The "China Digital Economy Development Research Report (2023)" released by the China Academy of Information and Communications Technology shows that in 2022, the scale of China's digital economy reached 50.2 trillion yuan, accounting for 41.5% of the GDP. The digital economy is not only an important path to promote the transformation and upgrading of traditional industries and create new business forms and models, but also provides new ideas for achieving green economic transformation [12].

As the digital economy increasingly integrates with the real economy [13], digital technologies are reshaping manufacturing enterprises' operational models through innovative technologies, business models, and industry paradigms, driving their digital transformation [14]. This transformation has introduced new research challenges to traditional management theories and corporate growth frameworks. Scholars are now focusing on how digital transformation drives management reforms and impacts business development [15,16,17]. Micro-level studies have demonstrated that digital transformation yields significant economic benefits [18], including enhanced resource integration capabilities, optimized operational processes [19], enhance enterprise innovation capabilities [20,21], and improved efficiency with value creation [22]. While digital transformation has become a key driver of technological innovation and reshaping corporate resources and capabilities, its effects on environmental governance practices require further validation.

Theoretically, digital transformation may exert dual impacts on corporate environmental governance practices [23]. On one hand, digital empowerment drives innovation in environmental management approaches, enabling enterprises to swiftly identify and analyze stakeholders' environmental needs [24], thereby enhancing green innovation capabilities [25] and potentially encouraging increased environmental investments and proactive governance efforts. On the other hand, the digital transformation process itself requires substantial investments in technological infrastructure, which may divert attention from environmental governance responsibilities and reduce compliance efforts. Furthermore, the operational complexity and technological disruptions brought by digital transformation create operational and financial risks, increasing uncertainty in corporate environmental governance actions [26]. Against this backdrop, this study focuses on the following research questions:

- (1) Does corporate digital transformation have a positive impact on environmental governance?
- (2) What are the key mechanisms through which corporate digital transformation impacts environmental governance?

To answer the above questions, this paper takes China A-share manufacturing listed companies from 2014 to 2023 as samples to empirically test the impact of corporate digital transformation on environmental governance behavior and the underlying transmission mechanism. The research contributions of this paper are as follows: First, it broadens the study of the economic consequences of corporate digital transformation. Existing research mainly focuses on the impact of corporate digital transformation on production efficiency [27], organizational structure [28], and change [29], while a few studies on the impact of corporate green transformation are mainly concentrated at the theoretical and technological innovation levels [30], lacking exploration of the influence on corporate environmental governance decisions. This paper provides micro-level empirical evidence based on China A-share manufacturing listed companies in Shanghai and Shenzhen, incorporates corporate environmental governance into the analytical framework of the economic consequences of digital transformation, and expands the applicability boundaries of existing international digital transformation research under the institutional background of emerging markets. Second, this paper

examines the impact mechanism of corporate digital transformation from two aspects: improving internal control quality and alleviating exogenous financing constraints, which helps clarify the mechanism by which technological changes such as digital transformation affect corporate environmental governance. Third, based on the differences in corporate characteristics, this paper analyzes the heterogeneous impacts of market competition intensity and corporate size, thereby providing deeper theoretical support for how enterprises can enhance environmental governance levels through digital transformation, and offering insights for relevant government departments to formulate targeted policies to promote corporate digital transformation.

2. Theoretical Analysis and Research Hypothesis

Digital transformation for enterprises goes beyond merely adopting digital technologies or investing in digital infrastructure. It involves leveraging cutting-edge digital technologies to digitize production resources and processes, while restructuring business workflows, product services, organizational management [31], and business models [32]. The rise of digital technologies has created new opportunities for manufacturing enterprises to achieve green transformation, serving as a crucial lever for realizing the "dual carbon" goals [33]. Advanced digital technologies like big data and cloud computing can enhance emission reduction and efficiency [34], enabling enterprises to conduct precise environmental simulations and analyses. This helps identify current environmental issues and trends, providing robust support for proactive environmental governance [35]. Consequently, it empowers enterprises to adopt forward-looking environmental strategies and elevate their environmental investment levels [36].

First, digital transformation enables enterprises to increase environmental investments and enhance environmental management capabilities [37]. By leveraging emerging intelligent technologies like big data and cloud computing, companies can establish comprehensive environmental management systems [38]. These systems enable real-time monitoring of production processes, provide timely insights into equipment performance, facilitate preventive maintenance and upgrades, and drive environmental management toward precision and standardization [39]. Enterprises can utilize digital technologies to effectively integrate and share environmental data—including carbon emissions and waste discharge across production chains—while structuring scattered green data to identify key environmental governance priorities [40,41]. Digital technologies also accelerate information flow between markets, objectively documenting market behaviors and choices under green consumption trends [42]. This helps better understand public environmental awareness and preferences for green products, guiding enterprises toward sustainable transformation [43].

Secondly, digital transformation helps enterprises reduce production costs and preventively lower capital expenditures. By embedding digital technologies across various production activities and technical sectors, it creates supply-demand-aligned production models that significantly cut production costs [44], supply chain information transmission costs, and value chain management expenses [45]. This enhances operational efficiency and achieves cost reduction with efficiency gains [46]. When market conditions change, the deep integration of digital technologies enables enterprises to promptly access internal and external information regarding market demands, competitors, and industry trends [47]. This improves risk identification capabilities and allows timely development of risk response strategies [48]. Digital transformation helps businesses reduce operational uncertainties [49], decrease cash flow volatility, and minimize daily cash reserves [50]. Consequently, management can reallocate funds previously reserved for risk mitigation to environmental protection investments, providing financial support for environmental governance initiatives [51].

Third, digital transformation can reduce compliance-related environmental expenditures while increasing governance-oriented environmental investments, driving enterprises to achieve efficient pollution control and emission reduction [52]. In practice, common issues such as non-standardized environmental record-keeping, incomplete documentation, and inaccurate data often leave companies in a passive position during environmental inspections. Insufficient self-monitoring

frequency and non-compliant testing during production also hinder accurate emission tracking [53]. The widespread application of digital technologies across process design, manufacturing, and recycling helps enterprises optimize traditional production methods, enhance resource and energy recycling capabilities, and reduce pollutant output [54]. Guangdong Dongjiang Environmental Protection Co., Ltd. has established a smart environmental operation platform utilizing next-generation digital technologies like IoT and AI. Through applications such as smart tags, mobile traceability, and intelligent weighbridges, the company achieves comprehensive, all-round, and meticulous management of hazardous waste throughout its lifecycle—from generation to disposal—improving upstream-downstream coordination efficiency by over 20%. Comprehensive digital supervision enables earlier detection and resolution of environmental incidents, helping enterprises reduce compliance costs including pollution fees and environmental penalties [55]. This approach not only boosts corporate cash flow but also minimizes irreversible losses and marginal costs associated with environmental investments, ultimately enhancing corporate motivation for environmental governance [56].

Based on the above analysis, this paper proposes the following hypothesis:

Hypothesis H1: Digital transformation can enhance corporate environmental governance practices.

3. Research Design

3.1. Sample Selection and Data Sources

China's manufacturing sector has ranked first in the world in terms of scale, but it also dominates carbon emissions across various industries. This paper selects China A-share listed manufacturing companies from 2014 to 2023 as the research sample. Based on the initial sample, we excluded samples processed as ST, *ST, or PT, as well as those with missing values in related variables, and companies that delisted or went public during the sample period. Ultimately, we obtained 19,428 "company-year" observations from 3,149 manufacturing enterprises. To eliminate the interference of outliers, we performed Winsorization on continuous variables by truncating the upper and lower 1% quantiles. Data on corporate environmental investments and digital transformation were sourced from manually collected audited annual financial reports of listed companies, while other data were obtained from the financial statement database and governance structure database of the Guotai An database.

3.2. Model Setting

To examine the impact of digital transformation on corporate environmental governance, this study adopts the research methodology of Xiao Hongjun et al. and constructs the following model to test the research hypothesis:

$$EPI_{it} = \alpha + \beta_1 Digital_{it} + \sum \beta CVs + \sum Year + \sum Indus + \varepsilon_{it} \quad (1)$$

Here, EPI denotes corporate environmental investment, Digital represents corporate digital transformation, and CVs denote a series of control variables, with ε being the random disturbance term. If Hypothesis 1 holds, the coefficient of β_1 should be significantly positive. The regression employs a two-way fixed effects model controlling for industry (Indus) and time (Year) to absorb fixed effects as much as possible. Cluster-robust standard error-adjusted t-statistics were used throughout the regression analysis.

3.3. Variable Definitions

3.3.1. Dependent Variable: Environmental Performance Index (EPI)

Due to the limited availability of micro-level corporate data, previous studies on environmental governance practices in listed companies have yet to establish unified measurement standards. Most researchers have adopted subjective evaluation methods to comprehensively score multiple environmental indicators. However, these indicators often lack reliable sources, and subjective scoring may not be entirely accurate. Patten (2005) pointed out that corporate environmental capital expenditure serves as a relatively accurate objective indicator of environmental performance [57]. As a resource allocation strategy that translates environmental goals and strategies into concrete actions, corporate environmental investments reflect corporate environmental governance decisions and evaluate the implementation of long-term pollution control mechanisms. In summary, this section aggregates data from environmental-related expenditures in the "Construction in Progress" and "Administrative Expenses" sections of corporate annual reports, including desulfurization projects, exhaust gas treatment, wastewater treatment, dust removal, energy conservation, reclaimed water systems, electrostatic precipitator upgrades, landscaping fees, and pollution discharge fees. The aggregated data represents the annual increase in corporate environmental investments, which is then logarithmically transformed.

3.3.2. Explanatory Variable: Enterprise Digital Transformation (Digital)

The definition and measurement methods of corporate digital transformation remain inconclusive. Early scholars primarily assessed it through investment metrics in digital projects, such as intangible assets related to digitalization or expenditures on ERP systems and other digital transformation initiatives, which failed to comprehensively reflect the actual progress. For listed companies, annual reports disclose strategic directions, business overviews, significant investments, new business expansions, major R&D breakthroughs, and management's future development plans—key indicators of corporate strategy. Recent studies have employed text analysis to extract digital-related keywords from corporate reports, exemplified by Zhang Yao and Guo Xuemeng [58]. Drawing inspiration from Zhang Yao's approach, this paper categorizes digital transformation into two dimensions: "underlying technology application" (emphasizing digital technology integration) and "digital technology practice application" (focusing on digital business scenarios). The "underlying technology application" dimension is further divided into four specific technological directions: artificial intelligence, blockchain, cloud computing, and big data, thereby identifying characteristic keywords for corporate digital transformation. The measurement of digital transformation is conducted through two specific steps.

First, construct a list of keywords for enterprise digitalization. By reviewing relevant policies issued by the State Council of China (including the "14th Five-Year Plan for Digital Economy Development" (State Council Document [2021] No.29) and the "Government Work Report of the State Council" over the past five years) and related documents issued by the Ministry of Industry and Information Technology (including the "Digital Implementation Guidelines for Quality Management in Manufacturing" (MIIT Document [2021] No.59) and the "Digital Transformation Action Plan for Intelligent Manufacturing in the Building Materials Industry (2021-2023)" (MIIT Document [2020] No.39)), we have determined the basic list of keywords for enterprise digital transformation in this article, as shown in Table 3.1.

Table 1. Construction of Enterprise Digital Transformation Index and Keyword Selection.

dimension	Dimensional indicators	Keywords
Application of digital underlying technology	artificial intelligence technology	Artificial Intelligence, Intelligent Technology, Image Understanding, Intelligent Data Analysis, Intelligent Robots, Machine Learning, Deep Learning, Semantic Search, Biometric Technology, Facial Recognition, Speech Recognition, Natural Language Processing, Authentication
	blockchain technology	blockchain, digital currency, distributed computing, differential privacy technology, smart financial contract
	cloud computing technology	Cloud platform, cloud service, cloud ecosystem, cloud computing, cognitive computing, 100 million concurrent users, EB-level storage, Internet of Things, cyber-physical systems, stream computing, graph computing, in-memory computing, multi-party secure computing, neuromorphic computing, green computing
Application of Digital Technology	Big Data Technology	Big Data, Data Mining, Text Mining, Data Visualization, Heterogeneous Data, Credit Reporting, Data Center, Digital Control
	Internet, e-commerce, intelligent, intelligent	Mobile Internet, Industrial Internet, Industrial Internet Solutions, Internet Technology, Internet Thinking, Internet Actions, Internet Business, Internet Mobile, Internet Applications, Internet Marketing, Internet Strategy, Internet Platform, Internet Model, Internet Ecosystem, E-commerce, E-commerce, Internet, "Internet Plus", Online-Offline, O2O, B2B, C2C, B2C, C2B, Digital Economy, Smart Devices, Smart Manufacturing, Smart Connectivity, Smart Systems, Intelligence, Smart Robots, Automatic Control, Automatic Monitoring, Automatic Supervision, Automatic Inspection, Automatic Production, Autonomous Driving, Industrial Cloud

Secondly, we scrape corporate annual reports from Juchao Information Network and convert them from PDF to TXT format. Using Python's open-source "Jieba" word segmentation tool, we perform text analysis on relevant sections to extract the number of keywords related to various dimensions of digital transformation. This process establishes measurement metrics for corporate digital transformation: the overall indicator (natural logarithm of the total word frequency of digital transformation plus 1) and sub-indicators (natural logarithm of the word frequency of each sub-dimension plus 1).

3.3.3. Control Variables

This study identifies key control variables affecting corporate environmental investments, including fundamental factors and governance characteristics. These variables encompass: return on equity (ROE), firm size, debt-to-asset ratio (Lev), growth potential, state-owned enterprise (SOE) status, cash flow position, asset turnover ratio (ATO), equity concentration (Top1), and listing duration (ListAge). Detailed definitions and explanations are provided in Table 2.

Table 2. Variable Definitions and Explanations.

Variable name	variable symbol	variable-definition
environmental protection investment of enterprise	EPI	$\ln(\text{total environmental investment} + 1)$
Digital Transformation	Digital	$\ln(\text{Digital Transformation Total Word Frequency} + 1)$
profitability	ROE	net profit/shareholders' equity average balance
scale	Size	$\ln(\text{Total Assets at End of Period})$
asset-liability ratio	Lev	total liabilities at the end of the period / total assets at the end of the period
growth potential	Growth	increase rate of business revenue
property right nature	SOE	State-owned holding enterprises: 1; otherwise, 0
cash holding level	Cashflow	net cash flow from operating activities/total assets
turnover of total capital	ATO	Operating revenue/average total assets

stock concentration	Top1	Number of shares held by the largest shareholder / Total shares × 100%
listing age	ListAge	ln(Year of Current Year-Year of Listing + 1)
trade	Indus	Industry dummy variables, based on the 2001 industry classification standard by the China Securities Regulatory Commission (CSRC), categorize manufacturing enterprises into 10 secondary industries.

4. Empirical Analysis

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

4.1. Descriptive Statistics

Table 2 presents the descriptive statistics of key variables. The results indicate that the Environmental Protection Investment (EPI) of enterprises averages 20.524,0.241 above the median, with a standard deviation of 1.315. The range spans from 16.319 to 26.612, highlighting significant disparities in environmental investment scales across enterprises, with most companies still below the average level. Similarly, the Digital Transformation (Digital) score averages 1.428,0.242 above the median, and a standard deviation of 1.366, revealing substantial variations in digitalization levels across enterprises and years, with most demonstrating relatively low digital transformation progress. The high heterogeneity of key variables provides a solid foundation for the regression analysis in this study. All other control variables fall within reasonable ranges.

Table 3. Descriptive Statistics.

variable symbol	sample number	mean	standard deviation	least value	median	crest value
EPI	19428	20.524	1.315	16.319	20.283	26.614
Digital	19428	1.428	1.366	0	1.186	4.834
ROE	19428	0.064	0.132	-0.926	0.070	0.439
Size	19428	22.142	1.263	19.585	21.987	26.512
Lev	19428	0.401	0.191	0.046	0.391	0.913
Growth	19428	0.170	0.382	-0.658	0.110	4.026
SOE	19428	0.260	0.447	0	0	1
Cashflow	19428	0.051	0.069	-0.205	0.048	0.267
ATO	19428	0.656	0.379	0.057	0.581	2.902
Top1	19428	33.010	13.947	8.020	30.738	75.530
ListAge	19428	2.084	0.805	0.356	2.201	3.402

4.2. Analysis of Benchmark Regression Results

Based on the framework of Model (1), we conducted an OLS regression analysis to empirically test the research hypothesis regarding the specific impact of corporate digital transformation on environmental investment decisions, thereby verifying the validity of the hypothesis. Table 3 presents the regression estimation results for Model (1), with robust standard error estimation method applied. Column (1) displays univariate regression results, where the regression coefficient of corporate digital transformation (Digital) is positive at the 1% significance level, indicating that digital transformation enhances corporate environmental investment. Column (2) shows the regression results after adding control variables, where the regression coefficient of digital transformation (Digital) remains positive at the 1% significance level. Column (3) presents the regression results after incorporating fixed effects of control variables and industry/year. The results in column (3) demonstrate that even after controlling for fixed effects, the regression coefficient of

digital transformation (Digital) remains positive at the 1% significance level. This indicates that corporate digital transformation promotes environmental investment, as it enables enterprises to reshape environmental management models through innovative technological approaches, adopt more proactive environmental responsibilities, reduce compliance expenditures, and increase environmental investment levels. The research hypothesis is thus validated.

As shown in Table 1, corporate digital transformation is a comprehensive concept encompassing sub-dimensional indicators with distinct structural characteristics. To further examine the impact of digital transformation indicators on corporate environmental investments, this study categorizes the total digital transformation index into five sub-indicators: Artificial Intelligence Technology (Digital_AI), Blockchain Technology (Digital_BD), Cloud Computing Technology (Digital_CC), Big Data Technology (Digital_DT), and Digital Technology Application (Digital_ADT). Regression analysis using Model (1) yielded results presented in Table 4. The table reveals that all digital transformation sub-indicators demonstrate significantly positive regression coefficients, consistent with our research expectations and demonstrating robustness of the regression model. Notably, blockchain technology exhibits the most pronounced effect on enhancing corporate environmental investment levels (coefficient: 0.172, substantially higher than other sub-indicators' coefficient elasticity). This indicates differential effects of digital technologies in driving corporate environmental investments. Unlike other technologies that primarily focus on auxiliary aspects like environmental data analysis and computational optimization, blockchain technology leverages unique features such as decentralization, immutability, and smart contracts to address core pain points in corporate environmental activities—including trust deficits, inefficient transactions, and inadequate supervision—thereby more effectively promoting increased environmental investment levels. By leveraging blockchain technology, environmental data collected through IoT sensors is instantly recorded as timestamped, immutable records. This ensures verifiable emission reduction outcomes from corporate environmental investments, enhancing the data-driven credibility of such investments and transforming environmental performance into tangible financial credit and market competitiveness. Blockchain also enables cross-regional emission trading, breaking geographical barriers to expand transaction scope. This allows surplus emission reduction credits generated from environmental investments to be more easily monetized, boosting return expectations. Furthermore, blockchain establishes a distributed data-sharing platform across enterprises, enabling precise tracking of carbon footprints throughout product lifecycles. Supply chain participants can clearly identify high-pollution emission stages in production processes, facilitating collaborative optimization of workflows. This collaborative model extends environmental investments beyond individual enterprises, creating industrial chain synergies that amplify investment value.

Table 4. Benchmark Regression Results and Impact of Sub-indicators of Digital Transformation on Corporate Environmental Protection Investment.

Variable	Benchmark Regression Results			Impact of Sub-indicators of Digital Transformation on Corporate Environmental Protection Investment				
	(1) EPI	(2) EPI	(3) EPI	(4) EPI	(5) EPI	(6) EPI	(7) EPI	(8) EPI
Digital	0.050*** (6.90)	0.051*** (8.32)	0.086*** (12.80)					
Digital_AI				0.019*** (7.20)				
Digital_BD					0.172*** (2.62)			
Digital_CC						0.003* (1.80)		
Digital_DT							0.022*** (9.41)	

Digital_ADT								0.009***	(8.74)
Digital_AI				0.019***					(7.20)
Ctrl	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
IndusFE	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
YearFE	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	19428	19428	19428	19428	19428	19428	19428	19428	19428
R2_adj	0.020	0.312	0.332	0.328	0.326	0.326	0.329	0.328	

4.3. Robustness Test and Endogeneity Issues

In order to ensure the robustness of the results, this paper changes the measurement index of dependent and independent variables, extends the observation window, and uses the double difference method to test the robustness and alleviate the endogeneity problem.

4.3.1. Change of Measurement and extended Observation Window

First, this study modifies the measurement metric for the dependent variable. The environmental protection investment scale (EPI) of enterprises is measured using relative numbers, calculated as the ratio of the total expenditure directly related to environmental protection in the "construction in progress" item of the annual report to the total assets at the end of the period, multiplied by 100. This metric is then used to regress Model (1), with the results presented in Column (1) of Table 5. Column (1) shows that the regression coefficient for digital transformation (Digital) remains significantly positive, demonstrating the robustness of the regression results even with the modified dependent variable.

Secondly, we modify the measurement of the independent variable. To examine how the degree of digital transformation exceeding the industry average affects corporate environmental investment scale, this study calculates the excess digital transformation indicator (Digital_abn) by subtracting the industry's annual average digital transformation level from each firm's annual digital transformation value. This indicator serves as a proxy for corporate digital transformation in regression analysis of Model (1), with results presented in Column (2) of Table 5. The analysis shows that Digital_abn is statistically significant at the 1% level, consistent with the primary regression results in Table 3.

Given the inconsistent measurement approaches for corporate digital transformation in existing literature, this study adopts the Management Discussion and Analysis (MD&A) section from annual reports as the textual foundation for digital transformation term frequency extraction, referencing Wang Aiping et al. (2024). By quantifying the frequency of keywords related to each digital transformation dimension listed in Table 1, we derive a surrogate indicator (Digital_2) for corporate digital transformation and conduct regression analysis using Model (1). The regression results are presented in Column (3) of Table 5. The MD&A section typically outlines corporate strategic vision and objectives, analyzes business models and core competencies, evaluates operational environments and risks, and details key initiatives implemented during the reporting period to achieve strategic goals along with their outcomes, directly reflecting the company's development trajectory. The results demonstrate consistency with the primary regression findings.

4.3.2. Extended Observation Window

This study extends the temporal analysis window for assessing the impact of corporate digital transformation on environmental investment. We re-run regression analysis on Model (1), with results presented in Table 6. Columns (1)-(3) of Table 6 apply 1-3 period lagging to the independent variable "Digital Transformation" (Digital), while columns (4)-(6) apply 1-3 period leading to the dependent variable "Environmental Investment Scale" (EPI), enabling cross-comparison. Regression results demonstrate that both lagging treatment of independent variables and leading treatment of dependent variables yield significantly positive coefficients for digital transformation. This indicates

that digital transformation exerts a highly significant positive catalytic effect on environmental investment, which remains robust across extended time windows. The findings confirm that digital transformation can generate cumulative positive impacts on environmental investment levels over extended periods, substantially enhancing corporate environmental investment. This corroborates the research hypothesis presented in this study.

Table 5. Robustness Test 1: Replacement of Measurement Indicators and robustness Test 2: Extended Observation Window.

Variable	(1) LnEPI	(2) EPI	(3) EPI	(4) EPI	(5) EPI	(6) EPI	(7) F1.EPI	(8) F2.EPI	(9) F3.EPI
L1.Digital				0.094*** (12.97)					
L2.Digital					0.100*** (12.35)				
L3.Digital						0.097*** (10.61)			
Digital	0.690*** (9.78)						0.090*** (11.98)	0.091*** (10.70)	0.086*** (9.00)
Digital_abn		0.090*** (13.33)							
Digital_2			0.076*** (10.11)						
Ctrl	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
IndusFE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
YearFE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	19428	19428	19428	17201	14397	12100	15967	13185	10912
R2_adj	0.321	0.332	0.330	0.329	0.326	0.317	0.325	0.312	0.308

4.3.3. Testing with the Multi-Period Difference-in-Differences Method

The measurement indicators for core variables address the issue of different measurement scales, while the extended observation window confirms temporal causality, both of which further validate the core hypothesis of this paper: "Corporate digital transformation enhances environmental protection investment levels." However, the regression model may still contain omitted variable bias, potentially indicating endogeneity. Considering that digital technologies provide essential tools and capabilities for corporate digital transformation, the phased implementation of digital transformation by enterprises as digital technologies mature constitutes a quasi-natural experiment. Drawing on Wu Fei et al. (2021) [24], this study adopts a multi-period difference-in-differences (DID) model to mitigate endogeneity issues. By conducting two separate differences between the experimental group and control group before and after implementing digital transformation strategies, we eliminate biases caused by individual differences and time trends, thereby obtaining the net effect of corporate digital transformation on environmental protection investment. The following DID model is constructed to examine the impact of corporate digital transformation on environmental protection investment levels:

$$EPI_{it} = \alpha + \varphi_1(du_{it} \times dt_{it}) + \sum \beta CVs + \varepsilon_{it} \quad (2)$$

Here, du indicates whether an enterprise has implemented digital transformation, where $du=0$ represents firms that have not undergone digital transformation during the sample period, and $du=1$ denotes those that have completed the transformation. dt is a dummy variable for the period, with $dt=0$ indicating no digital transformation in the current year and $dt=1$ signifying active transformation. Given that double-difference samples require observations spanning several years before and after policy changes, the regression model selected firms with at least five consecutive

years of data. Enterprises with less than two years of digital transformation implementation were categorized as $du=0$ to ensure sufficient post-difference observation periods. Additionally, firms that had been continuously implementing digital transformation throughout the sample period were excluded.

To further validate the robustness of the difference-in-differences (DID) model, this study extends Equation (2) by incorporating time and industry fixed effects for a retest.

$$EPI_{it} = \alpha + \varphi_1'(du_{it} \times dt_{it}) + \sum \beta' CVs + \sum Year + \sum Indus + \varepsilon_{it} \quad (3)$$

To further examine the impact of enterprise digital transformation intensity, we employ a double-difference model with adjustment effects for estimation. The specific model specification is presented in Equation (4):

$$EPI_{it} = \alpha'' + \varphi_1''(du_{it} \times dt_{it} \times Digital_{it}) + \sum \beta'' CVs + \sum Year + \sum Indus + \varepsilon_{it} \quad (4)$$

Table 7 presents the regression results from the multi-period difference-in-differences (DID) test. Column (1) shows the regression test for Equation (2), where the regression coefficient of $du \times dt$ is significantly positive (coefficient: 0.210, t-value: 8.72), indicating that corporate environmental investment levels significantly increase after digital transformation. Column (2) presents the regression test for Equation (3), showing that the regression coefficient of $du \times dt$ remains significantly positive (coefficient: 0.288, t-value: 11.08). The regression results in both columns demonstrate that digital transformation enhances corporate environmental investment levels through the DID method. Column (3) presents the regression results after introducing the digital transformation degree (Digital), where the coefficient of $du \times dt \times Digital$ remains significantly positive, indicating that higher digital transformation degrees correlate with greater environmental investment increases. Additionally, this study examines the temporal trend characteristics of this impact, with regression results shown in Column (4) of Table 7. Column (4) reveals that the regression coefficients show no statistical significance in the year of digital transformation implementation and the preceding 1-3 years, confirming the parallel trend test. However, coefficients become significantly positive one year ($dt \times after1$), two years ($dt \times after2$), and three years ($dt \times after3$) post-implementation, demonstrating the sustained positive impact of digital transformation on environmental investments. This finding aligns with Table 6's findings on extended observation windows. Through robustness and endogeneity testing, all hypotheses remain highly consistent.

Table 6. Robustness Test 3: Difference-in-Differences Test.

variable	(1) EPI	(2) EPI	(3) EPI	(4) EPI
$du \times dt$	0.182*** (7.61)	0.279*** (10.75)		
$du \times dt \times Digital$			0.132*** (11.39)	
$du \times dt \times before3$				-0.002 (-1.12)
$du \times dt \times before2$				-0.001 (-0.83)
$du \times dt \times before1$				-0.001 (-0.90)
$du \times dt \times current$				0.002 (1.34)
$du \times dt \times after1$				0.002** (2.08)
$du \times dt \times after2$				0.004*** (3.27)

du×dt×after3				0.007*** (3.82)
ROE	1.940*** (17.68)	1.932*** (17.41)	1.928*** (17.40)	1.813*** (15.72)
Size	1.013*** (9.41)	1.011*** (9.72)	1.016*** (9.15)	1.010*** (9.07)
Lev	2.819*** (38.49)	2.891*** (39.15)	2.888*** (39.31)	2.254*** (36.18)
Growth	0.035 (1.02)	0.016 (0.46)	0.011 (0.32)	0.020 (0.42)
SOE	0.189*** (6.68)	0.162*** (5.66)	0.174*** (6.08)	0.143*** (6.04)
Cashflow	1.970*** (10.30)	1.930*** (9.94)	1.916*** (9.86)	1.647*** (9.28)
ATO	-0.078** (-2.43)	-0.122*** (-3.66)	-0.128*** (-3.84)	-0.110*** (-3.16)
Top1	0.012*** (13.92)	0.011*** (13.61)	0.011*** (13.59)	0.011*** (13.72)
ListAge	0.402*** (22.20)	0.392*** (21.03)	0.393*** (21.35)	0.341*** (18.41)
constant term	17.505*** (345.21)	17.589*** (239.86)	17.611*** (240.27)	16.427*** (201.17)
IndusFE	No	Yes	Yes	Yes
YearFE	No	Yes	Yes	Yes
N	10717	10717	10717	10717
R2_adj	0.327	0.348	0.350	0.352

4.4. Mechanism Analysis

Previous studies have examined the impact of corporate digital transformation on environmental investments, providing empirical data support. However, these comprehensive analyses failed to reveal the underlying mechanisms. Therefore, this paper will identify and test the channel mechanisms through which digital transformation influences corporate environmental investments. Digital transformation enhances enterprises' ability to process non-standardized and unstructured data, improves communication quality, and alleviates information asymmetry. This helps monitor and constrain managerial opportunistic behavior, increases transparency in internal control operations, elevates internal control standards, and encourages better fulfillment of environmental responsibilities. Digital transformation also improves environmental information transparency, providing a foundation for public oversight, raising public awareness of environmental issues, and ultimately driving increased environmental investment levels. By optimizing production processes and improving resource allocation efficiency, digital transformation attracts financial institution funding, alleviates corporate financing constraints, and reduces the cost and risk of environmental investments. Therefore, this study selects two channels—enhancing internal control standards and easing financing constraints—for verification. To examine the mechanism pathways through which digital transformation affects environmental investment levels, this paper constructs the following mediating effect model based on the aforementioned Model (1):

$$EPI_{it} = \alpha + \beta_1 Digital_{it} + \sum \beta CVs + \sum Year + \sum Indus + \varepsilon_{it} \quad (3)$$

Inter_Var serves as the mediating variable, comprising two components: internal control level

$$Inter_Var_{it} = \alpha + \phi_1 Digital_{it} + \sum \beta CVs + \sum Year + \sum Indus + \xi_{it} \quad (3)$$

$$Epi_{it} = \alpha + \beta_1' Inter_Var_{it} + \beta_2' Digital_{it} + \sum \beta CVs + \sum Year + \sum Indus + \tau_{it} \quad (3)$$

(ICQ) and financing constraints (including endogenous financing constraint INFIAN and exogenous financing constraint EXFIAN). The recursive mediation test indicates the presence of a mediating effect when both coefficients Φ_1 and β_1' are statistically significant. Specifically, if β_2' is not significant, Inter_Var functions as a full mediator; if β_2' is significant and its sign aligns with $\Phi_1 \times \beta_1'$, it indicates partial mediation. To account for potential time lags in variable transmission within the mediation model and to control for reverse causality, this study applies a one-period lag to independent variables, retains current-period data for mediating variables, and uses one-period lag for dependent variables. Other variables follow the same methodology as previously described.

4.4.1. The Mediating Role of Internal Control Quality

As an institutional framework addressing internal agency issues in enterprises, effective internal control enhances principal-agent relationships and reduces operational risks, serving as a critical safeguard for high-quality corporate development. According to the "Guidance on the Application of Enterprise Internal Control No.4-Social Responsibility," companies should strengthen internal controls in environmental protection, resource conservation, and product quality assurance, demonstrating that environmental, social, and governance responsibilities have been embedded into their internal control systems. Firstly, digital transformation enables enterprises to integrate business process upgrades with internal control management. By leveraging digital resources and information technologies, companies can enhance the transparency and precision of internal controls, effectively improve compliance risk management, and elevate internal control quality. Secondly, digital transformation strengthens information communication. It transforms hierarchical information transmission structures into networked systems, boosting communication efficiency. Thirdly, digital transformation enhances monitoring capabilities. Through technologies like big data analytics and artificial intelligence, enterprises can collect real-time operational data and energy consumption metrics from sensors installed on production equipment, promptly identify potential failures and energy waste, and achieve refined production management. Finally, digital transformation improves risk assessment capabilities. Digital transformation empowers enterprises to monitor and analyze market dynamics, policy shifts, and competitor intelligence, enabling proactive identification of potential environmental policy risks and market competition threats. This allows companies to develop tailored risk mitigation strategies, keeping risks within manageable limits. Fourth, digital transformation streamlines internal control processes. By leveraging digital technologies like automated approval workflows and smart contract management systems, businesses can automate and optimize internal controls, reducing operational risks while ensuring effective compliance.

Effective internal control systems enable enterprises to identify and assess potential risks in environmental protection investments, while developing tailored risk mitigation strategies. By proactively formulating contingency plans, companies can reduce environmental investment risks and ensure smooth project implementation and operation. High-quality internal controls are closely tied to corporate governance structures and organizational culture development. Digital transformation drives enterprises to enhance internal control standards, with heightened emphasis on environmental accountability. This integration of sustainability principles into corporate strategies and daily operations fosters proactive environmental investments.

This study adopts the "Dibo Listed Companies Internal Control Index" published by Shenzhen Dibo Big Data Research Center, a widely recognized metric among scholars, to measure internal control quality. Given the broad value range (0-1000) of the Dibo Internal Control Index, we use the index value divided by 100 as the final measurement indicator for internal control quality, resulting

in a range of 0-10. The regression results with internal control quality (ICQ) as the mediator variable are presented in Table 8. Column (2) shows that the coefficient of corporate digital transformation (L.Digital) is significantly positive, indicating that digital transformation enhances internal control quality. Column (3) reveals that both the digital transformation coefficient (L.Digital) and internal control quality (ICQ) coefficients are significantly positive, suggesting that improved internal control quality partially mediates the relationship with corporate environmental investment levels. The mechanism test results in Table 8 demonstrate that digital transformation strengthens information communication and sharing among internal departments and across enterprises, effectively mitigating principal-agent problems and improving internal control quality. Enhanced internal control quality facilitates resource optimization and improves capital utilization efficiency. Companies can more accurately assess the investment returns and risks of environmental projects, directing limited funds to those with the greatest potential and value. This establishes a positive feedback loop: "corporate digital transformation → (improved) internal control quality → (increased) environmental investment."

Table 7. Mechanism Test 1: Using Internal Control Quality as a Mediating Variable.

variable	(1) EPI	(2) EPI	(3) EPI	(4) EPI
du×dt	0.182*** (7.61)	0.279*** (10.75)		
du×dt×Digital			0.132*** (11.39)	
du×dt×before3				-0.002 (-1.12)
du×dt×before2				-0.001 (-0.83)
du×dt×before1				-0.001 (-0.90)
du×dt×current				0.002 (1.34)
du×dt×after1				0.002** (2.08)
du×dt×after2				0.004*** (3.27)
du×dt×after3				0.007*** (3.82)
ROE	1.940*** (17.68)	1.932*** (17.41)	1.928*** (17.40)	1.813*** (15.72)
Size	1.013*** (9.41)	1.011*** (9.72)	1.016*** (9.15)	1.010*** (9.07)
Lev	2.819*** (38.49)	2.891*** (39.15)	2.888*** (39.31)	2.254*** (36.18)
Growth	0.035 (1.02)	0.016 (0.46)	0.011 (0.32)	0.020 (0.42)
SOE	0.189*** (6.68)	0.162*** (5.66)	0.174*** (6.08)	0.143*** (6.04)
Cashflow	1.970*** (10.30)	1.930*** (9.94)	1.916*** (9.86)	1.647*** (9.28)
ATO	-0.078** (-2.43)	-0.122*** (-3.66)	-0.128*** (-3.84)	-0.110*** (-3.16)
Top1	0.012*** (13.92)	0.011*** (13.61)	0.011*** (13.59)	0.011*** (13.72)

ListAge	0.402*** (22.20)	0.392*** (21.03)	0.393*** (21.35)	0.341*** (18.41)
constant term	17.505*** (345.21)	17.589*** (239.86)	17.611*** (240.27)	16.427*** (201.17)
IndusFE	No	Yes	Yes	Yes
YearFE	No	Yes	Yes	Yes
N	10717	10717	10717	10717
R2_adj	0.327	0.348	0.350	0.352

4.4.2. The Mediating Effect of Financing Constraints

According to the financing constraint theory, corporate financing methods can be categorized into endogenous and exogenous financing based on funding sources. Exogenous financing is primarily constrained by external factors such as market information asymmetry and transaction costs, while endogenous financing is mainly influenced by a company's own profitability. Financing constraints not only significantly impact business operations but also, to some extent, alter corporate decision-making. Environmental protection investments typically require substantial capital for purchasing eco-friendly equipment, adopting sustainable production processes, or conducting environmental technology R&D. With sufficient funding, companies can enhance their environmental protection investments to better plan and implement eco-friendly projects. When both internal and external financing constraints are alleviated, this helps ensure production safety and stability while expanding environmental protection investments.

Digital transformation in enterprises may influence internal and external financing constraints in the following ways: First, it alleviates external financing constraints by eliminating information asymmetry, expanding financing channels, and enhancing financial transparency. Through digital transformation, companies can more accurately collect and organize operational data, providing financial institutions with detailed financial statements that truly reflect their financial status. Financial institutions can thus more accurately assess a company's repayment capacity and operational risks when evaluating loan applications, making them more willing to provide financing support. Additionally, enterprises can leverage blockchain technology to convert carbon quotas and nationally certified voluntary emission reductions into tradable digital assets for collateral financing. For instance, in 2021, Xinpu Chemical Taixing Co., Ltd. secured a 5 million yuan special "Carbon Credit Loan" from Jiangsu Taixing Rural Commercial Bank by pledging 110,000 tons of carbon emission rights.

Secondly, digital transformation can help enterprises enhance production efficiency and reduce costs, thereby alleviating internal financing constraints. By utilizing sensors and IoT devices to collect real-time production data, companies can optimize processes, adjust equipment layouts, and improve material flow through big data analysis, ultimately boosting overall equipment efficiency. Additionally, digital technologies like barcode systems can integrate demand forecasting with real-time inventory data to achieve lean inventory management. This reduces overstocking of raw materials, work-in-progress, and finished goods, freeing up tied-up working capital while lowering warehousing, management, and expiration/devaluation risks—ultimately enhancing profitability.

This study adopts the methodology of Zhang Tongbin and Liu Wenlong (2024) [28], categorizing financing constraints into endogenous and exogenous types to examine their mediating role in the impact of corporate digital transformation on environmental investment levels. Specifically, the endogenous financing constraint (INFIAN) is measured by the ratio of 1 minus the balance of cash and cash equivalents to total assets at the end of the period, where higher values indicate stronger endogenous constraints. The exogenous financing constraint (EXFIAN) is measured by the ratio of 1 minus (current assets minus current liabilities) to total assets at the end of the period, with higher values indicating stronger exogenous constraints. The regression results using financing constraints as mediating variables are presented in Table 9. Column (2) shows that the coefficient for digital transformation (L.Digital) is not statistically significant, while column (3) indicates that the coefficient

for endogenous financing (INFIAN) is also insignificant, suggesting that digital transformation does not enhance environmental investment through alleviating endogenous constraints. Column (4) reveals a significantly negative coefficient for digital transformation (L.Digital), indicating that it mitigates exogenous financing constraints. Column (5) demonstrates that the coefficient for digital transformation (L.Digital) is significantly positive, while the coefficient for exogenous financing constraints (EXFIAN) is significantly negative, suggesting that the reduction of exogenous constraints partially mediates the effect on environmental investment levels. Mechanism testing results indicate that financing constraints primarily mediate the impact of corporate digital transformation on environmental investment levels by alleviating exogenous financing constraints. This may be because digital transformation helps enterprises mitigate external financing constraints, enhance environmental information transparency, reduce external financing costs, and establish green industry-finance integration channels, thereby increasing environmental investment levels and forming a closed loop of "corporate digital transformation → (reduction) of external financing constraints → (increase) of environmental investment". Endogenous financing mainly relies on internal capital accumulation through profit retention and depreciation. Although digital transformation improves operational efficiency, the process may involve high upfront costs and prolonged technology adaptation periods, resulting in non-linear growth of endogenous capital accumulation. Additionally, even if enterprises implement digital transformation, the short-term economic benefits may not be sufficient to effectively support environmental investments, making endogenous financing an ineffective intermediary channel for digital transformation's impact on environmental investment.

Table 8. Mechanism Test 2: Financing Constraints as an Mediating Variable.

variable	(1) F.EPI	(2) INFIAN	(3) F.EPI	(4) EXFIAN	(5) F.EPI
L.Digital	0.097*** (11.83)	-0.006*** (-9.32)	0.099*** (11.93)	-0.008*** (-8.48)	0.106*** (12.86)
INFIAN			0.267*** (2.66)		
EXFIAN					1.092*** (15.30)
ROE	2.108*** (20.49)	-0.054*** (-8.95)	2.126*** (20.62)	-0.187*** (-16.49)	2.321*** (21.94)
Size	1.013*** (15.48)	-0.002** (-2.14)	1.012*** (16.12)	0.006*** (7.34)	0.998*** (17.28)
Lev	2.753*** (43.72)	0.183*** (38.24)	2.704*** (40.96)	0.882*** (127.30)	1.781*** (19.89)
Growth	0.122*** (4.08)	0.003 (1.25)	0.121*** (4.05)	0.019*** (5.60)	0.097*** (3.27)
SOE	0.199*** (7.63)	-0.025*** (-12.88)	0.205*** (7.80)	-0.021*** (-7.43)	0.223*** (8.58)
Cashflow	2.282*** (13.49)	-0.229*** (-17.21)	2.340*** (13.73)	0.308*** (15.88)	1.915*** (11.26)
ATO	-0.064** (-2.17)	-0.003 (-1.35)	-0.063** (-2.15)	-0.047*** (-14.09)	-0.013 (-0.45)
TOP1	0.009*** (12.47)	-0.000*** (-4.05)	0.009*** (12.52)	-0.000*** (-3.62)	0.009*** (13.23)
ListAge	0.362*** (21.15)	0.005*** (3.35)	0.362*** (21.07)	0.027*** (13.74)	0.335*** (19.60)
constant term	17.768*** (269.63)	0.771*** (122.22)	17.561*** (171.91)	0.444*** (55.21)	17.282*** (235.56)
IndusFE	Yes	Yes	Yes	Yes	Yes

YearFE	Yes	Yes	Yes	Yes	Yes
N	14161	17212	14161	17212	14161
R2_adj	0.325	0.203	0.325	0.627	0.338

4.5. Heterogeneity Analysis

4.5.1. Heterogeneity of Market Competition

Companies with strong monopolistic positions in their industries face relatively low market competition, enjoy more stable market shares, and possess greater risk resistance capabilities. They have stable funds for digital transformation to enhance resource allocation efficiency and production operations, thereby generating more capital for environmental protection investments. Enterprises with strong market monopolies often prioritize technological innovation, as digital transformation provides them with more technical means and innovation opportunities. These companies can effectively utilize digital technologies to develop new eco-friendly products, processes, or services, improving the efficiency and effectiveness of environmental protection investments, thus becoming more proactive in such investments. In contrast, companies facing intense market competition experience greater survival pressure and focus more on expanding market share to maintain operations. To sustain core businesses, these companies may have to cut digital expenditures, making it difficult to pursue in-depth technological innovation and integration. As a result, the promoting effect of digital transformation on environmental protection investments remains limited. Therefore, this section calculates the Lerner Index by dividing (revenue-operating costs-selling expenses-administrative expenses) by sales revenue. A higher Lerner Index indicates stronger pricing power within the industry and lower market competition intensity. Companies are grouped into two categories based on the median market competition intensity of their respective industries: high-market-competition-intensity enterprises and low-market-competition-intensity enterprises. Columns (1)-(2) of Table 10 present the heterogeneity analysis results of market competition intensity. In the high-competition group, the coefficient of digital transformation (Digital) is not statistically significant, whereas in the low-competition group, it shows a significant positive effect. This indicates that digital transformation primarily enhances environmental investment in firms with lower market competition levels, consistent with our expectations.

4.5.2. Heterogeneity of Enterprise Size

Large-scale enterprises typically possess stronger financial capabilities. Digital transformation requires substantial capital investment, including the acquisition of advanced digital equipment, software systems, and relevant technical talent. Leveraging their financial advantages, large enterprises can more effectively implement digital transformation initiatives. Simultaneously, digital transformation can enhance production efficiency and reduce costs, allowing funds to be redirected toward environmental investments. Small-scale enterprises, however, face relatively limited financial resources, and their digital transformation investments may exert significant pressure on their financial conditions. They may only undertake basic digital upgrades, making it difficult to achieve comprehensive digital transformation like large-scale enterprises. Moreover, due to their smaller scale, even if digital transformation reduces costs, the savings remain relatively limited, making it challenging to support large-scale environmental investments. Therefore, this section groups enterprises by median annual scale into large and small enterprise groups. Columns (3)-(4) of Table 10 report the heterogeneity analysis results of enterprise scale. In the small enterprise group, the coefficient of digital transformation (Digital) is not statistically significant; in the large enterprise group, the coefficient of digital transformation (Digital) is significantly positive. This indicates that the promoting effect of digital transformation on environmental investments is primarily observed in large enterprises, consistent with expectations.

Table 9. Heterogeneity Test Results.

variable	(1)	(2)	(3)	(4)
	EPI low market competition Intensive group	EPI high market competition Intensive group	EPI Small-scale enterprises	EPI large-scale corporation
Digital	0.095*** (12.33)	0.072*** (5.22)	0.032*** (4.83)	0.035*** (3.87)
ROE	1.805*** (19.73)	1.684*** (10.04)	0.336*** (4.13)	1.311*** (13.92)
Size	1.024*** (14.35)	0.971*** (12.64)	0.913*** (11.3)	1.047*** (11.91)
Lev	2.831*** (46.42)	2.501*** (22.12)	1.086*** (19.87)	2.059*** (29.21)
Growth	0.047* (1.68)	-0.087* (-1.81)	0.032 (1.34)	-0.040 (-1.37)
SOE	0.213*** (8.67)	0.313*** (5.95)	-0.008 (-0.34)	0.124*** (4.83)
Cashflow	1.877*** (11.92)	2.057*** (6.83)	0.825*** (6.23)	1.612*** (8.66)
ATO	-0.123*** (-4.36)	0.151** (2.32)	0.067** (2.56)	-0.104*** (-3.45)
TOP1	0.008*** (12.13)	0.011*** (8.74)	0.001** (2.31)	0.008*** (10.48)
ListAge	0.308*** (23.82)	0.365*** (14.09)	-0.029** (-2.48)	0.219*** (12.47)
constant term	17.827*** (289.27)	17.620*** (143.68)	18.954*** (345.44)	18.955*** (240.48)
IndusFE	Yes	Yes	Yes	Yes
YearFE	Yes	Yes	Yes	Yes
N	15702	3726	9694	9734
R2_adj	0.315	0.419	0.113	0.218

5. Research Conclusions and Recommendations

Based on the development trend of digital transformation in China enterprises and the practical issue of environmental governance, this paper examines the impact of digital transformation on environmental governance in China manufacturing enterprises. The research results show that digital transformation enhances environmental protection investment levels, and this conclusion remains valid after a series of robustness tests. Further mechanism analysis indicates that improving internal control quality and alleviating exogenous financing constraints are two channels through which digital transformation positively affects environmental protection investment levels. Heterogeneity analysis reveals that the enhancing effect of digital transformation on environmental protection investment is mainly reflected in enterprises with relatively low market competition intensity and large-scale enterprises.

From a theoretical perspective, this study addresses the characteristics of manufacturing enterprises primarily focused on physical production, expanding the research on non-economic benefits of corporate digital transformation from the perspective of environmental governance, achieving the intersection and theoretical advancement of digital economy theory and the concept of green development. This exploration provides valuable insights for promoting green and low-carbon economic transformation and high-quality corporate development through digital governance mechanisms. Secondly, this study not only aims to provide empirical evidence for the promotion and

effective implementation of digital transformation in developing countries but also offers policy implications for developed countries to address environmental issues and advance corporate low-carbon transformation. Although this study is based on China data, the findings are particularly valuable for reference for emerging economies facing similar institutional transitions and market conditions, as well as those at comparable stages of development.

Based on the above conclusions, the following recommendations are proposed: (1) At the government policy level, the government should continuously optimize the macro policy framework for promoting corporate digital transformation. By establishing a policy system that combines innovation policies and industrial policies oriented toward digital strategies, enterprises can accelerate the construction of digital systems during their journey toward high-quality development. Priority should be given to advancing digital transformation among large-scale enterprises with low market competition levels, while considering providing targeted support policies for key enterprises to more effectively promote corporate environmental governance. (2) At the corporate strategy level, enterprises should actively adapt to the rapid development of digital technologies, fully grasp the opportunities of digital transformation, and emphasize the role of digital transformation in enhancing corporate environmental governance to achieve a win-win situation of economic value and social benefits. At the corporate governance level, the empowering effect of digital technology on internal governance should be strengthened. Enterprises need to proactively innovate internal governance methods and models under digital scenarios, utilize digital technologies to informatize and code traditional work processes, improve the quality of internal controls, and restrain managerial opportunistic behaviors. By leveraging digital technologies to build dynamic information disclosure platforms, enterprises can enhance transparency with stakeholders, gain support from investors and financial institutions, alleviate financing constraints, increase environmental investment levels, and actively engage in environmental governance.

Although this paper systematically examines the mechanisms by which corporate digital transformation impacts environmental governance and provides empirical evidence, the study still has limitations and room for further expansion. First, the empirical test was conducted using a sample of China's listed manufacturing enterprises, so the applicability of the conclusions is primarily limited to China's domestic institutional system and industrial ecosystem. Significant differences exist among countries in terms of policy frameworks, market operation mechanisms, and stages of development, which means the cross-contextual generalizability of the conclusions needs further validation. Future research could expand the sample scope to other emerging Asian markets and developing countries, utilizing cross-economy comparative analysis to enhance the universality and international adaptability of the research conclusions. Second, the study subjects were limited to listed companies with relatively mature governance structures. Small and medium-sized enterprises or unlisted companies may exhibit different characteristics in terms of resource endowments, governance models, and the degree of digital transformation. Therefore, future research needs to expand the sample scope to improve the universality of the conclusions.

Author Contributions: Z.H.: Data curation, funding, Writing—review & editing. J.Q.: Methodology, Supervision, Writing—review & editing. X.F.: Formal analysis, Writing—original draft, Writing—review & editing. Y.S.: Validation, Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the following projects: National Natural Science Foundation of China, grant number 72274042; Guangdong Provincial Marine Development Planning Research Center (no grant number). The APC was funded by Guangdong Ocean University.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used are all public data that can be downloaded from the websites mentioned in the paper.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Dogaru, L. Green Economy and Green Growth—Opportunities for Sustainable Development. In Proceedings of the The 14th International Conference on Interdisciplinarity in Engineering—INTER-ENG 2020; MDPI, January 22 2021; p. 70.
2. Meng, F.; Zhao, Y. How Does Digital Economy Affect Green Total Factor Productivity at the Industry Level in China: From a Perspective of Global Value Chain. *Environ Sci Pollut Res* 2022, 29, 79497–79515.
3. Zhang, G.; Liu, G. Does Global Value Chain Embedment Contribute to Environmental Pollution in Emerging Economies? *Sustainability* 2023, 15, 1031.
4. Wang, S.; Wang, H. Can Global Value Chain Participation Drive Green Upgrade in China’s Manufacturing Industry? *IJERPH* 2022, 19, 12013.
5. Tomás, G.-C.; José-Antonio, C.-A.; Julennys-Carolina, C.-M.; Alejandro, D.-P. Linking Environmental Sustainability, Digital Transformation, and Innovation: Evidence from Micro-Enterprises and SMEs. *Journal of Innovation & Knowledge* 2025, 10, 100849.
6. Habib, Md.A.; Bao, Y.; Nabi, N.; Dulal, M.; Asha, A.A.; Islam, M. Impact of Strategic Orientations on the Implementation of Green Supply Chain Management Practices and Sustainable Firm Performance. *Sustainability* 2021, 13, 340.
7. Kou, G.; Yüksel, S.; Dinçer, H.; A.Hefni, M. Integrated Approach for Sustainable Development and Investment Goals: Analyzing Environmental Issues in European Economies. *Ann Oper Res* 2024, 342, 429–475.
8. Zhang, Y.; Chen, Y.; Ning, Y. Environmental Information Disclosure, Central Environmental Protection Supervision, and Industrial Green Transformation—Empirical Evidence from Listed Companies. *Environ Dev Sustain* 2024, 27, 11579–11601.
9. Mo, S.; Liu, X. How Does Artificial Intelligence Affect Energy Intensity? The Role of Digital Economy. *International Journal of Green Energy* 2026, 23, 265–281.
10. Chen, H.; Xu, H. The Impact Mechanism of Digital Economy Platforms Supported by Blockchain and Artificial Intelligence on Consumer Green Payment Behavior. *Discov Artif Intell* 2025, 5, 401.
11. ShenpeiYilin Cloud Computing Environment: Research on Big Data Security and Privacy Protection Strategies. *jaip* 2025, 8.
12. Chen, X.; Zhou, P.; Hu, D. Influences of the Ongoing Digital Transformation of the Chinese Economy on Innovation of Sustainable Green Technologies. *Science of The Total Environment* 2023, 875, 162708.
13. Jin, X.; Xie, Q. The Impact of Digital Transformation on Excessive Financialization in the Real Economy. *Sustainability* 2024, 16, 10464.
14. Li, J.; Saide, S.; Ismail, M.N.; Indrajit, R.E. Exploring IT/IS Proactive and Knowledge Transfer on Enterprise Digital Business Transformation (EDBT): A Technology-Knowledge Perspective. *JEIM* 2022, 35, 597–616.
15. Qin, S. Impact of Enterprise Digital Transformation on Key Core Technology Innovation: The Mediating Effect of Total Factor Productivity. *ESS* 2026, 10, 187–197.
16. Wang, W.; Yan, Z.; Zhang, J. The Impact of Digital Infrastructure on Ambidextrous Innovation: Evidence from Specialized, Sophisticated, Distinctive, and Innovative Enterprises in China. *International Journal of Innovation Studies* 2026, 10, 106–121.
17. Zhou, J.; Wang, G.; Diao, Z. Enabling Digital Transformation of Traditional Enterprises through Industrial Internet Platforms: A Study from an Ecosystem Perspective. *Engineering, Construction and Architectural Management* 2026, 33, 413–434.
18. Baah, C.; Agyabeng-Mensah, Y.; Afum, E.; Acquah, I.S.K.; Agyeman, D.O. Digital Co-Transformation, Interfirm Knowledge Creation, and Collaborative Innovation: Symmetrical and Asymmetrical Drivers of B2B SME Performance under Threats. *Industrial Marketing Management* 2026, 132, 117–134.
19. Karimi, J.; Walter, Z. The Role of Dynamic Capabilities in Responding to Digital Disruption: A Factor-Based Study of the Newspaper Industry. *Journal of Management Information Systems* 2015, 32, 39–81.

20. Mu, X.; Chen, D.; Zhang, H. The Impact of Digital Transformation on the Sustainable Development of Enterprises: An Analysis from the Perspective of Digital Finance. *Journal of Applied Economics* **2025**, *28*, 2464488.
21. Qiu, D.; Qiu, J. Unraveling How Digital Transformation Affects Innovation Capability in China's Smart Manufacturing Enterprises. *Sci Rep* **2025**.
22. Hänninen, M.; Smedlund, A. Same Old Song with a Different Melody: The Paradox of Market Reach and Financial Performance on Digital Platforms. *J Management Studies* **2021**, *58*, 1832–1868.
23. Ayadi, I.; Abderrahman, J. The Impact of Economic Policy Uncertainty and Digital Integration on ESG Practices in European Companies. *Research in International Business and Finance* **2025**, *76*, 102826.
24. Liu, W.; Wu, C.-H.; Tsai, S.-B.; Shao, X.; Waclawek, M. Corporate Environmental Management in the Context of Digital Transformation. *Ecological Chemistry and Engineering S* **2023**, *30*, 91–92.
25. Xu, P.; Chen, L.; Dai, H. Pathways to Sustainable Development: Corporate Digital Transformation and Environmental Performance in China. *Sustainability* **2022**, *15*, 256.
26. Chen, W.; Zhang, L. Corporate Digital Transformation and Tax Uncertainty: Evidence from China. *IJOEM* **2025**.
27. Lv, C.; Fan, J.; Lee, C.-C. Can Green Credit Policies Improve Corporate Green Production Efficiency? *Journal of Cleaner Production* **2023**, *397*, 136573.
28. Gao, T. Effects of Digital Transformation on Firm Performance: -- Take Company in Chaoyang District, Beijing, China. *AJMSS* **2024**, *7*, 20–24.
29. Pan, W.; Xie, T.; Wang, Z.; Ma, L. Digital Economy: An Innovation Driver for Total Factor Productivity. *Journal of Business Research* **2022**, *139*, 303–311.
30. Wang, L.; Yang, S. The Impact of Green Technology on Corporate ESG Performance: The Moderating Role of Corporate Green Responsibility. *Journal of Environmental Management* **2025**, *395*, 127947.
31. Xu, C. Research on Organizational Structure Change of Enterprises under the Background of Digital Transformation. *Forum on Research and Innovation Management* **2025**.
32. Brynjolfsson, E.; Collis, A. How Should We Measure the Digital Economy?
33. Tan, L.; Li, K.; Liu, M. How Can Digital Transformation Drive a Green Future?—Intermediary Mechanisms for Supply Chain Innovation: Evidence from Chinese A-Share Listed Companies. *Sustainability* **2025**, *17*, 8298.
34. Mai, W.; Xiong, L.; Liu, B.; Liu, S. Spatial–Temporal Evolution, Drivers, and Pathways of the Synergistic Effects of Digital Transformation on Pollution and Carbon Reduction in Heavily Polluting Enterprises. *Sci Rep* **2025**, *15*, 11963.
35. Gebauer, H.; Fleisch, E.; Lamprecht, C.; Wortmann, F. Growth Paths for Overcoming the Digitalization Paradox. *Business Horizons* **2020**, *63*, 313–323.
36. Shi, X.; Geng, S. Double-Edged Sword? Heterogeneous Effects of Digital Technology on Environmental Regulation-Driven Green Transformation. *Journal of Environmental Management* **2025**, *389*, 125960.
37. Yu, Y.; Chen, H.; Xu, N. Data Governance, Financial Environmental Regulation, and Enterprise Digital Transformation. *Finance Research Letters* **2026**, *89*, 109274.
38. Song, Z.; Jia, M.; Ma, Y. Digital Technology Innovation Promotes Green Transformation: Empirical Evidence from Chinese Manufacturing Enterprises. *Sustainable Futures* **2025**, *10*, 100964.
39. Guedes, B.T.; Fettermann, D.C.; Hribernik, K.A.; Thoben, K.-D. How Digital Transformation Is Changing Product Development: A Comprehensive Analysis. *Journal of Industrial Information Integration* **2026**, *50*, 101064.
40. Li, X.; Xu, X. The Bidirectional Spillover of Carbon Emission Reduction Effects from Enterprise Digital Transformation under the Dual Networks of Supply Chain. *Journal of Cleaner Production* **2026**, *540*, 147448.
41. Şahin, S. Digital-Economic Transformation's Environmental Impact: Transportation CO₂ Emissions in Fragile and Transition Economies. *Transportation Research Part D: Transport and Environment* **2026**, *150*, 105132.
42. Khurram, M.U.; Abbassi, W.; Chen, Y.; Chen, L. Outward Foreign Investment Performance, Digital Transformation, and ESG Performance: Evidence from China. *Global Finance Journal* **2024**, *60*, 100963.

43. Hoque, M.M.; Lee, S.-J. How Digital Transformation Drives Green Innovation: An Empirical Study. *Journal of Cleaner Production* **2025**, *522*, 146236.
44. Bag, S.; Routray, S.; Aytac, B. Linking Digital Transformation to ESG Outcomes: A Mixed-Methods Study on SRM Capability and Cooperation in Supply Networks. *Journal of Environmental Management* **2025**, *392*, 126801.
45. Shi, H.; Liu, Y.; Yang, Y. Enterprise Digital Transformation and Supply Chain Stability. *Finance Research Letters* **2024**, *63*, 105299.
46. Tian, H.; Shi, T. Corporate Digital Transformation and Supply Chain Synergy Effects. *Finance Research Letters* **2024**, *62*, 105247.
47. Singh, K.; Chaudhuri, R.; Chatterjee, S. Assessing the Impact of Digital Transformation on Green Supply Chain for Achieving Carbon Neutrality and Accelerating Circular Economy Initiatives. *Computers & Industrial Engineering* **2025**, *201*, 110943.
48. Li, Z.; Zhang, X.; Tao, Z.; Wang, B. Enterprise Digital Transformation and Supply Chain Management. *Finance Research Letters* **2024**, *60*, 104883.
49. Wen, H. The Research on the Impact of Digital Transformation on Corporate Financialization - Evidence from China. *Journal of Economics and Law* **2025**.
50. Sang, Y.; Huang, R. The Impact of Enterprise Digital Transformation on Operational Flexibility. *Finance Research Letters* **2025**, *86*, 108634.
51. Cui, L.; Wang, Y. Can Corporate Digital Transformation Alleviate Financial Distress? *Finance Research Letters* **2023**, *55*, 103983.
52. Zhao, S.; Deng, H.; Cao, J.; Gustaf, M. Digital Transformation of Construction Enterprises and Carbon Emission Reduction: Evidence from Listed Companies. *Front. Environ. Sci.* **2025**, *13*, 1570182.
53. Quttainah, M.A.; Ayadi, I. The Impact of Digital Integration on Corporate Sustainability: Emissions Reduction, Environmental Innovation, and Resource Efficiency in the European. *Journal of Innovation & Knowledge* **2024**, *9*, 100525.
54. Wang, G.; Li, L. Impacts of Enterprise Digital Transformation on Industrial Structure Adjustment—Evidence from China. *Sage Open* **2025**, *15*, 21582440251384530.
55. Magrizos, S. The Dark Side of Companies' Digital Transformation: The Carbon Footprint of Online Activities. *International Marketing Review* **2025**, *42*, 1360–1381. <https://doi.org/10.1108/IMR-10-2024-0398>.
56. Hein, N.; Münter, M.T.; Zimmermann, V. Green, Digital, or Twin Strategic Orientation: What Drives Environmental Sustainability and Digitalization in German Innovative SMEs? *Journal of Innovation & Knowledge* **2026**, *12*, 100896. <https://doi.org/10.1016/j.jik.2025.100896>.
57. Patten, D.M. The Accuracy of Financial Report Projections of Future Environmental Capital Expenditures: A Research Note. *Accounting, Organizations and Society* **2005**, *30*, 457–468.
58. Zhang, Y.; Guo, X. Digital Transformation of Enterprises and the Governance of Executive Corruption: Empirical Evidence Based on Text Analysis. *Journal of Global Information Management* **2022**, *30*, 1–18.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.