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The Role of Digital Transformation in Supply Chain Sustainability Development: A Perspective Based on Supply Chain Spillovers

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Abstract: Digital transformation (DT) is a core driver of supply chain sustainable development (SCSD). From the perspective of supply chain spillovers, this study empirically examines the impact of customer enterprises' DT on the ESG performance of supply chain partners, using a sample of Chinese A-share listed firms and their disclosed suppliers and customers during 2012–2023. The results show that customer enterprises' DT exerts a significant positive spillover effect on the ESG performance of supply chain partners, namely an enabling effect on SCSD, and this effect presents an asymmetric characteristic that is more prominent when customers' DT level exceeds that of their partners. Mechanism tests reveal that this positive spillover is realized through two paths: supply chain coordinated development and supply chain innovation development. Heterogeneity analysis further finds that the above effect is more significant among non-heavy polluting enterprises, state-owned enterprises and enterprises in eastern China. This study enriches the theoretical research on DT and SCSD, and provides empirical evidence and practical guidance for enterprises to formulate DT strategies and optimize supply chain coordination mechanisms, thus contributing to the improvement of overall SCSD level.

Keywords: digital transformation; supply chain sustainable development; supply chain spillover; ESG level

JEL Classification: O33; G34; D22

1. Introduction

Against the backdrop of the digital economy and global green development becoming increasingly intertwined, SCSD has evolved from a "nice-to-have" into a strategic imperative for firms intent on securing long-term value and obtaining an enduring competitive advantages. DT has emerged as the foremost catalyst propelling this process [1]. From the United Nations' 2030 Sustainable Development Goals (SDGs) to China's 14th Five-Year Plan, environmental, social, and governance (ESG) performance is no longer merely the responsibility boundary of enterprises themselves but a systematic project that penetrates upstream and downstream and reshapes the industrial ecosystem. Sustainable development of enterprises requires coordinated development from economic, environmental, and social dimensions [2]. The sustainable development level of supply chain partners is usually measured by ESG [3], a metric that comprehensively evaluates enterprises' performance in internal governance, social responsibility fulfillment, and ecological conservation. Supply chain disruptions have intensified due to global challenges such as trade conflicts, epidemics, and natural disasters [4], highlighting the necessity for enterprises to enhance SCSD. However, the widespread inconsistency of interests, information asymmetry, and differences in financing capabilities among supply chain node enterprises hinder the transmission of sustainable development factors across the chain, which creates the so-called "ESG barrel effect" [5]. How to transcend organizational boundaries and accomplish sustainable performance spillover from core enterprises to the entire chain has become the focus of both academia and industry.

Meanwhile, the accelerating advance of digital technologies is opening up unprecedented opportunities for enterprises to reinvent collaborative models and operate seamlessly beyond traditional organizational frontiers [6]. By optimizing resource allocation and improving collaborative efficiency, digital technologies can empower supply chains to transition to greener and more efficient operations. In particular, as the core node on the demand side of the supply chain, client enterprise can utilize their DT to reshape the upstream and downstream value co-creation mechanism through real-time demand data sharing, collaborative prediction, and risk linkage [7]. Practically, DT has already reshaped supply chains for a number of industry leaders. Big data analytics is employed by e-commerce enterprises to forecast supply chain demand with precision, minimizing resource waste caused by inventory backlogs [8]; Internet platforms are employed by manufacturers to share green manufacturing technologies with upstream and downstream partners, promoting the improvement of environmental protection levels throughout the entire chain [9].

However, the majority of current research concentrates on the impact of supply chain diversification on enterprise ESG performance [10], the influence of supply chain digitalization on corporate ESG performance [11], the influence of DT on enterprise ESG performance [12], and the effect of digitalization on ESG performance [13]. There is a dearth of systematic and in-depth discussion on how DT affects the sustainable development of supply chain partners, especially through what internal logic drives the improvement in ESG levels. On the one hand, most studies focus on the correlation between enterprises' own digitalization and sustainability, ignoring spillover transmission at the supply chain level. Yet, systematic and comprehensive empirical research on the precise mechanisms by which DT affects supply chain partners' sustainability remains scarce, especially concerning the dual dimensions of supply chain coordination and innovation.

As the pivotal node in the supply chain, the impact of client enterprises' DT extends beyond their own operations. It has the potential to produce a "spillover effect" that impacts the ESG level of supply chain partners through information transmission, resource sharing, technology spillover, and other means. Can the client enterprise DT significantly enhance the ESG level of its supply chain partners? If so, through what mechanism is its function realized? In which types of businesses or regions is this influence more prominent? This study investigates the disclosed suppliers and customers of Chinese A-share listed companies from 2012 to 2023 in order to resolve these inquiries. It examines the impact of client enterprises' DT on supply chain partners' ESG and investigates the underlying mechanisms from a supply chain spillover perspective. This study advances theoretical research in the domains of DT and SCSD while offering empirical evidence that can be used by enterprises to develop DT strategies and strengthen supply chain collaboration to enhance overall sustainable development level. Consequently, it contributes theoretical and practical value to advancing the national supply chains toward greener, smarter, and more sustainable development.

The following are the contributions of this paper: First, this paper is the first to empirically investigate the influence of client enterprises' DT on the sustainability levels of their supply chain partners from a supply chain spillover perspective, which is a departure from previous research on the impact of DT on enterprise ESG performance [12], enterprise ESG [14], and manufacturing enterprises' ESG [15]. Second, this study investigates the mechanism by which DT influences enterprises' ESG from the perspectives of supply chain coordinated development and supply chain innovative development, thereby deepening the understanding of how DT affects enterprises' ESG. Third, this study has substantial practical implications for improving enterprise SCSD level by examining the heterogeneous effects of DT on ESG, which are influenced by differences in corporate pollution attributes, property rights characteristics, and geographic location.

As follows is the remaining portion of this paper: Section 2 is the literature review and research hypotheses; Section 3 is the sample, data, model design, and variable selection; Section 4 is the regression outcomes and mechanism tests; Section 5 is heterogeneous effects; and Section 6 concludes.

2. Theoretical Hypothesis

2.1. Theoretical Foundations of Supply Chain Spillover Effect of Client Enterprises' DT

Network externalities theory holds that the value of a network is positively correlated with the number of participants in the network, and the joining of new participants will bring additional benefits to all existing participants [16]. In digital supply chains, customer enterprises' DT establishes collaborative networks centered on information sharing [17], resource integration [18], and risk linkage [19], replacing traditional linear supply chains with multi-node digital ecosystems. On one hand, core customers' digital innovations generate direct network externalities: unified digital platforms reduce information costs [20], enabling efficient transfer of digital technologies and sustainable resources among supply chain partners [21]. On the other hand, broader participation creates indirect network externalities: larger data scales enhance analytical accuracy, generating greater ESG benefits for all participants. Consequently, supply chain partners benefit from the positive externalities of customer digital investments, which improve their ESG performance through network spillovers. When customers' DT levels exceed those of partners, the scale effects and externalities of digital networks become more pronounced, leading to more significant ESG spillovers that support the asymmetric nature of this spillover effect.

In traditional supply chains, clients and partners maintain a classic principal-agent relationship [22]. While clients expect partners to fulfill ESG responsibilities, information asymmetry may lead to moral hazards or adverse selection, causing partners to deviate from sustainability goals [23]. This conflict hinders sustainability transmission, creating the "ESG barrel effect" in supply chains [5]. Digital technology mitigates this conflict through two key mechanisms, enhancing sustainable governance spillovers. First, digital solutions reduce information asymmetry by enabling real-time [24], end-to-end monitoring of partners' ESG performance, thereby curbing moral hazards. Second, DT supports more effective incentive mechanisms [25]: clients can link ESG evaluation results with contractual terms via digital platforms. By resolving principal-agent issues, clients can effectively communicate their ESG requirements and governance resources to partners, driving continuous improvement in partners' ESG performance.

2.2. Sustainable Supply Chain Development and ESG Research

The notion of "sustainable development" first surfaced in the 1987 Brundtland Report [26]. Robert et al. (2005) [27] frame sustainable development as resting on three interlocking pillars: environmental, social, and economic. The supply chain is a system that involves the delivery of products or services from suppliers to end customers, and it is composed of organizations, people, activities, information, and resources [28]. Integrated processes and inter-firm trust let supply chains gain synergistic advantages in reducing opportunity costs and monitoring costs, thereby improving SCSD levels [29]. Across the entire supply chain process, SCSD seeks to align economic with social and environmental [30]. Elkington and Rowlands (1999) [31] proposed the "triple bottom line" theory, which provides a basic framework for research in this field, emphasizing that enterprises need to balance economic performance, social impact, and environmental responsibility.

Today, sustainable development has attracted global attention within supply chains. ESG reports are widely adopted to assess the level of sustainable development [32]. ESG reports have been widely used to assess sustainable development levels [32]. With advancing research, ESG has emerged as a key metric system integrating environment, society, and corporate governance dimensions, serving as a key tool to evaluate enterprise SCSD levels. ESG embodies firms' commitment to upgrade their environment, society, and governance outcomes [33]. Within the environmental pillar, the focus rests on managing carbon footprints, resource use, and climate-related risks [34]. Employee rights, community engagement, and diversity-and-inclusion practices comprise the social side [35]. Employee relations and corporate behavior [36], internal corporate governance [35], comprise the governance side. These dimensions have emerged as critical metrics for measuring an enterprise's SCSD capabilities [10,37].

2.3. Digital Transformation and Supply Chain Sustainable Development

Currently, digital technology has become the core engine of SCSD and serves as a key force in advancing enterprise ESG [14]. DT comprehensively reshapes enterprises' production models, operational processes, and collaborative mechanisms by leveraging digital technologies. For instance, big-data analytics sharpens demand forecasts and minimizes inventory fluctuations [38], while blockchain guarantees reliable product traceability and heightens transparency [24]. Lu et al. (2024) [12] demonstrated from a resource orchestration perspective that digital technologies significantly enhance the green and operational efficiency of supply chains by reallocating resources and tightening cooperation. Nadkarni and Prügl (2021) [39] frame DT as "technology-led organizational change." Under the digital wave, the client enterprises' DT will not only reshape their own production, operation, and management, while produce spillover effects through supply chain network, significantly affecting SCSD.

After undergoing digital transformation, client enterprises can establish efficient information transmission and sharing systems [40]. The digital transformation of customer enterprises has a comprehensive impact, including boosting corporate investment [41], accelerating energy transition [42], reducing corporate emissions [43], and stimulating economic growth [44]. Furthermore, DT fundamentally improves the way enterprises collect and process information in their supply networks [4]. In terms of production and operation decisions, partner enterprises can conduct capacity planning more accurately based on the market demand information shared by client enterprises [45], avoiding overcapacity or insufficiency caused by deviation in demand forecasting. DT is a critical driving factor for implementing sustainable supply chains and achieving SCSD, providing essential decision-support information for sustainable supply chain practices [21]. After DT, client enterprises establish more stringent and explicit environmental standards and social responsibility requirements for their supply chains to fulfill these responsibilities. Additionally, they can employ digital technologies to more effectively monitor and restrict the relevant behaviors of partner companies, thereby promoting enhancements in ESG levels. Building on the preceding discussion, we advance the following hypothesis:

H1: *The client enterprises' DT has a significant positive spillover effect on SCSD level.*

2.4. Coordinated Development of Supply Chain

The client enterprise can leverage digital technology to deeply reshape the collaboration model of the supply chain upstream and downstream, sharply lifting supply chain transparency and risk management coordination. Thus, DT as a critical intermediary connecting supply chain partners' sustainable development with digitalization of the client enterprises. In terms of transparency and coordination, the client enterprises promote DT and can build a more efficient information-sharing platform by utilizing digital technology [17,46]. By leveraging digital technologies, client enterprises can markedly elevate their information disclosure quality, thereby boosting enterprise transparency [25]. Real-time data exchange powered by digital technologies across supply chain nodes reduces information asymmetry [24]. This boost in transparency and coordination sharpens resource-allocation efficiency and promotes SCSD from an economic perspective, thereby improving enterprise ESG [14]. Next, partner enterprises can clearly grasp the environmental and social responsibility requirements of client enterprises and the entire supply chain through transparent information sharing, thereby improving ESG performance in the environmental and social domains.

In terms of the degree of risk management synergy, DT empowers clients with stronger risk identification, assessment, and response capabilities [19]. Following DT, for real-time monitoring and analysis of risks, client enterprises can harness digital technologies. Enterprises' capacity for swiftly diagnosing risks and resolving disruptions is expanded by digital technologies [47]. Li et al. (2025) [48] highlighted that DT heightens enterprises' risk foresight by delivering real-time data and analytics and enhances the reconfiguration ability of enterprises by facilitating rapid adjustment of resources and processes. A smoothly running supply chain underpins the SCSD of partner enterprises [19], which can reduce economic losses caused by risk shocks. It also helps enterprises to plan environmental and social responsibility projects in the long term, thereby enhancing ESG levels. Building on the preceding discussion, we advance the following hypothesis:

H2: *The coordinated development of the supply chain (transparency synergy and risk management synergy) plays an intermediary role in the relationship between client enterprises' DT and the sustainable development levels of supply chain partners.*

2.5. Innovative Development of the Supply Chain

With DT, client enterprises can utilize digital technologies to obtain more precise and real-time access to operational data from supply chain partner enterprises [40]. In terms of financing constraints, these data furnish lenders with a richer credit-evaluation footprint for supply-chain partners, easing the financing constraints they face [49]. Financing constraints are primarily caused by information asymmetry between the client and supply chain partners. Existing research indicates that DT and supply chain participation both alleviate these constraints [25,50]. He et al. (2024) [25] have shown that by reducing information asymmetry and transaction costs between financing parties, DT alleviates corporate financing constraints. When financing constraints are eased for supply chain partners, there will be more sufficient funds invested in the fields related to sustainable development [51]. Therefore, DT of client enterprises positively impacts the sustainable development level of supply chain partners by alleviating their financing constraints, thereby improving ESG level.

In the realm of green-tech innovation, the client enterprise DT provides technical support and a cooperation platform for green technology innovation of supply chain partners. Ecological innovation is a major force behind the shift to sustainable development [52], while DT is a significant force behind green activities. Client enterprise DT is beneficial for promoting green supply chain integration among partner enterprises [18]. Client enterprises can more clearly convey green demand signals to supply chain partners based on their own digital capabilities. Supply chain partners can utilize green technologies to optimize product production processes and improve raw material usage efficiency [53]. Simultaneously, client enterprises accelerate green-tech breakthroughs by reshaping industry structures and advancing marketization [54]. Green-tech feeds back into greater digitization and transparency for both clients and partners [54], thereby enhancing the SCSD level of partner enterprises. Building on the preceding discussion, we advance the following hypothesis:

H3: *The innovative development of the supply chain (financing constraints, green technology innovation) plays an intermediary role in the relationship between client enterprises' DT and the sustainable development levels of supply chain partners.*

The study's framework is depicted in Figure 1.

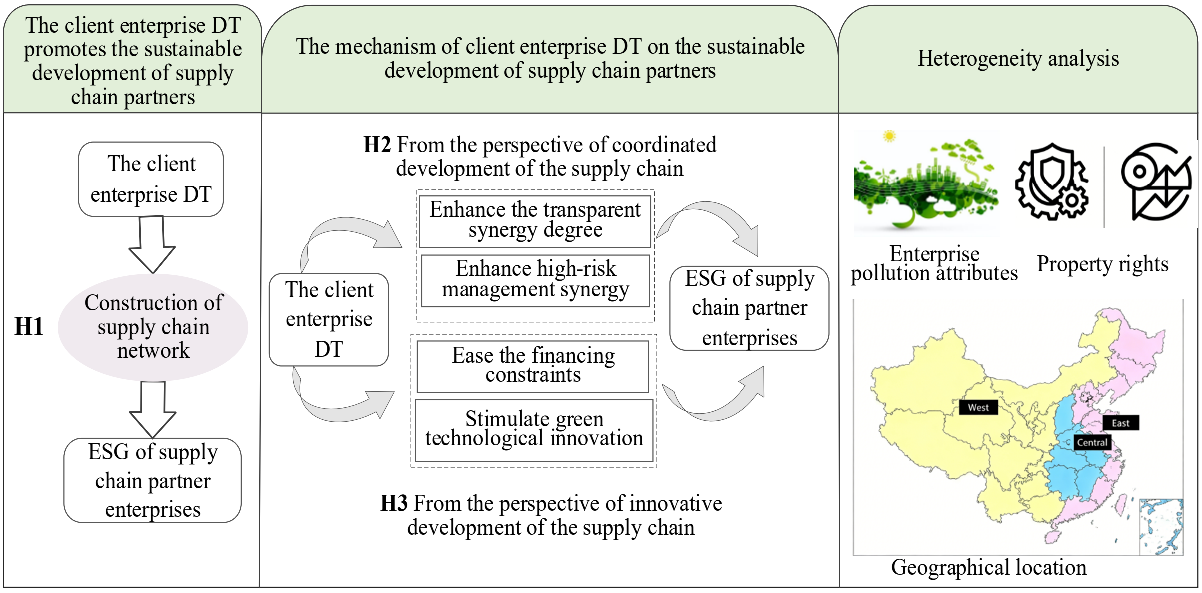

Figure 1. Research framework.

3. Model Design

3.1. Data Source

This study investigates the disclosed suppliers and clients of Chinese A-share listed enterprises, with a sample period that takes place from 2012 to 2023. The enterprises' annual reports are the source of textual statistical data, while the level of enterprise sustainable development is measured by the Huazheng ESG rating score. All other company-level financial data is obtained from CSMAR.

This study used Chu et al. (2018) [55]'s research technique to establish the supply chain network. We ultimately acquired 4961 "firm-supplier/client-year" observation data by gathering the top five suppliers and clients disclosed by listed enterprises. Samples of non-listed firms, samples of firms with operational anomalies, such as ST and *ST designations, and samples with excessive missing values are all excluded during the compilation process.

3.2. Model Construction

This study builds the following multiple linear regression model to examine how client enterprises' DT affects supply chain partners' sustainable development level:

$$ESG_{i,t} = \alpha_0 + \alpha_1 DIGA_{j,t} + \alpha_2 Control_{i,t} + Ind + Year + \varepsilon_{i,t} \quad (1)$$

Here, i denotes supply chain partner enterprises, j denotes the enterprise's suppliers or clients, t denotes the year. $ESG_{i,t}$ denotes the sustainable development level of supply chain partner enterprises i in t year; $DIGA_{j,t}$ denotes the digitalization level of supplier or client enterprises j in t year; $Control_{i,t}$ represents control variables; Ind is the industry fixed effect; $Year$ is the year fixed effect; $\varepsilon_{i,t}$ is the random disturbance term.

3.3. Variable Selection

The dependent variable (ESG) is denoted by the sustainable development level of supply chain partners. Referring to the studies of Ding and Lee (2024) [56], Zheng and Aishan (2023) [57], and Yu and Xiao (2022) [58], the level of enterprise sustainable development is measured by the Huazheng ESG rating score. Every quarter, all A-share listed enterprises are subject to the Huazheng ESG rating, which has nine levels ranging from low to high.

For enterprise ESG rating scores: Step 1: Assign quarterly ESG ratings to enterprises from lowest to highest, assigning values 1–9 accordingly; Step 2: Determine each enterprise's average ESG rating score for the same year.

The independent variable (DIGA) is denoted by digitalization of client enterprises. Following Liu et al. (2023) [59], Lu et al. (2024) [12], and Chu et al. (2019) [55], we built a firm-level digitalization index through text analysis and keyword-frequency counts. This article uses logarithmic processing on the overall word frequency to extract the etymologies associated with "digitalization" from five dimensions: artificial intelligence technology, big data technology, cloud computing technology, blockchain technology, and the application of digital technology. The enterprise digitalization feature vocabulary used in the benchmark regression comprised 76 digitalization-related keywords, which were replaced with 99 in the robustness test.

Referencing Ning and Yao (2023) [60], Wu and Li (2023) [61], and Lu et al. (2024) [53] as reference, this paper selects the following control variables: Book-to-Market Ratio (BM), Shareholding Concentration-Top Shareholder Holding Ratio (Top1), Dual Role (Dual), Debt-to-Asset Ratio (Lev), Cash Flow Ratio (CashFlow), Board Size (Board), Return on Assets (ROA), Previous Year Loss (Loss), and Independent Director Proportion (Indep).

4. Empirical Analysis

4.1. Descriptive Statistics

The descriptive statistics for key variables and the results of the multicollinearity analysis are presented in Table 1. The ESG mean in the table is 4.308, with a standard deviation of 0.897, a minimum of 1, and a high of 7. This suggests that supply chain partners' sustainability levels, which are typically in the middle range, vary somewhat. DIGA has a mean of 1.462, a standard deviation of 1.399, a minimum value of 0, and a maximum value of 6.163. This suggests that the DT process varies significantly between client enterprises. Some enterprises have actively promoted digitalization and achieved certain results, while others are relatively lagging behind in digital construction. With all VIFs ranging from 1.05 to 1.94, multicollinearity is negligible.

Table 1. Descriptive statistics.

Variables	N	Mean	SD	Min	Max	VIF
ESG	4961	4.308	0.897	1	7	
DIGA	4961	1.462	1.399	0	6.163	1.05
BM	4961	0.343	0.169	−0.347	1.108	1.62
Top1	4961	0.372	0.165	0.0184	0.900	1.15
Dual	4961	0.229	0.420	0	1	1.09
Lev	4961	0.491	0.211	0.0239	1.685	1.94
CashFlow	4961	0.0502	0.0672	−0.464	0.539	1.23
Board	4961	2.188	0.223	1.386	2.944	1.36
ROA	4961	0.0334	0.0647	−1.387	0.602	1.42
Loss	4961	0.0766	0.266	0	1	1.10
Indep	4961	0.373	0.0527	0.222	0.714	1.24

4.2. Baseline Regression

The estimation of the multiple linear regression model is shown in Table 2. The coefficient of 0.0585 for DIGA is significant at the 1% level, as indicated by column (1), which excludes control variables and fixed effects. This suggests that supply chain partners' sustainable development level is initially positively influenced by the DT of client enterprises. In column (2) we add industry- and year-fixed effects while omitting all other controls; the DIGA coefficient stays positive at 0.0263 and retains its 1% significance level, corroborating that client enterprises' DT exerts a robust upward influence on partner sustainability after netting out pure time trends and industry-wide shocks. The coefficient of DIGA is 0.0411, which is still significant at the 1% level, and the control variables and the fixed effects of industry and year are added at the same time. This demonstrates significant economic implications: When all other factors remain constant, each one-unit increase in the client company's DT (Developmental Transparency) level elevates its supply chain partners' ESG rating scores by 0.0411. Given that the ESG ratings in this study range from 1 to 9 (with a sample mean of 4.308), the marginal improvement effect of the client company's DT carries substantial economic weight. This further verifies H1.

Table 2. Benchmark regression.

Variables	(1) ESG	(2) ESG	(3) ESG
DIGA	0.0585 ***	0.0263 ***	0.0411 ***
	(0.0089)	(0.0100)	(0.0096)
Control variables	N	N	Y
Constant	4.2224 ***	4.2697 ***	1.2784 ***
	(0.0182)	(0.0188)	(0.2037)
Observations	4961	4959	4959
R-squared	0.008	0.121	0.227
ind	N	Y	Y
year	N	Y	Y

Note: Standard errors in parentheses, *** $p < 0.01$.

4.3. The Asymmetric Influence of DIGA in Supply Chain

When investigating transmission effects of DT within supply chains, it is crucial to examine whether these effects are altered when the DIGA level of a supply chain partner is greater or less than that of the enterprise. The regressions that test for asymmetric impact of DIGA in supply chains are presented in Table 3. Firms are split into two subsamples according to whether their own or their partners' DIGA levels. In the first group, the enterprise's DIGA outranks its supply chain partners; in the second group, the partners' DIGA surpasses that of the enterprise. The DIGA coefficient is significantly positive in column (1) but loses significance in column (2). This suggests that when a client enterprise's level of digitalization surpasses that of its partners, the positive spillover impact of the client enterprise's DT on the sustainable development level of its supply chain partners is more noticeable. In contrast, the spillover effect is not obvious. This might be because when a client enterprise has a high level of digitalization, it possesses stronger technological and resource advantages and can more effectively drive the development of supply chain partners.

Table 3. The asymmetric impact of DIGA in the supply chain.

Variables	(1) ESG	(2) ESG
DIGA	0.0877 ***	0.0272
	(0.0132)	(0.0184)
Control variables	Y	Y
Constant	1.2578 ***	1.4001 ***
	(0.2588)	(0.3285)
Observations	2993	1966
R-squared	0.265	0.191
ind	Y	Y
year	Y	Y

Note: Robust standard errors in parentheses, *** $p < 0.01$.

4.4. Robustness Test

4.4.1. Replace the Core Explanatory Variable

In benchmark regression, we measure enterprises' digitalization by analyzing the frequency of digitalization-related terms from listed enterprises' annual reports. Although this paper selected 76 high-precision terms for building the digitalization dictionary, it is possible that other digitalization-related vocabulary was overlooked. In the robustness test, we replace it with 99. The updated DIGA index is named DIGB and is used to replace DIGA in the benchmark model. The regression results in column (1) of Table 4 are presented after the core explanatory variable has been substituted. The DIGB coefficient is 0.0427 and is statistically significant at the 1% level. Thus, after the expansion of the word bank, the positive spillover effect of the client enterprise's DT on the sustainable development level of its supply chain partners still exists, and the preliminary verification results show robustness.

Table 4. Robustness test.

Variables	**(1) ESG**	**(2) ESG**	**(3) ESG**
DIGA		0.0605 ***	0.0415 ***
		(0.0091)	(0.0100)
DIGB	0.0427 ***		
	(0.0113)		
Control variables	Y	Y	Y
Constant	1.2186 ***	0.8457 ***	1.1905 ***
	(0.2075)	(0.2044)	(0.2104)
Observations	4959	4905	4689
R-squared	0.227	0.321	0.227
ind	Y	N	Y
year	Y	Y	Y
city	N	Y	N

Note: Standard errors in parentheses, *** $p < 0.01$.

4.4.2. Adjust the Fixed Effect

Benchmark regression adopts the year-industry fixed effect, controlling for industry commonalities and temporal trends. However, industry classification may not fully capture regional heterogeneity in economic and policy differences that also shape supply chains. Consequently, the substitution of fixed effects with year-city controls the macro shocks and policy heterogeneity at the city level. According to the results in Table 4, Column (2), the DIGA coefficient is significantly positive. The core conclusion has not changed substantially due to fixed effect adjustment, indicating that even after considering regional differences at the city level, the regression conclusion is still stable.

4.4.3. Eliminate the Interference of the Epidemic

The COVID-19 shock of 2020 delivered an unprecedented disruption to global supply chains, potentially distorting the regression estimates. Therefore, samples from 2020 were excluded to eliminate interference of special events. According to the results in Table 4, column (3), the DIGA coefficient is considerably positive and close to the benchmark regression coefficient. This indicates that the impact of the epidemic has not changed the positive spillover effect of DT on SCSD, and the conclusion remains robust.

4.5. Endogeneity Test

4.5.1. Instrumental Variable Method

Regional digital infrastructure policies have a substantial impact on DT. Consequently, this paper utilizes the Broadband China Pilot Program as the instrumental variable (iv), satisfying relevance (it accelerates enterprise digitalization) and exclusion (it affects partner sustainability solely through client DT). The policy pilot directly enhances the digital infrastructure level of the region through central government subsidies and resource tilt, providing objective conditions for the digitalization of client enterprises; meanwhile, the policy pilot is a national macro strategy and does not exhibit a direct correlation with individual enterprises' ESG performance, thereby satisfying the instrument variables' requirements for exogeneity and relevance. Phase 1: Examine the correlation between instrumental variables and DIGA. As shown in column (1) of Table 5, the iv coefficient is considerably positive, suggesting a robust correlation between the instrumental variable and DIGA. With an F-statistic of 17.23—well exceeding the empirical critical value of 10—the iv is deemed strong, ruling out weak-IV concerns. Phase 2: Substitute the DIGA predicted in Phase 1 and return to ESG. As shown in column (2) of Table 5, the DIGA coefficient is significantly positive. This affirms that the benchmark finding remains unchanged, corroborates their robustness, and largely eliminates endogeneity-induced bias in the core conclusion.

Table 5. Endogeneity test.

	(1)	(2)	(3)
	First	**Second**	**PSM**
Variables	**DIGA**	**ESG**	**ESG**
DIGA		0.6396 ***	0.0415 ***
		(0.2161)	(0.0124)
iv	0.1797 ***		
	(0.0433)		
F-statistic in the first stage	17.23		
Kleibergen-Paap LM statistic	17.21		
	[0.0000]		
Cragg-Donald Wald F statistic	18.34		
Observations	4959	4959	2942
Control variables	Y	Y	Y
ind	Y	Y	Y
year	Y	Y	Y

Note: The values in parentheses () represent robust standard errors; the values in square brackets [] denote the *p*-values of the test statistics, *** $p < 0.01$.

4.5.2. PSM

The PSM test is adopted in this investigation to mitigate sample selection bias and improve the dependability of the research conclusions. Utilizing the industry's annual median, treat is established (if greater than the median, 1 was taken as the treatment group; otherwise, 0 was taken as the control group). The full sample 1:1 nearest neighbor matching and annual 1:1 nearest neighbor matching methods were adopted to balance the covariates between the treatment and the control group, thereby attenuating self-selection bias. The DIGA coefficient is 0.0415, as indicated in Column (3) of Table 5, which is highly close to the benchmark regression result. This shows that the positive spillover effect of DIGA on ESG remains significant even after accounting for enterprises' self-selection characteristics, which further verifies the robustness of the core conclusions.

4.6. Mechanism Analysis

4.6.1. The Perspective of Coordinated Development of the Supply Chain

Supply chain coordination serves as the key carrier for DT transmission within supply chain, encompassing dimensions such as information transparency and risk sharing. Referring to the studies of Kim & Verrecchia (2001) [62] and Bushman et al. (2004) [63], the text selects to use the KV index of information disclosure quality of listed companies to measure enterprises transparency. Based on this, in order to better reflect the degree of transparent synergy between suppliers and clients in the supply chain, we have constructed a coupling coordination model, as shown in Equations (2)–(4):

$$C1 = 2 * \left[\frac{KV_{sup\,plier} * KV_{customer}}{(KV_{sup\,plier} + KV_{customer})^2}\right]^{\frac{1}{2}} \tag{2}$$

$$T1 = \beta KV_{\mathrm{psu}pplier} + \lambda KV_{coustomer} \tag{3}$$

$$Transparent = (C1 * T1)^{\frac{1}{2}} \tag{4}$$

Among these, C1 represents the coupling of enterprise transparency between suppliers and clients in the supply chain. $KV_{\mathrm{psu}pplier}$ and $KV_{coustomer}$ respectively represent the enterprise transparency index of suppliers and clients. $T1$ is a comprehensive evaluation index for supplier transparency and client transparency. When calculating $T1$, since the upstream and downstream enterprises along the supply chain need to collaborate, and the participation degree of each enterprise is equal, so the values of β and γ are both 1/2. Transparent represents the degree of transparent synergy between suppliers and clients, with a value range of 0 to 1, where higher values denote stronger alignment.

When measuring the degree of risk management synergy (IndexB), referring to the studies of Ding and Chen (2024) [64], this study computes the coupled-coordination value for risk management from the DeBo internal-control index, as shown in Equations (5)–(6):

$$Index_0 = 2 * \left[\left(\frac{C\_Risk * S\_Risk}{C\_Risk + S\_Risk} \right)^2 \right]^{\frac{1}{2}} \quad (5)$$

$$Index = \left(Risk\_Coulpling * (\mu C\_risk + \theta \text{S\_Risk}) \right)^{\frac{1}{2}} \quad (6)$$

Among these, $Index_0$ and $Index$ where and respectively denote the coupled value of risk management and its coupled coordination degree. C_Risk and S_Risk where and respectively denote the risk-management capability of clients and suppliers. Given that supply chain collaborative management hinges on collaborative cooperation, clients and suppliers are assumed to contribute equally, with the values of both μ and θ are 1/2.

Table 6 shows the mechanism analysis from the perspective of supply chain coordinated development. This investigation uses OLS regression to verify whether supply chain transparent synergy degree and risk management synergy can be enhanced through the implementation of enterprise DIGA. Columns (1) and (2) take the transparency synergy degree of upstream and downstream enterprises as intermediary variables. The results of column (1) indicate a DIGA coefficient is significantly positive, which implies that the supply chain transparency synergy degree is substantially enhanced by client enterprises' digitalization. The application of digital technology breaks down information barriers within supply chains, thereby establishing the foundation for effective collaboration among partners. In column (2), Transparent enters with a coefficient of 0.8418 and DIGA with 0.0406; each is significant at the 1% level. This suggests that the degree of transparent synergy positively influences ESG. By facilitating a transparent degree of supply chain synergy, client enterprises indirectly contribute to supply chain partners improving ESG performance. The improvement of the transparent synergy degree not only helps supply chain partner enterprises precisely match market demands but also reduces transaction costs through efficient collaboration. The intermediary variable in columns (3) and (4) is the risk management synergy degree among upstream and downstream supply chain enterprises. The coefficient of DIGA in column (3) is significantly positive, which implies that the supply chain risk management synergy degree is substantially enhanced by client enterprises' digitalization. Digital technology enables supply chain risks to be identified and responded to in a timely manner, enhancing the ability to resist risks. In column (4), IndexB has a coefficient of 0.1965 and DIGA has 0.0363; each is significant at the 1% level. This suggests that the degree of risk management synergy positively influences ESG. By facilitating the degree of supply chain risk management synergy, client enterprises DT indirectly promotes supply chain partners to improve ESG performance. The impact of risks such as supply chain disruptions and environmental violations on supply chain partner enterprises can be effectively mitigated by the enhancement of risk management synergy, ensuring their stable performance in economic, social, and environmental dimensions, and thereby improving ESG levels. Thus, H2 was verified.

Table 6. Mechanism analysis from the perspective of coordinated supply chain development.

Variables	**(1) Transparent**	**(2) ESG**	**(3) IndexB**	**(4) ESG**
DIGA	0.0025 **	0.0406 ***	0.0127 ***	0.0363 ***
	(0.0012)	(0.0096)	(0.0034)	(0.0102)
Transparent		0.8418 ***		
		(0.1176)		
IndexB				0.1965 ***
				(0.0557)
Control variables	Y	Y	Y	Y
Constant	0.6162 ***	0.7581 ***	0.7653 ***	1.1899 ***
	(0.0240)	(0.2156)	(0.0658)	(0.2198)
Observations	4929	4929	4542	4542
R-squared	0.236	0.237	0.075	0.229
ind	Y	Y	Y	Y
year	Y	Y	Y	Y

Note: Standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$.

4.6.2. The Perspective of Innovative Development of the Supply Chain

Supply chain innovation development is the engine of sustainability; its resources and directions of supply chain innovation can be influenced by DT, which in turn can affect ESG. This investigation utilizes the financing constraints (SA) and green innovation index (GRE) of supply chain partners as intermediary variables. Calculating the SA index of enterprise supply chain partners by referring to the studies of Hadlock and Pierce (2010) [65]. A higher SA value indicates that firms have fewer financing constraints [48]. GRE is calculated as the log of one plus the count of green invention applications filed by listed companies [66]. Table 7 displays regression results with SA as the mediating variable in Columns (1) and (2). Column (1) indicates that DIGA coefficient is significantly positive, which implies that as the client enterprises' digitalization level improves, the financing constraints of supply chain partners are significantly alleviated. This is because after the client enterprise undergoes digital transformation, it can rely on digital platforms to reduce the financing difficulty and cost for supply chain partner enterprises. The results of Column (2) indicate that SA with a coefficient of 0.4843 and DIGA with 0.0337; each is significant at the 1% level. This suggests that SA positively influences ESG. Client enterprises' digitalization alleviates the financing constraints of supply chain partners, providing financial support for their sustainable development-related investments and indirectly promoting ESG improvement. Columns (3) and (4) present the regression results with green technological innovation of supply chain partners as intermediary variables. The results of Column (3) indicate that the DIGA coefficient is significantly positive, which implies that as client enterprises' digitalization level improves, the green technological innovation level of supply chain partners is significantly alleviated. After client enterprises' digitalization level is enhanced, on the one hand, it can assist the supply chain partner enterprises in green research and development by sharing digital technologies. On the other hand, it can more accurately convey green market demand and force supply chain partner enterprises to carry out green technological innovation. In column (4), GRE has a coefficient of 0.1720, and DIGA has 0.0370. Compared with the benchmark regression, the DIGA coefficient decreased significantly after the introduction of GRE, and GRE positively influences ESG. This indicates that client enterprises' digitalization can stimulate green technological innovation among supply chain partner enterprises through methods such as technology spillover and demand guidance, thereby facilitating ESG improvement and enhancing the SCSD level. Therefore, H3 was verified.

Table 7. Mechanism analysis from the perspective of supply chain innovation and development.

Variables	(1) SA	(2) ESG	(3) GRE	(4) ESG
DIGA	0.0154 ***	0.0337 ***	0.0242 **	0.0370 ***
	(0.0044)	(0.0093)	(0.0119)	(0.0094)
SA		0.4843 ***		
		(0.0318)		
GRE				0.1720 ***
				(0.0109)
Control variables	Y	Y	Y	Y
Constant	−5.0728 ***	3.7350 ***	−4.3410 ***	2.0252 ***
	(0.0978)	(0.2652)	(0.2948)	(0.2082)
Observations	4959	4959	4959	4959
R-squared	0.522	0.259	0.220	0.262
ind	Y	Y	Y	Y
year	Y	Y	Y	Y

Note: Standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$.

5. Further Analysis

Within this part, heterogeneity analysis is done from three dimensions: enterprise pollution attributes, property rights nature, and geographic location, in order to further investigate the border conditions of DT's impact on ESG. Table 8 displays the empirical findings.

Table 8. Heterogeneity analysis.

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	**ESG**	**ESG**	**ESG**	**ESG**	**ESG**	**ESG**
DIGA	−0.0148	0.0475 ***	0.0715 ***	0.0150	0.0581 ***	−0.0084
	(0.0218)	(0.0106)	(0.0149)	(0.0124)	(0.0115)	(0.0165)
Constant	1.2544 ***	1.2362 ***	1.0362 ***	2.3328 ***	1.2419 ***	1.6128 ***
	(0.3858)	(0.2380)	(0.2851)	(0.3529)	(0.2534)	(0.3405)
Observations	1469	3490	2413	2544	3186	1767
R-squared	0.193	0.268	0.280	0.186	0.264	0.173
Control variables	Y	Y	Y	Y	Y	Y
ind	Y	Y	Y	Y	Y	Y
year	Y	Y	Y	Y	Y	Y

Note: Standard errors in parentheses, *** $p < 0.01$.

5.1. Heterogeneity Based on Enterprise Pollution Attributes

The samples were categorized into two categories: highly polluting enterprises and non-heavily polluting enterprises. Table 8's columns (1) and (2) display the regression results: The sample of substantially polluting businesses has a coefficient of DIGA of −0.0148, which has failed to pass the significance test; the sample of non-heavily polluting businesses has a coefficient of DIGA of 0.0475, which is significantly positive. This is because heavily polluting enterprises are more constrained by environmental protection policies, and the "compliance" component of their own ESG improvement is higher, making it difficult to positively impact their ESG. Non-heavy polluters are more flexible in improving ESG in the economic and social dimensions, and are easily driven by the digitalization of client enterprises, thereby significantly improving ESG performance.

5.2. Heterogeneity Based on Property Rights Characteristics

Table 8's columns (3) and (4) display the regression results: The sample of state-owned businesses has a coefficient of DIGA of 0.0715, which is significantly positive; the sample of non-state-owned businesses has a coefficient of DIGA of 0.0150, which has failed to pass the significance test. This is due to the fact that state-owned enterprises have more stable supply chain relationships, more abundant resources, and policy support. The digitalization of client enterprises can rely on these advantages to efficiently achieve supply chain collaboration, which positively influences ESG. However, non-state-owned enterprises are confronted with fiercer market competition and resource constraints, and the stability and efficiency of supply chain collaboration are relatively weak, which makes it difficult for the spillover effects of the digitalization of client enterprises to be fully transmitted to the ESG level.

5.3. Heterogeneity Based on Geographic Location

The grouping is based on the registered location of the enterprise in either the eastern region or the central and western regions (all provinces except the eastern region). Table 8's columns (5) and (6) display: The sample of the eastern region has a coefficient of DIGA of 0.0581, which is significantly positive; the sample of the central and western regions has a coefficient of DIGA of −0.0084, which has failed to pass the significance test. This is due to the presence of mature supply chain networks and a well-developed digital infrastructure in the eastern region. As a result, the digitalization of client enterprises can be more effectively transmitted to partners through the supply chain, resulting in a more pronounced positive influence on ESG. Conversely, the central and western regions are plagued by inadequate digital infrastructures and low efficiency of supply chain collaboration. The collateral effects of client enterprises' digitalization are restricted by these constraints, which complicate the process of achieving a substantial positive influence on ESG.

6. Conclusions and Recommendations

6.1. Conclusions

This research focuses on the key topic of SCSD. Focusing on supply chain spillovers, it takes Chinese A-share listed enterprises and their disclosed suppliers and clients from 2012 to 2023 as the research objects. An in-depth analysis was conducted on the intrinsic connection between the DT of the client enterprise and the sustainable development level of its supply chain partners, and the mediating role played by the coordinated and innovative development of the supply chain in this process was explored. This research explores the relationship between the digital transformation of client enterprises and the sustainability levels of their supply chain partners. This study further examines the mediating roles of coordinated development and innovative development within the established framework. The conclusions drawn are as follows: First, the DT of client enterprises positively influences the ESG of supply chain partner enterprises. And this influence is asymmetric, which is more significant when the DT of customer enterprises is higher than that of supply chain partner enterprises. Second, mechanism analysis indicates that this positive spillover effect is achieved through two paths: (1) the coordinated development path of the supply chain —the DT of client enterprises enhances the transparency synergy and risk management synergy, reduces information asymmetry, and curbs overall risks; and (2) the innovative development path of the supply chain—customer enterprises' DT eases financing constraints and stimulates their green technological innovation. Third, heterogeneity tests indicate that the above-mentioned spillover effects are more significant among non-heavily polluting businesses, state-owned businesses, and enterprises in the eastern region. This study utilizes instrumental variables and PSM to control endogeneity concerns, thereby ensuring robustness. In addition, robustness tests were conducted by substituting explanatory variables, adjusting fixed effects, and eliminating the interference of the epidemic. The research have significant implications for supply chain partner enterprises, client enterprises, and policymakers.

This study contributes to enriching the research on the influence of client enterprise DT on the sustainable development mechanism of supply chain partners in the field of SCSD, and to clarifying the transmission path of coordinated development and innovative development of supply chain. The practical significance is that it provides a feasible development direction for client enterprises and supply chain partners. Client enterprises should actively promote DT strengthen supply chain coordination and innovative development, while supply chain partners should leverage the leading role of client enterprises to enhance the level of SCSD.

That being said, this study does have some flaws. In the scope of research, it only focuses on the supply chain of specific industries and fails to cover a wider range of industry fields, so the generality of the research results needs to be further verified. In the research method, quantitative analysis is mainly adopted, and some factors that are difficult to quantify are not considered enough. Future research can be expanded to more industries, comprehensively applying various research methods to deeply explore the influencing factors not covered. This will make the research system for supply chain sustainable development even better, giving businesses more comprehensive and accurate instructions on how to put it into action.

6.2. Recommendations

Client enterprises should continuously deepen DT and leverage digital technology to build a supply chain digital hub with real-time synergy and full-chain governance. On the one hand, break down data silos between upstream and downstream nodes by building a unified cloud-based supply chain data platform, and open up real-time data interfaces for production plans, inventory turnover, and market demand forecasts to core suppliers and distributors. For instance, opening up data interfaces such as production plans and inventory levels to suppliers to help them precisely arrange production and reduce overcapacity and resource waste. On the other hand, construct a digital risk monitoring system for supply chain ESG by embedding environmental compliance, labor rights protection, and corporate governance indicators into the digital platform, set up automatic early warning thresholds for abnormal indicators, and conduct real-time dynamic supervision of partner enterprises' ESG behaviors to enhance the synergy of supply chain risk management. Meanwhile, client enterprises should release a digital green demand guide through the platform, clearly transmitting green product design standards, low-carbon production processes, and recyclable packaging requirements to partners, and link DT investment and green performance with supply chain cooperation thresholds to guide the direction of partners' green technological innovation.

To maximize their operations, supply chain partners should proactively integrate into the digital ecosystems of their client enterprises and utilize the digital tools provided by clients. In terms of financing, supply chain partners actively cooperate with the digital credit assessment of client enterprises, share real-time operational data with financial institutions through the client's platform to form a supply chain digital credit certificate, and apply for green credit, carbon financial bonds and other preferential financing products, thereby reducing financing costs and alleviate financing constraints. In terms of green technology innovation, supply chain partners carry out joint research and development with client enterprises, share digital R&D resources, and carry out collaborative research on key green technologies. For non-heavy polluting enterprises, focus on digital transformation of the service link; for manufacturing partners, accelerate the digital transformation of production lines to improve raw material utilization efficiency. In addition, partners in China's eastern region should leverage the advantages of mature digital infrastructure, set up a special DT fund for supply chain synergy, and carry out inter-enterprise digital talent sharing programs with client enterprises to cultivate professional talents who master both digital technology and supply chain sustainable development, and strengthen their competitive position in the supply chain.

The government can introduce special policies to offer tax reductions, financial subsidies, and other support to client enterprises that carry out DT and drive SCSD, encouraging them to increase their investment in DT. Green finance policies should be refined for supply chain partner enterprises, especially those encountering substantial financing constraints. Concurrently, the eastern region should enhance digital infrastructure development to furnish hardware support for digitization and sustainable growth of supply chains. Implement more rigorous environmental regulations and digital monitoring mandates for industries with significant pollution to facilitate corporate transformation and enhancement.

The government should formulate targeted industrial support policies and institutional guarantees to amplify the positive spillover effect of client enterprises' DT on SCSD. First, the government will introduce DT incentive policies for leading enterprises in the supply chain: The government can introduce special policies to offer tax reductions, financial subsidies, and other support to client enterprises that carry out DT and drive SCSD, encouraging them to increase their investment in DT. Second, improve the supply chain green finance support system: guide financial institutions to launch exclusive digital supply chain green credit products, lower the credit threshold for small and medium-sized partner enterprises. Third, strengthen the construction of regional digital infrastructure differentiation: the eastern region should enhance digital infrastructure development to furnish hardware support for digitization and sustainable growth of supply chains; for the central and western regions, increase investment in 5G base stations and industrial digital transformation service platforms, and set up DT training bases for small and medium-sized supply chain enterprises to solve the problem of insufficient digital capability of local partners. Fourth, for heavy polluting industries, implement more rigorous environmental regulations and digital monitoring mandates for industries with significant pollution to facilitate corporate transformation and enhancement; for non-heavy polluting industries, adopt a reward-based regulatory model, and give financial rewards to enterprises that achieve double improvement in DT level and ESG performance.

Author Contributions

Y.S.: conceptualization, software, methodology, visualization, formal analysis, data acquisition, funding acquisition, resources and supervision; J.W.: writing—original draft, data curation and software; J.M.: investigation, project administration, supervision and supervision; H.X.: writing—reviewing and editing, data curation and investigation. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used Qianwen to assist with translation and language polishing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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