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Does digital transformation improve supply chain efficiency of agricultural enterprises?

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Enhancing supply chain efficiency (SCE) of agricultural enterprises is crucial for building sustainable agriculture and food systems. While digital transformation (DT) presents a potential pathway to this end, it constitutes a high-risk, systemic organizational change whose impact on SCE remains theoretically and empirically ambiguous. Using panel data from Chinese agricultural listed companies and a two-way fixed effects model, the empirical results identify a significant U-shaped relationship between DT and SCE in agricultural enterprises. This finding indicates that DT initially undermines efficiency before generating positive returns as implementation advances. Moreover, contractual and relational governance negatively moderates the DT–SCE relationship, flattening the U-shaped curve. Further analysis reveals significant heterogeneity in these effects across different organizational life cycle stages and regional business cooperation cultures. Specifically, regarding the organizational life cycle, the U-shaped relationship and relational governance’s moderating effect are more pronounced in growth or decline stage firms, whereas contractual governance’s effect is stronger in maturity or decline stage firms. From a regional perspective, the U-shaped relationship and contractual governance’s moderating effect are more salient in areas with weak business cooperation cultures, while relational governance’s effect is more influential where it is strong. This study contributes to the literature on SCE and digitalization paradox by delineating the complex, nonlinear trajectory of DT in agricultural enterprises and specifying the governance-related contingencies that shape its efficacy. These findings offer valuable insights into how agricultural enterprises leverage DT and governance mechanisms to improve SCE and advance agricultural supply chain sustainability.

KEYWORDS

agriculture supply chain, contractual governance, digital transformation, relational governance, supply chain efficiency

Introduction

The sustainable development of global supply chains is increasingly challenged by intensifying external competition and growing geopolitical uncertainties. Agricultural supply chains, in particular, are inherently vulnerable due to their reliance on weather conditions, the perishability of products, difficulties in ensuring quality and logistics control, and heightened political sensitivities (Belhadi et al., 2024). In developing economies such as China, agricultural supply chains face additional operational constraints, including high production uncertainty, significant inventory and distribution losses, fragmentation information systems, and widespread opportunistic behaviors among stakeholders (Huang, 2020; Guo and Yao, 2022). These challenges collectively undermine agricultural supply chain efficiency (SCE) and constrain long-term enterprise growth (He et al., 2024). Corporate SCE directly shapes market

competitiveness and financial performance while also significantly influencing industrial upgrading and sustainable development (Yin and Sun, 2025). Examining how to boost SCE in agricultural enterprises is therefore practically important for advancing high-quality, sustainable growth both at the firm and industry levels.

Digital transformation (DT) is a strategic process of leveraging digital technologies and intelligent tools to optimize business, enhance capability, improve efficiency and reshape value creation (Vial, 2019; Li N. et al., 2023; Yu et al., 2024). It provides a more intelligent and intensive development pathway for agricultural supply chains (Fu et al., 2020). Although the consequences of DT have been widely discussed (Zhao et al., 2024; Chen et al., 2025; Yuan et al., 2025), significant gaps remain in the literature. First, most existing studies focus on DT's influence at the intra-organizational level, with limited attention to its broader, systemic impact on supply chain collaboration (Fu et al., 2023). Empirical evidence on the role of DT in improving SCE in agriculture sector remains limited. Second, while the potential drawbacks of DT are acknowledged, most empirical studies emphasize its positive linear effects. The assumption that DT consistently enhances SCE is increasingly contested. Some studies support a positive linear DT-SCE relationship in listed firms (He et al., 2024), while others highlight potential challenges such as financing constraints, technical complexities, managerial skill mismatches, and increased operating costs factors that may suppress asset turnover and efficiency (Li R. et al., 2023; Guo et al., 2023; He et al., 2025). These challenges may be particularly salient in agricultural enterprises due to their structurally underdeveloped supply chains and the higher complexity and cost of digital adoption. Thus, the net effect of DT on SCE may be nonlinear and even negative at certain stages. Recent empirical evidence further suggests a nonlinear relationship between digital economy and agricultural development (Liu et al., 2024), implying that the effect of DT on SCE is likely more complex than previously assumed. However, this potential nonlinear relationship has been largely overlooked in current research. To address this critical gap, we propose the first research question. RQ1: What characterizes the nonlinear relationship between DT and SCE in agricultural enterprises, and under what contingent conditions does DT exert either enhancing or diminishing effects?

The success of DT and the effective supply chain operations critically rely on close collaboration and support among supply chain stakeholders. According to transaction cost theory and relational exchange theory, supply chain governance mechanisms are institutional arrangements that coordinate, motivate, regulate, and constrain cooperative actions, consisting primarily of contractual and relational governance (Keller et al., 2021; Zeng and Wan, 2024). They influence the progress and effectiveness of DT as well as supply chain performance (Cao and Lumineau, 2015; Lin et al., 2023). Yet, how governance mechanisms influence the effectiveness of DT remains underexplored. Furthermore, although the relationship between governance mechanisms and supply chain performance has been extensively examined, findings remain inconclusive. Empirical results are ranged from positive to unclear or even negative (Cao and Lumineau, 2015; Keller et al., 2021). These inconsistencies may reflect the context-dependent nature and situational advantages of different governance mechanisms (Abdi and Aulakh, 2017). For agricultural enterprises, which often operate in uncertain and fragmented environments, selecting appropriate governance mechanisms is essential for aligning stakeholder interests and ensuring the success of DT. However, limited

research has examined how governance mechanisms influence the DT-SCE relationship. To fill this gap, we raise the second research question. RQ2: How do contractual and relational governance mechanisms moderate the DT-SCE relationship in agricultural enterprises?

To address the proposed research questions, this study aims to investigate the nonlinear impact of DT on SCE and to examine how governance mechanisms shape this relationship within agricultural enterprises. To this end, we develop a research model grounded in resource orchestration, transaction cost, and relational exchange theories and test the proposed hypotheses using a fixed-effects model on panel data of Chinese listed agricultural firms from 2012 to 2024. The empirical findings offer practical insights for policymakers and managers to better harness DT and governance mechanisms in enhancing SCE, thereby contributing to agricultural supply chain sustainability. Theoretically, this research makes three key contributions. Theoretically, this research makes three key contributions. First, it extends resource orchestration theory and contributes to the literature on the DT paradox. Specifically, by applying this theoretical lens, we challenge the simple linear assumption regarding the DT-SCE relationship and empirically identify a U-shaped DT-SCE relationship in agricultural firms. This empirical insight provides a powerful resolution to prior contradictions and advances theoretical understanding of DT's complex impact. Second, it contributes to supply chain management literature by illustrating that contractual and relational governance serve as critical contingency factors shaping the DT-SCE relationship. This insight enhances contextualized understanding of how governance arrangements can either facilitate or hinder DT outcomes within agricultural supply chains. Moreover, it provides a more comprehensive and dialectical perspective on the selection of governance mechanisms. Third, this study advances the theoretical understanding of the DT-SCE relationship by revealing how organizational life cycle and regional business cooperation culture shape this relationship, along with the contingent roles of contractual and relational governance. These findings offer a more comprehensive analytical framework for explaining the conditions under which DT effectively enhances corporate SCE, especially within the agricultural sector.

The remainder of this study is arranged as follows. Section 2 develops the theoretical framework and research hypotheses, drawing on resource orchestration, transaction cost, and relational exchange theories. Section 3 describes the methodology, including sample selection, data sources, variable measurement, and model specification. Section 4 presents the empirical results. It employs fixed-effects models to test the proposed hypotheses, along with a series of endogeneity and robustness checks. Heterogeneity analyses are further conducted based on internal firm characteristics (lifecycle stage) and external environmental factors (regional business collaboration culture). Finally, Section 5 discusses the main findings, outlines theoretical and practical implications, and acknowledges limitations alongside suggestions for future research.

Theory and hypotheses

The nonlinear impact of DT on SCE

Resource orchestration theory offers a theoretical foundation to elucidate the consequences of DT (Yin, 2023). This theory posits that

firms achieve competitive advantages through three core activities: structuring resources (acquiring, accumulating, and divesting to form and manage a resource portfolio), bundling resources (combining them to construct or alter capabilities), and leveraging resources (deploying them to create and deliver value) (Sirmon et al., 2007, 2011; Baert et al., 2016; Chen and Tian, 2022). It highlights that competitive advantage stems not merely from possessing resources and capabilities, but from their effective orchestration and synchronization (Baert et al., 2016; Lee et al., 2023). Viewed through this lens, DT can be conceptualized as a strategic process of orchestrating digital resources to improve enterprise competitive advantage (Yin, 2023). The effectiveness of DT largely depends on how efficiently a firm structures, bundles, and leverages its digital resources. Thus, we draw upon resource orchestration theory to develop a framework (Figure 1) that investigates how DT affects SCE in agricultural enterprises.

We propose that DT may promote SCE by generating information effects, capability effects, and diffusion effects corresponding to the core orchestration activities. First, in the resource structuring stage, DT facilitates the systematic aggregation and refinement of data and information. This generates an information effect that mitigates information asymmetry and enhances visibility across the supply chain. Due to the decentralized nature of agricultural production, strong environmental dependencies, and a large number of supply chain actors, agricultural supply chains are particularly prone to information fragmentation and collaboration failures. DT enables the digitization and integration of internal and external information flows (Zou and Mishra, 2022), facilitating more efficient, accurate, and cost-effective data transmission and interaction (Yin, 2023; Yin and Sun, 2025). Enhanced information transparency can reduce opportunistic behavior (Guo and Yao, 2022), optimize production and supply decision, and improve the accuracy of supply and demand matching, ultimately contributing to improving SCE. Second, in the resource bundling stage, DT enables the integration of digital assets to build new or enhance existing operational capabilities, creates new opportunities for industrial technology upgrading (Bai et al., 2023),

thereby generating a capability effect. DT empowers agribusinesses to acquire, process, and apply supply chain-related data to improve their perceptive, predictive, decision-making, and adaptation capabilities (Lezoche et al., 2020). These enhanced dynamic capabilities strengthen cross-functional collaboration and supply chain synchronization, thereby fostering greater efficiency. Third, in the resource leveraging stage, DT allows firms to deploy these enhanced capabilities externally. Through governance linkages and knowledge spillovers (Fu et al., 2020), this creates a diffusion effect, propagating DT value and best practices to partners. As digital practices diffuse to upstream and downstream partners, they contribute to performance improvements in related entities (Guo and Yao, 2022), enhancing the overall resilience and efficiency of the agricultural supply chain system (Zhang et al., 2025).

However, as a complex organizational transformation, DT entails substantial investment, operational uncertainty, and extended gestation periods (Nambisan et al., 2019). In its initial phases, the orchestration of digital resources may generate issues such as resource crowding-out effects, coordination failures, and escalated management costs, which could potentially have a negative impact on SCE. First, during the resource structuring stage, early digital investments may divert finite resources away from essential supply chain development activities, creating a resource-crowding-out effect that can temporarily hinder SCE. Agricultural enterprises must often allocate significant funds toward digital infrastructure, including hardware, software, and production equipment (Ghosh et al., 2022). For firms with constrained financial capacity, this may reduce investment in logistics capabilities, training, and other key SCE drivers (Fan et al., 2024). Second, during the resource bundling and leveraging stage, early-stage DT frequently encounters a resource-to-capability transition challenge, characterized by insufficient coordination capacity and high management costs. This is primarily because DT involves restructuring organizational structure, updating business technologies, and redesigning processes, generating considerable risk and ambiguity during initial implementation. The resulting adjustments in supply chain workflows and partnerships often breed resistance and friction

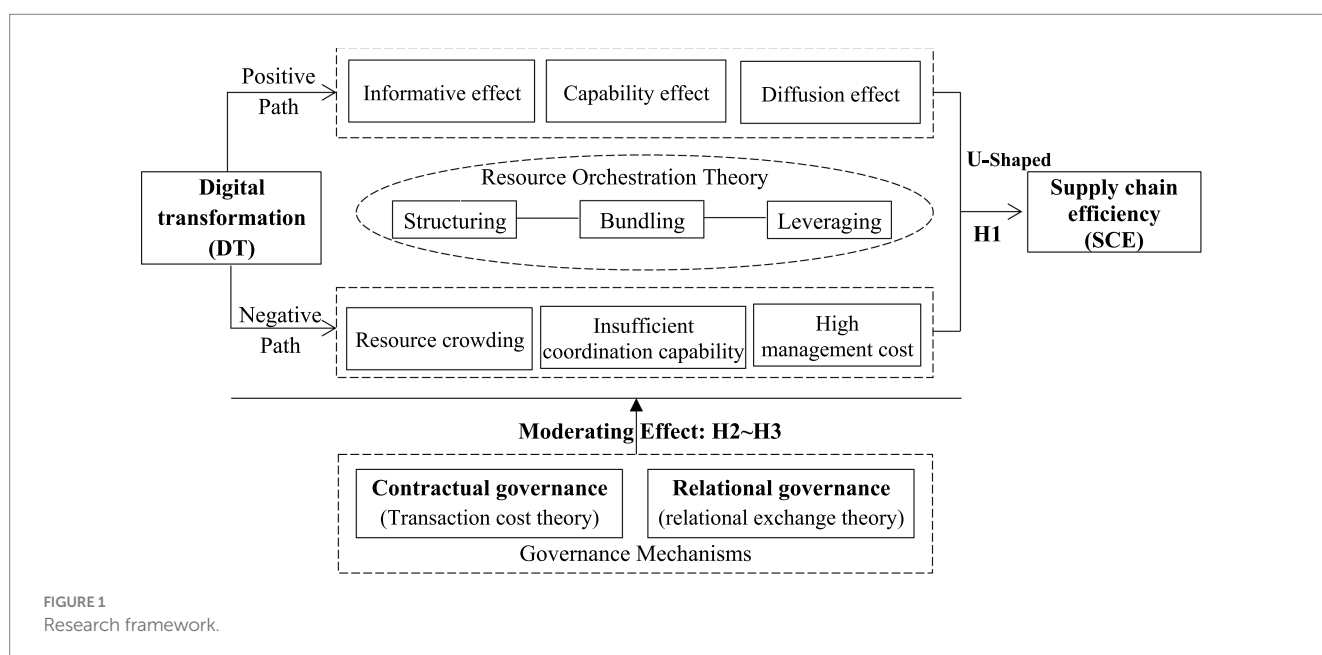


FIGURE 1 Research framework.

among stakeholders, increasing coordination overhead. These factors collectively hinder gains in production and SCE.

This phenomenon is particularly salient in the agricultural context. Many Chinese agricultural enterprises exhibit limited financial capacity and weak managerial expertise (Lu and Chen, 2021). Moreover, the broader agricultural digital infrastructure remains underdeveloped (Hassoun et al., 2023), especially in rural regions (Fu et al., 2023). Farmers, cooperatives, and other stakeholders frequently possess limited digital literacy and exhibit high risk aversion, exacerbating early implementation challenges. As a result, the initial stages of DT are often characterized by high costs and low returns, potentially exerting a net negative effect on SCE. However, as DT progresses and stakeholders gain familiarity and confidence, digital applications become more mature, integrated, and impactful. Investment returns begin to materialize, enabling enterprises to realize the informative, capability, and diffusion benefits described above. Empirical evidence from related sectors supports this nonlinear dynamic. For example, in the aquaculture industry, Yang and Cui (2022) found that the benefits of digitalization emerge gradually and become more pronounced as DT deepens across the industry chain. These arguments suggest a nonlinear relationship between DT and SCE, in which initial investments and organizational disruptions may depress efficiency, but long-term maturity in digital capabilities generates substantial performance gains. Accordingly, we propose the following hypothesis:

H1: There is a U-shaped relationship between DT and SCE in agricultural enterprises.

The moderating role of governance mechanisms

The governance mechanism functions to align the interests of cooperating partners (Bijman et al., 2013). It may shape the efficiency and effectiveness of resource orchestration throughout DT, thus affecting the impact of DT on SCE. Contractual and relational governance are two main types of governance mechanisms in inter-organizational relationships (Lu et al., 2015; Zeng et al., 2023). Contractual governance utilizes formal rules and procedures to clearly delineate the rights, obligations, and behavioral boundaries of the transacting parties, as well as to explicitly describe the corresponding resolution methods for potential future situations and disputes (Poppo and Zenger, 2002). It emphasizes the application of legal provisions, standardized operating procedures, and the formulation of self-protection measures (Ryall and Sampson, 2009). Contractual governance originates from transaction cost theory. According to this theory, the contractual arrangement established between the parties serves to curb opportunistic behavior and mitigate transactional hazards, thereby safeguarding their cooperative relationship (Williamson, 1985). Relational governance primarily refers to the use of relational norms or relational expectations by transacting parties to curb opportunistic behavior (Lusch and Brown, 1996). It is characterized by self-enforcement, enabling contract implementation without requiring intervention from third parties such as courts or arbitrators (Baker et al., 2002). Relational governance stems from the relational exchange theory, which emphasizes that formal contracts are not an effective means of preventing transaction risks (Dyer and Singh, 1998; Wuyts and Geyskens, 2005). Instead, it is important to

utilize relational mechanisms such as trust and relational norms to constrain opportunistic behavior and promote cooperation between parties (Handfield and Bechtel, 2002; Li et al., 2010). In sum, contractual and relational governance mechanisms play a critical role in ensuring supply chain coordination and mitigating opportunistic behavior (Keller et al., 2021). While both mechanisms are designed to facilitate collaboration, they both have some limitations. In complex and dynamic transactional environments, contractual and governance may inhibit trust and provoke conflict due to its rigidity and legalistic nature. In contrast, relational governance, though flexible and trust-based, may be undermined by opportunism, ambiguity, and enforcement difficulties (Cao and Lumineau, 2015). Fundamentally, contractual and relational governance differ in their theoretical foundations, behavioral expectations, and operational mechanisms (Poppo and Zenger, 2002; Zeng and Wan, 2024). These mechanisms may exert divergent effects on DT-SCE in agricultural enterprises, particularly given the high uncertainty, coordination complexity, and risk sensitivity of agricultural supply chains.

In the early stages of DT, agricultural enterprises typically face significant ambiguity and coordination challenges, which amplify the importance of governance mechanisms. However, contractual governance, with its rigid and often incomplete contractual terms, may lack the flexibility required to adapt to dynamic and uncertain environments. The difficulties in drafting, enforcing, and adapting contracts in high-uncertainty contexts may lead to misunderstanding, resistance, or even conflict between supply chain partners. Prior research has shown that environmental dynamism intensifies the conflict-inducing effect of contractual control mechanisms (Schilke and Lumineau, 2018). In contrast, relational governance, based on trust, shared norms, and mutual understanding, offers greater adaptability and responsiveness. It leverages flexible informal norms, such as trust and communication (Wan et al., 2019; Möllering, 2002), to reduce coordination friction and increase resilience to uncertainty (Abdi and Aulakh, 2017). These positive effects are more likely pronounced in Chinese agribusiness deeply embedded in rural social networks, as relational governance has more advantage than contractual governance in managing cooperation relationships built upon a relational foundation (Zeng et al., 2023). Agricultural enterprises navigating the initial, high-risk phase of DT particularly benefit from relational governance's ability to mitigate misunderstanding and cooperation breakdowns, thereby reducing the cost of DT and enhancing early-stage efficiency. Thus, in low DT contexts, contractual governance may intensify the negative 'pain period' effect of DT on SCE, while relational governance may alleviate it.

As DT deepens and the organization moves beyond the 'pain period', the uncertainty and ambiguity associated with early-stage transformation tend to diminish. In this more stable environment, contractual governance becomes more effective and complementary to DT for several reasons. First, digitalization reduces mitigates information asymmetry and enhances transparency, enabling more complete and adaptive contracting (Ghosh et al., 2022). It facilitates low-cost design, optimization, and enforcement of contracts, thereby reducing coordination misunderstandings and enhancing partner alignment. Second, well-defined contractual arrangements can help clarify digital responsibilities, enhance collaborative confidence, and reinforce the strategic value of digital tools. Conversely, at higher DT levels, relational governance may become less effective and even redundant. On one

hand, excessive reliance on informal relationships may discourage the proper enforcement of DT procedures, particularly if partners bypass or compromise digital protocols to preserve relational harmony (Lioliou et al., 2014). On the other hand, DT may exert a functional substitution effect on relational governance by embedding governance capabilities into digital infrastructure. For instance, technologies like block chain can automate trust and enforcement functions, reducing the need for informal trust-based coordination (Lumineau et al., 2021). Moreover, relational governance typically entails increasing marginal costs—due to the need for constant investment in relationship maintenance, vulnerability to interpersonal disruptions, and lack of authoritative enforcement. In contrast, contractual governance benefits from economies of scale and authoritative clarity, offering a more scalable and institutionally enforceable governance structure (Wan and Zeng, 2020). Therefore, as DT matures, contractual governance is likely to amplify the positive effects of DT on SCE, while relational governance may weaken them due to redundancy, cost, or behavioral conflict with digital norms. Based on this reasoning, we propose the following hypotheses:

H2: Contractual governance positively moderates the U-shaped relationship between DT and SCE, such that the U-shape becomes steeper in agricultural enterprises with higher level of contractual governance than in those with lower level.

H3: Relational governance negatively moderates the U-shaped relationship between DT and SCE, such that the U-shape is steeper in agricultural enterprises with lower level of relational governance than those with higher level.

Methodology

Sample and data

This study utilizes panel data from Chinese A-share agricultural listed firms over the period 2012–2024. Several considerations guided the sample selection process. First, the year 2012 is chosen as the starting point because it marks the implementation of updated disclosure regulations by Chinese authorities, which significantly enhanced the transparency and standardization of corporate reporting. These regulatory changes mandated more detailed disclosures regarding supplier and customer transactions, asset composition, and other key operational metrics, thereby ensuring the completeness and reliability of the financial and governance data used in this study. Second, the focus on A-share listed agricultural firms is justified by their strategic importance in China's agricultural modernization. These firms represent the leading entities within the national agricultural supply chain and typically function as key nodes in supply chain coordination, technology adoption, and digital innovation. As such, they are at the forefront of DT and play a pivotal role in promoting SCE and sustainable agriculture development. Third, we identify agricultural firms based on the China Securities Regulatory Commission 2012 Industry Classification Standard. To ensure sample quality, we exclude firms classified as ST and ST*, as well as firms with severe data omission. Data for DT are obtained from the annual reports of listed companies. Data for all other variables, including the measures for SCE, contractual governance, relational governance, organizational life cycle and the control variables were collected from the China Stock Market and Accounting Research

(CSMAR). CSMAR is a premier database for Chinese listed firms and has been extensively used in management research (Zhang and Greve, 2019; Zhong and Ren, 2023). The final sample consists of 1,675 firm-year observations from 222 agriculture firms, forming an unbalanced panel. To mitigate potential biases arising from outliers, all continuous variables were winsorized at the 1st and 99th percentiles.

Measurement

- (1) DT. Corporate DT is typically measured using two primary methodological approaches. The first approach involves quantifying DT through the scale of enterprise investments related to digital initiatives. The second relies on textual analysis of corporate disclosures, such as the frequency of DT-related terminology in annual reports. While textual frequency analysis can provide insights into managerial attention and the strategic emphasis placed on DT (Fu et al., 2023), it may not accurately reflect actual implementation. The lexical content of annual reports is susceptible to impression management and symbolic disclosure, as managers may selectively emphasize certain terms to meet stakeholder expectations or signal legitimacy (Leung et al., 2015). In contrast, financial data on digital intangible assets offers a more objective and verifiable proxy for DT, as these assets are recognized under formal accounting standards and subject to external auditing. Following the methodology of Fu et al. (2023) and Luo et al. (2025), this study adopts the ratio of digital intangible assets to total intangible assets as the primary indicator of a firm's degree of DT. This approach captures the tangible financial commitment of firms to DT initiatives. Specifically, digital intangible assets refer to those labeled under categories such as 'network', 'software', 'e-commerce', 'intelligent platform', and other DT-relevant descriptions explicitly listed in the intangible asset line items of corporate financial statements. This ratio reflects both the depth and scope of DT embedded within the firm's resource structure, offering a reliable proxy for the level of enterprise digitalization.
- (2) Contractual Governance. Following the approach of Yu and Sun (2014), this study measures contractual governance using the ratio of related-party transaction value to total assets. Related-party transactions refer to sales of products and purchases made between listed companies and their affiliated entities. A higher intensity of related-party transactions reflects a firm's strategic preference for substituting market-based governance mechanisms with hierarchical control structures. This substitution suggests a deliberate reliance on formalized, internally enforceable institutional arrangements to manage transaction risks and coordinate inter-organizational activities. As such, a greater proportion of related-party transactions indicate a stronger orientation toward contractual governance as a coordination mechanism. This proxy aligns with the theoretical premise that firms operating under complex or uncertain environments may internalize transactions to reduce opportunism, strengthen control, and enhance compliance through formal contractual safeguards.
- (3) Relational Governance. Drawing on Zhang et al. (2022), the ratio of business entertainment expenses to sales revenue serves as a proxy for relational governance. In the Chinese institutional and

cultural context, business entertainment expenditures are closely associated with the cultivation and maintenance of relational capital. These expenses are officially recognized as legitimate and tax-deductible under Chinese fiscal regulations. Influenced by traditional culture and social customs, enterprises in China have the business habit of using business hospitality to build and maintain social relationships with customers and suppliers. Higher levels of such expenditures are indicative of more frequent and deeper interactions with supply chain partners, reflecting a stronger reliance on informal, relational governance mechanisms for facilitating cooperation and reducing transaction frictions. Thus, the magnitude of business entertainment expenses serves as a valid proxy for the degree of relational governance, capturing the firm's embeddedness in social networks and its use of relational norms, such as trust, reciprocity, and personal ties, to manage supply chain relationships.

- (4) SCE. SCE is primarily reflected in the speed and smoothness of material and information flows across the supply chain (Modi and Mabert, 2010). Among various operational indicators of supply chain, inventory turnover performance is widely recognized as a key proxy, as it effectively captures the firm's capability to coordinate production, distribution, and demand in a timely and cost-effective manner (Fu et al., 2023). Following He et al. (2024), this study measures SCE for agricultural enterprises using the negative natural logarithm of the inventory turnover period, specifically calculated as $-\ln(365/\text{Inventory Turnover Ratio})$. Hence, a higher value of this measure indicates a shorter inventory cycle, faster inventory conversion, and consequently, a higher level of SCE.
- (5) Control Variable. To ensure the robustness of the empirical results, this study controls for key organizational characteristics, including firm age, firm size, number of employees, ownership type, ownership concentration, CEO duality, and financial leverage. Variable definitions is provided in Table 1.

Modelling

To determine the appropriate estimator for our unbalanced panel data, we conducted a systematic model selection procedure. The

Lagrange Multiplier (LM) test significantly rejected the null hypothesis of no individual random effects at the 1% level, favoring a random-effects model over a pooled regression. The subsequent Hausman test also rejected its null hypothesis ($p < 0.01$), indicating that the fixed-effects model is more appropriate than the random-effects model. Consequently, a fixed-effects model is employed for the empirical analysis using STATA 16.

- (1) Baseline Regression Model. Following prior research testing nonlinear relationships (Yang et al., 2023; Ma et al., 2023), this study employs a fixed-effect regression model incorporating a squared term of DT to examine its hypothesized U-shaped effect on SCE. The empirical model is specified as follows:

$$SCE_{it} = c + \alpha_1 DT_{it} + \alpha_2 DT_{it}^2 + \alpha_3 Z_{it} + \delta_i + \sigma_t + \epsilon_{i,t} \quad (1)$$

In Equation 1, Z represents a series of control variables, δ_i and σ_t capture individual-fixed effects and time-fixed effects, respectively, and c and $\epsilon_{i,t}$ are the constant term and random interference items, respectively. To address potential multicollinearity, all squared and interaction terms are mean centered prior to estimation.

- (2) Model for Testing Moderating Effects. Referring to existing studies (He and Wang, 2023; Ma et al., 2023), this study incorporates interaction terms to examine the moderating effects of contractual and relational governance on the relationship between DT and SCE. The corresponding econometric models are specified as follows:

$$SCE_{it} = c + \beta_1 DT_{it} + \beta_2 DT_{it}^2 + \beta_3 Cogit + \beta_4 Cogit * DT_{it} + \beta_5 Cogit * DT_{it}^2 + \beta_6 Z_{it} + \delta_i + \sigma_t + \epsilon_{it} \quad (2)$$

$$SCE_{it} = c + \lambda_1 DT_{it} + \lambda_2 DT_{it}^2 + \lambda_3 Regit + \lambda_4 Regit * DT_{it} + \lambda_5 Regit * DT_{it}^2 + \lambda_6 Z_{it} + \delta_i + \sigma_t + \epsilon_{it} \quad (3)$$

TABLE 1 Variable definitions.

Variable	Definition	Source
Digital transformation (DT)	Ratio of digital-related intangible assets to total intangible assets	Fu et al. (2023), and Luo et al. (2025)
Contractual governance	Proportion of an enterprise related-party transaction value to total assets	Yu and Sun (2014)
Relational governance	Ratio of business entertainment expenses to sales revenue	Zhang et al. (2022)
Supply chain efficiency (SCE)	Negative value of the natural logarithm of firm's inventory turnover period	He et al. (2024)
Firm age	The age of a firm in a given year	Yu et al. (2024), and Zhang et al. (2025)
Firm size	Natural logarithm of total assets	
Number of employees	Natural logarithm of total number of employees	
Ownership type	1 = state-owned enterprise, 0 = otherwise	
Shareholding concentration	Sum of the top 10 shareholders' ownership ratios	
CEO duality	1 = chairman also serves as CEO, 0 = otherwise	
Leverage ratio	Ratio of total debt to total assets	

In Equations 2, 3, Cog and Reg denote contractual governance and relational governance, respectively, the other variables remain consistent with those defined in Equation 1.

Results

Descriptive statistics and correlation analysis

Table 2 shows the descriptive statistics and correlation analysis for the key variables. The DT exhibits a mean of 0.067 with a standard deviation of 0.085, indicating significant difference in digitalization level across Chinese agricultural firms. SCE is significantly correlated with DT, contractual governance, and relational governance, offering initial evidence for their postulated relationships. Furthermore, the absolute values of all correlation coefficients are below 0.5 and all variance inflation factors (VIF) are below 5, indicating that multicollinearity does not pose a threat to the validity of our regression results.

Baseline results: impact of DT on SCE

Table 3 presents the baseline regression results for the DT-SCE relationship. Column (1) controls for individual-fixed. The coefficients of DT and DT² are -0.801 and 2.803 , respectively, and both are statistically significant. This provides initial evidence of a significant U-shaped relationship between DT and SCE in agricultural enterprises. To address potential omitted variable bias, Column (2) introduces a set of control variables to the baseline specifications. Column (3) further includes both control variables and time-fixed effects. Across all specifications, the coefficients of DT² remain positive and significant at the 1% level ($\beta = 3.280, p < 0.01$; $\beta = 3.449, p < 0.01$). These results confirm the high robustness of U-shaped DT-SCE relationship and offer strong empirical support for H1. The findings reveal a 'double-edged sword' effect of DT in the agricultural sector. Specifically, when the level of DT is below a certain threshold, its impact on SCE is negative. However, once DT surpasses this critical threshold, it begins to enhance SCE.

Endogeneity test

- (1) Instrumental variable method. As SCE is a key indicator of operational strength, the DT-SCE relationship may pose endogeneity concerns due to potential reverse causality. To mitigate this issue, an instrumental variable for DT, defined as the average DT value of other firms within the same industry and region (excluding the focal firm), is employed following Guo et al. (2023). The validity of the instrumental variable is supported by diagnostic tests. The Kleibergen-Paap rk LM statistics is significant at the 1% level, indicating that the model is not underidentified. Additionally, the Crag-Donald Wald F statistics exceeds the critical value of the Stock-Yogo weak identification test at the 10% level, suggesting that the instrument is sufficiently strong. These results confirm the appropriateness and relevance of the selected instruments. As

shown in Column (1) of Table 4, the coefficients of DT² remain significantly positive ($\beta = 7.498, p < 0.05$) when using instrumental variable estimation. This finding reinforces the earlier conclusion of the U-shaped DT-SCE relationship and confirms the robustness of the results after accounting for potential endogeneity.

- (2) Propensity score matching method. Given the potential self-selection bias in firms' adoption of DT, the Propensity score matching method is employed to mitigate possible endogeneity and sample selection issues in analyzing DT-SCE relationship. Specifically, firms are classified into high and low DT groups by the sample median. Nearest-neighbor matching ($k = 3$) is used to create a matched sample. The matching quality is validated by a balance test. The results indicate that the absolute values of the standardized biases for all covariates are below 10%, and the p -values of the t -tests are greater than 0.1. This confirms that the balance test is satisfied, with no significant differences between the treatment and control groups after matching. The matched sample is thus valid. We re-estimate our model using the matched sample of 1,053 firms. The results in Column (2) of Table 4 show a positive and significant coefficient for DT² ($\beta = 3.101, p < 0.10$). This supports Hypothesis 1. Furthermore, this study employs radius matching (caliper = 0.05) and kernel density matching methods to obtain matched samples for regression analysis. The results, presented in Columns (3) and (4) of Table 4, remain consistent with our baseline findings ($\beta = 3.509, p < 0.01$; $\beta = 3.499, p < 0.01$). This robustness reinforces the evidence for a U-shaped relationship between DT and SCE relationship.

Robustness tests

The robustness of results was verified through two key tests. First, given the unbalanced and short-panel nature of the dataset, a pooled OLS regression model is employed as a robustness test. As reported in Column (5) of Table 4, the coefficient of DT² remains significantly positive ($\beta = 4.527, p < 0.10$), confirming the persistence of a U-shape relationship between DT and SCE. The findings underscore the robustness and reliability of the main conclusion. Second, to mitigate potential distortions from the COVID-19 pandemic on supply chains, robustness checks were conducted using two alternative sample periods: the pre-pandemic period (2012–2019) and a full-period sample that excludes the peak pandemic years (2012–2019 and 2023–2024). The results, presented in Columns (6) and (7) of Table 4 respectively, indicate that the significance and the sign of DT² coefficients remain consistent with the baseline findings ($\beta = 5.374, p < 0.01$; $\beta = 3.719, p < 0.05$). This stability across these temporal specifications confirms the robustness of our main results.

Analysis of moderating effect of governance mechanisms

Table 5 presents the results concerning the moderating roles of contractual and relational governance in the DT-SCE relationship. The interaction term between contractual governance and DT² is significantly negative ($\beta = -0.425, p < 0.01$). This suggests that

TABLE 2 Descriptive statistics and correlation analysis of variables.

No.	Variable	Mean	Std. Dev	Min	Max	1	2	3	4	5	6	7	8	9	10	11
1	Digital transformation (DT)	0.067	0.085	0	0.434	1										
2	Contractual governance	4.009	6.594	0.009	38.300	0.008	1									
3	Relational governance	3.831	3.901	0.197	23.70	0.098***	-0.173***	1								
4	Supply chain efficiency (SCE)	-4.885	1.065	-7.822	-2.906	0.046*	0.252***	-0.224***	1							
5	Firm age	20.330	5.549	7	34	0.093***	0.016	-0.023	-0.103***	1						
6	Firm size	22.190	1.079	20.260	25.830	0.052**	0.082***	-0.353***	-0.092***	0.185***	1					
7	Number of employees	7.827	1.133	5.165	10.820	0.020	0.173***	-0.404***	0.154***	-0.020	0.762***	1				
8	Ownership type	0.367	0.482	0	1	-0.070***	0.090***	-0.297***	-0.224***	0.116***	0.139***	0.105***	1			
9	Shareholding concentration	59.590	15.010	25.320	90	0.079***	0.055*	-0.104***	0.210***	-0.264***	0.091***	0.188***	-0.155***	1		
10	CEO duality	0.327	0.469	0	1	0.088***	-0.042	0.074**	0.139***	-0.078***	-0.129***	-0.047*	-0.368***	0.119***	1	
11	Leverage ratio	0.380	0.195	0.0426	0.963	0.090***	0.159***	-0.209***	0.060**	0.069***	0.214***	0.177***	0.133***	-0.252***	-0.074***	1

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

TABLE 3 Results of digital transformation (DT) on supply chain efficiency (SCE).

Variables	(1)	(2)	(3)
DT	−0.801**	−1.008***	−1.092***
	(−2.510)	(−2.890)	(−3.152)
DT ²	2.083*	3.280***	3.499***
	(1.754)	(2.692)	(2.889)
Firm age		0.018***	−0.100***
		(4.493)	(−2.647)
Firm size		−0.183***	−0.201***
		(−5.313)	(−5.840)
Number of employees		0.124***	0.134***
		(3.558)	(3.855)
Ownership type		−0.056	−0.048
		(−0.935)	(−0.816)
Shareholding concentration		0.003**	0.003**
		(2.239)	(2.105)
CEO duality		−0.068**	−0.066**
		(−2.148)	(−2.096)
Leverage ratio		−0.279***	−0.301***
		(−3.132)	(−3.381)
Cons	−4.846***	−2.153***	−0.146
	(−283.171)	(−3.701)	(−0.183)
Individual-fixed effects	Yes	Yes	Yes
Time-fixed effect			Yes
R ²	0.005	0.044	0.069

t-values in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

contractual governance has a significant negative moderating effect on the U-shaped relationship between DT and SCE. Compared to agricultural enterprises with lower levels of contractual governance, the U-shaped relationship between DT and SCE is weaker in those with higher contractual governance. In other words, an increase in contractual governance attenuates both the early-stage suppression and later-stage enhancement of SCE by DT. Therefore, H2 is not supported. This finding could be attributed to two reasons. Firstly, agricultural business cooperation is often embedded in dense rural social networks, which promote trust-based and flexible collaborations (Zeng and Wan, 2024). These networks enable agricultural enterprises to effectively mitigate the rigidity and limited adaptability of contractual governance in supply chain cooperation. This enhances the cooperative benefits of contractual governance and helps alleviate the early negative impact of low-level DT on SCE. Secondly, high-level DT helps reduce collaboration conflicts and constrain opportunistic behavior. It serves a governance role in promoting supply chain collaboration, forming a functional substitutive relationship with contractual governance. When both DT and contractual governance are at high levels, contractual governance diminishes the marginal effect of DT on enhancing SCE through collaboration promotion. According to the results in Column (2) of Table 5, the interaction term between relational governance and DT² is negative and significant ($\beta = -1.206$, $p < 0.01$). This indicates that relational governance exerts

a significant negative moderating effect on the U-shaped DT–SCE relationship. Specifically, relational governance weakens the influence of DT on SCE, thereby flattening their U-shaped relationship. Thus, H3 is supported. A comparison of the interaction term coefficients reveals that relational governance weakens the U-shaped DT–SCE relationship more than contractual governance. This finding echoes Zeng et al. (2023) regarding the superior role of relational governance in agricultural cooperation. Both contractual and relational governance help agricultural firms manage early DT challenges, such as high investment, slow learning, weak absorptive capacity, and low returns. However, as DT advances, its effect on SCE depends less on either governance mechanism. Mature digital systems enhance information transparency and coordination, thereby promoting supply chain collaboration. They functionally substitute for contractual and relational governance mechanisms.

Further analysis

The advantages and challenges associated with DT and supply chain governance vary significantly across heterogeneous agricultural firms. These variations are likely to influence the relationships among DT, governance mechanisms, and SCE. Consequently, we extend our analytical framework to incorporate internal firm-level attributes and external environmental conditions, exemplified by organizational life cycle and regional business cooperation culture, respectively. This expanded framework helps reveal the contingent effects of DT and governance on SCE across diverse firm and environmental contexts.

(1) *Heterogeneity analysis across organizational life cycle.* Organizational life cycle theory posits that enterprises develop through distinct stages. Each stage has unique attributes, resource endowments, and capabilities. Consequently, firms at different life cycle stages tend to vary in their motivation, resources, and needs for both DT and governance mechanisms. This heterogeneity may lead to varying effects of DT on SCE and result in differential moderating effects of governance mechanisms. Following Anthony and Ramesh (1992), we classify agricultural firms' life cycle stages using a composite index. This index integrates four financial indicators: revenue growth rate, capital expenditure ratio, retained earnings ratio, and firm age. The sample firms are categorized into three life cycle stages—growth, maturity, and decline—to examine heterogeneous effects. Results in Columns (1)–(3) of Table 6 show a significantly positive coefficient for DT² in the growth and decline stage subsamples ($\beta = 8.792$, $p < 0.05$; $\beta = 3.376$, $p < 0.10$), whereas it is statistically insignificant in the maturity stage. Following Cohen et al. (2003) and Zeng et al. (2023), we employ a Z-test to analyze inter-group coefficient difference. The null hypothesis of coefficient equality is rejected at the 5% level if the absolute value of the Z-values exceeds 1.96. As reported in Column (1) of Table 7, in all pairwise comparisons (i.e., growth vs. maturity, maturity vs. decline), the Z-statistics for the difference in the DT² coefficients far exceed 1.96. This confirms that the U-shaped impact of DT on SCE differs significantly across agricultural firms' life cycle stages, with the effect being most pronounced for growth and decline stage firms. Mature agricultural enterprises generally have solid financial resources and strong absorptive capacity. This robust capability base allows them to navigate early DT challenges effectively. Thus, the initial suppressing effect of DT on SCE is likely to be minimal or insignificant in these firms.

TABLE 4 Results of endogeneity and robustness test.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
DT	-1.675**	-1.042**	-1.094***	-1.092***	-1.282***	-1.087**	-0.958**
	(-2.34)	(-2.172)	(-3.152)	(-3.152)	(-3.071)	(-2.235)	(-2.224)
DT ²	7.498**	3.101*	3.509***	3.499***	4.527***	5.374***	3.719**
	(2.05)	(1.793)	(2.891)	(2.889)	(2.679)	(2.917)	(2.379)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R ²	0.509	0.099	0.069	0.069	0.509	0.091	0.062

DT = digital transformation; Z-values are in parentheses in Columns (1), t-values are in parentheses in Columns (2) to (7); only key explanatory variables' results are shown due to space limitations. *p < 0.10, **p < 0.05, ***p < 0.01.

TABLE 5 Results of moderating effect of contractual and relational governance.

Variables	(1)	(2)
DT	-0.459	-0.694
	(-1.062)	(-1.366)
DT ²	0.783	3.012*
	(0.467)	(1.663)
Cog	0.012***	
	(3.782)	
Cog*DT	0.159***	
	(3.152)	
Cog*DT ²	-0.452***	
	(-2.617)	
Reg		-0.027***
		(-4.495)
Reg*DT		0.332***
		(3.811)
Reg*DT ²		-1.206***
		(-3.731)
Control variable	Yes	Yes
Fixed effect	Yes	Yes
R ²	0.079	0.207

DT = digital transformation; Cog = denote contractual governance; Reg = relational governance; t-values in parentheses; only key explanatory variables' results are shown due to space limitations. *p < 0.10, **p < 0.05, ***p < 0.01.

We further investigated whether the moderating effects of contractual and relational governance on the U-shaped DT-SCE relationship are contingent on the organizational life cycle of agricultural firms. As shown in Columns (1) to (3) of Table 8, the interaction terms between the contractual governance and DT² are negative and significant in the subsamples of maturity- and decline-stage firms ($\beta = -1.747, p < 0.01$; $\beta = -0.828, p < 0.05$), but insignificant for growth-stage firms. Columns (2) in Table 7 shows, the Z-values for the coefficient differences of the contract governance-DT² interaction terms are all greater than 2.48, confirming that the differences across life-cycle groups are statistically significant. Together, these findings indicate that the negative moderating effect of contractual governance on the

U-shaped DT-SCE relationship is particularly pronounced in agricultural firms at mature or decline stages. Specifically, for these firms, contractual governance more effectively mitigates the inhibitory effect of low DT levels on SCE, while also more significantly suppressing the promoting effect of high DT levels on SCE. As reported in Columns (4)–(6) of Table 8, the interaction term between the relational governance and DT² is significant negative for agricultural firms in the growth and decline stages, but insignificant for those in the maturity stage. The statistical significance of these inter-group differences is firmly established in Table 7, Column (3), with all Z-values greater than 2.48. Thus, it can be concluded that the negative moderating effect of relational governance on the U-shaped DT-SCE relationship is more pronounced among agricultural enterprises in the growth and decline stage. For mature agricultural enterprises, this non-significance may stem from their well-established formal institutions, substantial resource reserves, profit income, market reputation, and stable supply chain partnerships. These advantages inherently cushion the transformation shock of DT, reducing the reliance on and effectiveness of relational governance as a mitigating mechanism.

(2) *Heterogeneity analysis across regional business cooperation culture.* Drawing on social cognitive theory, regional culture constitutes a critical component of the external institutional environment, shaping the cognitive frameworks and behavioral norms of economic actors. Both DT and relational governance in agricultural enterprises are highly context-dependent. The difficulty of their implementation and the effectiveness of their application may vary across different regional business cooperation cultures. This may result in differences in the DT-SCE relationship and the moderating role of governance mechanisms, across various regional business cooperation cultures. To test this hypothesis, this study draws upon the research of Du et al. (2017) by employing the birthplace of China's traditional 'Top Ten Merchant Guilds' as a proxy for regional business cooperation culture. Based on whether a firm's registered province includes the birthplace of any of these merchant guilds, the sample is divided into two subsamples, regions with stronger and weaker business cooperation cultures—for subgroup analysis. As shown in Columns (4) to (5) of Table 6, the coefficients of DT² are significantly positive in the weak regional business cooperation culture sample ($\beta = 3.614, p < 0.10$). This indicates that the U-shaped effect of DT on SCE is more pronounced among agricultural enterprises located in regions with weak business cooperation culture. A possible explanation lies in the low-trust environment in such regions, which

TABLE 6 Heterogeneity test results of the DT–SCE relationship.

Variables	Organizational life cycle			Regional business cooperation culture	
	(1) Growth stage	(2) Maturity stage	(3) Decline stage	(4) Stronger	(5) Weaker
DT	−2.128***	0.395	−0.726	−0.542	−1.145**
	(−3.031)	(0.449)	(−1.308)	(−1.250)	(−2.215)
DT ²	8.792**	−0.462	3.376*	1.452	3.614*
	(2.514)	(−0.167)	(1.867)	(1.080)	(1.693)
Control Variable	Yes	Yes	Yes	Yes	Yes
Fixed effect	Yes	Yes	Yes	Yes	Yes
R ²	0.168	0.079	0.099	0.170	0.090

DT = digital transformation; SCE = supply chain efficiency; *t*-values in parentheses; only key explanatory variables' results are shown due to space limitations. **p* < 0.10, ***p* < 0.05, ****p* < 0.01.

TABLE 7 The Z-values of the regression coefficient variations.

Variable	DT ²	Cog*DT ²	Reg*DT ²
	(1)	(2)	(3)
Strong vs. weak cooperation culture	25.293	30.079	14.484
Growth vs. maturity stage	42.315	27.044	29.086
Growth vs. decline stage	28.662	14.370	34.654
Maturity vs. decline stage	26.196	24.427	6.075

DT, digital transformation; Cog, contractual governance; Reg, relational governance.

can intensify conflict and uncertainty in the early stages of DT, thereby amplifying its negative impact on SCE. Conversely, as DT implementation matures, its ability to reduce information asymmetry and improve coordination may generate more substantial performance gains in these contexts, thus strengthening its positive effect.

Table 9 presents how the moderating effects of contractual and relational governance on the U-shaped DT–SCE relationship vary by regional business cooperation culture. As shown in Columns (1)~(2), the interaction term between contractual governance and DT² is significantly negative in both stronger and weaker regional business cooperation culture samples, with a larger absolute coefficient in the latter ($\beta = -0.287, p < 0.10; \beta = -0.796, p < 0.005$). Table 7 confirms that the difference between these two coefficients is statistically significant ($Z > 2.58$). Therefore, the negative moderating effect of contractual governance is stronger among agricultural enterprises in regions with lower levels of business cooperation culture. Further evidence from Columns (3)~(4) indicates that the interaction term between relational governance and DT² is significantly negative only for agricultural enterprises in regions with a stronger business collaboration culture. This implies that the suppressive effect of relational governance on the U-shaped DT–SCE relationship is more pronounced where cooperative norms are well-established. In such environments, relational governance more effectively leverages informal institutions like trust, reciprocity, and behavioral flexibility to foster supply chain collaboration. These normative mechanisms help to mitigate the early-stage “pains” of DT and intensify its functional substitution effect of DT on relational governance, thereby weakening the U-shaped DT–SCE relationship. As a result, the U-shaped effect of DT on SCE is notably flattened in these contexts.

Conclusion and discussion

Amid the rapid proliferation of the digital economy and heightened supply chain vulnerabilities in agriculture, understanding the impact of DT on SCE in agricultural enterprises has become increasingly critical. While the positive organizational outcomes of DT at the intra-organizational level are well described in the literature, its potential dark side and paradoxical effects remain underexplored, particularly within the agricultural sector. By integrating perspectives from resource orchestration, transaction cost, and relational exchange theories, this study seeks to explore the non-linear effects of DT on SCE and investigate the moderating role of governance mechanisms. Using a dataset of 1,675 unbalanced panel observations from 222 Chinese agricultural listed companies, the empirical results reveal a significant U-shaped relationship between DT and SCE in agricultural enterprises. Once DT reaches a certain level, the positive effects of digitalization outweigh its negative impacts, leading to a net positive influence on SCE. The U-shaped relationship is more pronounced for agricultural enterprises in the growth or decline stages and those located in regions with weaker business cooperation cultures. Furthermore, both contractual and relational governance play significant negative moderating roles in the U-shaped DT–SCE relationship. Specifically, contractual governance is particularly effective in flattening the U-shaped curve for firms at the maturity or decline stages and those with less regional business collaboration cultures. Relational governance shows a stronger overall attenuating effect, which is most evident for firms in the growth and decline stage or embedded in regions with stronger business cooperation culture. The findings highlight the importance of considering non-linear effects and contextual contingencies in DT research, while offering actionable

TABLE 8 Heterogeneity in the moderating role by organizational life cycle.

Variables	(1) Growth stage	(2) Maturity stage	(3) Decline stage	(4) Growth stage	(5) Maturity stage	(6) Decline stage
DT	-1.088	0.471	-0.713	-1.174	0.974	0.149
	(-1.057)	(0.357)	(-1.061)	(-0.968)	(0.533)	(0.159)
DT ²	2.113	-4.633	3.973	-7.267	0.269	-0.736
	(0.433)	(-0.865)	(1.566)	(-0.664)	(0.042)	(-0.253)
Cog	0.003	0.047***	0.020***			
	(0.296)	(3.672)	(3.682)			
Cog*DT	0.015	0.510***	0.205**			
	(0.105)	(2.720)	(2.568)			
Cog*DT ²	-0.031	-1.747***	-0.828**			
	(-0.038)	(-2.880)	(-2.458)			
Reg				-0.001	-0.022	-0.029***
				(-0.106)	(-0.946)	(-3.634)
Reg*DT				0.920***	0.518	0.297**
				(3.328)	(1.347)	(2.516)
Reg*DT ²				-9.079***	-1.426	-0.745*
				(-2.790)	(-0.888)	(-1.733)
Control variable	Yes	Yes	Yes	Yes		Yes
Fixed effect	Yes	Yes	Yes	Yes		Yes
R ²	0.244	0.189	0.112	0.324	0.246	0.332

DT, digital transformation; Cog, contractual governance; Reg, relational governance; *t*-values in parentheses; only key explanatory variables' results are shown due to space limitations. **p* < 0.10, ***p* < 0.05, ****p* < 0.01.

insights for both managers and policymakers seeking to enhance the return on digital investments in agriculture.

Theoretical implications

This study makes several important theoretical contributions to the existing literature on DT and supply chain management. First, by uncovering the U-shaped DT-SCE relationship, this research enriches the literature on the consequences of DT and extends resource orchestration theory. Most existing studies have focused on the positive linear effects of DT from the perspectives of the resource-based view and dynamic capabilities theory (Zhao et al., 2024; Yin, 2023), while empirical investigation into its dark side remains relatively limited (Li R. et al., 2023). Unlike Liu and Chi (2024) and Liao et al. (2024), who suggest a linear positive effect of DT on SCE in manufacturing firms and Chinese A-share listed companies, our findings indicates a U-shaped DT-SCE relationship in agricultural enterprises. This divergence underscores the unique and serious challenges of DT in agriculture. The dual disadvantage of limited resource endowments and low digital literacy among agricultural operators leads to a core bottleneck in the initial DT phase, manifesting as a long payback period due to high upfront costs, a steep technological learning curve, and slow capacity building. This U-shaped DT-SCE relationship advances understanding of DT's complex consequences and contributes to the literature on the DT paradox. Furthermore, resource orchestration theory emphasizes the critical role of resource structuring, bundling, and leveraging in

enhancing competitive advantage, providing a valuable lens for examining the economic outcomes of DT (Sirmon et al., 2007; Chen et al., 2025). However, prior research has predominantly focused on the benefits of orchestration (Yin, 2023), paying scant attention to its potential inefficiencies and unintended negative consequences. The application of this theoretical lens to understand DT's impact within the specific context of agricultural enterprises remains underexplored. This study employs resource orchestration theory to explore the positive and negative impacts of DT on SCE. On the positive side, we theorize three primary mechanisms: the informational, capability, and diffusion effects mainly arising from the structuring, bundling, and leveraging of digital resources, respectively. Conversely, we delineate corresponding negative pathways, including resource crowding-out during the structuring stage, and coordination failures alongside escalated managerial costs arising from complex bundling and leveraging activities. By doing so, this research responds to calls for extending resource orchestration theory into the digital context (Amit and Han, 2017) and extends resource orchestration theory by considering both the bright and dark sides of resource orchestration in the DT process.

Second, this study advances supply chain management literature by examining how contractual and relational governance mechanisms shape the U-shaped DT-SCE relationship. While numerous studies have examined the effects of contractual and relational governance on supply chain performance, findings remain inconsistent due to varying theoretical models and contextual factors (Cao and Lumineau, 2015; Keller et al., 2021). In contrast, Limited attention has been paid to how these governance mechanisms influence the effectiveness of

TABLE 9 Heterogeneity in the moderating role by regional business cooperation culture.

Variables	(1) Stronger	(2) Weaker	(3) Stronger	(4) Weaker
DT	0.316 (0.523)	-0.704 (-1.163)	-1.872*** (-3.468)	1.286 (1.414)
DT ²	-0.246 (-0.115)	0.252 (0.102)	8.107*** (4.442)	-5.533 (-1.231)
Cog	0.006* (1.704)	0.019*** (3.456)		
Cog*DT	0.109** (2.085)	0.246*** (2.749)		
Cog*DT ²	-0.287* (-1.669)	-0.796** (-2.129)		
Reg			-0.017** (-2.089)	-0.030*** (-3.176)
Reg*DT			0.425*** (3.929)	0.196 (1.252)
Reg*DT ²			-1.920*** (-5.290)	-0.997 (-0.847)
Control variable	Yes	Yes	Yes	Yes
Fixed effect	Yes	Yes	Yes	Yes
R ²	0.215	0.101	0.407	0.202

DT, digital transformation; Cog, contractual governance; Reg, relational governance; *t*-values in parentheses; only key explanatory variables' results are shown due to space limitations; **p* < 0.10, ***p* < 0.05, ****p* < 0.01.

DT. Given this fact, this study investigates the moderating roles of contractual and relational governance in the DT–SCE relationship within the agricultural companies. The results indicate that both contractual and relational governance significantly weaken the U-shaped impact of DT on SCE, with the effect of relational governance being more pronounced. This finding aligns with the view that governance effectiveness is context-dependent (Jap and Anderson, 2003; Lu et al., 2015) and corroborates earlier evidence that relational governance yields stronger governance effects than contractual governance in the context of Chinese agricultural supply chains (Zeng et al., 2023). Furthermore, when the level of enterprise DT is high, contractual and relational governance mechanisms tend to inhibit the positive effect of DT on SCE. This suggests that a high level of DT likely exerts effective governance functions, thereby creating a substitutive effect on both contractual and relational governance. This finding echoes earlier studies that blockchains, by functioning as a governance mechanism within and across organizations, could substitute contractual and relational governance mechanisms to some extent (Lumineau et al., 2021). Overall, this study contributes to a deeper understanding of the application of contractual and relational governance in the digital age and enriches supply chain management literature.

Third, this study offers new insights into how agricultural enterprises can effectively leverage DT and governance mechanisms to better improve SCE by incorporating enterprise life cycle stages and regional institutional contexts as boundary conditions. While

existing research has extensively explored the economic outcomes of corporate DT, little attention has been paid to examining these outcomes from the perspective of SCE (He et al., 2024; Liao et al., 2024). This gap is particularly evident in the agricultural sector. This study extends the SCE literature by empirically revealing the U-shaped impact of DT on SCE in the context of agricultural enterprises. Considering the context-dependent characteristics of DT and governance mechanism (Li R. et al., 2023; Lu et al., 2015), we further develop a framework that integrates internal and external contextual factors to elucidate the boundary conditions under which DT affects SCE through contractual and relational governance. The results show that the DT–SCE relationship and the moderating role of contractual and relational governance vary across the enterprise lifecycle and regional business cooperation culture. This variation underscores the importance of embedding DT research within broader socio-institutional frameworks, responding to calls for greater attention to contextual factors in supply chain management scholarship (Belhadi et al., 2024). These findings contribute to deepening our understanding of how agricultural enterprises can effectively use DT to enhance SCE in a particular context.

Managerial implications

Drawing upon the above findings, this research provides a set of actionable managerial implications. First, given the significant U-shaped relationship between DT and SCE, agricultural enterprises should attach importance to the double-edged sword impact of DT on SCE, and take full use of its enabling benefits. Agricultural enterprises should not be put off by the DT's 'pain period'. They should promote DT appropriately based on internal and external characteristics such as organizational development stage and regional business cooperation culture, and maximize the benefits of DT by capitalizing on their strengths and avoiding their weaknesses. Simultaneously, enterprises should actively and patiently deal with the DT's 'pain period' to boost SCE as soon as possible. Second, both contractual and relational governance exert a significant negative moderating effect on the U-shaped DT–SCE relationship. Agricultural enterprises should align proper contractual and relational governance mechanisms with their DT maturity levels in order to effectively improve SCE. Agricultural enterprises with lesser levels of DT can strengthen contractual and relational governance to mitigate the 'pain period' of DT on SCE. For organizations with a higher level of DT, contractual and relational governance can be moderately decreased in order to reduce their functional substitution effects for DT, thus lowering supply chain governance costs. The benefits of such adaptive adjustments are particularly pronounced for agricultural enterprises in the decline stage. Third, considering that the moderating effects of contractual and relational governance on the DT–SCE relationship vary across corporate life cycles and regional business cooperation cultures, the government should pay attention to the establishment and improvement of a precisely oriented, differentiated and dynamic incentive policy system for the DT of agricultural enterprises. They should focus on providing more assistance and encouragement to agricultural enterprises in the growth and decline stages of development, as well as in the early stages of DT. Furthermore, the government should assist and guide agricultural enterprises to effectively mitigate and eliminate the DT's 'pain period', as well as better leveraging DT to increase SCE.

Limitations and future research

This study has several limitations that suggest avenues for future research. First, the sample is limited to Chinese agricultural listed companies, which may constrain the generalizability of findings to other geographical contexts or enterprise types. Future research should examine whether the U-shaped DT–SCE relationship holds across different national institutional environments and among small and medium-sized agricultural enterprises. Second, the measurement of DT relies on textual analysis of annual reports, which may not fully capture the multidimensional nature of digitalization. Future research could incorporate primary survey data to delineate specific types of DT and employ more granular metrics. This would allow for a finer-grained analysis of how different types of DT affect SCE. Finally, exploring additional moderating mechanisms, such as organizational culture, top management team characteristics, and supply chain network structures, would further enrich our understanding of the boundary conditions governing the DT–SCE relationship.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

LZ: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Software, Supervision, Writing – original draft, Writing – review & editing. JuW: Conceptualization, Formal analysis, Resources, Software, Supervision, Validation, Writing – review & editing. LC: Formal analysis, Writing – review & editing. JiW: Formal analysis, Methodology, Validation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Correction note

A correction has been made to this article. Details can be found at: [10.3389/fsufs.2026.1815204](https://doi.org/10.3389/fsufs.2026.1815204).

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