



Research article

Supply chain digitalization and risk management: A scoping review, systematic review, and meta-analysis

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Abstract: The aim of this article was to investigate how supply chain digitalization interacts with proactive risk management to improve operational performance and resilience. A three-phase research design was employed. First, a scoping review of 1750 publications (2015–2025) was conducted to identify the main conceptual, technological, and methodological trajectories structuring the field. Second, a systematic review across five academic databases identified 40 relevant studies addressing digitalization with an explicit risk-related dimension. Among these, 20 relied on quantitative empirical designs, and 11 provided statistically compatible data for meta-analytical synthesis. A random-effects meta-analysis using restricted maximum likelihood (REML) estimation was performed based on 71 statistically tested relationships extracted at the hypothesis level. The combined effect size indicates that digitalization has a positive and statistically significant effect on performance and risk-related outcomes ($\beta = 0.2511$; $p < 0.0001$), despite substantial heterogeneity across studies. The findings confirm that digitalization contributes to performance primarily through the development of risk-related and adaptive capabilities, rather than acting as a standalone driver. By integrating these insights, this study provides an analytical basis for future optimization-oriented research and for the design of integrated digital risk management strategies.

Keywords: supply chain digitalization; digital supply chain; Industry 4.0; supply chain resilience; risk management; risk-related capabilities; systematic literature review; meta-analysis

Mathematics Subject Classification: 90B06, 90B30, 90C90

1. Introduction

Digitalization has become a central driver of supply chain transformation, reshaping organizational processes and performance outcomes [1]. Recent research highlights that digitalization capabilities, such as data analytics, connectivity, and process automation, play a decisive role in enhancing firms' competitiveness and supporting innovation [2]. The pandemic context has further accelerated this shift, revealing both vulnerabilities and opportunities for firms adopting digital technologies [3].

Within supply chains, digitalization contributes to greater visibility, integration, and responsiveness, supported by technologies such as internet of things (IoT), artificial intelligence, cloud platforms, and digital twins [1,4]. These technologies enhance coordination and support performance improvements across various contexts, including manufacturing and logistics operations [5,6]. Industry 4.0 developments reinforce this evolution by enabling automation, real-time monitoring, and advanced decision-making [7].

In parallel, firms are exposed to a growing variety of disruptions, environmental volatility, and technological risks. Several studies underline challenges related to digital transformation, such as adoption barriers, integration constraints, and cybersecurity concerns, which influence firms' abilities to achieve expected performance outcomes [8,9]. Other works emphasize the emerging role of digitalization in strengthening resilience and enabling proactive responses to disruptions [10,11].

Despite these advances, existing research examining the relationships between digitalization and risk management remains fragmented, and limited empirical synthesis has been conducted to understand how digitalization and risk-related capabilities jointly influence supply chain performance. To address this gap, this study combines a scoping review, a systematic review, and a meta-analysis to consolidate dispersed evidence and quantify the effects reported across empirical studies. By integrating these insights, the research provides an analytical foundation for understanding the relationships between digitalization, risk management, and performance in supply chains.

Beyond consolidating existing evidence, this study provides an analytical basis for optimization-oriented research by clarifying how digitalization and proactive risk management jointly inform decision-making and performance improvement in complex supply chain systems.

2. Theoretical background

2.1. Digitalization and supply chain capabilities

Digitalization has progressively reshaped supply chain management by transforming traditionally fragmented and sequential processes into integrated, data-driven systems. In this context, the concept of the digital supply chain (DSC) has emerged to describe a supply chain model in which digital technologies are used to enhance connectivity, coordination, and value creation across organizational boundaries. Rather than referring to the simple adoption of digital tools, the DSC is generally conceptualized as an intelligent, value-oriented system that enables end-to-end integration, real-time information flows, and adaptive decision-making in increasingly complex and dynamic contexts [1,4,10].

Existing literature highlights that the transition toward a digital supply chain represents a structural transformation from traditional configurations characterized by fragmented activities and

localized information. Digitalization enables tighter coupling between actors, processes, and information systems; this, in turn, facilitates a systemic and interconnected mode of operation. From this perspective, the DSC is commonly described as a networked system in which information sharing, coordination mechanisms, and organizational ties jointly contribute to improved alignment across supply chain partners [1,11]. This integrated logic is central to managing the growing complexity and interdependence of modern supply chains.

Importantly, recent studies emphasize that the performance implications of digitalization depend less on the technologies themselves than on the organizational capabilities developed around them. In this sense, digitalization should be distinguished from the capabilities it enables, as technologies constitute enabling infrastructures while capabilities represent the mechanisms through which value is created. Accordingly, the literature increasingly adopts a capability-based perspective, suggesting that digitalization generates value through the development of digital capabilities, including enhanced visibility, integration, analytics, and coordination [12–14]. These capabilities reflect a firm's ability to mobilize digital resources, skills, and routines to support supply chain processes, rather than the simple presence of advanced technologies.

From this perspective, digital technologies associated with Industry 4.0, including cloud platforms, data analytics, artificial intelligence, and cyber-physical systems, are best conceptualized as enablers of supply chain capabilities. Their contribution lies in supporting real-time connectivity, information transparency, and process automation, which collectively enhance the ability of supply chains to coordinate activities and respond to operational requirements [7,15]. In particular, improved connectivity and data integration facilitate end-to-end visibility and more informed decision-making across supply chain networks, thereby reinforcing the operational foundations of digital supply chain management [16].

The development of digital supply chain capabilities has been widely related to enhanced operational and organizational performance. Both conceptual and empirical contributions suggest that capabilities associated with visibility, coordination, and analytics contribute to greater efficiency, responsiveness, and alignment across supply chain activities, particularly in manufacturing and logistics contexts [2,5,6]. However, the literature also recognizes that these capabilities may introduce new forms of complexity and vulnerability, underscoring the need to consider digitalization within a broader framework that incorporates risk management and resilience. This observation provides a natural transition toward examining how digital capabilities interact with risk-related mechanisms in shaping supply chain performance.

2.2. Risk management, resilience, and proactive capabilities

Supply chains increasingly operate in environments characterized by heightened uncertainty, volatility, and exposure to multiple sources of disruption. These disruptions may stem from operational failures, environmental shocks, market fluctuations, or technology-related vulnerabilities, all of which can propagate rapidly across interconnected supply chain networks. Therefore, risk management has become a major concern in supply chain research and practice, with growing attention shifting from isolated risk events toward systemic vulnerabilities inherent in complex and interdependent structures.

Traditional approaches to supply chain risk management have largely been reactive, focusing on responding to disruptions after they occur. However, recent literature emphasizes the limitations of such reactive strategies in highly interconnected and digitally enabled supply chains. As a result, the

literature increasingly calls for proactive risk management approaches that prioritize anticipation, prevention, and preparedness, rather than reactive recovery strategies [17]. In this context, effective risk management involves not only identifying potential sources of disruption but also developing organizational capabilities that allow supply chains to detect emerging risks and adapt accordingly.

The concept of supply chain resilience is closely related to proactive risk management, which has gained significant attention in recent years. Resilience is commonly conceptualized as the ability of a supply chain to resist, absorb, adapt to, and recover from disruptions while maintaining or quickly restoring desired performance levels. Importantly, resilience is not viewed as a static attribute but rather as a dynamic and systemic capability that emerges from the interaction of multiple organizational and operational mechanisms across the supply chain. This perspective highlights that resilience depends on coordination, flexibility, and information sharing among supply chain partners, rather than on isolated firm-level actions [8,9].

While digitalization can support resilience-building efforts, recent studies also suggest that it may introduce new forms of risk and vulnerability within supply chains. Increased dependence on digital infrastructures can expose firms to cybersecurity threats, technological dependencies, and intellectual property concerns, which can undermine performance if not adequately managed [18]. This dual role of digitalization highlights the importance of integrating risk management considerations into digital transformation strategies.

From a capability-based perspective, resilience and proactive risk management can be understood as higher-order capabilities that build upon underlying digital and organizational resources. In this sense, digital technologies act as enabling infrastructures, while risk-related and resilience capabilities represent the mechanisms through which supply chains anticipate, adapt, and respond to disruptions. These proactive capabilities enable supply chains to reconfigure processes, adjust decision-making, and coordinate responses across organizational boundaries in the face of uncertainty. Accordingly, recent contributions suggest that resilience should be understood not as an outcome of digitalization alone but as the result of deliberate capability development that integrates digital technologies with risk-aware managerial practices [8,9].

Taken together, this body of literature suggests that understanding supply chain performance in digitally enabled environments requires an integrated perspective that simultaneously considers digitalization, risk management, and resilience. Rather than treating these dimensions independently, recent research calls for analytical frameworks capable of capturing their joint influence on supply chain outcomes. This integrated view provides a foundation for examining how digital and risk-related capabilities interact to shape performance and directly informs the empirical synthesis developed in the subsequent sections of this study.

2.3. Linking digitalization, risk management, and performance

Building on this integrative perspective, the literature emphasizes that neither digitalization nor risk management alone is sufficient to ensure sustained supply chain performance in complex and uncertain environments. While digital technologies enhance visibility, connectivity, and coordination, their performance benefits remain contingent upon the capacity of organizations to manage risks proactively and to translate digital resources into effective operational and managerial capabilities [15]. As a result, supply chain performance should be understood as the outcome of complementary and interacting mechanisms.

From a systemic perspective, digitalization alters decision-making by increasing the availability, speed, and granularity of information across supply chain networks. Nevertheless, greater information intensity and technological interdependence may simultaneously amplify exposure to disruptions and operational complexity. In this context, proactive risk management and resilience-oriented capabilities play a critical role in moderating these effects by enabling anticipation, adaptation, and coordinated responses to uncertainty [8]. Performance can thus be achieved through a balance between efficiency-oriented digital capabilities and robustness-oriented risk management practices [9].

This interaction highlights the presence of inherent trade-offs in digitally enabled supply chains, particularly between efficiency and resilience, flexibility and stability, or responsiveness and control. Rather than eliminating these trade-offs, digitalization modifies their nature by shifting optimization toward the alignment of capabilities and decision processes within complex, interconnected systems [16]. Therefore, performance improvement increasingly depends on how organizations integrate digital and risk-related capabilities within their decision frameworks, rather than on technology adoption per se.

Overall, this integrated perspective highlights the need for analytical approaches capable of capturing the joint effects of digitalization and risk management on supply chain performance. Given the fragmented and heterogeneous nature of existing empirical evidence, a systematic and quantitative synthesis of findings is required, thereby motivating the multi-stage review and meta-analytical approach adopted in this study.

For analytical clarity, this study distinguishes between three related but distinct dimensions. First, *digitalization* refers both to technological enablers (e.g., IoT, artificial intelligence, blockchain, and data analytics) and to the capabilities they support, including visibility, integration, coordination, and information processing. Second, *risk management* refers to managerial practices aimed at identifying, mitigating, and responding to disruptions, while *risk-related capabilities* refer to higher-order capacities such as resilience, adaptability, and proactive response. Third, *outcomes* refer to the range of supply chain effects examined in prior studies, including operational performance, resilience, agility, and disruption-related outcomes. This distinction provides the conceptual basis for structuring and interpreting the relationships synthesized in the meta-analysis.

3. Methodology

Given the dispersed and heterogeneous state of existing research on supply chain digitalization, risk management, and performance, this study adopts a multi-stage research design combining a scoping review, a systematic review, and a meta-analysis. This sequential approach is designed to progressively structure the field, refine the analytical focus, and quantitatively assess the empirical evidence reported across prior studies. Figure 1 provides an overview of the methodological framework adopted in this study.

The scoping review represents the first stage of the research design and serves an exploratory purpose. Its aim is to provide a broad mapping of academic research on supply chain digitalization, identify dominant themes and methodological trends, and define the boundaries of the field. By adopting flexible inclusion criteria consistent with the principles of scoping studies, this stage enables a comprehensive overview of the literature and informs the subsequent, more targeted stages of analysis.

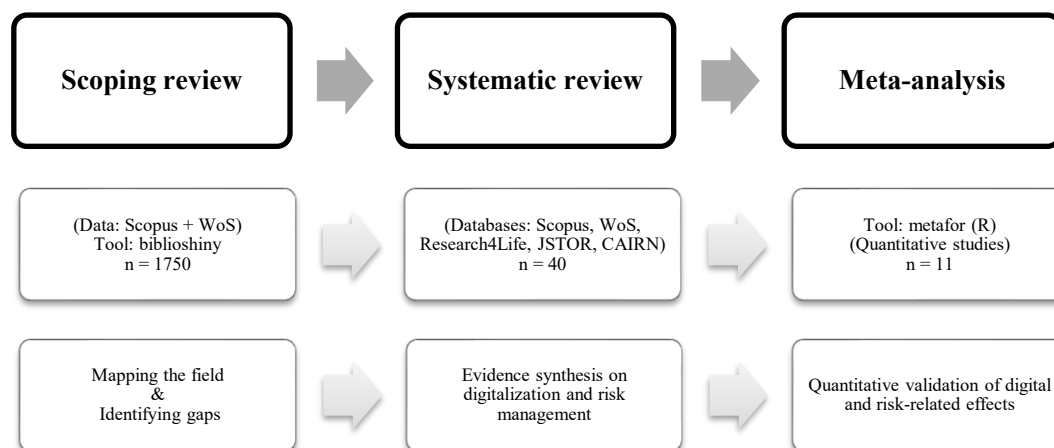


Figure 1. Three-step methodological approach.

Building on the insights obtained from the scoping review, the second stage consists of a systematic review focused explicitly on the relationship between digitalization and risk management in supply chains. This phase follows a structured and methodical process inspired by preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines, with stricter inclusion and exclusion criteria applied to ensure analytical rigor. The review was conducted by a single researcher; however, methodological consistency was ensured through the use of a predefined protocol, systematic screening procedures, and iterative validation of inclusion decisions. The systematic review allows for a detailed examination of how digital technologies and risk-related mechanisms are addressed and empirically investigated in the literature.

The final stage of the research design is a meta-analysis, conducted to quantitatively synthesize the results of compatible empirical studies selected during the systematic review. Through the aggregation of effect sizes across studies, the meta-analytical approach facilitates an assessment of the magnitude, direction, and variability of the relationships between digitalization-related factors and supply chain outcomes. Given the diversity of empirical designs and measurement approaches, particular attention was paid to ensuring the comparability of effect sizes and the consistency of data extraction procedures. This step is particularly suited to addressing inconsistencies across prior findings and supports a more robust evaluation of performance implications under uncertain and heterogeneous contexts.

Collectively, this three-stage methodological design ensures both breadth and depth of analysis. It combines exploratory mapping, systematic evidence synthesis, and quantitative aggregation. This integrated design provides a robust foundation for investigating the joint effects of digitalization and proactive risk management on supply chain performance.

3.1. Scoping review protocol

The scoping review represents the first empirical stage of the research design and follows a structured approach inspired by the PRISMA extension for scoping reviews (PRISMA-ScR). Its exploratory purpose is to map the literature on supply chain digitalization and to identify key thematic and methodological trends within the field.

3.1.1. Data sources and search strategy

The scoping review was conducted using two major academic databases, Scopus and Web of Science, selected for their broad coverage of peer-reviewed literature in operations management, supply chain management, and information systems. The search strategy targeted publications addressing digitalization in supply chains and related domains, without imposing restrictions on specific technologies or performance outcomes at this stage.

The temporal scope was set to 2015–2025, reflecting the rapid acceleration of research on supply chain digitalization in the context of Industry 4.0. This time frame was determined based on a preliminary examination of publication trends in both databases, which indicated a marked increase in relevant contributions from 2015 onwards. The aim was to capture both the emergence and consolidation of the field over the past decade.

3.1.2. Eligibility criteria and screening process

In line with the objectives of a scoping review, relatively flexible inclusion criteria were applied. Publications were considered eligible if they addressed digitalization in supply chains or closely related contexts, regardless of research design or empirical orientation. Both peer-reviewed journal articles and conference papers written in English were retained to capture a broad range of academic contributions.

After removing duplicates, titles and abstracts were screened for relevance. In keeping with the exploratory aim of the scoping review, no methodological exclusions were applied, resulting in a final dataset of 1750 publications. Methodological details related to the scoping review are provided in Appendix A.

3.1.3. Data analysis and outcomes

To analyze the resulting dataset, a bibliometric analysis was performed using Biblioshiny, the web-based interface of the bibliometrix package in R. This analysis facilitated the identification of key publication trends, influential sources, dominant keywords, and thematic clusters within the literature. The scoping review thus provided a structured overview of the research landscape and highlighted both dominant areas of investigation and underexplored themes.

In this sense, the scoping review served as a foundational step that ensured coherence and relevance in the progression toward more targeted evidence synthesis.

3.2. *Systematic review procedure*

3.2.1. Data sources and search strategy

Building on the insights generated by the scoping review, the systematic review aimed to investigate in greater depth the relationship between supply chain digitalization and risk management. This phase followed a structured and transparent procedure inspired by PRISMA guidelines, with adaptations reflecting the constraints of an individually conducted review.

The search was extended to five academic databases (Scopus, Web of Science, Research4Life, JSTOR, and CAIRN) to ensure comprehensive coverage of the literature, including French-language publications. Unlike the scoping review, no temporal restriction was applied at this stage. This choice reflects the relatively emergent nature of the research field and was intended to avoid the premature exclusion of potentially relevant studies.

The search strategy combined keywords related to digital supply chains with risk-related concepts and industrial contexts. Given the diversity of terminology used in the literature, the keyword strategy was designed to capture studies addressing risk both explicitly and implicitly (e.g., resilience, disruption, uncertainty). These related constructs were also considered during the screening process, even when not explicitly labeled as “risk” in the search query. Detailed search strings, database-specific filters, and search dates are reported in Appendix B.

3.2.2. Eligibility criteria and screening process

In contrast to the exploratory logic of the scoping review, stricter inclusion and exclusion criteria were applied in the systematic review to ensure analytical rigor. Studies were considered eligible if they constituted academic publications, were written in English or French, and were available in full text. Moreover, studies were required to address supply chain digitalization with a clearly defined or interpretable risk-related component.

To ensure consistency in study selection, a coding logic was applied to identify risk-related dimensions. Studies explicitly referring to risk management, disruption, uncertainty, or resilience were included, provided that they examined supply chain digitalization within an industrial or organizational context. In cases where risk was not explicitly stated, studies focusing on resilience or disruption management were included when they addressed mechanisms related to risk anticipation, mitigation, or response.

The study selection process followed a multi-stage screening procedure. Initially, duplicate records were removed across databases. Titles and abstracts were then screened to assess relevance with respect to the research focus. Subsequently, full-text screening was performed to ensure compliance with the inclusion criteria. Studies were excluded if they did not align with the research scope, lacked a relevant risk-related dimension, or did not provide adequate empirical evidence.

3.2.3. Study selection and final sample

Following the screening and eligibility assessment, a final set of 40 studies was retained. Among these, 11 quantitative studies met the methodological requirements for inclusion in the subsequent meta-analysis.

Through this selection process, the systematic review provided a focused and coherent body of evidence addressing the interaction between digitalization and risk management in supply chains, while also supporting a robust quantitative synthesis in the final stage of the research design. The overall study selection process is summarized in the PRISMA flow diagram presented in Figure 2.

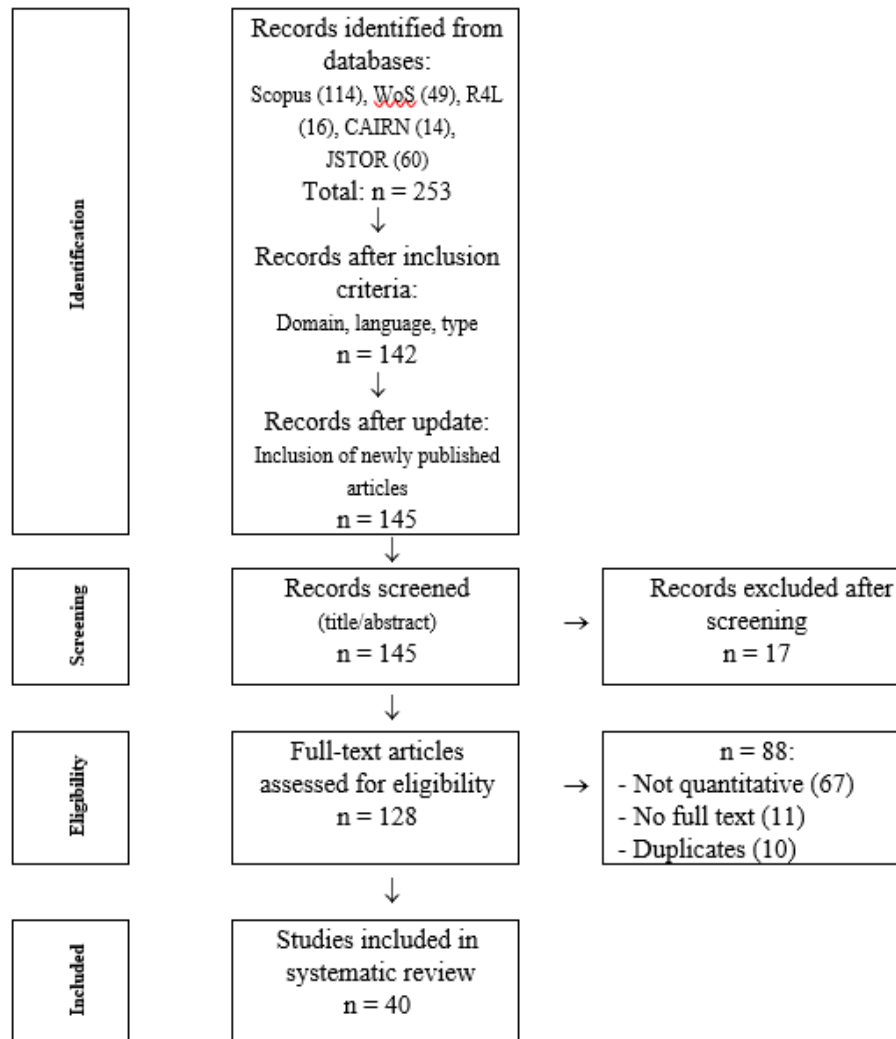


Figure 2. PRISMA flow diagram for the systematic review.

3.3. Meta-analysis procedure

3.3.1. Study selection and data extraction

The meta-analysis represents the final stage of the research design and was conducted to quantitatively synthesize evidence drawn from the systematic review. Among the 40 studies retained for qualitative synthesis, 11 quantitative studies met the methodological requirements and provided sufficient statistical information to compute effect sizes. A detailed list of the studies included in the meta-analysis is provided in Table 1.

Table 1. Studies included in the meta-analysis.

Ref	Title	Author(s)	Year	Journal
[19]	Risk mitigation in supply chain digitization: System modularity and information technology governance	Xue et al.	2013	<i>Journal of Management Information Systems</i>
[20]	Role of information processing and digital supply chain in supply chain resilience through supply chain risk management	Rashid et al.	2024	<i>Journal of Global Operations and Strategic Sourcing</i>
[21]	Sustainable performance through digital supply chains in Industry 4.0 era: Amidst the pandemic experience	Joshi et al.	2022	<i>Sustainability</i>
[22]	Impact of supply chain 4.0 and supply chain risk on organizational performance: An empirical evidence from the UAE food manufacturing industry	Al Kurdi et al.	2023	<i>Uncertain Supply Chain Management</i>
[23]	The role of artificial intelligence on digital supply chain in industrial companies: Mediating effect of operational efficiency	Sharabati et al.	2024	<i>Uncertain Supply Chain Management</i>
[24]	Navigating the Industry 4.0 frontier: Unveiling perceived risk and cost moderators in technology adoption	Jum'a et al.	2024	<i>E M Ekonomie a Management</i>
[25]	Digital supply chain adoption: An empirical result from food industry	Barqawi et al.	2023	<i>Uncertain Supply Chain Management</i>
[26]	Supply chain performance in the age of Industry 4.0: Evidence from manufacturing sector	Khan et al.	2025	<i>Brazilian Journal of Operations and Production Management</i>
[27]	The impact of COVID-19 on value relevance in distribution and service industries	Moon et al.	2024	<i>Journal of Distribution Science</i>
[28]	Assessing the impact of digital supply chain management on the sustainability of construction projects	Aziz et al.	2024	<i>Review of Business and Economics Studies</i>
[29]	The effects of justice and top management beliefs and participation: An exploratory study in the context of digital supply chain management	Wei et al.	2020	<i>Journal of Business Ethics</i>

For each study, data were extracted on the relationships between digitalization-related or organizational variables and supply chain outcomes. Rather than limiting the analysis to a single effect per article, multiple relevant relationships reported within each study were considered. Given the limited number of available studies, multiple effect sizes were retained to capture the diversity of relationships examined across studies. To address potential dependence between effect sizes derived from the same study, particular attention was paid to the consistency of extraction and interpretation, and sensitivity analyses were conducted to assess the robustness of the results.

This procedure resulted in a total of 71 effect sizes, enabling a more comprehensive representation of the empirical evidence. Data extraction included effect estimates (standardized regression coefficients or equivalent statistics), associated standard errors or information enabling their calculation, sample sizes, and contextual characteristics. Extraction procedures were applied

consistently across studies to ensure comparability. The coding of hypothesized relationships and effect directions was based on a detailed examination of each study's reported models and statistical results (see Appendix C, Table 2, for a partial summary).

3.3.2. Effect size computation

Effect sizes were expressed as standardized regression coefficients (β), which provide a comparable measure of the strength and direction of the relationships examined across studies. When standard errors were not explicitly reported, they were calculated from available statistical information following established meta-analytical procedures.

Given the diversity of empirical models and measurement approaches, effect sizes were standardized prior to aggregation. While the use of standardized regression coefficients may introduce variability due to differences in model specifications, this approach was retained to preserve the interpretability of relationships reported in the primary studies. Positive values indicate a favorable association between digitalization-related or organizational factors and supply chain outcomes, while negative values reflect detrimental effects. This limitation is acknowledged and taken into account when interpreting the meta-analytical results.

3.3.3. Statistical model and heterogeneity assessment

Owing to substantial variation across studies in terms of contexts, sectors, technologies, and empirical designs, a random-effects model was employed to estimate the combined effect size. This model accounts for both within-study sampling error and between-study variability.

The meta-analysis was performed using the metafor package in R, with effect sizes estimated through restricted maximum likelihood (REML). Statistical heterogeneity was evaluated using the Q statistic, I^2 index, and τ^2 (tau squared), providing complementary indicators of variability across studies.

3.3.4. Robustness checks and publication bias

To assess the robustness of the meta-analytical results, several diagnostic procedures were conducted. Egger's test was applied to evaluate potential publication bias, while Baujat plots were used to detect studies exerting disproportionate influence on overall heterogeneity. In addition, sensitivity analyses were performed to examine the stability of the results under alternative specifications, including the exclusion of influential observations.

Collectively, these procedures strengthen the reliability of the meta-analytical findings and support a cautious interpretation of the combined effects reported in the subsequent results section.

4. Results

4.1. Results of the scoping review

The scoping review analyzed a corpus of 1750 publications retrieved from the Scopus and Web of Science databases, covering the period from 2015 to 2025. This body of literature represents a broad and multidisciplinary research landscape addressing supply chain digitalization across various

industrial contexts. The review incorporates studies published in peer-reviewed journals and conference proceedings, addressing academic contributions related to digital technologies, supply chain transformation, and associated operational dimensions. The purpose of this stage was to map the overall structure of the literature, identify dominant research directions, and characterize the scope of existing studies.

4.1.1. Temporal evolution of publications

The temporal analysis of the literature indicates a progressive increase in the number of publications on supply chain digitalization over the period from 2015 to 2025. While research activity remained relatively limited during the early years of the period, a pronounced rise in annual scientific production is observed from 2019 onwards. Publication output reached its highest levels between 2020 and 2024. This temporal evolution is illustrated in Figure 3.

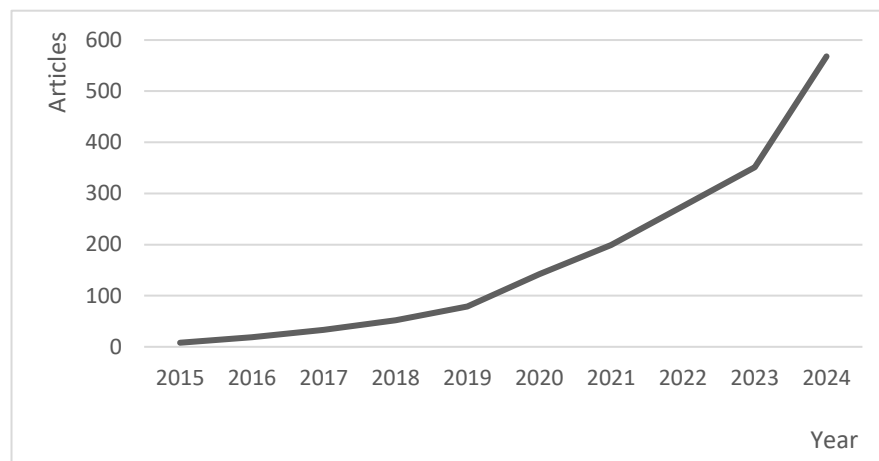


Figure 3. Annual scientific production related to supply chain digitalization between 2015 and 2025.

4.1.2. Trend topics over time

The trend topic analysis provides a temporal perspective on the evolution of research themes within the supply chain digitalization literature. As shown in Figure 4, early topics such as *value chain*, *supply chain design*, and *cyber-physical systems* appear at the beginning of the period (2018). From 2019 onwards, attention shifts toward *smart factory*, *simulation*, and *supply chain management*. The year 2021 is marked by the prominence of *logistics*, *Industry 4.0*, *blockchain*, *digitalization*, and *supply chain*. In 2022, topics such as *artificial intelligence* and *digital transformation* become more visible. Finally, in 2023, *resilience* emerges as a salient topic, highlighting its growing presence within the recent supply chain digitalization literature.

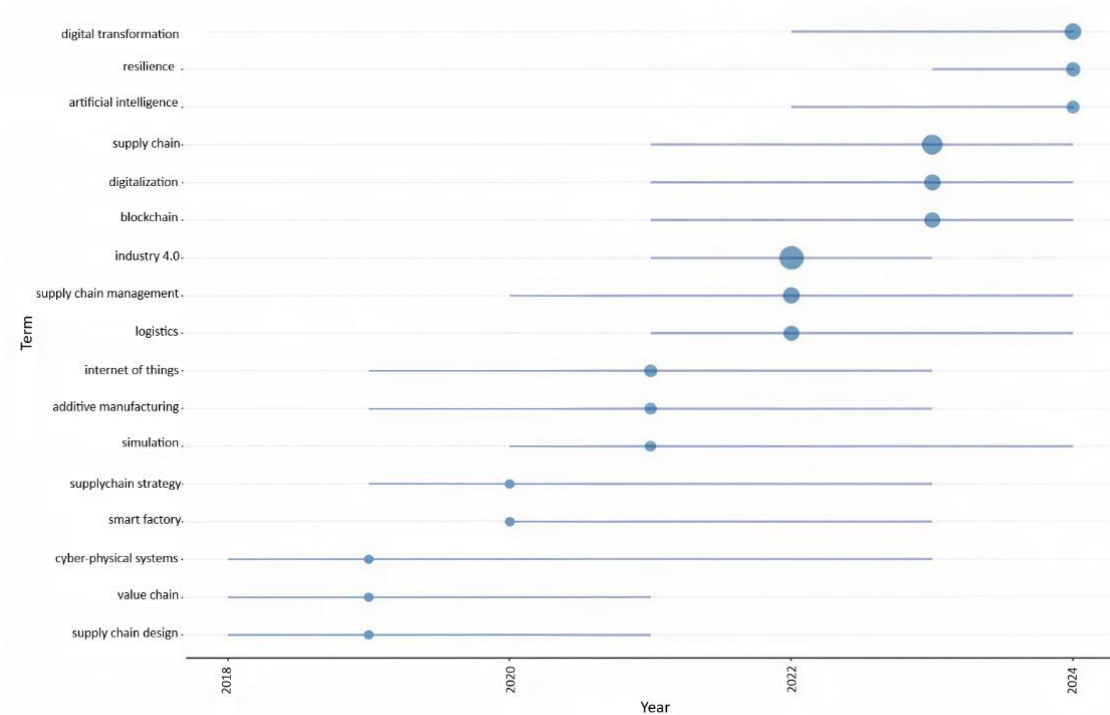


Figure 4. Evolution of dominant research topics in supply chain digitalization.

4.1.3. Dominant themes and technologies

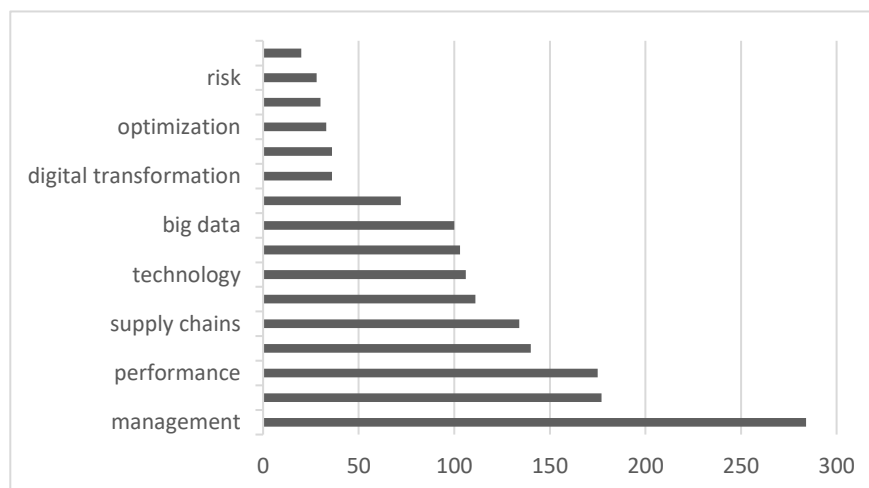


Figure 5. Most frequent keywords in the supply chain digitalization literature.

Figure 5 highlights the most frequently used keywords in the supply chain digitalization literature. Core terms such as *management*, *supply chain management*, *logistics*, and *Industry 4.0* appear most frequently, reflecting the strong managerial and operational orientation of existing research. Performance-related concepts, including *impact*, *performance*, and *optimization*, also feature prominently, indicating a sustained interest in outcome-oriented analyses within digital supply chain studies.

Keywords related to *technology*, *big data*, *systems*, and *digital transformation* appear with high frequency. References to *Industry 4.0* are also recurrent, alongside terms associated with *automation*, *connectivity*, and *information systems*.

Risk-related concepts such as *risk*, *risk management*, *risk assessment*, and *resilience* are also present in the keyword set, although with lower frequencies compared to technology- and performance-oriented terms. Their presence motivates a more focused investigation of the digitalization–risk relationship in the subsequent systematic review.

As shown in Figure 6, the keyword co-occurrence network reveals a structured set of interrelated concepts within the supply chain digitalization literature. Several highly connected nodes appear at the center of the network, notably, *Industry 4.0*, *Digitalization*, *Digital Transformation*, and *Supply Chain Management*. These nodes reveal multiple co-occurrence associations with a wide range of other keywords, forming the central structure of the network.

The visualization further highlights the presence of distinct clusters of keywords. One cluster is concentrated on *Industry 4.0* and contains terms associated with *digital technologies*, *manufacturing*, *sustainability*, *resilience*, and *dynamic capabilities*. Another cluster groups concepts related to *supply chain management*, *logistics*, *blockchain*, *Internet of Things*, and *digital twins*. A smaller cluster is composed of terms linked to *business models*, *strategy*, and *additive manufacturing*.

The keyword *automotive* appears within the co-occurrence network and is connected to a cluster primarily composed of terms related to *resilience*, *disruption*, *agility*, and *collaboration*. Its co-occurrence links with central technological concepts, such as *artificial intelligence* and the *Internet of Things*, are present but less dense compared to those observed within the main *Industry 4.0* cluster.

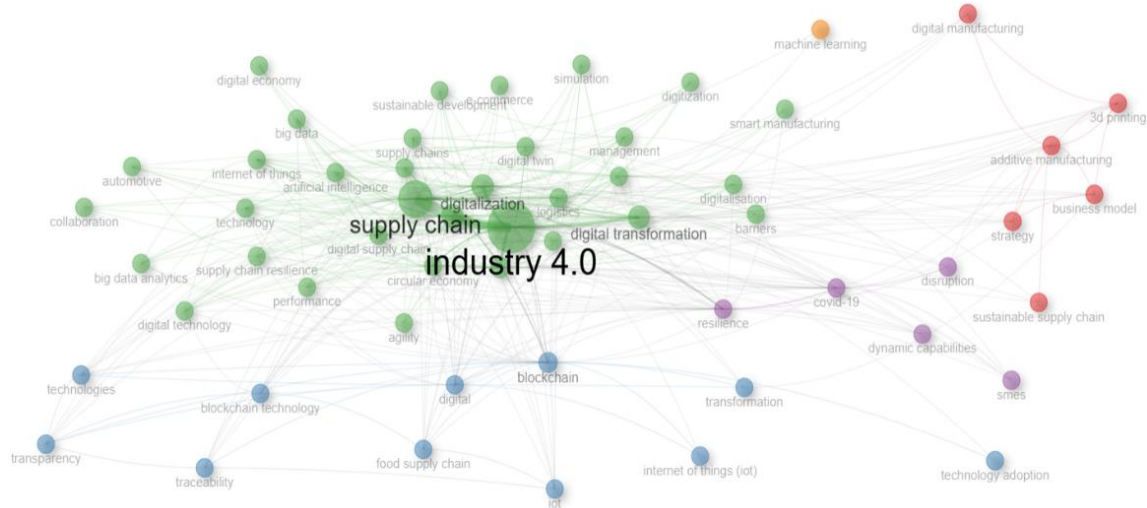


Figure 6. Keyword co-occurrence network of the supply chain digitalization literature.

To complement the exploratory insights of the scoping review, a systematic review was therefore undertaken to analyze studies explicitly addressing digitalization and risk management in supply chains.

4.2. Results of the systematic review

4.2.1. Overview of the selected studies

The systematic review identified forty studies addressing supply chain digitalization with an explicit risk dimension. Following full-text assessment, twenty studies relied on quantitative empirical designs consistent with the analytical objectives of this research. The full list of included studies is provided Table 3.

Table 3. Studies included in the systematic-review.

Ref	Title	Author(s)	Year	Journal
[19]	Risk mitigation in supply chain digitization: System modularity and information technology governance	Xue et al.	2013	<i>Journal of Management Information Systems</i>
[20]	Role of information processing and digital supply chain in supply chain resilience through supply chain risk management	Rashid et al.	2024	<i>Journal of Global Operations and Strategic Sourcing</i>
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[29]	The effects of justice and top management beliefs and participation: An exploratory study in the context of digital supply chain management	Wei et al.	2020	<i>Journal of Business Ethics</i>
[30]	Dynamic voting classifier for risk identification in supply chain 4.0	Ali Salamai et al.	2021	<i>Computers, Materials & Continua</i>

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[31]	The future of Industry 4.0 and supply chain resilience after the COVID-19 pandemic: Empirical evidence from a Delphi study	Spieske et al.	2023	<i>Computers & Industrial Engineering</i>
[32]	Developing supply chain capabilities through digitalization and viability for controlling the ripple effect	Kumar et al.	2024	<i>IEEE Transactions on Engineering Management</i>
[33]	Digital transformation of supply chains and company's performance	Mielcarek et al.	2023	<i>LogForum</i>
[34]	PrFAHP-GT: A new privacy risk analysis framework using FAHP and game theory for digital supply chain management	Haghsefat et al.	2024	<i>IEEE Transactions on Engineering Management</i>
[35]	Investment strategies in Industry 4.0 for enhanced supply chain resilience: An empirical analysis	Al-Banna et al.	2024	<i>Cogent Business & Management</i>
[36]	Towards trustworthy AI for link prediction in supply chain knowledge graph: A neurosymbolic reasoning approach	Kosasih et al.	2025	<i>International Journal of Production Research</i>
[37]	A framework for smart supply chain risk assessment: An empirical study	Khan et al.	2023	<i>International Journal of Information Systems and Supply Chain Management</i>
[38]	The impact of manufacturing digital supply chain on supply chain disruption risks under uncertain environment: Based on dynamic capability perspective	Song et al.	2024	<i>Advanced Engineering Informatics</i>

These quantitative studies constitute the empirical core of the systematic review and examine the relationships between digitalization-related variables, risk management practices, and supply chain or organizational performance across diverse industrial contexts. The remaining studies were excluded from the quantitative synthesis due to the absence of exploitable empirical data.

4.2.2. Analytical focus and relationships examined

The quantitative studies retained in the systematic review investigate the contribution of supply chain digitalization to risk management, resilience, and performance outcomes. Rather than focusing on individual technologies in isolation, most studies adopt an integrated analytical perspective in which digitalization is conceptualized as a combination of technological enablers, organizational capabilities, and governance mechanisms.

From an analytical perspective, digitalization is generally treated as a multidimensional construct involving connectivity, information integration, and decision-support capabilities. Several studies analyze digitalization as a precursor to risk-related capabilities, including visibility, agility, flexibility, and coordination, which in turn influence supply chain resilience and organizational or supply chain performance.

Regarding the technologies examined, the empirical literature focuses on a core set of Industry 4.0 enablers. Internet of Things (IoT) technologies are frequently mobilized to enhance real-time visibility and traceability. Artificial intelligence and data analytics are investigated to support

predictive decision-making, disruption detection, and operational optimization. Digital twin technologies are employed to simulate disruption scenarios and assess system behavior under uncertainty, particularly in relation to ripple effects. Blockchain is addressed in a more limited number of studies, mainly in connection with transparency, trust, and security considerations, while information systems governance and modular IT architectures are examined as mechanisms for mitigating digitalization-related risks.

Overall, the analytical focus of the reviewed studies positions digital technologies as infrastructures supporting the development of operational and risk-related capabilities and performance improvement in digital supply chains, rather than as isolated technological solutions.

4.2.3. Methodological characteristics of the quantitative evidence

From a methodological perspective, the quantitative studies selected in the systematic review are mainly based on survey data, with empirical analyses conducted using regression techniques or structural equation modeling. Data are collected across a variety of sectors, including manufacturing, food supply chains, logistics, and industrial networks, often in contexts characterized by uncertainty or exposure to disruptions.

Despite differences in empirical contexts and variable operationalization, these studies converge in their objective to empirically assess how digitalization and risk-related mechanisms jointly influence supply chain outcomes. This methodological convergence supports their inclusion within a unified analytical framework.

4.2.4. Implications for meta-analytical synthesis

Among the twenty quantitative studies identified, eleven provided sufficient and methodologically compatible statistical information, including standardized coefficients or equivalent statistics, to allow for quantitative aggregation. These studies were therefore retained for the meta-analysis. The remaining quantitative studies were excluded due to limitations in statistical reporting, incompatibility of effect measures, or insufficient data availability.

4.3. *Meta-analysis results*

Based on eleven quantitative studies examining the relationship between supply chain digitalization, risk-related mechanisms, and performance outcomes, a random-effects meta-analysis using restricted maximum likelihood (REML) estimation was conducted. Detailed results are illustrated in the forest plot presented in Figure 7.

The meta-analysis was performed at the level of individual statistically tested relationships. Across the eleven included studies, a total of 71 distinct effect sizes were identified, each reflecting an empirically tested relationship linking a digitalization-related or organizational factor (e.g., digital adoption, modularity, risk perception) to a supply chain outcome (e.g., performance, resilience, agility, visibility, or risk management).

For each relationship, the standardized regression coefficient (β) was either extracted directly from the reported models or calculated when necessary using available statistical information. To ensure consistency and comparability across studies, associated statistics including standard errors,

p-values, t-values, and coefficients of determination (R^2) were systematically collected. This fine-grained extraction strategy was adopted to address the multidimensional and heterogeneous nature of the empirical evidence.

Despite variations in the operationalization of variables across studies, the analyzed relationships converge toward a shared analytical objective: examining how digital and risk-related dynamics influence supply chain performance and resilience. Therefore, the aggregation of these effects within a unified meta-analytical framework is methodologically justified.

The results indicate a positive and statistically significant combined effect of digitalization-related factors on supply chain outcomes ($\beta = 0.2511$; 95% $CI [0.1716; 0.3305]$; $p < 0.0001$). Substantial heterogeneity was observed across the estimated relationships ($Q(70) = 2655.89$, $p < 0.0001$; $I^2 = 97.94\%$; $\tau^2 = 0.1097$), justifying the use of a random-effects model.



Figure 7. Forest plot of the meta-analysis.

Potential publication bias was assessed using Egger's regression test, which did not indicate a statistically significant bias ($p = 0.2392$), despite a slight visual asymmetry in the funnel plot (Figure 8). To further assess the robustness of the findings, a Baujat plot was applied to identify influential observations. One relationship (No. 56) was found to contribute disproportionately to overall heterogeneity. Sensitivity analysis excluding this observation confirmed the stability of the results, with the combined effect remaining positive and statistically significant ($\beta = 0.2302$; 95% CI [0.163; 0.2970]; $I^2 = 97.07\%$; $\tau^2 = 0.0752$).

Building on these results, the following section discusses the findings in light of existing literature and theoretical frameworks on supply chain digitalization and risk management.

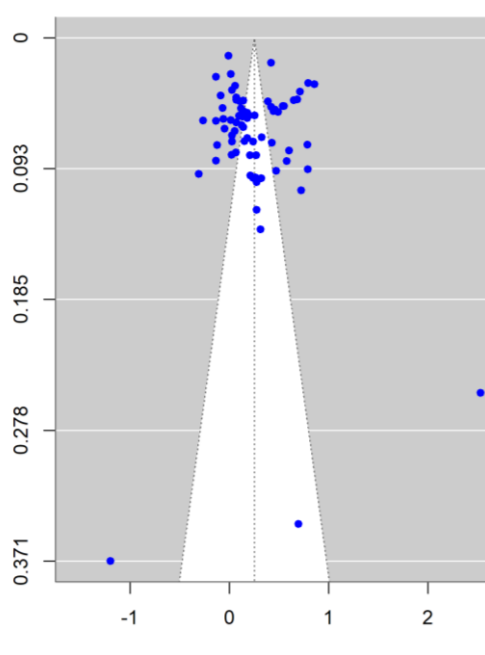


Figure 8. Funnel plot of the meta-analysis.

5. Discussion

5.1. Interpretation of the meta-analytical findings

The meta-analysis reveals a positive and statistically significant combined effect of supply chain digitalization on performance and risk-related outcomes. This finding indicates that, across the quantitative studies considered, higher levels of digitalization are associated with improvements in supply chain performance, resilience, visibility, agility, and risk management capabilities.

Rather than suggesting a uniform or deterministic impact, the observed effect reflects an overall tendency whereby digitalization enhances supply chain functioning under conditions of uncertainty. The moderate magnitude of the combined effect is consistent with the complex and contingent nature of digital transformation processes in supply chain contexts. These findings suggest that digitalization contributes to performance outcomes primarily through its interaction with organizational practices, coordination mechanisms, and risk management capabilities, rather than acting as an isolated driver.

Importantly, the meta-analytical evidence indicates that digital technologies function primarily as enabling infrastructures that support the development of higher-order capabilities. Across the

relationships analyzed, digitalization is most often associated with improvements in information visibility, decision-making, and coordination across supply chain actors, which in turn contribute to more effective anticipation, mitigation, and recovery from disruptions.

The results further suggest that the benefits of digitalization extend beyond efficiency gains to include risk-related outcomes, particularly supply chain resilience and robustness. This finding supports the notion that digital transformation contributes to a shift toward more proactive rather than reactive approaches to risk management, as improved data availability and analytical capabilities enable supply chains to better identify vulnerabilities, evaluate disruption scenarios, and adjust operations accordingly.

Taken together, the meta-analytical findings confirm that supply chain digitalization constitutes a significant, but non-sufficient, lever for enhancing supply chain performance and resilience. Its effectiveness depends on the extent to which digital tools are embedded in coherent organizational processes and aligned with structured risk management strategies.

5.2. Explaining heterogeneity across studies

The meta-analysis results indicate a substantial level of heterogeneity across the analyzed relationships, as reflected by the high I^2 value. This variability suggests that the effects of supply chain digitalization on performance and risk-related outcomes vary across contexts and are contingent upon multiple structural, organizational, and environmental factors.

One key source of heterogeneity lies in the diversity of empirical contexts represented in the quantitative studies. The analyzed studies span different industries, geographic regions, and levels of digital maturity. These contextual differences influence both the types of digital technologies adopted and the mechanisms through which digitalization relates to performance or resilience outcomes.

Methodological differences further contribute to heterogeneity. Although all studies rely on quantitative designs, they differ in terms of variable operationalization, model specification, and analytical techniques. Digitalization is alternately measured through indicators of technology adoption, perceived digital maturity, or specific technological capabilities, whereas outcome variables range from operational efficiency to resilience, agility, or disruption risk reduction.

Importantly, the observed heterogeneity does not undermine the validity of the combined effect. Instead, it highlights the complexity and context-dependence of digital transformation in supply chains. Robustness and sensitivity analyses confirm the stability of the overall positive effect. Consequently, heterogeneity should be interpreted as an intrinsic characteristic of the phenomenon studied rather than a methodological weakness.

5.3. Role of risk-related capabilities in digital supply chains

Beyond the direct association between digitalization and performance, the meta-analysis highlights the central role of risk-related capabilities in determining the effectiveness of digital transformation in supply chains. Across the analysis, digitalization contributes to improved outcomes primarily through intermediate capabilities related to risk management and operational adaptation.

Such capabilities include enhanced visibility, faster information processing, improved coordination among supply chain actors, and greater flexibility in responding to disruptions. Digital technologies contribute to the development of these capabilities through real-time data access,

analytical decision support, and inter-organizational integration. This highlights the mediating role of risk-related capabilities, rather than attributing performance improvements directly to technology adoption alone.

The results further suggest that risk-related capabilities mediate the relationship between digitalization and higher-level outcomes such as resilience and robustness. Supply chains using digital tools to proactively identify vulnerabilities, simulate disruption scenarios, and coordinate responses are better positioned to absorb shocks and recover effectively. This aligns with a shift toward more anticipatory and adaptive risk management approaches.

Overall, the study highlights that digitalization alone is not sufficient to enhance supply chain performance or resilience. Value is created when digital technologies are combined with organizational routines and risk management practices that enable the development of effective risk-related capabilities.

5.4. Contributions to the literature

This study contributes to the supply chain digitalization literature by combining a scoping review, a systematic review, and a meta-analysis within a single research design. While previous studies have often relied on narrative reviews, bibliometric analyses, or isolated empirical investigations, this multi-stage approach enables both an extensive mapping of the field and a rigorous quantitative synthesis of empirical evidence.

At an empirical level, the meta-analysis provides a consolidated quantitative assessment of the relationship between supply chain digitalization, risk-related mechanisms, and performance outcomes. The aggregation of 71 statistically tested relationships extracted from eleven compatible quantitative studies offers a more robust estimation of the overall effect of digitalization across diverse contexts.

From a theoretical perspective, the results support a capability-based interpretation of digital supply chains. The findings demonstrate that value emerges primarily through the development of risk-related and adaptive capabilities, rather than from digital technologies as direct performance drivers. This perspective helps explain divergent findings in the literature and clarifies the mechanisms through which digitalization contributes to resilience and performance.

5.5. Managerial implications

The findings highlight that investments in digital technologies should not be pursued as isolated technological initiatives. Instead, greater benefits are achieved when such investments are aligned with an integrated risk management approach designed to enhance supply chain visibility, coordination, and decision-making capabilities.

The results further emphasize the importance of organizational alignment. Digitalization tends to generate stronger outcomes when supported by appropriate governance structures, data-sharing practices, and cross-functional coordination.

5.6. Limitations and future research directions

Several limitations should be acknowledged. First, the meta-analysis is based on a relatively limited number of quantitatively compatible studies, reflecting both the emerging nature of the research

field and the diversity of empirical designs. Second, the high level of heterogeneity indicates that contextual factors play an important role in shaping digitalization outcomes, which could not be fully accounted for within the scope of the present synthesis.

Future research could extend this work by conducting meta-regressions to explicitly assess the moderating role of contextual variables such as industry, geographic region, or digital maturity. Longitudinal designs would also help clarify the dynamic effects of digitalization and risk-related capabilities over time. Further theoretical integration is also needed to consolidate fragmented perspectives on digitalization, risk management, and performance outcomes.

6. Conclusion

This study provides an integrated synthesis of the literature on supply chain digitalization and risk management through a three-stage research design combining a scoping review, a systematic review, and a meta-analysis. The findings confirm that supply chain digitalization is positively and significantly associated with performance and risk-related outcomes, including resilience, visibility, and agility.

Beyond direct performance effects, the results highlight the central role of risk-related capabilities in translating digital investments into tangible benefits. Digital technologies contribute primarily by enabling proactive risk management, improved coordination, and adaptive responses to disruption, rather than acting as standalone performance drivers.

Overall, this study adopts a capability-based perspective on digital supply chains and provides evidence-based insights for both researchers and practitioners seeking to design resilient and digitally enabled supply chain strategies in increasingly uncertain environments.

Author Contributions

N.H. conceived the study, designed the methodology, conducted the literature review, performed the analyses, and drafted the manuscript. A.M. provided scientific supervision, methodological validation, and critically revised the manuscript. All authors approved the final version of the manuscript.

Use of Generative-AI tools declaration

The authors declare that generative artificial intelligence tools (ChatGPT, OpenAI) were used for language editing and stylistic refinement during the preparation of the manuscript. The tool were not used for data collection, data analysis, interpretation of results, or decision-making. The authors take full responsibility for the content of the manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

References

1. G. Büyüközkan, F. Göçer, Digital supply chain: Literature review and a proposed framework for future research, *Comput. Ind.*, **97** (2018), 157–177. <https://doi.org/10.1016/j.compind.2018.02.010>
2. M. M. H. Shahadat, A. H. M. Y. Chowdhury, R. J. Nathan, M. Fekete-Farkas, Digital technologies for firms' competitive advantage and improved supply chain performance, *J. Risk Financ. Manag.*, **16** (2023), 94. <https://doi.org/10.3390/jrfm16020094>
3. F. Almeida, J. D. Santos, J. A. Monteiro, The challenges and opportunities in the digitalization of companies in a post-COVID-19 world, *IEEE Eng. Manag. Rev.*, **48** (2020), 97–103. <https://doi.org/10.1109/EMR.2020.3013206>
4. H. W. Zhang, Y. Lv, S. Zhang, Y. D. Liu, Digital supply chain management: A review and bibliometric analysis, *J. Glob. Inf. Manag.*, **32** (2024), 1–20. <https://doi.org/10.4018/JGIM.336285>
5. A. A. A. Ali, A. A. S. Fayad, A. Alomair, A. S. A. Naim, The role of digital supply chain on inventory management effectiveness within engineering companies in Jordan, *Sustainability*, **16** (2024), 8031. <https://doi.org/10.3390/su16188031>
6. M. Nasiri, J. Ukko, M. Saunila, T. Rantala, Managing the digital supply chain: The role of smart technologies, *Technovation*, **96** (2020), 102121. <https://doi.org/10.1016/j.technovation.2020.102121>
7. B. Tjahjono, C. Esplugues, E. Ares, G. Pelaez, What does Industry 4.0 mean to supply chain? *Procedia Manuf.*, **13** (2017), 1175–1182. <https://doi.org/10.1016/j.promfg.2017.09.191>
8. H. Aslam, A. Ur Rehman, A. Iftikhar, M. Z. U. Haq, U. Akbar, M. M. Kamal, Digital transformation: Unlocking supply chain resilience through adaptability and innovation, *Technol. Forecast. Soc. Change*, **219** (2025), 124234. <https://doi.org/10.1016/j.techfore.2025.124234>
9. H. Mak, Z. M. Shen, When Triple-A supply chains meet digitalization: The case of JD.com's C2M model, *Prod. Oper. Manag.*, **30** (2021), 656–665. <https://doi.org/10.1111/poms.13307>
10. J. K. Shah, M. Sharma, S. Joshi, Digital supply chain management: A comprehensive review using cluster analysis, with future directions and open challenges, *Int. J. Supply Oper. Manag.*, **10** (2023), 337–364. <https://doi.org/10.22034/ijssom.2023.109914.2739>
11. R. Ishfaq, B. Davis-Sramek, B. Gibson, Digital supply chains in omnichannel retail: A conceptual framework, *J. Bus. Logist.*, **43** (2022), 169–188. <https://doi.org/10.1111/jbl.12277>
12. A. Annarelli, C. Battistella, F. Nonino, V. Parida, E. Pessot, Literature review on digitalization capabilities: Co-citation analysis of antecedents, conceptualization and consequences, *Technol. Forecast. Soc. Change*, **166** (2021), 120635. <https://doi.org/10.1016/j.techfore.2021.120635>
13. D. Tortora, R. Chierici, M. F. Briamonte, R. Tiscini, 'I digitize so I exist': Searching for critical capabilities affecting firms' digital innovation, *J. Bus. Res.*, **129** (2021), 193–204. <https://doi.org/10.1016/j.jbusres.2021.02.048>
14. B. Dethine, M. Enjolras, D. Monticolo, Digitalization and SMEs' export management: Impacts on resources and capabilities, *Technol. Innov. Manag. Rev.*, **10** (2020), 18–34. <https://doi.org/10.22215/timreview/1344>
15. M. M. Queiroz, S. C. F. Pereira, R. Telles, M. C. Machado, Industry 4.0 and digital supply chain capabilities: A framework for understanding digitalisation challenges and opportunities, *Benchmarking Int. J.*, **28** (2021), 1761–1782. <https://doi.org/10.1108/BIJ-12-2018-0435>

16. A. Dolgui, D. Ivanov, 5G in digital supply chain and operations management: Fostering flexibility, end-to-end connectivity and real-time visibility through internet-of-everything, *Int. J. Prod. Res.*, **60** (2022), 442–451. <https://doi.org/10.1080/00207543.2021.2002969>
17. P. Agrawal, R. Narain, I. Ullah, Analysis of barriers in implementation of digital transformation of supply chain using interpretive structural modelling approach, *J. Model. Manag.*, **15** (2020), 297–317. <https://doi.org/10.1108/JM2-03-2019-0066>
18. K. Adu-Amankwa, A. Daly, Securing innovation in digital manufacturing supply chains: An interdisciplinary perspective on intellectual property, technological protection measures and 3D printing/additive manufacturing, *J. Intellect. Prop. Law Pract.*, **18** (2023), 615–618. <https://doi.org/10.1093/jiplp/jpad062>
19. L. Xue, C. Zhang, Risk mitigation in supply chain digitization: System modularity and information technology governance, *J. Manag. Inf. Syst.*, **30** (2013), 325–352. <https://doi.org/10.2753/MIS0742-1222300110>
20. A. Rashid, R. Rasheed, A. H. Ngah, M. D. R. Jayaratne, S. Rahi, M. N. Tunio, Role of information processing and digital supply chain in supply chain resilience through supply chain risk management, *J. Glob. Oper. Strateg. Sourc.*, **17** (2024), 429–447. <https://doi.org/10.1108/JGOSS-12-2023-0106>
21. S. Joshi, M. Sharma, Sustainable performance through digital supply chains in Industry 4.0 era: Amidst the pandemic experience, *Sustainability*, **14** (2022), 16726. <https://doi.org/10.3390/su142416726>
22. B. A. A. Kurdi, H. M. Alzoubi, M. T. Alshurideh, E. K. K. Alquqa, S. Hamadneh, Impact of supply chain 4.0 and supply chain risk on organizational performance: An empirical evidence from the UAE food manufacturing industry, *Uncertain Supply Chain Manag.*, **11** (2023), 111–118. <https://doi.org/10.5267/j.uscm.2022.11.004>
23. A. A. A. Sharabati, H. Z. Awawdeh, S. Sabra, H. K. Shehadeh, A. Ali, The role of artificial intelligence on digital supply chain in industrial companies: Mediating effect of operational efficiency, *Uncertain Supply Chain Manag.*, **12** (2024), 1867–1878. <https://doi.org/10.5267/j.uscm.2024.2.016>
24. L. Jum'a, D. Alkhodary, Navigating the Industry 4.0 frontier: Unveiling perceived risk and cost moderators in technology adoption, *EM Ekon. Manag.*, **27** (2024), 53–71. <https://doi.org/10.15240/tul/001/2024-5-006>
25. B. Y. Barqawi, M. S. A. Shibly, M. H. A. Jomaa, M. Alharafsheh, S. M. Abulehyeh, Digital supply chain adoption: An empirical result from food industry, *Uncertain Supply Chain Manag.*, **11** (2023), 755–762. <https://doi.org/10.5267/j.uscm.2023.1.005>
26. T. Khan, M. M. H. Emon, Supply chain performance in the age of Industry 4.0: Evidence from manufacturing sector, *Braz. J. Oper. Prod. Manag.*, **22** (2025), 2434. <https://doi.org/10.14488/BJOPM.2434.2025>
27. B. Moon, S. J. Chae, The impact of COVID-19 on value relevance in distribution and service industries, *J. Distrib. Sci.*, **22** (2024), 101–108. <https://doi.org/10.15722/jds.22.11.202411.101>
28. S. Aziz, P. Kumar, A. B. Khan, Assessing the impact of digital supply chain management on the sustainability of construction projects, *Rev. Bus. Econ. Stud.*, **12** (2024), 60–73. <https://doi.org/10.26794/2308-944X-2024-12-3-60-73>

29. S. B. Wei, W. L. Ke, A. A. Lado, H. F. Liu, K. K. Wei, The effects of justice and top management beliefs and participation: An exploratory study in the context of digital supply chain management, *J. Bus. Ethics*, **166** (2020), 51–71. <https://doi.org/10.1007/s10551-018-04100-9>
30. A. A. Salamai, E. S. M. El-Kenawy, I. Abdelhameed, Dynamic voting classifier for risk identification in supply chain 4.0, *Comput. Mater. Contin.*, **69** (2021), 3749–3766. <https://doi.org/10.32604/cmc.2021.018179>
31. A. Spieske, M. Gebhardt, M. Kopyto, H. Birkel, E. Hartmann, The future of Industry 4.0 and supply chain resilience after the COVID-19 pandemic: Empirical evidence from a Delphi study, *Comput. Ind. Eng.*, **181** (2023), 109344. <https://doi.org/10.1016/j.cie.2023.109344>
32. M. Kumar, R. D. Raut, A. Gunasekaran, M. Venkateshwarlu, V. K. Choubey, Developing supply chain capabilities through digitalization and viability for controlling the ripple effect, *IEEE Trans. Eng. Manag.*, **71** (2024), 10341–10357. <https://doi.org/10.1109/TEM.2022.3233860>
33. P. Mielcarek, A. Piekarczyk, Digital transformation of supply chains and company's performance, *LogForum*, **19** (2023), 47–57. <https://doi.org/10.17270/J.LOG.2023.829>
34. S. Haghsefat, M. T. T. Ahvanooey, H. Song, C. Z. Liu, K. K. R. Choo, PrFAHP-GT: A new privacy risk analysis framework using FAHP and game theory for digital supply chain management, *IEEE Trans. Eng. Manag.*, **71** (2024), 11718–11733. <https://doi.org/10.1109/TEM.2024.3428840>
35. A. Al-Banna, M. Yaqot, B. C. Menezes, Investment strategies in Industry 4.0 for enhanced supply chain resilience: An empirical analysis, *Cogent Bus. Manag.*, **11** (2024), 2298187. <https://doi.org/10.1080/23311975.2023.2298187>
36. E. E. Kosasih, A. Brintrup, Towards trustworthy AI for link prediction in supply chain knowledge graph: A neurosymbolic reasoning approach, *Int. J. Prod. Res.*, **63** (2025), 2268–2290. <https://doi.org/10.1080/00207543.2024.2399713>
37. K. Khan, A. Keramati, A framework for smart supply chain risk assessment: An empirical study, *Int. J. Inf. Syst. Supply Chain Manag.*, **16** (2023), 1–17. <https://doi.org/10.4018/IJISSCM.316167>
38. H. C. Song, R. Chang, H. S. Cheng, P. Liu, D. W. Yan, The impact of manufacturing digital supply chain on supply chain disruption risks under uncertain environment-Based on dynamic capability perspective, *Adv. Eng. Inform.*, **60** (2024), 102385. <https://doi.org/10.1016/j.aei.2024.102385>



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