How does supply chain concentration influence the digital transformation-collaborative innovation nexus in the Chinese textile industry?

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ABSTRACT – REZUMAT

How does supply chain concentration influence the digital transformation-collaborative innovation nexus in the Chinese textile industry?

Supply chain concentration, defined as the reliance on a few customers and suppliers, presents both opportunities and risks for firms, particularly when seeking to drive innovation through digital transformation. In the Chinese textile industry, this supply chain concentration could either facilitate or hinder the effectiveness of digital strategies designed to promote collaborative innovation. Realising the economic significance of the Chinese textile industry, this study explains how supply chain concentration influences the relationship between digital transformation and collaborative innovation in the Chinese textile sector. Using data of 942 A-share listed textile firms in China, this study reveals a robust positive relationship between digital transformation and collaborative innovation, demonstrating that digital strategies have the potential to foster innovation in the sector. To address potential endogeneity concerns, we further validate this finding using the two-stage least squares (2SLS) regression model. However, the study uncovers that textile companies operating within highly concentrated supply chains face constraints that prevent them from fully leveraging digital transformation for collaborative innovation. Furthermore, heterogeneity analysis shows that industry-specific factors, such as pollution levels, and firm characteristics, including firm size (FS), significantly moderate this relationship. These findings suggest that policymakers should focus on improving digital infrastructure, promoting financial inclusion, and diversifying supply chains to enable textile firms to more effectively utilise digital transformation for driving collaborative innovation.

Keywords: *digital transformation, collaborative innovation, supply chain concentration*

Cum influențează concentrarea lanțului de aprovizionare legătura dintre transformarea digitală și inovarea colaborativă în industria textilă din China?

Concentrarea lanțului de aprovizionare, definită ca dependența de un număr redus de clienți și furnizori, prezintă atât oportunități, cât și riscuri pentru întreprinderi, în special atunci când acestea urmăresc să stimuleze inovarea prin transformarea digitală. În industria textilă din China, această concentrare a lanțului de aprovizionare ar putea fie să faciliteze, fie să împiedice eficacitatea strategiilor digitale menite să promoveze inovarea colaborativă. Având în vedere importanța economică a industriei textile din China, acest studiu explică modul în care concentrarea lanțului de aprovizionare influențează relația dintre transformarea digitală și inovarea colaborativă în sectorul textil din China. Folosind date de la 942 de întreprinderi textile listate pe piața de acțiuni de tip A din China, acest studiu relevă o relație pozitivă puternică între transformarea digitală și inovarea colaborativă, demonstrând că strategiile digitale au potențialul de a stimula inovarea în acest sector. Pentru a aborda potențialele preocupări legate de endogenitate, a fost validată în continuare această constatare, folosind modelul de regresie cu cele mai mici pătrate în două etape (2SLS). Cu toate acestea, studiul relevă faptul că întreprinderile textile care își desfășoară activitatea în cadrul unor lanțuri de aprovizionare puternic concentrate se confruntă cu constrângeri care le împiedică să valorifice pe deplin transformarea digitală în scopul inovării colaborative. În plus, analiza eterogenității arată că factorii specifici industriei, precum nivelurile de poluare, și caracteristicile întreprinderilor, inclusiv dimensiunea întreprinderii (FS), moderează în mod semnificativ această relație. Aceste concluzii sugerează că factorii de decizie ar trebui să se concentreze pe îmbunătățirea infrastructurii digitale, promovarea incluziunii financiare și diversificarea lanțurilor de aprovizionare, pentru a permite întreprinderilor din sectorul textil să utilizeze mai eficient transformarea digitală în vederea stimulării inovării colaborative.

Cuvinte-cheie*: transformare digitală, inovare colaborativă, concentrarea lanțului de aprovizionare*

INTRODUCTION

Digital transformation has emerged as a cornerstone of the modern world's economic strategy, driving an unprecedented growth of various sectors. China's digital economy accounts for 41.5% of its GDP, reaching a valuation of $7.1 trillions, with enterprises increasingly adopting the technological solutions of artificial intelligence, Internet of Things (IoT), cloud computing, and blockchain to foster operational excellence [1]. The "Broadband China" initiative, launched by the Chinese government in 2014, accelerated China's digital infrastructure investments across various sectors and enabled a cross-regional collaboration and innovation among enterprises [2].

Such investments allowed enterprises to reduce their transaction costs and facilitate real-time data sharing, thus positioning China as a global lead of digital adoption. Researchers argue that enterprises can foster their resilience by boosting market performance through process and product innovation [3]. Consequently, innovations within supply chain networks emerged as a strategic solution for businesses to address both internal and external environmental shifts [4]. As more companies are involved in these innovations, the collaborative networks become more transparent and effective to enable faster decision-making that further helps in adapting to the disruptions and extending the capacity to manage external shocks and risks [5]. During the uncertain times, supply chain innovations allow collaborative networks to rapidly recover by dynamically adjusting their resources, processes, and structures. Therefore, we can claim that collaborative innovation has emerged as a key solution for enterprises to boost their resilience and strengthen their antifragility within collaborative networks [6]. Despite significant progress, Chinese textile enterprises face systemic challenges to leverage digital transformation for collaborative innovations. Essential technologies that support digital transformation remain insufficient [7, 8]. First, High transaction costs, knowledge barriers, and a mismatch of business philosophies hinder cross-regional collaborations, particularly among the small and medium-sized enterprises (SMEs) [7]. Second, the uneven distribution of resources and power creates friction in supply chain collaborations [9]. Third, information overloading from excessive digitalisation risks overwhelming firms, stifling the innovation efficacy of enterprises. Fourth, the structural rigidity in a concentrated supply chain limits the adaptability, as firms are heavily relying on a few partners [10]. Lastly, conflicts of interest and misaligned incentives among supply chain partners impede collaborative innovations. The rapid pace of technological development has exacerbated these issues, which require an agile response that many Chinese firms are struggling to execute [11]. This necessitates an urgent need to identify effective strategies that may help enterprises to achieve effective outcomes from supply chain collaborative networks. However, the lack of standardised digital protocols across industries complicates data sharing, while cybersecurity concerns limit firms from being fully involved in collaborative platforms [12]. Further, regional differences also undermine the trust and cooperation between enterprises, such as firms in Eastern China, with access to advanced digital infrastructure, may hesitate to collaborate with Western China enterprises. These barriers collectively constrain the potential of digital transformation to drive innovation, emphasising the need for strategic interventions to foster a more collaborative ecosystem. Addressing these challenges could be possible through unlocking the full potential of digital transformation.

The rapid advancement and application of cutting-edge information technologies amplify digital empowerment, which plays a crucial role in driving collaborative innovation in the supply chain of textile enterprises. Digitalisation offers essential strategic resources such as data [13], digital platforms [9], and digital thinking frameworks [14] to support supply chain collaborative innovations. Previous studies show that digitalisation fosters automation and intelligence [15], lowers innovation costs [16], and stimulates employees' innovative capacity [14], thereby improving the overall collaborative innovation capabilities and effectiveness. The success of digitalisation can be demonstrated in various business contexts, such as JingDong (JD) automated almost 95% of its inventory processes through a network of digital alliances with various suppliers. Similarly, Nike reduces its labour costs by 50% and raw materials' costs by 20% by leveraging its manufacturers' digital procurement systems. Silva and Gomes [17] find that real-time analytics platforms allowed firms to shorten their R&D cycles by 30%. Digital strategies promote innovative ecosystems, where firms utilise resources through collaborations and mitigate their potential risks [18]. Institutionalising digital workflows allows firms to transcend geographical and organisational boundaries and create a synergistic innovation network. Based on these views, it can be argued that digital transformation unlocks new opportunities for collaborative innovation and drives sustainable growth and competitiveness.

Supply chain concentration (SCC) – relying on a limited number of suppliers/customers – can significantly moderate the nexus of digital transformation with collaborative innovation within the Chinese textile industry. Highly concentrated supply chains benefit from deeper integration, as repeated interactions foster trust and knowledge codification [19]. Using digital tools for co-design enabled a concentrated supplier network of Toyota for rapid prototyping [20]. Conversely, overly concentrated supply chain risks rigidity, as over-reliance on fewer partners can expose the organisation to diverse ideas and business philosophies [10]. Digital platforms can mitigate the supply chain concentration's negative effects by presenting a transparent look at interactions, and thus enabling firms to engage niche suppliers without physical proximity. In this way, supply chain concentration's impact hinges on how firms orchestrate digital tools to optimise partner diversity and depth [21]. For example, firms with moderated supply chain concentration can leverage digital tools to diversify their supplier base while maintaining a strong relationship with key partners, and thus promoting innovation and resilience [22]. Additionally, supply chain concentration influences the distribution of digital resources, with a concentrated supply chain often prioritising investments in core partners, potentially marginalising the smaller players. However, digitalisation can democratize access to resources, ensuring that all partners are equally benefiting from innovative initiatives. This dynamic interplay between supply chain

concentration and digital transformation necessitates the importance of strategic partner management to maximise innovative outcomes.

In this context, the rapid growth of the digital economy presents a crucial framework to guide enterprises to enhance supply chain collaborative innovation through digital transformation, and supply chain concentration may influence the digital transformation – innovative nexus. This study aims to examine the nexus between digital transformation, supply chain collaborative innovation, and the moderating role of supply chain concentration. These are the specific research questions answered by this study:

RQ1: How does digital transformation influence the supply chain collaborative innovation in Chinese textile enterprises?

RQ12: How does supply chain concentration (SCC) moderate the nexus between digital transformation and supply chain collaborative innovations?

The remainder of the paper is structured as follows: 2nd section provides a review of relevant literature on key aspects and develops hypotheses; 3rd section outlines research methodology and data; 4th section covers results and discussion of empirical tests, 5th section concludes the paper with theoretical and practical implications.

LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

Digital transformation involves leveraging digital technologies to transform and extend an organisation's business model to alter the value creation capacity of the organisation [23]. This transformation includes corporate strategy, organisational structure, business processes, human resources, and product offerings, all aimed at adapting to dynamic changes in the business environment of an organisation [24]. Some researchers consider digital transformation as a single-dimensional concept [25], while others involve both breadth and depth [15, 26]. Additionally, some scholars focused on specific dimensions of digital transformation, such as capability and strategy. Proksch and Rosin [27] argue that digital strategy significantly influences the digitalisation process of new ventures, and Khin and Ho [28] show that digital capabilities influence corporate performance.

On a global scale, digital strategy catalyses to guide digital transformation and aid firms to integrate, coordinate, and allocate digital resources more effectively [29]. Hess and Matt [30], from a collaboration and integration perspective, state that digital strategy serves as the organisational blueprint which is created and executed to deliver differentiated value by using various digital resources. Managers may use digital technologies for streamlining the operational models both pre- and post-transformation, promoting deeper interactions with customers, suppliers, and competitors. In the face of disruptions, managers are required to establish and execute digital strategies to optimise the company's operational excellence. Digital capability sets the foundation of digital transformation and enables businesses to sense and respond to customers' needs, and also creates a mutually beneficial situation for both companies and their key partners [31].

Supply chain (SC) collaborative innovation is defined as the process of joint research, development, and introduction of new products, services, and processes with partners to boost enterprise competitiveness [32]. This approach helps enterprises enhance innovation capabilities by sharing knowledge with external partners, such as suppliers, customers, competitors, and research organisations [23]. SC collaborative innovation has been widely adopted by companies, with applications in joint procurement, marketing cooperation, and research and development (R&D). This collaboration enables organisations to better handle future crises, significantly improving SC resilience and antifragility.

Supply chain collaboration can be categorised in several way. First, it may be based on the participants involved in a collaborative network, such as suppliers, competitors, customers, and research institutes. Second, supply chain collaborative innovations can be categorised into incremental or radical innovations, depending on the innovative intensity [33]. Third, it can be viewed from the content of innovation, such as a process, product, or management innovation [34]. This study considers collaborative innovation from the perspective of jointly gained patents by Chinese companies through partnerships with suppliers and customers [17, 35]. This perspective involves sharing of technical information and resources with supply chain partners to enhance design, research and development, production, and sales methods. There can be collaboration with suppliers and customers to introduce new products, enter new markets, and diversify the product portfolio to meet the changing customer demands.

Getting basis from strategic choice, it is argued that a company's business strategy must align with the dynamic external environment to remain competitive in the industry. As digitalisation becomes a key business strategy, digital strategy reflects a company's approach of inclusiveness, innovation, growth, and change. Organisations with digital strategies, when compared to those without them, tend to foster entrepreneurial thinking among employees, and enhance their performance to promote process innovation [36]. Ferreira and Fernandes [14] state that digital strategy formulation and execution reflect a company's openness and progressive culture, and inspire employees to innovate and broaden their thinking. Additionally, Matt and Hess [29] indicate that executing a digital strategy leads companies to prioritise process improvement and innovation of digital and emerging technologies within business processes.

Furthermore, digital strategies allow companies to strengthen their connections with other enterprises, supply chain members, and become more exposed to the market. The data gathered from these connections allows managers to create the foundation for

collaborative innovations in supply chain networks [37]. For example, Several Chinese textile companies have successfully adopted digital transformation strategies. For instance, Shenzhou International Group, a leading Chinese textile manufacturer, significantly enhanced its operational efficiency by integrating smart manufacturing processes. Similarly, Youngor Group introduced digital design systems that substantially shortened their production cycles and improved market responsiveness. Lee et al. [38] Highlight how data resources can help enterprises to accurately predict market demand changes, thereby empowering responsive and efficient supply chain collaborative innovations. Similarly, Kwak and Seo [39] state that digital strategies help companies to undertake differentiated product innovations based on market insights.

The nexus between digital transformation and supply chain collaborative innovation can be viewed through the lenses of resource-based view and dynamic capabilities theory. The resource-based view argues that digital transformation equips enterprises with unique capabilities such as data analytics, cloud computing, IoT integration, AI, and others, for reconfiguring the SC resources for innovation [31]. These capabilities allow companies to develop a digital infrastructure that further reduces search coordination costs, and enable firms to externalise R&D costs [2, 40]. On the other hand, the dynamic capabilities theory states that digital tools promote absorptive capacity and thus allow enterprises to assimilate external knowledge [41].

For instance, JD.com's AI-driven inventory system allowed the company to automate supplier communication and helped to cut lead times by 40% [42]. In the textile sector, Jiangsu Sunshine Group, a prominent Chinese textile company, implemented advanced digital analytics and IoT solutions, significantly increasing its collaboration with suppliers and enhancing product innovation. This case exemplifies how digital transformation can actively drive collaborative innovation in China's textile industry. This theory and discussion collectively portray digital transformation as a key solution to establish an open innovation ecosystem. By investing in digital training programs and fostering an innovative culture, firms could be better positioned to leverage digital tools for collaborative R&D. Together, these empirical findings and theoretical frameworks provide a comprehensive understanding of how digital transformation can influence collaborative innovation, and based on this understanding, we can propose this hypothesis:

H1: Digital transformation fosters collaborative innovation in a supply chain network of Textile enterprises.

Supply chain concentration leads the firms to rely on a limited number of suppliers to source the materials/inputs and to sell the final products/outputs to a limited number of customers. This concentration can lead enterprises to leverage digital technologies to foster collaborative innovations. Empirical studies present the dual impact of supply chain concentration to foster or hinder the relationship with key business partners. Tian and Lu [2] show that relying on fewer suppliers/customers can foster collaborative innovations within enterprises as they have balanced integration with flexibility. On the other hand, overreliance on suppliers/customers can exhibit rigidity as digital investments yield diminishing returns due to limited exposure to diverse ideas and business philosophies [21]. In the case of Huafang Textile Co., Ltd, it is found that a decentralised supplier base allows this company to have enhanced control over the business processes [32]. These findings present an inverted U-shaped nexus, where optimal supply chain concentration promotes integration and flexibility. Firms that maintain a close relationship with a few trusted partners to get routine materials and engage suppliers for specialised materials can achieve stability and innovation. This approach is found to be highly effective in industries where technological uncertainty is high, as firms are required to continuously adapt to emerging trends. Firms with excessive levels of supply chain concentration face challenges in adapting to market shifts because of their reliance on a few dominant partners [9]. Additionally, studies show that moderate supply chain concentration can enable firms to collaborate with startups and research institutions, and thus drive breakthrough innovation in solar and wind technologies [43].

The moderating role of supply chain concentration to influence the nexus of digital transformation with collaborative innovation can be explained through the lens of contingency theory. This theory posits that supply chain concentration has a varying impact, depending on the environmental dynamics. In a stable market environment, high supply chain concentration promotes trust and coordination, thereby amplifying the efficiency gains of digital tools [19]. Firms with concentrated suppliers' networks can benefit from streamlined communications and shared technological standards, thus facilitating the rapid prototyping and co-development of products and services [44]. Conversely, in volatile sectors, low supply chain concentration enables firms to pivot while using digital platforms for engaging with a broader range of partners [45].

Resource dependency theory argues that supply chain concentration determines firms' power of negotiation for data-sharing terms and thus affects innovation equity [46]. For example, Huafu Top Dyed Melange Yarn Co., Ltd., and Jiangsu Sunshine Co., Ltd, have the overall control on their resources to shift toward the radical innovations in their processes. They collaborate with their partner firms to exchange resources and achieve the potential business goals [47]. These theoretical perspectives present the potential role of supply chain concentration to shape digital transformation's outcomes toward innovation. Firms are required to balance the benefits of deep integration with the need for flexibility while adapting to market trends. In highly regulated industries, concentrated supply chains can prioritise compliance over innovation, whereas in tech-driven

sectors, decentralised networks can foster agility and creativity. Thus, supply chain concentration can be contingent on both market conditions and industry-specific factors, and thus underscores the importance of strategic partner management to maximise digital transformation benefits. Based on these views, we can propose this hypothesis:

H2: Supply chain concentration influences the nexus between digital transformation and collaborative innovation in the supply chain network of textile enterprises.

METHODOLOGY

Data and sample

The initial sample of this study comprises all A-share textile enterprises of China listed on the Shenzhen and Shanghai Stock Exchanges. The data we collected includes supply chain concentration, financial, and digital transformation of these enterprises for the period of 2011–2022. First, we removed those having spatial or partial treatment in any of the sample years; second, we excluded the firms having missing data for any of the variables for the sample duration; Last, we normalised the sample as per 1% and 99% distribution. The final sample of this study is an unbalanced panel data set of 942 textile firms. The firms studied vary considerably in terms of size, strategies, and digital maturity. Among the sampled companies, approximately 30% are large-sized enterprises with substantial resources dedicated to digital transformation and innovation, around 50% are medium-sized enterprises gradually adopting digital technologies, and roughly 20% are small enterprises at the early stages of digital adoption. Strategies ranged from complete automation and intelligent manufacturing adopted by larger firms to basic digital tools and incremental process enhancements used by smaller companies. The sample is finalised based on the data availability of all variables of the study. While the sampled textile companies share industry-level similarities, variations exist in automation levels, equipment modernity, employee training, and business strategies. Large enterprises typically possess advanced automation systems and extensive training programs, contrasting with smaller firms that rely on manual processes and limited formal training. This heterogeneity is controlled for in our analysis using firm size and growth as control variables. Data on financial, supply chain, and digital transformation is obtained from the China Stock Market and Accounting Research (CSMAR) database. Additional data, such as provincial internet penetration and regional economic growth, is sourced from Chinese Statistical Yearbooks.

Variable selection

Dependent variable: Collaborative Innovation (INOV)
This study uses the natural logarithm of the total number of joint patents obtained by the enterprises within a supply chain network. The calculation is performed by getting the data of joint patents from the CNRDS database. A joint patent is considered a collaborative innovation effort where enterprises engage with their suppliers and customers to promote joint inventions.

Independent variable: Digital transformation
In this study, corporate digital transformation serves as the independent variable, primarily measured by the frequency of digitisation-related terms appearing in the firms' annual reports [48–50]. A similar method is applied by the CSMAR database, and it measures a firm's digital transformation by considering the words relevant to strategic leadership score (SL), technology-driven score (TD), organisational empowerment score (OE), environmental support (ES), digital achievement score (DAC) and digital application score (DAP). This study uses the digital transformation index, provided by CSMAR, for empirical analysis, which is measured as:

$$DigiT_{i,t} = (0.3472 * SL_{i,t}) + (0.162 * TD_{i,t}) + \\ + (0.0969 * OE_{i,t}) + (0.0342 * ES_{i,t}) + \\ + (0.0884 * DAC_{i,t}) + (0.0884 * DAP_{i,t}) \quad (1)$$

where $DigiT_{i,t}$ denotes firm *i*'s digital transformation index in year *t*. $SL_{i,t}$, $TD_{i,t}$, $OE_{i,t}$, $ES_{i,t}$, $DAC_{i,t}$ and $DAP_{i,t}$ represent the firm's strategic leadership score, technology-driven score, organisational empowerment score, environmental support score, digital achievement score, and digital application score, respectively, in year *t*.

Moderating variable: Supply chain concentration
This study uses two primary measures to detect the supply chain concentration's extent [51, 52]. Customer concentration (*CustConc*) is measured as the sum of sales to the five largest customers divided by the total sales of the enterprise *i*. Supplier concentration (*SupConc*) is the sum of purchases from the top five suppliers to the total enterprise's purchases. Therefore, we measure *CustConc* and *SupConc* as follows:

$$CustConc_{i,t} = \left(\frac{sales_{i,j,t}}{sales_{i,t}}\right) \quad (2)$$

$$SupConc_{i,t} = \left(\frac{purchases_{i,j,t}}{purchases_{i,t}}\right) \quad (3)$$

where $sales_{i,j,t}$ denotes the firm *i*'s sales to the top five customers *j* at *t* year, and $sales_{i,t}$ represents the firm *i's* total sales in *t* year. $purchases_{i,j,t}$ denotes firm *i*'s purchases from its top five suppliers *j* at *t* year, and $purchases_{i,t}$ indicates the firm *i*'s total purchases in *t* year. Hence, our study is considering supply chain concentration, so it will comprise both customer concentration (*CustConc*) and supplier concentration (*SupConc*), and take the average of both. So, the formula for supply chain concentration for firm *i* in year *t* will be as follows:

$$SC_{i,t} = (CustConc_{i,t} + SupConc_{i,t})/2 \quad (4)$$

where $SC_{i,t}$ denotes the firm's supply chain concentration of firm *i* in year *t*. Hence, the higher the value of $SC_{i,t}$, *the* higher the supply chain concentration.

Table 1

VARIABLES DEFINITIONS			
Variable type	**Variable name**	**Symbol**	**Variable description**
Explained variable	Collaborative innovation	INOV	The logarithm of the total number of jointly obtained patents.
Independent variable	Firm's digital transformation	DIG	Digital transformation is measured as the digitalisation-related words appearing in annual reports of Chinese manufacturing firms.
Moderator	Supply chain concentration	SCC	Measured as the average of the sum of supplier and customer concentration.
Firm level – Control variables	Firm size	Size	The log of the total assets of the firm.
	Firm growth	Growth	The growth ratio of the total assets of enterprises.
	Financial leverage	FL	The ratio of total liabilities to total assets.
	Firm profitability	-	Return on assets ratio.
	Debt to equity	D/E	Total liabilities to total owners' equity.
Regional level – Control variables	Regional economic development	GDP	The natural logarithm of GDP per capita.
	Financial development level	FIN	The sum of deposits and loans as a proportion of GDP.

Control variables

Following prior work [7, 53], we employ control variables that influence the collaborative innovation of enterprises. In our study, we include the variables of firm size (size), Firm growth (growth), Financial leverage (fl), Firm profitability (profit), Debt to equity ratio (D/E), Regional economic growth (GDP), and Provincial financial development level (fin). The definition for each of the variables of this study is given in table 1.

Econometric modeling

Based on hypothesis 1, we framed this econometric model:

$$CINV_{i,t} = \alpha_0 + \alpha_1 DIG_{i,t} + \alpha_2 X_{i,t} + \varepsilon_{i,t} \quad (7)$$

where $CINV_{i,t}$ is the collaborative innovation level of firm i in year t. $DIG_{i,t}$ reflects the digital transformation level of the firm i in year t. X is the list of control variables, α represents the coefficient value and ε denotes error term.

Further, we examine the Moderating role of supply chain concentration to influence the nexus between digital transformation and collaborative innovation. For state purposes, we introduce SCC in the baseline empirical model and frame the next model. In the next phase, we introduced supply chain concentration (*SCC*) as the Moderating variable to check the Moderating effects of supply chain concentration:

$$SCC_{i,t} = \alpha_0 + \alpha_1 DIG_{i,t} + \alpha_2 X_{i,t} + \varepsilon_{i,t} \quad (8)$$

$$CINV_{i,t} = \alpha_0 + \alpha_1 DIG_{i,t} + \alpha_2 DIG * SCC_{i,t} + \alpha_3 X_{i,t} + \varepsilon_{i,t} \quad (9)$$

where $SCC_{i,t}$ represents the supply chain concentration of firm i in year t. $SCC_{i,t}$ denotes the Moderating effect of firm i's supply chain concentration on the nexus of digital transformation and collaborative innovation.

RESULTS AND DISCUSSION

Descriptive statistics

Table 2 reports the descriptive statistics for the explanatory, Moderating, and control variables of this study. As shown in table 2, INOV has a mean value

Table 2

DESCRIPTIVE STATISTICS OF VARIABLES					
Variable	**Obs.**	**Mean**	**Std. Dev.**	**Min**	**Max**
INOV	7,416	1.497168	1.46388	0	9
DIG	7,416	37.42654	10.53028	21.2208	79.8123
SCC	7,416	29.26578	15.59583	0	91.27
Size	7,416	22.71735	1.458046	19.2226	28.63649
Growth	7,416	0.1839429	0.2960165	–0.725322	3.757947
FL	7,416	1.305545	0.8619252	–3.29385	8.459463
Profit	7,416	0.0691573	0.0522442	–0.020147	0.721492
D/E	7,416	1.090671	1.365666	0.030342	32.89984
GDP	7,416	11.3084	0.4358811	9.705829	12.15643
FIN	7,416	7.500966	2.408341	0	9.378038

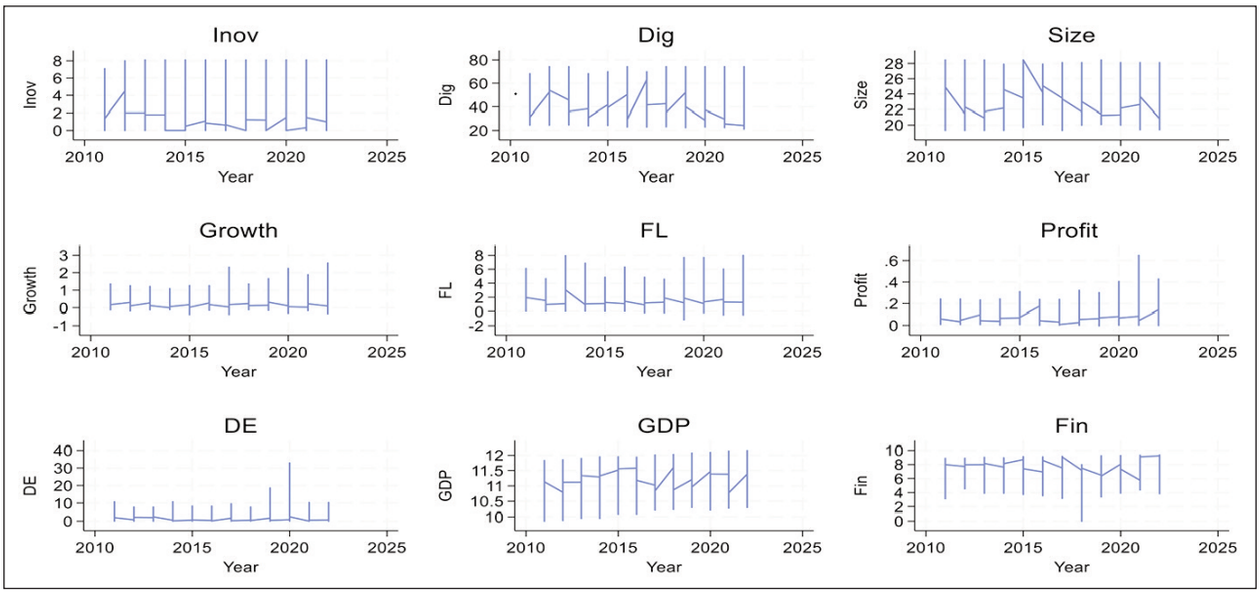

Fig. 1. Variable trends

of 1.4972, indicating the extent to which firms in China have jointly obtained patents or made collaborative innovation efforts. Digital transformation (DIG) has a mean value of 37.4265 with a standard deviation of 10.53028, suggesting that most of the Chinese enterprises are engaged in using digital technologies to gain operational excellence. Supply chain concentration (SCC) reports the mean value of 29.26578, showing the extent to which firms are relying on their major suppliers and customers. Other control variables have shown the normal tendency of the descriptive statistics for the sample period (figure 1).

Pairwise correlation matrix

As per the pairwise correlation matrix results (table 3), DIG shows a positive nexus with INOV, indicated by a correlation coefficient of 0.221. This result implies that an increase in digital transformation of the Chinese listed enterprises results in enhancing the collaborative innovations within supply chain networks. SCC presents a negative coefficient, showing that when firms rely on fewer customers/suppliers, they are likely to compromise on collaborative innovations. They may be influenced by the rigid philosophies and ideas of their partners, and they have to embrace them in their own operations. The nexus between digital transformation (DIG) and supply chain concentration (SCC) is also found to be negative, reflected by a correlation coefficient of –0.114. This indicates that relying on a limited number of customers/suppliers hinders the firms' ability to digitally transform their operations. The correlation values of variables are within an acceptable range and align with prior work [7, 53, 54].

Baseline regression results

The results presented in three columns of table 4 test Hypothesis 1. In column (1), where no fixed effects or control variables are included, the coefficient of DIG is 0.0269, which is highly significant. This suggests a robust positive impact of digital transformation on collaborative innovation within the supply chain network

Table 3

PAIRWISE CORRELATION MATRIX RESULTS

Variable	INOV	DIG	SCC	Size	Growth	FL	Profit	D/E	GDP	FIN
INOV	1.000									
DIG	0.221***	1.000								
SCC	–0.111***	–0.114***	1.000							
Size	0.363***	0.122***	–0.187***	1.000						
Growth	–0.050***	–0.025**	0.082***	–0.117***	1.000					
FL	–0.005	–0.060***	0.005	0.121***	–0.114***	1.000				
Profit	0.016	–0.092***	–0.039***	–0.014	0.187***	–0.213***	1.000			
D/E	0.046***	–0.006	–0.052***	0.341***	–0.076***	0.369***	–0.220***	1.000		
GDP	0.103***	0.130***	0.085***	0.049***	0.034***	–0.141***	0.039***	–0.075	1.000	
FIN	0.039**	0.013	0.008	–0.022*	0.069***	–0.056***	0.008	–0.023**	0.211***	1.000

Note: *, **, and *** indicate the significance level at 10%, 5%, and 1%, respectively.

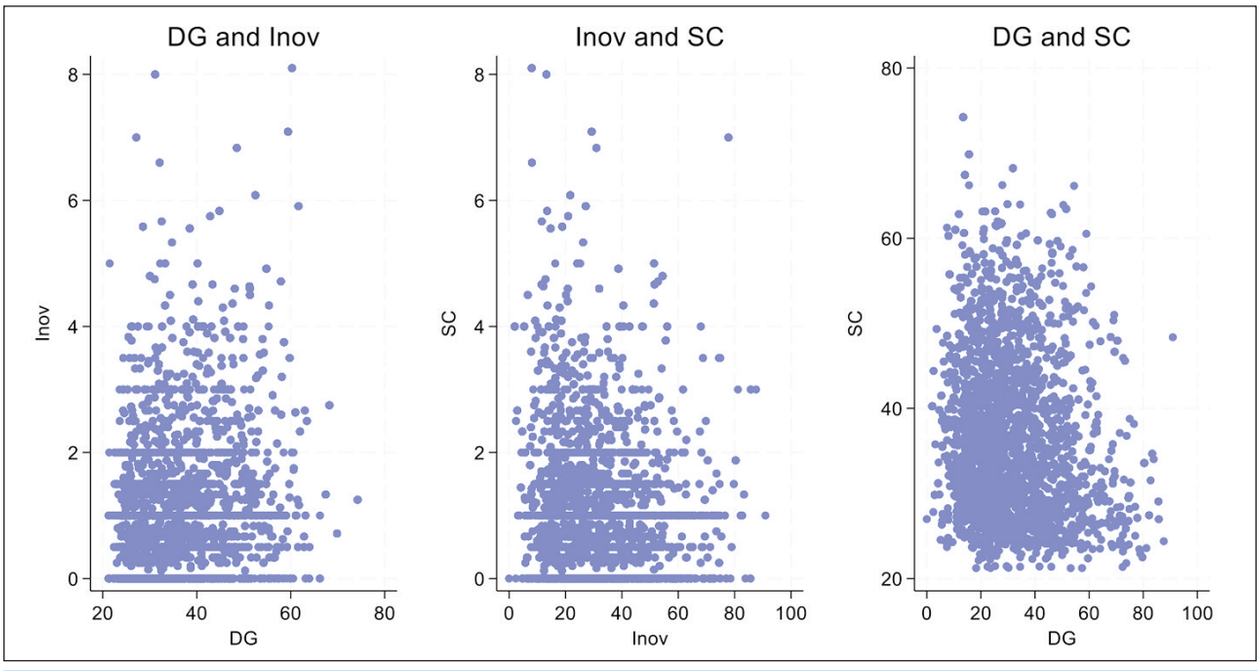

Fig. 2. Nexus between DG, Inov and SCC

Table 4

BASELINE REGRESSION RESULTS			
Variable	**Column (1)**	**Column (2)**	**Column (3)**
	INOV	**INOV**	**INOV**
DIG	0.0269***	0.0149***	0.063**
	(15.23)	(8.39)	(2.23)
SIZE		0.3081***	0.2379***
		(20.71)	(6.61)
GROWTH		–0.0761*	–0.0938**
		(–1.81)	(–1.98)
FL		–0.0018	0.0041
		(–0.11)	(0.23)
PROFIT		–0.0339	–0.3570
		(–0.12)	(–1.07)
D/E		–0.0412***	–0.0314*
		(–3.42)	(–2.07)
GDP		0.3170***	0.6696***
		(7.69)	(8.35)
FIN		0.0184***	0.0187***
		(3.93)	(3.91)
Constant	0.2034***	–9.9429***	–11.7827***
	(2.98)	(–19.93)	(–16.63)
R-squared	0.0486	0.1674	0.1254
N	7,416	7,416	7,416
Firm FE	No	No	Yes
Year FE	No	No	Yes

Note: *, **, and *** indicate the significance level at 10%, 5%, and 1%, respectively. T-statistics are reported in brackets.

of Chinese textile enterprises. This result emphasises the importance of digital transformation in enterprises as they experience an increase in their collaborative innovation efforts when they are more digitally transformed. The column (2), when firm and regional level control variables are included in the model, the coefficient of DIG reduces to 0.0149. Based on this result, we can claim that unobserved firm-level and regional-level variables affect the nexus between digital transformation and collaborative innovation in Chinese textile enterprises. This model further supports the idea that digital transformation is a crucial driver to promote collaborative innovation within the supply chain network of textile companies. The reduction in coefficient suggests that firms with a strong digital transformation strategy possess other capabilities such as leadership, external collaborations, and organisational resources that collectively influence innovation outcomes [55].

In column (3) of table 4, when both firm and year are fixed, and control variables are also included, the coefficient of DIG is reported as 0.063. This increased coefficient in this column suggests that digital transformation, when controlled for temporal and firm-specific factors, has a significant effect on collaborative innovation within the supply chain network of the textile sector of China. This result supports hypothesis 1, claiming the positive impact of digital transformation on collaborative innovation within the supply chain network of Chinese textile enterprises. However, the magnitude of influence is lower than column 1, where no fixed effects and control variables were included, indicating that effects can be moderated by other firm-specific and external factors, such as market conditions, supply chain concentration, or access to digital facilities [56]. This model confirms the direct role of digital transformation in influencing collaborative innovation within the supply chain network, and further argues that there can be other internal or external factors to influence the nexus [57].

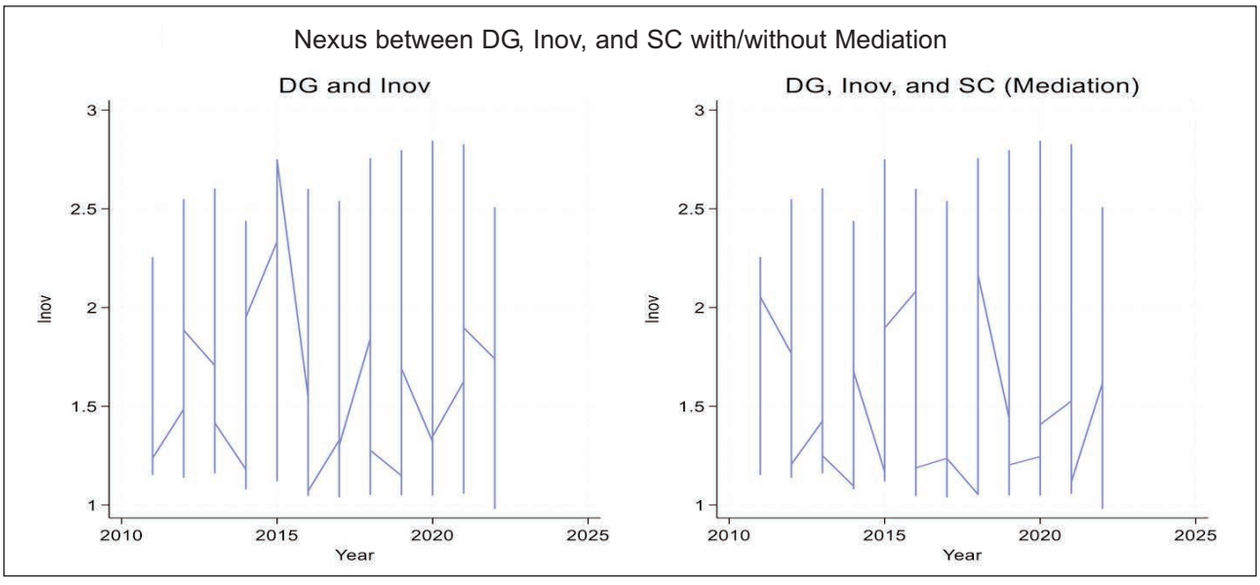

Fig. 3. The baseline and mediation effects

Overall, the baseline results demonstrate that digital transformation has a significant positive impact on collaboration within the supply chain network of Chinese textile enterprises. The findings imply that as firms invest more in digital transformation, they experience a significant increase in their collaborative innovation efforts, which aligns with the growing body of academic literature, demonstrating the role of digital transformation to foster innovations in organisational settings [47, 53, 58]. Digital technologies can be leveraged by enterprises to promote faster decision-making, get access to global knowledge networks, and participate with various partners to gain patents [59]. The positive relationship, presented by the current study, supports the notion that digital transformation enhances a firm's ability to innovate collaboratively, which could be particularly important in industries where innovation is the key to achieving a competitive edge [60]. The varying sizes across the columns suggest that there can be other organisational and environmental factors that may play a significant role in mediating or moderating the nexus between digital transformation and collaborative innovations.

Robustness check using two-stage least squares (2SLS)

To confirm the robustness of baseline results, we employed a two-stage least squares (2SLS) regression approach with an instrumental variable of provincial internet penetration. This variable is widely used in academic literature [54, 61], and this is a valid and effective choice to address endogeneity concerns. Provincial internet penetration could be a strong instrument as it is exogenous to a firm's innovation efforts; however, it shapes the environment for enterprises to adopt digital technologies. The first regression results, reported in column (1) of table 5, present the coefficient of *INTERNET* as 0.1074, which is highly significant. This suggests that increased internet penetration across Chinese regions leads to greater digital transformation within firms, which is consistent with the argument that increased internet access

Table 5

2SLS REGRESSION RESULTS (FIRST AND SECOND STAGE)

Variable	First-Stage	Second Stage
	Column (1)	Column (2)
	DIG	INOV
INTERNET	0.1074***	
	(8.07)	
DIG		0.1007***
		(5.37)
SIZE	0.9204***	0.2868***
	(10.43)	(12.57)
GROWTH	–0.1634	–0.0806
	(–0.39)	(–1.29)
FL	–0.8368***	0.0620**
	(–5.52)	(2.22)
PROFIT	–23.7373***	2.4668***
	(–9.89)	(4.28)
D/E	–0.3512***	–0.0454**
	(–3.49)	(–2.75)
GDP	0.4114	–0.0514
	(1.00)	(–0.75)
FIN	–0.0861*	0.0242***
	(–1.70)	(3.14)
Constant	8.8133*	–8.5746***
	(1.94)	(–14.29)
N	7,416	7,416
F-statistic	F(8,7407) = 54.43	Wald chi2(8) = 993.49
Prob > F	0.0000	0.0000

Note: *, **, and *** indicate the significance level at 10%, 5%, and 1%, respectively. T-statistics are reported in brackets.

fosters digitalisation in a country [62]. Moreover, the f-statistic value of 54.43 considers INTERNET as a strong instrument for DIG. The second-stage regression result, reported in column (2) of table 5, shows the coefficient of 0.1007, demonstrating the positive influence of digital transformation on collaborative innovation within the supply chain network of Chinese listed enterprises. This result confirms the robustness of baseline results that argue the positive impact of digital transformation on collaborative innovation in Chinese textile enterprises.

Mechanism analysis: Moderating effects of supply chain concentration

To further investigate the mechanism through which digital transformation could influence collaborative innovation, we perform moderating effects analysis and report the results in table 6. Supply chain concentration (SCC), relying on fewer customers/suppliers, is employed as the moderating variable to examine its influence on the nexus between digital transformation and collaborative innovation within the textile sector. Column (1) of table 6 presents the direct effects of digital confirmation on collaborative innovation, which are positive, supporting the first hypothesis of the study. Column (2) presents the regression results of model 8, demonstrating the effects of explanatory and control variables on SCC. As per these results, DIG has a regression coefficient of –0.058, indicating that higher digitalisation tends to reduce the supply chain concentration within Chinese textile enterprises. This result implies that when firms are relying on fewer customers/suppliers, the potential to adopt digital technologies may be hindered. In other words, a high level of concentration reduces the number of partners with whom firms may collaborate, and thus limits access to diverse ideas, technologies, and business philosophies [63].

Column (3) shows a negative coefficient of –0.0984 for the interaction term (DIG_SCC), implying that when textile firms are relying on a limited number of suppliers/customers, the effect of digital transformation on collaborative innovation is weakened. This finding argues that while digital transformation serves as the key tool to promote collaborative innovation, its impact gets less pronounced when firms are embedded in concentrated supply chains. This finding supports the idea that competitive dynamics in less concentrated supply chains can spur more innovative behaviour, while concentrated networks can stifle such efforts because of limited external collaboration opportunities [6]. Overall, these results highlight the complexity of the nexus between digital transformation and collaborative innovation in the Chinese textile sector. The moderating effects analysis shows that the benefits of digital technologies to foster innovation could be based on the structure of supply chains. Textile firms in less concentrated supply chains may gain strong innovative benefits from digitalisation, as they have the diversification in their partnerships across various suppliers and customers, which influences their ability to innovate [64].

Table 6

MODERATING EFFECTS OF SUPPLY CHAIN CONCENTRATION (SCC)

Variable	Column (1)	Column (2)	Column (3)
	INOV	SCC	INOV
DIG	0.0633**	–0.058**	0.0087*
	(2.23)	(–2.26)	(1.90)
SIZE	0.2379***	–1.7773***	0.2333***
	(6.61)	(–6.15)	(6.47)
GROWTH	–0.0938*	1.9494***	–0.0864*
	(–1.98)	(5.14)	(–1.82)
FL	0.0041	–0.1414	0.0033
	(0.23)	(–0.98)	(0.18)
PROFIT	–0.3570	4.9452*	–0.3372
	(–1.07)	(1.85)	(–1.01)
D/E	–0.0314**	0.4517***	–0.0296**
	(–2.07)	(3.72)	(–1.95)
GDP	0.6696***	8.6590***	0.6967***
	(8.35)	(13.45)	(8.60)
FIN	0.0187***	–0.0788**	0.0185***
	(3.91)	(–2.05)	(3.86)
DIG_SCC			–0.0984**
			(–2.27)
Constant	–11.7827***	–28.4780***	–11.9728***
	(–16.63)	(–5.01)	(–16.79)
R-squared	0.0879	0.0440	0.0887
N	7,416	7,416	7,416
Firm FE and Year FE	Yes	Yes	Yes

Note: *, **, and *** indicate the significance level at 10%, 5%, and 1%, respectively. T-statistics are reported in brackets.

Additionally, geographic clustering significantly impacts firms' innovation capabilities. Companies located in industrially advanced regions like Zhejiang and Jiangsu exhibit better digital infrastructure, facilitating innovation-driven collaborations. Conversely, companies in less-developed inland regions face infrastructural constraints hindering their collaborative innovation efforts. Policies that enhance digital infrastructure and encourage regional collaboration could bridge this gap, improving overall industry performance.

Heterogeneity analysis

We further perform heterogeneity analysis to show how varying pollution levels of enterprises and firm sizes could influence the nexus between digital transformation and collaborative innovation in the textile sector. Previous studies show that environmental challenges, such as high pollution levels, could necessitate the demand for more partnerships for innovations [65], as firms may leverage digital advancements to comply with strict regulations. As shown in table 7, DIG has a statistically significant value of 0.078 for only heavily polluted industries' enterprises. This finding supports the idea that in

Table 7

FIRM LEVEL HETEROGENEITY – HEAVILY POLLUTED OR NOT		
Variable	Column (1)	Column (2)
	Heavily polluted	Non-Heavily polluted
	INOV	INOV
DIG	0.078**	0.056
	(1.97)	(1.37)
SIZE	0.2524***	0.2546***
	(4.64)	(4.83)
GROWTH	–0.1084*	–0.1145
	(–1.75)	(–1.53)
FL	0.0009	–0.0055
	(0.03)	(–0.22)
PROFIT	–0.0758	–0.8458
	(–0.18)	(–1.60)
D/E	–0.0271	–0.0344*
	(–0.94)	(–1.86)
GDP	0.6385***	0.6660***
	(5.00)	(6.08)
FIN	0.0208***	0.0169**
	(3.01)	(2.57)
Constant	–11.8801***	–12.0099***
	(–11.58)	(–11.74)
R-squared	0.0946	0.0838
N	3,311	4,105

Note: *, **, and *** indicate the significance level at 10%, 5%, and 1%, respectively. T-statistics are reported in brackets.

Table 8

FIRM LEVEL HETEROGENEITY – SMALL SIZE VS LARGE SIZE		
Variable	Column (1)	Column (2)
	Small Size	Large Size
	INOV	INOV
DIG	0.0121***	–0.0097
	(2.95)	(–0.23)
SIZE	0.2631***	0.2698***
	(4.16)	(4.14)
GROWTH	0.0367	–0.1460***
	(0.36)	(–2.67)
FL	–0.0127	0.0106
	(–0.53)	(0.37)
PROFIT	–1.3934**	0.6699
	(–2.66)	(1.41)
D/E	–0.0317	–0.0211
	(–1.59)	(–0.86)
GDP	0.7827***	0.3751***
	(6.65)	(2.98)
FIN	0.0218***	0.0071
	(3.18)	(1.10)
Constant	–13.7071***	–8.9899***
	(–11.52)	(–7.27)
R-squared	0.1065	0.0372
N	3,691	3,725

Note: *, **, and *** indicate the significance level at 10%, 5%, and 1%, respectively. T-statistics are reported in brackets.

industries where pollution is a major concern, firms use more digital technologies to promote collaborative innovations [66]. Moreover, we can see that GDP and FIN have positive effects on INOV, indicating the role of economic growth and financial performance in promoting collaborative innovations [67]. Overall, these findings highlight the environmental challenges and firm characteristics to frame the effects of digital transformation on collaborative innovations.

Firm size could be another factor influencing the ability of enterprises to adopt and benefit from digital technologies [68]. Previous studies show that large-sized firms typically have more resources, better infrastructure, and better capabilities to deploy digital solutions and innovate more [69]. Firm-size heterogeneity analysis results are shown in table 8, showing the greater and significant effects of digitalisation for small-sized firms. This finding suggests that small-sized firms have fewer resources and they have to rely more on digital transformation for growth and innovation, so they deploy more technologies in their processes [70]. The large-sized firms may have bureaucratic and rigid structures, so they may not effectively employ digital technologies to foster collaborative innovations. Overall, the findings of the current study highlight how firm size could moderate the role of digital transformation to drive innovation, with smaller-sized firms showing greater reliance on digitalisation.

CONCLUSION AND POLICY IMPLICATIONS

Textile firms, relying on fewer customers and suppliers, could be exposed to opportunities and challenges. This concentration can influence their digital strategies, employed to achieve collaborative innovations, and may promote or hinder them. Based on this idea, this study primarily examines the nexus between digital transformation and collaborative innovation. Secondly, it analyses the moderating effects of supply chain concentration on the nexus between digital transformation and supply chain concentration. Using the data of 942 Chinese A-share listed textile firms from 2011 to 2022, this study shows that digital transformation has a significant positive impact on collaborative innovation within firms' supply chain networks. Robustness check also supports the benchmark results of the positive impact of digital transformation on collaborative innovations within Chinese textile enterprises. However, moderating effects analysis shows that relying on limited suppliers/customers hinders the ability of firms to fully leverage the benefits of digitalisation for fostering collaborative innovations. Furthermore, industry pollution level and firm size are found to be significant

factors influencing the firms' ability to leverage digital technologies to foster collaborative innovation. Our findings highlight specific companies like Shenzhou International and Jiangsu Sunshine Group as successful exemplars leveraging digital transformation for collaborative innovation. To assist firms struggling with digital transformation, we recommend targeted solutions, including increased government support for digital literacy programs, incentives for digital infrastructure investments, and strategies encouraging diversified partnerships within supply chains. Other textile firms (those that don't employ digital technologies in their processes today) could follow these companies to enhance their strategic capability to partner with other firms and achieve their potential goals. It could be critically important for those firms to understand their digitalisation requirements to bring strategic collaborations in different areas.

There are several policy implications presented by the findings of this study. First, from a government perspective, policymakers should promote policies that can promote digital infrastructure, as expanding digitalisation across all regions, improving financial inclusion, and offering benefits to enterprises, allowing them to own efficient resources. Second, policymakers of Chinese textile enterprises should set those innovation targets for enterprises that can be achieved through cooperation, so they can be ready to participate with each other. Third, from a firm perspective, managers in Chinese textile enterprises should diversify their customer base and supplier base to have more partners in a position to achieve the benefits of digitalisation for collaborative innovations. They should promote the development of competitive and diverse supply chains so that there can be collaborations across various enterprises. Fourth, Chinese textile firms should not only leverage digital technologies for operational efficiency, but they should also use them to ensure environmental sustainability. Last, textile companies can practically apply the study's insights through actions such as: (1) Investing in modular digital platforms that enhance supplier interaction and flexibility, (2) Establishing joint digital training initiatives with suppliers and customers to improve collective digital capabilities, and (3) Diversifying their supplier/customer bases to leverage broader innovation networks, thus reducing the risks associated with high supply chain concentration.

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