

Article

Unlocking Sustainable Value: The Dual Pathways from Digital Innovation to Corporate ESG Performance

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Abstract

Against the backdrop of the dual convergence of the digital economy and sustainable development strategies, digital innovation has emerged as a pivotal driver for reshaping firms' competitive advantages and fulfilling social responsibilities. In this study, the analysis draws on a sample of Chinese listed firms from 2014 to 2023. ESG performance is measured with Hua Zheng ESG scores, digital innovation is captured via digital patent identification, and a dual-mediation framework is employed to examine internal organizational and external supply chain mechanisms, along with heterogeneity analysis. The findings indicate that digital innovation exerts a significant positive effect on ESG performance and reveal a unique dual mediating mechanism: within the internal boundary of the firm, digital innovation releases available organizational slack significantly through internal resource orchestration, and this abundant slack provides a necessary resource buffer for ESG investment; within the external network of the firm, digital innovation reduces supplier concentration significantly, thereby enhancing bargaining and supply chain discourse power, which in turn improves corporate ESG performance. Heterogeneity analysis further demonstrates that the promoting effect of digital innovation on ESG performance is more pronounced in subsamples characterized by CEO duality, low technological intensity, and high levels of marketization. By drawing on the resource-based view and resource dependence theory respectively to explain internal and external mediating pathways, this study advances understanding of the complementary mechanisms through which digital innovation enhances ESG performance. It demonstrates how digital innovation comprehensively reshapes firm capabilities, providing valuable insights for formulating strategic ESG initiatives in the digital era.

Keywords: digital innovation; ESG performance; organizational slack; supplier concentration; strategic management

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1. Introduction

Since the 18th National Congress of the Communist Party of China, the country has placed a high priority on ecological civilization, and the philosophy of green and sustainable development has increasingly become a dominant trend in economic and social progress. China has set the “dual carbon” goals of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060. These targets encourage firms to proactively reduce emissions and pursue low-carbon development, while facilitating the integration of environmental, social, and governance principles into national development strategies and

policy frameworks. As a core indicator of corporate sustainability, ESG performance is drawing growing attention from global capital markets, regulators, and academia.

Against this backdrop, the vigorous expansion of the digital economy has fueled widespread digital innovation, which can provide a core driving force for the transformation and upgrading of ESG performance. For example, Contemporary Amperex Technology Co., Limited (CATL) has leveraged digital innovation to deploy digital twin platforms across its battery manufacturing plants, enabling real-time energy consumption monitoring and intelligent waste sorting. The company reduced its energy consumption intensity per unit of product by 28% and its carbon emission intensity by approximately 77% between 2022 and 2025. Similarly, Alibaba Group's Cainiao Network utilizes big data algorithms to optimize delivery routes and promote recyclable packaging through a blockchain-based tracking system, significantly cutting logistics-related plastic waste and carbon footprint. By embedding digital technologies into firm production and innovation processes [1], digital innovation generates new products and services with broad influence and diverse application scenarios, representing the frontier of technological progress [2,3]. Furthermore, digital innovation can combine digital technologies with critical complementary resources, knowledge-sharing platforms, and knowledge-driven activities, thereby restructuring existing innovation resources and processes [4]. This restructuring, achieved through the absorption of new knowledge and technologies, also creates additional opportunities to enhance ESG performance.

In recent years, corporate ESG performance in the digital era has been regarded as a critical pillar for achieving high-quality development and sustainable development, attracting widespread scholarly attention. Huang [5] indicates that digital innovation can improve corporate ESG performance through two pathways: enhancing operational performance and attracting analyst attention. Che [6] argues that a high level of digital innovation can significantly improve corporate ESG performance, and the advancement of digital technology can substantially elevate firms' overall environmental, social, and governance performance. Although existing studies have investigated digital innovation and ESG performance, the majority have focused on the effects of digital transformation and digital technology on ESG performance [7–9], while empirical research on the direct association and the internal and external transmission mechanisms remains in its infancy. Hence, the question of through what resource allocation logic and structural reconfiguration digital innovation influences ESG performance still urgently requires in-depth theoretical analysis and empirical testing.

Building on the foregoing analysis and considerations, a panel dataset of Chinese A-share listed firms spanning the period from 2014 to 2023 is used in this study. Digital innovation is measured through the identification of digital patents, and ESG performance is measured with Hua Zheng ESG scores. The impact of digital innovation on ESG performance as well as the underlying internal and external mechanisms is rigorously examined. The findings reveal that digital innovation significantly enhances ESG performance by improving organizational slack and reducing supplier concentration. Heterogeneity analysis reveals that the impact of digital innovation on ESG performance is more pronounced in subsamples characterized by CEO duality, low technology intensity, and high levels of marketization.

Compared with prior studies, this paper's potential contributions primarily lie in the following aspects. First, it robustly validates the causal relationship between digital innovation and ESG performance, constructs a comprehensive theoretical framework that integrates internal resource reconfiguration and external network restructuring, and thus enriches the body of research on the impact of digital innovation on social responsibility. Second, by empirically examining the positive effect of digital innovation on organizational slack and the positive spillover of organizational slack to ESG performance, this

paper enriches the theoretical insights of the resource-based view in the digital economy era. Third, by demonstrating that digital innovation negatively affects supplier concentration and that supplier concentration, in turn, negatively affects ESG performance, this study extends the application of resource dependence theory to the domains of supply chain resilience and corporate social responsibility.

2. Literature and Hypotheses Development

2.1. *The Impact of Digital Innovation on Corporate ESG Performance*

Corporate ESG performance is the outcome of the interplay among multiple interacting factors, among which the application of digital technologies constitutes the core driving engine. In its essence, digital innovation embodies the creative application of such digital technologies. Digital innovation, as a heterogeneous resource of the firm, represents an endogenous impetus actively constructed within the firm and serves as an important pathway for driving corporate value growth [10]. Through the internalization and absorption of new knowledge and new technologies, digital innovation enables firms to identify innovation opportunities and create a more favorable innovation environment, thereby enhancing innovation efficiency [11]. Digital innovation strengthens firms' resource integration and reconfiguration capabilities, facilitates the transformation of corporate strategy toward novel business models [12], boosts investor sentiment, reduces financing costs, and increases operating revenue, thereby alleviating the financing constraints faced by firms in conducting ESG practices and continuously improving corporate ESG performance [13]. Therefore, digital innovation can not only fundamentally enhance iterative innovation capabilities by virtue of its inherent knowledge-driven characteristics but also improve resource allocation efficiency, thus promoting corporate ESG performance.

Digital innovation can transform data into a driving force for endogenous growth through its unbounded possibilities for recombination, and alleviate the problem of diminishing marginal returns to traditional production factors effectively by virtue of the continuous accumulation and spillover effects of knowledge [14], thereby laying the groundwork for improvements in ESG performance. Digital innovation can leverage digital technologies to transform accumulated market information into knowledge capital, integrate concepts such as green production, quality management, and brand building into production processes, proactively adapt to changes in the external environment, achieve personalized product innovation through feedback mechanisms, and respond to consumer demands with greater agility [15]. Meanwhile, digital innovation possesses knowledge spillover effects that diffuse through two pathways [16]: vertical innovation provides a knowledge base for subsequent innovations by other firms, while horizontal innovation facilitates the diffusion of complementary knowledge through the development of new products or services, thereby promoting technological upgrading in related industries and generating innovation cluster effects. These two pathways jointly reduce firms' innovation costs, shorten the technology development cycle, and ultimately improve ESG performance.

Digital innovation also plays a significant role in resource integration by providing a platform for data mining and information analysis, and by enabling real-time analysis of mined market information, thereby helping firms obtain valuable operational insights [17]. By employing digital technologies such as real-time digital simulation (RTDS), firms can effectively compress innovation costs and precisely meet customers' personalized demands [18]. This approach not only enhances customer satisfaction but also promotes innovative outcomes and advanced technologies [19], thereby elevating social reputation and ultimately optimizing corporate ESG performance. Meanwhile, digital innovation can drive firms to establish knowledge management systems and enhance the efficiency of

strategy formulation [20]. For instance, by leveraging digital tools such as quality management systems (QMS) and product lifecycle management systems (PLMS), firms can monitor production compliance in real time and trace product quality, which not only reduces environmental protection costs but also enables low-carbon upgrading, ultimately improving ESG performance. Therefore, the following hypothesis is proposed:

H1. *Digital innovation has a promoting effect on the enhancement of corporate ESG performance.*

2.2. *The Mediating Role of Organizational Slack in Digital Innovation and Corporate ESG Performance*

Organizational slack is typically defined as the portion of idle and discretionary actual or potential resources within a firm that exceeds the minimum requirements for actual operations. Such resources assist firms in coping with uncertain environmental factors and enable the organization to make strategic responses at appropriate moments [21]. In classical organization theory, traditional firms often need to maintain a relatively high level of organizational slack to obtain an effective buffer when facing environmental turbulence [22]. ESG performance, as a core capability for firms to address the non-market environment, essentially represents a strategic investment characterized by a long-term orientation and resource intensity, necessitating substantial and sustained internal resources as support. Digital innovation, through internal resource orchestration, can exert the resource supplying and buffering functions of organizational slack and ultimately transform resources into ESG outcomes. Specifically, digital innovation, by optimizing production and management processes, breaks traditional resource constraint boundaries and accumulates abundant organizational slack for the firm. These slack resources, which are not fully consumed by current operations, provide management with greater strategic flexibility and tolerance for error, enabling them to alleviate short term performance pressure and allocate more resources to ESG initiatives. Therefore, organizational slack plays an indispensable mediating role as an internal resource in the pathway through which digital innovation drives the improvement of ESG performance.

By leveraging digital technologies such as the Internet of Things, big data analytics, artificial intelligence, and cloud computing, digital innovation endows firms with unprecedented data insight and computing power [23], transforming internal resource orchestration from traditional experience driven and post hoc remediation to data driven and ex ante prediction. While enhancing organizational transparency, this transformation narrows managerial discretion over resource allocation and thus imposes greater accountability constraints on the deployment of slack resources. This shift enables firms to establish more precise internal resource orchestration mechanisms, reduce organizational information friction, and increase the availability of slack resources within the organization. Meanwhile, digital innovation exhibits strong spillover effects and economies of scope, enabling firms to accomplish cross departmental collaboration and product iteration at lower marginal costs [24] and to maintain established outputs with fewer core resources, thereby accumulating substantial slack resources within the organization [25]. Therefore, by optimizing internal resource orchestration mechanisms, digital innovation enhances the precision of resource orchestration while reducing organizational information friction, thus fundamentally increasing the actual increment of organizational slack.

Drawing on the resource-based view, an increase in organizational slack can provide direct resource guarantees for firms to improve ESG performance. ESG practices are essentially firms' responses to complex stakeholder demands [26], characterized by a long payback period and uncertain short term financial returns [27]. When available resources are limited, management often falls into short-termism, prioritizing limited resources to ensure the operation of core businesses [28]. Conversely, when a firm possesses abundant

organizational slack, it can not only maintain the critical safeguard for core business operations but also rapidly deploy resources to respond to crises, transforming slack resources into crisis recovery funds, thereby enhancing stakeholders' recognition of the firm's crisis recovery capability. Moreover, in the current Chinese institutional environment, ESG performance has become a critical means for firms to acquire legitimacy and for managers to build personal reputation. When managers allocate slack resources to readily observable ESG initiatives such as green manufacturing upgrades or employee welfare programs, they are more likely to gain recognition from government agencies, institutional investors, and the broader public, thereby aligning personal interests with stakeholder value. Therefore, the following hypothesis is proposed:

H2. *Digital innovation enhances ESG performance by improving organizational slack.*

2.3. The Mediating Role of Supplier Concentration in Digital Innovation and Corporate ESG Performance

According to resource dependence theory, the scarcity and irreplaceability of critical resources determine the level of supplier concentration for a firm. When the resources required by the firm simultaneously possess the characteristics of necessity, scarcity, and irreplaceability, the firm will strongly depend on a limited number of suppliers, ultimately resulting in high supplier concentration [29]. Digital innovation, by breaking the information monopoly of suppliers, substantially reduces firms' costs of searching for and evaluating new suppliers, and employs technological means to alter the scarcity of critical resources, thereby ultimately reducing dependence on a small number of core suppliers and achieving supply chain decentralization. A lower supplier concentration implies stronger bargaining power for the firm, which not only enables the firm to invest the saved resources and gained profit margins into ESG practices but also compels suppliers to comply with environmental and social responsibility standards. Therefore, reducing supplier concentration constitutes the core external pathway through which digital innovation improves ESG performance.

Digital innovation exhibits convergence and generativity [30], enabling the disaggregation of digital technologies to ultimately reduce supplier concentration. Convergence creates open technological architectures that span boundaries and integrate multisource information [31]. Through digital platforms, firms replace limited large suppliers with multiple smaller ones, altering resource irreplaceability, mitigating information asymmetry, and dismantling supplier monopolies. Generativity addresses resource scarcity by embedding digital technologies into layered modular architectures [32], enabling creative recombination of components. Traditional manufacturers once depended on few suppliers for irreplaceable high precision inspection equipment, but digital innovation now disrupts this reliance. For instance, machine vision AI systems from firms like Shanghai Betterway Automation replicate the functionality of formerly irreplaceable equipment, fostering a competitive supply market and suppressing supplier concentration.

When examining sustainable performance, such as ESG performance, the boundary of the modern firm is no longer confined to itself but must extend to the entire supply chain [33]. An increase in supplier concentration intensifies dependence on external resources, elevates procurement uncertainty for the firm, weakens its bargaining power [34], and ultimately triggers a cost squeeze effect [35], leading to a reduction in available funds allocated to environmental protection and social responsibility. Conversely, when supplier concentration decreases, the firm possesses stronger bargaining power and supply chain discourse power. On the one hand, under the condition of ensuring controllable costs and profits, the firm has more abundant financial resources to support long-term ESG project investments. On the other hand, the firm can compel suppliers to comply with

green procurement standards or to disclose their carbon footprints, thereby advancing the firm's overall ESG strategy. Therefore, the following hypothesis is proposed in Figure 1:

H3. *Digital innovation enhances ESG performance by suppressing supplier concentration.*

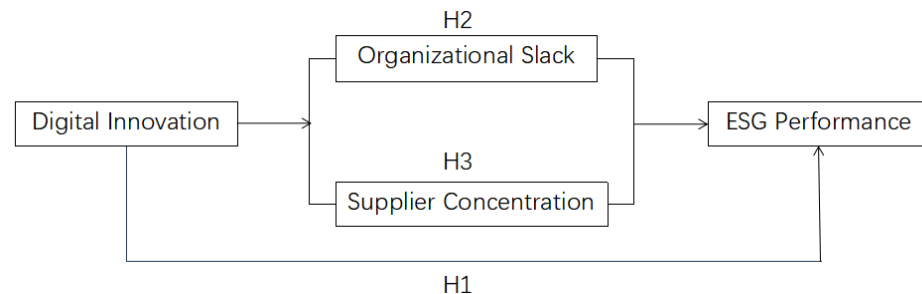


Figure 1. Conceptual framework.

3. Research Design

3.1. Sample and Data

This study focuses specifically on Chinese A-share listed companies from 2014 to 2023. Following established research conventions, the sample was processed as follows: excluding non-listed firm samples; removing financial industry samples; eliminating ST and *ST firm samples; and discarding observations with missing critical variables. Primary data sources include the Wind database, Wingo Financial Text Data Platform, and other variables' data from the China Stock Market & Accounting Research (CSMAR) database. To mitigate the influence of outliers, continuous variables were winsorized at the 1st and 99th percentiles. All empirical analyses were conducted using Stata 18 software.

3.2. Variables

3.2.1. Corporate ESG Performance

Following Xiong and Cai [36,37], corporate ESG performance is measured using the Hua Zheng ESG scores, which assign each firm a continuous score ranging from 0 to 100, based on a comprehensive evaluation of environmental, social, and governance dimensions. A higher score indicates superior ESG performance, and the measurement offers greater granularity for empirical analysis.

3.2.2. Digital Innovation

This study follows the approach of Li [38] by employing IPC classification codes derived from both the International Patent Classification correspondence table and the Key Digital Technology Patent Classification System (2023) issued by the National Intellectual Property Administration to identify and aggregate the annual total of digital invention patent applications for each firm. Subsequently, digital innovation is measured as the natural logarithm of one plus the total number of digital patent applications over the preceding three years, following Hanelt [39].

3.2.3. Organizational Slack

Following the theoretical classification of organizational slack [40], absorbed slack and unabsorbed slack represent the internal resource buffers that the firm already possesses and can deploy at its discretion. In contrast, potential slack merely signifies the firm's potential capacity to acquire additional resources from the external environment. Given that both digital innovation and ESG performance are highly dependent on liquid funds and human and organizational resources directly allocated by management, this

paper focuses on the internal slack that the firm actually possesses. Accordingly, the current ratio and the administrative expense ratio are employed to construct a composite index (OS). A larger index value indicates that the firm possesses more abundant internal slack resources that are actually controlled and can be freely deployed.

3.2.4. Supplier Concentration

Following the approach of Wang [41], this study further examines the mechanism through which digital innovation affects ESG performance by introducing supplier concentration (SC) as a mediating variable. Supplier concentration is measured using the Herfindahl Hirschman Index (HHI), calculated as the sum of squared proportions of procurement amounts from the top five suppliers to total procurement.

3.2.5. Control Variables

This study incorporates a set of control variables to account for the influence of firm characteristics. Specifically, firm size (Size) is measured as the natural logarithm of total assets. Return on equity (ROE) is defined as the ratio of net profit to total equity. The cash ratio (CR) is calculated as cash and cash equivalents at the end of the period divided by current liabilities. Fixed asset intensity (Fixed) is computed as the ratio of net fixed assets to total assets. Intangible asset intensity (Intan) is calculated as the ratio of net intangible assets to total assets. Firm age (Age) is measured as the natural logarithm of the number of years since the firm's inception.

3.3. Model Specification

$$ESG_{i,t} = \alpha_0 + \alpha_1 DI_{i,t} + \Sigma Control_{i,t} + Firm + Year + \varepsilon_{i,t} \quad (1)$$

In this model, $ESG_{i,t}$ captures the ESG performance of firm i in year t . $DI_{i,t}$ denotes the firm's digital innovation. $Control_{i,t}$ comprises a set of firm-level control variables. Firm and Year denote firm fixed effects and year fixed effects, respectively, while $\varepsilon_{i,t}$ is the random error term. A statistically significant positive α_1 , the coefficient of primary interest, would indicate that digital innovation enhances ESG performance. The definitions of the main variables are presented in Table 1.

Table 1. Definitions of variables.

Variable	Definition
ESG	Hua Zheng ESG scores
DI	Natural logarithm of one plus the total number of patent applications in the last three years
OS	Average of the Z-scores of the current ratio and the administrative expense ratio
SC	The sum of the squared proportions of procurement amounts from the top five suppliers to the total procurement amount
Size	Ratio of the net value of intangible assets to total assets
ROE	Ratio of net profit to total equity
CR	Ratio of cash and cash equivalents to current liabilities
Fixed	Ratio of net fixed assets to total assets
Intan	Ratio of the net value of intangible assets to total assets
Age	Natural logarithm of the years since the firm was founded

4. Empirical Results

4.1. Descriptive Statistics

Table 2 reports the descriptive statistics of this study, including the number of observations, means, standard deviations, minimum, and maximum values. The ESG performance ranges from 41.610 to 92.930, indicating substantial cross-sectional variation across the sample. The digital innovation (DI) ranges from 0.693 to 9.477, reflecting considerable heterogeneity among sample firms. The remaining variables are generally consistent with existing literature. Table 3 reports correlation matrix for the key variables. The correlations among the explanatory variables are generally moderate, with the absolute values all below 0.4, suggesting that multicollinearity is not a serious concern. This study further computed the variance inflation factors (VIF) for all variables. The results confirm that all VIF values fall well below the conventional threshold of 10, with a mean VIF of 1.14, suggesting that no serious multicollinearity concerns exist among the variables.

Table 2. Descriptive statistics of main variables.

Variables	N	Mean	SD	Min	Max
ESG	19,568	73.900	4.996	41.610	92.930
DI	19,568	2.696	1.406	0.693	9.477
Size	19,568	22.420	1.333	19.680	26.090
ROE	19,568	0.061	0.132	−0.636	0.354
CR	19,568	0.881	1.396	0.021	10.240
Fixed	19,568	0.192	0.143	0.002	0.710
Intan	19,568	0.042	0.043	0.000	0.308
Age	19,568	2.972	0.308	1.386	3.526

Table 3. Correlation analyses of main variables.

	ESG	DI	ROE	Age	Size	Intan	Fixed	CR
ESG	1							
DI	0.199 ***	1						
ROE	0.219 ***	0.010	1					
Age	0.012 *	0.047 ***	−0.065 ***	1				
Size	0.199 ***	0.373 ***	0.092 ***	0.204 ***	1			
Intan	−0.020 ***	−0.046 ***	−0.046 ***	0.036 ***	0.116 ***	1		
Fixed	−0.046 ***	−0.094 ***	−0.053 ***	0.083 ***	0.201 ***	0.103 ***	1	
CR	0.082 ***	−0.061 ***	0.095 ***	−0.148 ***	−0.270 ***	−0.116 ***	−0.217 ***	1

Note: Values in parentheses are standard errors. *** and * denote significance at the 1% and 10% levels, respectively.

4.2. Benchmark Regression

Columns (1) and (2) in Table 4 reports the baseline regression results. After controlling for firm and year fixed effects, column (1) includes only the core explanatory variable, while column (2) further incorporates a full set of control variables. The results reveal that the coefficients on DI are all statistically significant at the 5% level, suggesting that digital innovation exerts a substantial positive impact on ESG performance and thereby validating H1.

Table 4. Benchmark regression results.

	(1) ESG	(2) ESG
DI	0.268 *** (0.048)	0.102 ** (0.051)
ROE		1.834 *** (0.280)
Age		0.797 (0.702)
Size		0.822 *** (0.096)
Intan		−0.684 (1.482)
Fixed		−1.553 *** (0.540)
CR		0.239 *** (0.039)
Cons	72.998 *** (0.154)	53.137 *** (2.656)
Year	YES	YES
Firm	YES	YES
N	19,568	19,568
R ²	0.022	0.035

Note: Values in parentheses are standard errors. *** and ** denote significance at the 1% and 5% levels, respectively.

4.3. Examination of Mediating Mechanisms

4.3.1. Organizational Slack

Columns (2) and (3) in Table 5 examine the mediating effect of organizational slack. In column (2), DI is significantly positively correlated at the 1% level, indicating that digital innovation effectively improves organizational slack. In column (3), the coefficient on OS is significantly positive at the 1% level, while the coefficient on DI remains significantly positive at the 1% level. These findings confirm that digital innovation indirectly enhances ESG performance by increasing organizational slack, with a positive and statistically significant mediating effect. To further corroborate the mediating mechanism, this study employs the bootstrap procedure advocated by Hayes [42]. The results indicate that the bias-corrected 95% confidence intervals for the indirect and direct effects are [0.002, 0.008] and [0.381, 0.478], neither of which includes zero. These findings collectively confirm the mediating effect, thereby validating H2.

Table 5. Mechanism examination results.

	(1) ESG	(2) OS	(3) ESG	(4) SC	(5) ESG
DI	0.435 *** (0.025)	0.011 *** (0.004)	0.430 *** (0.025)	−0.002 *** (0.001)	0.500 *** (0.032)
OS			0.464 *** (0.048)		
SC					−3.052 *** (0.554)
ROE	6.693 *** (0.244)	0.332 *** (0.036)	6.545 *** (0.244)	−0.017 *** (0.005)	7.024 *** (0.296)

Age	0.048 (0.106)	−0.110 *** (0.016)	0.102 (0.106)	−0.008 *** (0.002)	0.421 *** (0.132)
Size	0.604 *** (0.028)	−0.146 *** (0.004)	0.672 *** (0.029)	−0.001 ** (0.001)	0.416 *** (0.038)
Intan	−0.980 (0.754)	−1.236 *** (0.112)	−0.430 (0.755)	−0.116 *** (0.017)	−3.484 *** (1.054)
Fixed	−1.103 *** (0.234)	−0.639 *** (0.035)	−0.804 *** (0.235)	0.037 *** (0.001)	−1.104 *** (0.313)
CR	0.371 *** (0.024)	0.745 *** (0.004)	0.026 (0.043)	0.007 *** (0.001)	0.392 *** (0.029)
Cons	58.600 *** (0.625)	4.439 *** (0.093)	56.540 *** (0.659)	0.099 *** (0.013)	61.600 *** (0.850)
Year	YES	YES	YES	YES	YES
Firm	YES	YES	YES	YES	YES
N	19,568	19,567	19,567	12,967	12,967
R ²	0.112	0.753	0.116	0.036	0.107

Note: Values in parentheses are standard errors. *** and ** denote significance at the 1% and 5% levels, respectively.

4.3.2. Supplier Concentration

Columns (4) and (5) in Table 5 examine the mediating effect of supplier concentration. In column (4), DI is significantly negative at the 1% level, indicating that digital innovation effectively curbs supplier concentration. In column (5), the coefficient on SC is significantly negative at the 1% level, while the coefficient on DI remains significantly positive at the 1% level. These findings confirm that digital innovation indirectly enhances ESG performance by suppressing supplier concentration, with a positive and statistically significant mediating effect. To further corroborate the mediating mechanism, this study employs the bootstrap procedure advocated by Hayes [42]. The results indicate that the bias-corrected 95% confidence intervals for the indirect and direct effects are [0.003, 0.011] and [0.438, 0.560], neither of which includes zero. These findings collectively confirm the mediating effect, thereby validating H3.

4.4. Endogeneity Tests

4.4.1. Instrumental Variable Method

Although the baseline model reveals a significant association between DI and ESG performance, this relationship may be susceptible to endogeneity due to reverse causality. Specifically, digital innovation may influence ESG performance, yet contemporaneous changes in ESG performance could simultaneously affect current digital innovation. Such reverse causation would create a correlation between the core explanatory variable and the error term, biasing the estimates. To mitigate this endogeneity issue, this study employs an instrumental variable approach with two-stage least squares (2SLS) estimation. The instrument, IV (Phone*IT), is constructed as the interaction between the historical provincial fixed-line telephone penetration rate and the lagged national revenue of information technology services. It passes the underidentification, weakinstrument, and overidentification tests. As reported in columns (1) and (2) of Table 6, after implementing the instrumental variable strategy, the impact of DI on ESG performance remains significantly positive, consistent with the baseline findings.

Table 6. Endogeneity tests.

	(1) DI	(2) ESG	(3) ESG	(4) ESG
IV (Phone*IT)	0.000 *** (0.000)			
DI		3.598 *** (1.143)	0.141 *** (0.053)	0.239 * (0.139)
Patcite			−0.135 * (0.082)	
ROE	−0.321 *** (0.059)	2.847 *** (0.586)	1.693 *** (0.285)	1.369 (0.946)
Age	0.509 ** (0.233)	−4.459 ** (1.889)	0.905 (0.722)	4.114 * (2.210)
Size	0.491 *** (0.030)	−0.952 (0.594)	0.888 *** (0.098)	1.178 *** (0.353)
Intan	1.606 *** (0.421)	−6.537 * (3.481)	−0.802 (1.512)	−9.532 * (5.329)
Fixed	0.566 *** (0.146)	−2.779 *** (1.015)	−1.560 *** (0.558)	−3.925 ** (1.637)
CR	−0.013 (0.009)	0.261 *** (0.056)	0.253 *** (0.042)	0.093 (0.128)
Cons	−10.276 *** (0.841)		51.388 *** (2.744)	35.360 *** (10.518)
Year	YES	YES	YES	YES
Firm	YES	YES	YES	YES
K-P rk LM statistic	22.398 *** (0.000)			
C-D Wald F statistic	99.051			
K-P Wald rk F statistic	23.000			
N	19,452	18,693	18,335	4770
R ²	0.346	−0.279	0.037	0.696

Note: Values in parentheses are standard errors. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

4.4.2. Add Control Variable

To examine whether the core findings are susceptible to omitted variable bias, this study introduces additional control variables as a robustness check. Rapid iteration is a characteristic of digital patents. An excessively high volume of patent citations, however, indicates intense industry competition. The resulting competitive pressure reduces innovation quality and temporarily suppresses ESG growth. To address omitted variable bias, this study introduces the number of backward patent citations a focal firm makes within one year as an additional control variable. As reported in column (3) of Table 6, after controlling for the patent citation variable (Patcite), the coefficient on DI remains significantly positive, consistent with the baseline regression results.

4.4.3. Propensity Score Matching

Given that DI is not randomly assigned but rather originates from firms' self-selection decisions, sample selection bias may arise from observable characteristics. For instance, CEO duality consolidates decision-making authority and accountability, which uniquely equips firms to translate digital innovation into superior ESG performance. To

mitigate this endogeneity concern stemming from observable confounders and to construct a more credible counterfactual framework, this study employs a 1:4 nearest neighbor propensity score matching (PSM) approach as the primary estimation strategy and endogeneity test, using the control variables introduced in this section as covariates. The matching procedure pairs each treated firm with a control firm based on the covariates specified in Model (1), ensuring that the two groups are well balanced across observable firm characteristics. Table 7 presents the balance test results for the PSM procedure. The standardized differences (% bias) for all covariates in the matched sample fall below 10%, indicating an acceptable balance between the treatment and control groups. Column (4) of Table 6 reports the regression results based on the PSM-matched sample. The coefficients on DI remain positive and statistically significant, confirming that the research findings are robust within the PSM sample.

Table 7. Balancing test of PSM.

Variable		Mean		%Reduct %Bias	Bias	t-Test	
		Treated	Control			t	$p > t $
ROE	U	0.085	0.060	20.200		7.030	0.000
	M	0.085	0.090	−4.200	79.100	−1.180	0.239
Age	U	2.981	2.972	2.800		1.090	0.278
	M	2.984	2.977	2.200	23.500	0.550	0.583
Size	U	24.103	22.295	129.600		52.100	0.000
	M	24.099	24.076	1.600	98.700	0.390	0.697
Intan	U	0.050	0.041	18.100		7.390	0.000
	M	0.050	0.053	−5.000	72.500	−1.070	0.286
Fixed	U	0.217	0.190	17.600		6.850	0.000
	M	0.217	0.212	3.300	81.500	0.760	0.449
CR	U	0.734	0.893	−11.700		−4.100	0.000
	M	0.734	0.789	−4.000	65.700	−1.020	0.308

4.5. Robustness Checks

4.5.1. Alternative Measurement of ESG

To assess robustness, this study re-estimates the baseline model using an alternative proxy for ESG performance. This study replaces the Hua Zheng ESG scores with Bloomberg ESG scores and re-estimates the regression; the positive effect of digital innovation remains materially unchanged. Column (1) of Table 8 reports the regression results based on Bloomberg ESG scores (ESG1). The coefficient on DI remains significantly positive, consistent with the baseline findings, thereby confirming the robustness of the results to alternative measurements of ESG performance.

Table 8. Robustness checks.

	(1) ESG1	(2) ESG	(3) ESG
DI	0.383 *** (0.117)	0.102 *** (0.033)	0.209 ** (0.102)
ROE	2.667 *** (0.688)	1.834 *** (0.481)	1.601 *** (0.533)
Age	−1.353 (1.642)	0.797 (1.351)	−0.163 (1.600)
Size	2.213 *** (0.219)	0.822 *** (0.090)	1.083 *** (0.190)
Intan	3.649	−0.684	−3.225

	(3.627)	(2.656)	(2.789)
Fixed	1.700	−1.553	−1.434
	(1.330)	(0.908)	(1.063)
CR	0.545 ***	0.239 ***	0.488 ***
	(0.118)	(0.023)	(0.091)
Cons	−27.857 ***	52.878 ***	49.412 ***
	(6.378)	(3.670)	(5.640)
Year	YES	YES	YES
Firm	YES	YES	YES
N	6278	18,805	7718
R ²	0.619	0.560	0.052

Note: Values in parentheses are standard errors. *** and ** denote significance at the 1% and 5% levels, respectively.

4.5.2. Industry Cluster Adjustment

Conventional standard error estimation may underestimate correlations within industries. After adjusting the clustering level of standard errors to the industry level, this study finds that the significance of the DI core coefficient remains at the 1% level. The regression results in column (2) of Table 8 show that the coefficient for DI remains significantly positive, consistent with the robustness conclusion mentioned earlier.

4.5.3. Exclude Eastern Region Samples

Considering that China's eastern coastal regions possess inherent advantages in terms of economic development, digital infrastructure, and policy support, this study re-estimates the regression after excluding the sample of eastern provinces. The results indicate that even in relatively less developed regions, the role of digital innovation in improving quality and enhancing efficiency remains established. The regression results in column (3) of Table 8 show that the coefficient for DI remains significantly positive, consistent with the baseline findings, thereby confirming the robustness of the results to exclude samples in the eastern region.

4.6. Heterogeneity Analysis

4.6.1. CEO Duality

CEO duality grants the top manager absolute authority over resource orchestration and decision making, significantly reducing communication costs and agency costs among the top management team regarding how resources are allocated for digital innovation [43], and ultimately enhancing ESG performance. This study partitions the sample into two groups: CEO-duality firms and non-CEO-duality firms. Assigning a value of 1 if the CEO also serves as board chair and 0 otherwise. The regression results in columns (1) and (2) of Table 9 reveal that firms with non-CEO duality show no significant effect of DI on ESG. In contrast, those with CEO duality show a positive, statistically significant effect at the 5% level. These findings demonstrate that the effect of corporate digital innovation on ESG performance is influenced by the CEO duality.

Table 9. Heterogeneity tests.

	(1) CEO Duality	(2) Non-CEO Dual- ity	(3) High Technology Inten- sity	(4) Low Technology Inten- sity	(5) High Marketiza- tion	(6) Low Marketiza- tion
DI	0.241 ** (0.098)	0.014 (0.064)	0.012 (0.063)	0.196 ** (0.089)	0.092 * (0.053)	0.171 (0.203)

ROE	1.218 ** (0.557)	1.504 *** (0.345)	1.757 *** (0.358)	1.147 ** (0.467)	1.883 *** (0.294)	1.168 (0.974)
Age	0.451 (1.445)	0.594 (0.887)	−0.246 (0.855)	1.122 (1.246)	0.968 (0.721)	−3.255 (3.643)
Size	0.863 *** (0.185)	0.828 *** (0.124)	0.925 *** (0.122)	0.781 *** (0.166)	0.810 *** (0.100)	1.142 *** (0.376)
Intan	1.215 (2.849)	−0.990 (1.814)	−4.465 ** (1.881)	4.955 ** (2.435)	−0.291 (1.560)	−1.653 (5.150)
Fixed	−3.619 *** (1.010)	−1.160 * (0.686)	−2.362 *** (0.704)	−1.021 (0.874)	−1.389 ** (0.567)	−1.892 (1.919)
CR	0.105 * (0.058)	0.323 *** (0.057)	0.194 (0.042)	0.399 *** (0.097)	0.229 *** (0.040)	0.360 * (0.210)
Cons	54.247 *** (5.142)	53.227 *** (3.500)	54.331 *** (3.215)	52.183 *** (4.898)	53.056 *** (2.746)	55.688 *** (12.244)
Year	YES	YES	YES	YES	YES	YES
Firm	YES	YES	YES	YES	YES	YES
N	6305	13,263	12,470	7098	18,022	1525
R ²	0.044	0.037	0.046	0.054	0.033	0.066

Note: Values in parentheses are standard errors. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

4.6.2. Technology Intensity

Technology intensity significantly moderates the relationship between digital innovation and corporate ESG performance. Firms with high technology intensity are generally already digitally equipped, rendering the marginal ESG transformation dividend from additional digital innovation relatively limited. In contrast, firms with low technology intensity have long been constrained by their heavy reliance on traditional supply chains. Once they undertake digital innovation, substantial latecomer dividends can be unleashed, generating a leapfrogging upgrading effect on the corporate social responsibility image and internal governance structure. Therefore, following Yin [44], this paper partitions the sample into two groups based on the ratio of R&D expenditure to total compensation: high-technology-intensity firms and low-technology-intensity firms. A dummy variable is set to 1 for high-technology-intensity firms and to 0 otherwise. The regression results in columns (3) and (4) of Table 9 reveal that firms with high technology intensity duality show no significant effect of DI on ESG. In contrast, those with low technology intensity show a positive, statistically significant effect at the 5% level. These findings demonstrate that the effect of corporate digital innovation on ESG performance is influenced by the technology intensity.

4.6.3. Marketization Level

The influence of digital innovation on ESG performance depends on the market environment. In regions characterized by a high marketization level, where property rights are well protected and information is more transparent, external stakeholders capture corporate ESG information with heightened sensitivity, thereby compelling firms to allocate resources to social and environmental initiatives. Following Ma [45], this study adopts the marketization index to gauge the market environment of each firm and divides the sample into two groups: high- and low-marketization firms. A dummy variable is set to 1 for firms whose regional marketization level exceeds the annual national mean, and to 0 otherwise. The regression results reported in columns (5) and (6) of Table 9 indicate that the effect of DI on ESG is positive and statistically significant at the 10% level for high marketization. In contrast, it is not significant at low levels of marketization. These findings suggest that

the extent to which digital innovation enhances ESG performance is contingent on the level of marketization in the operating environment.

5. Discussion and Implications

5.1. Theoretical Contributions

In terms of theoretical contributions, this study enriches the literature on the impact of digital innovation on social responsibility. It empirically validates the causal relationship between digital innovation and ESG performance, thereby providing concrete evidence for understanding the social impact of digital innovation. It systematically extends digital innovation research into the domain of ESG development, and simultaneously makes a valuable contribution to expanding the ESG literature. Second, this study effectively supplements the driving factors of enhancing corporate ESG performance from the perspective of internal resource orchestration. It reconfigures the understanding of organizational slack using empirical data, demonstrating that digital innovation can allocate resources rationally, release organizational slack with strategic buffering capacity, increase the quantity of high quality and effectively available resources, and fully elaborate on the dynamism of the resource-based view in the digital era. Third, this study effectively supplements the driving factors of enhancing corporate ESG performance from the perspective of external structural reconfiguration. The study demonstrates that digital technologies, by weakening the power of localized suppliers and reducing supplier concentration, enable firms to gain strategic dominance in redirecting resources from the zero-sum game between buyers and sellers to the harmonious coexistence of humans and nature, and extends resource dependence theory toward sustainable development.

5.2. Managerial Contributions

This study's investigation into the relationship between digital innovation and corporate ESG performance enables firms to gain a deeper understanding of the internal and external mechanisms through which digital innovation empowers ESG development, while also contributing to a better comprehension of the existing relevant research. Empirical evidence indicates that, against the backdrop of a flourishing digital economy, digital innovation serves as a key strategic instrument for driving improvements in ESG performance. Therefore, first, firms should prioritize the advancement of digital innovation, which possesses dual functions in endogenous knowledge growth and resource integration. The continuous accumulation and spillover of knowledge enhance firms' sustainable innovation capability. At the same time, resource integration directly improves resource allocation efficiency and promotes improvement in corporate ESG performance. Second, firms should regard digital innovation as a means to expand organizational buffering capacity. They should actively leverage digital innovation to eliminate information time lags across departments, replace costly physical buffers with efficiently circulating information buffers, compel and revitalize the available slack resources that have lain dormant within the organization, consciously increase organizational slack oriented toward green and sustainable directions, and invest such slack in social and environmental affairs. Third, firms should attach importance to synergistic effects with suppliers. They should actively expand their external supply chain networks, proactively dilute supplier concentration, and channel the saved transaction costs into core ESG issues, such as joint emission reduction with suppliers. Furthermore, firms in traditional industries and those at the early stage of digitalization should pay attention to corporate governance structures, grant moderately concentrated executive power to the board, such as phased CEO duality, to overcome the deep-seated resistance of hierarchy during the initial phase of transformation. In terms of policy and institutional aspects, policymakers also need to focus on

enhancing the degree of regional marketization and providing firms with a fair and transparent public platform.

5.3. Limitations and Future Research Directions

This study has several limitations that warrant attention. First, this study is primarily focused on Chinese listed firms. Institutional policies and cultural contexts across different countries may confound the findings. Future research could expand the sample scope by incorporating listed firms from a wider range of countries to enhance the generalizability of the findings. Second, a universally accepted evaluation standard for corporate ESG performance is currently lacking, which may lead to divergent interpretations of its impact on firms among various stakeholders. Third, given that internal slack is theoretically associated with the resource release triggered by digital innovation, this is examined as a mediating mechanism. Nevertheless, it should be noted that digital innovation may also influence potential slack through long-term process redesign or by enhancing firms' financing capacity. Future research could investigate the differentiated mediating roles of distinct slack types and explore whether the relationship between slack and ESG performance varies across these dimensions. Fourth, this study has methodological limitations in identifying causal mechanisms. The mediation analysis relies on traditional approaches, specifically the Baron and Kenny method and bootstrap inference. These techniques depend heavily on the strong assumption of sequential ignorability. Although a series of endogeneity tests have been conducted to mitigate general endogeneity concerns, including instrumental variable estimation, the inclusion of additional control variables, and PSM, isolating the pure causal mechanisms of the mediators remains an empirical challenge. Future research could adopt more advanced causal mediation frameworks, such as structural equation modeling that incorporates instrumental variables or causal mediation analysis under the sequential ignorability assumption, to more precisely disentangle and quantify the latent causal pathways of organizational slack and supplier concentration. Finally, although the panel data capture temporal trends, certain unobservable heterogeneity dynamics may still exist. Future research could employ methods such as difference in differences (DID) to evaluate the policy effects of specific digital policy shocks.

6. Conclusions

An in-depth investigation into how digital innovation enhances corporate ESG performance holds significant practical relevance. In this study, digital patent data and Hua Zheng ESG scores are employed as measures of digital innovation and corporate ESG performance, respectively, to examine Chinese A-share listed firms. Through empirical analysis and testing, the impact of digital innovation on corporate ESG performance is explored, as well as its underlying mechanisms and heterogeneity factors. The results indicate that digital innovation significantly enhances corporate ESG performance, and that organizational slack and supplier concentration, as key variables, play important roles in improving ESG performance. These conclusions remain robust after a series of endogeneity tests and robustness checks. Heterogeneity analysis reveals that the promoting effect of digital innovation is more pronounced in firms characterized by CEO duality, low technology intensity, and high levels of marketization. Compared with prior research, the findings of this study suggest that firms should regard digital innovation as a strategic cornerstone and optimize ESG practices according to their specific circumstances and external environments. Hopefully, these findings will provide valuable reference for future research in the field of corporate ESG development as well as inspire practitioners to promote the deep integration of digital innovation and ESG projects, thereby realizing the mutual embrace of technological progress and responsible commitment at an early date.

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