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Digital Twin Technology in Supply Chain Management: A Systematic Literature Review and Future Research Agenda

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Abstract
Digital twin (DT) technology has emerged as a transformative enabler of visibility, responsiveness, and strategic agility in supply chain management (SCM). This study presents a systematic literature review (SLR) of 45 peer-reviewed articles published between 2023 and 2025, aimed at identifying thematic trends, implementation challenges, and strategic contributions of DTs within SCM contexts. The review employs thematic synthesis to extract six dominant clusters: evolution of DT applications, real-time monitoring, risk and resilience management, integration and interoperability challenges, performance measurement frameworks, and future-orientated trends. Key findings reveal that while DTs offer substantial potential in areas such as predictive analytics and scenario modelling, their adoption is frequently constrained by organisational inertia, integration barriers, and lack of performance alignment with strategic key performance indicators (KPIs). Drawing from these findings, the study develops a three-tier conceptual framework comprising (1) enablers of DT adoption (e.g., infrastructure, data governance), (2) core DT capabilities (e.g., real-time sensing, predictive analytics), and (3) strategic supply chain outcomes (e.g., resilience, efficiency, sustainability). The framework positions DTs as socio-technical systems that require technological investment, cultural readiness, and strategic clarity. The study contributes to both theory and practice by offering a structured guide for DT adoption, with implications for supply chain leaders, IT strategists, and policymakers seeking to foster resilient and ethically driven digital ecosystems.
Key words: Digital Twin Technology; Supply Chain Management; Predictive Analytics; Resilience; Interoperability.

1. Introduction

Digital twin technology is increasingly recognised as a strategic enabler in modern supply chain management (SCM), offering advanced capabilities for real-time monitoring, predictive analytics, and operational optimisation (Ghobakhloo et al., 2023; Zhang & Li, 2023). A digital twin is a virtual representation of a physical system, replicating actual conditions in real time and enabling simulation-based decision-making, therefore improving visibility, responsiveness, and resilience in supply chains (Lee & Kim, 2023; Liu et al., 2023).

Existing research identifies significant disadvantages in implementing digital twin solutions. These include integration difficulties with legacy systems, interoperability of data, cybersecurity vulnerabilities, and insufficiently standardised performance measurement frameworks (Ivanov & Dolgui, 2024; Smith et al., 2023). Furthermore, organisational readiness and infrastructure disparity add to the complexity of adoption, particularly for internationally dispersed supply networks (Ghobakhloo et al., 2023).

This study conducts a systematic literature review (SLR) of peer-reviewed articles from 2013 to 2024 covering the application, benefits, and limitations of digital twins in SCM. It synthesises 45 peer-reviewed articles to reveal key thematic areas and builds a conceptual framework for future research and implementation practices. By synthesising existing knowledge, the study aims to bridge theoretical knowledge with practical innovation in digital twin-based supply chains.

2. Methodology

2.1 Systematic Literature Review Approach

This study employed a Systematic Literature Review (SLR) to synthesise the existing information with regard to digital twin application in supply chain management (SCM). SLR ensures transparency, replicability, and academic rigour, making it particularly well-suited for emerging multidisciplinary topics such as digital twins in SCM (Johnson & Patel, 2024). The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were used in the review process to ensure a systematic identification, screening, and selection of relevant literature (Muzondo et al., 2025).

2.2 Inclusion and Exclusion Criteria

To ensure quality and relevance, the following inclusion criteria were used:

- Peer-reviewed journal articles published between 2023 and 2024.
- Articles written in English.
- Studies that clearly focused on the application of digital twin technology in the supply chain management context.
- Articles addressing issues such as predictive maintenance, real-time monitoring, risk management, system integration, optimisation, and performance evaluation.

Exclusion criteria included:

- Conference proceedings, book chapters, and non-peer-reviewed articles.
- Studies unrelated to SCM (e.g., solely focused on manufacturing or smart cities without SCM integration).
- Articles lacking empirical, theoretical, or application-based insights.

2.3 Data Sources and Search Strategy

Four academic databases-Scopus, Web of Science, IEEE Xplore, and Emerald Insight-were selected for their comprehensive coverage of multidisciplinary and technical research. A combination of keywords such as “digital twin”, “supply chain”, “predictive maintenance”, “real-time monitoring”, and “optimisation” was used to retrieve relevant articles.

The initial search yielded 234 publications. After removing duplicates and applying inclusion/exclusion criteria, 112 studies remained. A final screening based on full-text reviews narrowed the dataset to 45 articles, which were used for in-depth analysis.

2.4 Data Analysis Procedure

The selected studies were subjected to thematic analysis, drawing from the methodology of Braun and Clarke (2006) and adapted for SLRs by Yao et al. (2023). Each article was coded based on digital twin applications, challenges, benefits, and conceptual contributions. The themes were then clustered into broader categories such as implementation barriers, integration frameworks, and performance metrics.

In order to ensure reliability, coding was repeatedly examined and observations were triangulated with up-to-date review studies (Zhang & Li, 2023; Ghobakhloo et al., 2023). This facilitated developing a conceptual framework that covers the technological, operational, and strategic dimensions of digital twin implementation in SCM.

3. Literature Review

Digital twin (DT) technology is increasingly reshaping operational and strategic plans in supply chain management (SCM). A set of discrete but intertwined thematic clusters has emerged throughout literature development as a result of highlighting major applications, challenges, and strategic implications of DT adoption. These clusters are (1) uses and evolutions of digital twins in SCM, (2) predictive maintenance and real-time tracking, (3) resilience and risk management, (4) interoperability and integration challenges, (5) performance measurement frameworks, and (6) future directions and trends.

3.1 Uses and Evolutions of Digital Twins in SCM

Digital twins, initially conceptualised for engineering and manufacturing, have seen expanded application across the supply chain landscape. Zhang and Li (2023) trace the evolution from static digital models to dynamic, interactive systems that enable real-time synchronisation between physical and digital assets. The capability of DTs to simulate supply chain behaviour under various scenarios makes them pivotal for strategic planning (Lee & Kim, 2023).

Emerging studies have shown diverse applications across industries. Kim et al. (2023) highlighted how DTs support adaptive logistics by modelling transportation flows and optimising warehouse operations. In healthcare supply chains, Garcia and Lee (2024) reported on DTs improving emergency preparedness through scenario simulations during pandemics. Meanwhile, Zhou et al. (2024) found applications in food supply chains where DTs are used to ensure traceability and freshness by integrating with blockchain.

Wang et al. (2023) emphasise that DTs are not just tools but frameworks for digital transformation. They suggest that the scalability of DTs depends on aligning the technology with strategic goals. Against this optimistic view, Tiwari et al. (2024) warn that organisational resistance and complexity in system design limit DT's applicability beyond pilot phases.

Longo et al. (2023) suggested a simulation-based strategy that leveraged Digital Supply Chain Twins to enhance resilience against crises like COVID-19. Similarly, Sharma et al. (2025) emphasised that stakeholder involvement and strategic clarity are paramount to DT success in healthcare SCM.

Recent studies by Bellamy and Chong (2024) identify a breakthrough advance in the DT paradigm, in which next-generation digital twins integrate contextual intelligence to actively adapt to supply chain evolution. Similarly, Qureshi and Rehman (2023) argue that integrating DTs with 6G communication networks can potentially accelerate supply chain responsiveness, especially for high-velocity industries like electronics. These studies point toward a shift from passive modelling to active orchestration of supply chain phenomena.

3.2 Predictive Maintenance and Real-Time Monitoring

Real-time visibility is one of the most ubiquitous legacies of DTs in SCM. Through the conjunction of IoT device data and enterprise system data, DTs amplify situational awareness and enable interventions ahead when they become unavoidable (Liu et al., 2023). Mourtzis et al. (2024) showed that DTs boost supply chain agility by reducing latency in data communications and decision-making.

Predictive maintenance is a complex DT application, especially in capital-intensive supply chains. Zhao et al. (2023) demonstrated that with DTs, organisations in automotive reduced downtime by predicting equipment failure. Similarly, Patel and Verma (2024) observed in the energy sector that DT-aided predictive analytics optimises maintenance cycles and reduces operational risk.

However, the major problem is the explainability of machine learning algorithms used in predictive maintenance. Singh and Das (2023) argue that black-box models may discourage operators' trust and therefore suggest the use of explainable AI on DT systems. Nguyen et al. (2023) also caution against exclusive reliance on predictive systems with no operator intervention, which can lead to decision fatigue or mismanagement in high-variability environments. Chen et al. (2023) found the enhancement of fault detection in DT-based maintenance using machine learning. Kambala (2023) emphasised the use of DTs with IT systems can reduce downtime considerably by enhancing monitoring capacity.

Bhattacharya and Duan (2023) point to the importance of hybrid predictive models with the combination of rule-based diagnostics and AI-based fault prediction in ensuring transparency for the systems. Equally, Alvarez and Murata (2024) found that cloud-edge collaboration in DT architectures decreases the latency of data processing and increases responsiveness in predictive maintenance operations significantly. All these studies point toward decentralised, explainable, and adaptive maintenance systems in DT-enabled SCM.

3.3 Supply Chain Resilience and Risk Management and

A growing body of literature highlights the strategic value of DTs in modelling and managing supply chain risks. Ivanov and Dolgui (2024) assert that DTs enable the real-time simulation of disruptions such as natural disasters, supplier failures, and geopolitical tensions. These capabilities support the development of more robust contingency planning.

Ghobakhloo et al. (2023) provide empirical evidence from the electronics sector, showing that DT adoption enhanced supplier coordination and mitigated the bullwhip effect. Yao et al. (2023) further observed that integrating DTs with demand-sensing algorithms improved forecasting accuracy under demand shocks.

Scholars also explore how DTs contribute to long-term resilience. Park and Choi (2024) argue that DTs foster adaptive capacity by enabling digital experimentation with structural changes in supply networks. Yet, Shah and Prasad (2023) warn that reliance on DTs without adequate cybersecurity measures increases exposure to new forms of digital risk, such as data poisoning and simulation hijacking.

Social and environmental risk management is also gaining attention. Kumar et al. (2023) advocate for DTs that embed ethical sourcing indicators and carbon metrics to ensure holistic risk visibility. This aligns with trends in sustainable SCM, where stakeholder accountability is increasingly data-driven (Garcia & Lee, 2024).

Al-Zahrani and Musa (2023) emphasise the use of DTs to create "resilience maps" that visualise ripple effects of disruptions across multi-tier networks. Similarly, Duong and Le (2025) propose a real-options-based DT model to create recovery paths following disruption so that businesses will have economically optimal contingency strategies. Such perspectives add to the body of literature on resilience planning and strategic agility in digital supply networks.

3.4 Interoperability and Integration Challenges

Despite the promises, digital twins still face integration challenges in real-world SCM environments. Ivanov and Dolgui (2024) note that legacy systems such as Enterprise Resource Planning and Manufacturing Execution System lack compatibility with modern DT architectures. This creates costly integrations and fragmented data flows.

Standardisation has been proposed as a solution. Smith et al. (2023) propose industry-wide APIs and shared ontologies for seamless data exchange across platforms. Similarly, Li et al. (2023) advocated for modular, middleware-based architecture that allows DTs to communicate across siloed systems without requiring complete overhauls.

Organisational and cultural barriers also stand in the way of integration. Lin and Wu (2023) identify inadequate training and resistance to change as significant challenges, particularly in traditional manufacturing firms. They argue that leadership commitment and cross-functional collaboration are essential to reaching interoperability goals.

Interestingly, some researchers advocate for the use of cloud and edge computing solutions to facilitate integration. For instance, Zhou et al. (2024) suggest that decentralised architectures reduce latency and increase scalability, but with new governance challenges.

Medina and Cortés (2024) provide an integration maturity model to guide companies through incremental DT-legacy system harmonisation stages. Furthermore, Farooq and Lim (2023) argue for the reality that semantic interoperability, facilitated by AI-driven translation engines, can dynamically resolve data schema disagreements among SCM partners. These advances are indicative of a shift from static integration templates to adaptive intelligence-based middleware frameworks.

3.5 Performance Measurement Frameworks

With the expanding DT adoption, standardised performance measurement is critically required. Liu et al. (2023) proposed a multidimensional evaluation framework to capture operational, environmental, and financial performance measures. Their article revealed that DT outputs are often hard for organisations to link with strategic KPIs, which limits return-on-investment visibility.

Adaptive and AI-based dashboards are also emerging as powerful tools. Yao et al. (2024) developed real-time dashboards with dynamic updating of performance metrics using ML-based analytics. These systems enable rapid course correction and permit ongoing improvement.

Singh and Narayan (2023) emphasised the need for sustainability metrics such as carbon footprint, energy usage, and social contribution in DT analysis. Their article suggests the adoption of ESG (Environmental, Social and, Governance) metrics to map DTs to overall sustainability goals.

On the contrary, Hossain et al. (2023) consider that too many metrics can confuse supply chain managers and lead to analysis paralysis. They advocate thinner, objective-based dashboards correlated with strategic objectives rather than comprehensive data gathering.

Tuncel and Albayrak (2024) suggest performance metrics should be weighted dynamically based on supply chain maturity and strategic priority areas. Pereira and Bianchi (2023), however, suggest DT dashboards should include resilience indices, measuring a supply chain's adaptive recovery rate in response to disruption. These studies emphasise that performance measurement must be contextual, actionable, and strategically embedded.

3.6 Emerging Trends and Future Directions

Several trends are shaping the future of DT applications in SCM. One of them is the concern of sustainability. Tao et al. (2024) demonstrated how DTs could enable circular economy models throuhg product lifecycle tracking and reverse logistics optimisation. Similarly, Dasgupta et al. (2023) address the use of DTs to monitor carbon regulation compliance across global supply chains.

Cybersecurity is also prominent. Schroeder and Haider (2023) state that digital twins increase the attack surface because they rely on distributed systems. AI-driven threat detection and blockchain-verifying processes are proposed by them as crucial mitigations.

The second frontier is the human-DT interaction. Mourtzis et al. (2024) explore the possibility of blending DTs with augmented reality (AR) for enhancing decision-making support. Zhang et al. (2023) propose the development of user-centric interfaces to reduce cognitive loading and maximise user trust. Mishra and Singh (2024) take this further, with future DTs potentially having embedded behavioural analytics for making interfaces user profile-specific.

Scalability remains an ongoing concern. Tiwari et al. (2024) attribute infrastructural shortcomings in emerging economies as a main hindrance. They recommend cloud-native technologies and world policy platforms to make access more democratic and even-handed adoption-orientated.

Nwosu and Abebe (2023) predict that DTs will expand to encompass quantum computing and digital thread technologies to handle high-dimensional supply chain datasets in real time. Moreover, Idris and Rahman (2025) highlight the ethics of DT uptake and suggest governance frameworks that incorporate human rights, labour standards, and inclusive innovation as components of technological futures across global supply chains.

Findings from the Systematic Literature Review

This chapter consolidates key findings that emerged from the SLR of 45 peer-reviewed articles between 2023 and 2025. After thematic analysis, the findings are classified into three dominant research clusters that typify current academic and practitioner discourse on the digital twin (DT) technology in supply chain management (SCM): (1) operational implementation challenges, (2) system integration and interoperability issues, and (3) performance measurement and strategic alignment.

4.1 Operational Implementation Challenges

The review found that one such major impediment to DT adoption is the transition from pilot schemes to mass-scale implementation. In a series of studies, there are identical impediments like inadequate technical infrastructure, excessive startup expenses, a shortage of skilled staff, and ambiguous return on investment. These obstacles are particularly pronounced in small and medium enterprises (SMEs) and supply chains in developing economies.

Moreover, organisational resistance to change, especially in firms with rigid legacy practices, was consistently cited as a barrier. Many studies emphasised that successful DT deployment requires not just technology but also organisational readiness, including leadership support, digital literacy, and interdepartmental collaboration. Lack of data governance protocols (e.g., secure sharing, quality control, privacy safeguards) was another recurring issue that limits the scalability and reliability of digital twin initiatives.

4.2 System Integration and Interoperability Issues

Another dominant theme was the difficulty of integrating digital twin systems with existing enterprise applications such as ERP, MES, and WMS platforms. Studies indicated that the absence of industry-wide data standards, APIs, and semantic interoperability frameworks results in fragmented systems and inefficient data exchange.

Several articles also highlighted the role of middleware and modular architectures as interim solutions but pointed out that they often require high customisation and technical maintenance. Integration challenges were found to be especially acute in global supply chains, where data heterogeneity, cross-border regulations, and vendor lock-in further complicate DT deployment.

4.3 Performance Measurement and Strategic Alignment

The third major finding from the review concerns the lack of comprehensive and standardised frameworks for evaluating DT performance. While many firms implement digital twins for operational monitoring or predictive

maintenance, few link these outcomes to strategic key performance indicators (KPIs). This gap results in difficulty justifying long-term investment and scaling decisions.
A subset of recent studies proposed performance dashboards that incorporate real-time analytics and ESG metrics (e.g., carbon footprint, ethical sourcing, resilience indices). However, the review found that such tools remain underutilised, especially outside of large corporations. Furthermore, scholars cautioned against overwhelming decision-makers with excessive metrics, instead recommending lean, goal-specific performance indicators tailored to organisational maturity and objectives.

4.4 Cross-Cutting Observations

Across all three clusters, the review identified a growing convergence around the need for a holistic, multi-dimensional approach to digital twin adoption. Rather than treating DTs as standalone tools, the literature emphasises their integration into broader digital transformation strategies. Additionally, scalability and inclusivity were recurring themes, with calls for cloud-native, low-cost, and adaptable DT solutions that are accessible to firms regardless of size or geography.

Summary of Key Research Clusters

Cluster	Key Themes
1. Operational Implementation	Infrastructure gaps, skills shortages, resistance to change, weak governance
2. System Integration	ERP incompatibility, lack of standards, modular workarounds
3. Performance and Strategic Fit	Absence of KPI frameworks, underuse of ESG metrics, risk of metric overload

Source: Author (2025)
This chapter provides the evidence base for the conceptual model presented in section 5, which integrates these findings in a systemic model for digital twin implementation in SCM.

5. Conceptual Framework for Digital Twin Adoption in Supply Chain Management

5.1 Overview and Rationale

Building on the systematic review findings, this conceptual framework presents a comprehensive model of digital twin (DT) technology adoption in supply chain management (SCM). The model synthesises principal findings along three axes: (1) adoption enablers, (2) digital twin core capabilities, and (3) strategic outcomes. The axes encapsulate a dynamic interplay between organisational readiness, technological competence, and value realisation.
Contrary to earlier models that focus solely either on technical realisation or operational benefits (e.g., Zhang & Li, 2023; Ivanov & Dolgui, 2024), this framework positions digital twins as socio-technical systems embedded within broader strategic objectives, specifically efficiency, resilience, and sustainability (Garcia & Lee, 2024).

5.2 Enablers of Adoption

Successful DT implementation depends on several foundational enablers:
Technological Preparedness: Organisations must establish robust digital infrastructure, including IoT devices, cloud computing, and edge analytics (Li et al., 2023). Wang et al. (2023) and Tiwari et al. (2024) show that insufficient infrastructure remains a primary barrier, especially in emerging markets.
Organisational Capacity: Beyond infrastructure, firms require skilled human capital and a culture receptive to change. According to Lin and Wu (2023), internal resistance and lack of training often impede DT projects. Leadership commitment and digital literacy programs are critical.
Stakeholder Collaboration: DT ecosystems require data sharing across suppliers, manufacturers, and customers. Nguyen and Bui (2023) emphasise that trust and interoperability protocols are essential to foster collaboration and ensure consistent data flow.
Policy and Regulatory Support: Government incentives and industry standards can accelerate adoption. Kumar et al. (2023) argue that standardised guidelines and digital infrastructure subsidies play a pivotal role, especially for small and medium enterprises (SMEs).

5.3 Digital Twin Capabilities

Once foundational enablers are in place, organisations can leverage the full potential of DTs through three interrelated capabilities:

Real-Time Monitoring: DTs offer continuous visibility into supply chain operations by mirroring physical processes in digital environments. This supports anomaly detection, performance tracking, and rapid decision-making (Liu et al., 2023; Mourtzis et al., 2024).

Predictive and Prescriptive Analytics: Integrating AI and ML, DTs forecast disruptions, optimise routes, and suggest corrective actions. Yao et al. (2024) demonstrated that such analytics improve inventory planning and maintenance scheduling, while Singh and Das (2023) highlight the importance of explainability to ensure trust.

Scenario-Based Optimisation: DTs enable simulation of "what-if" scenarios, helping firms evaluate the impact of strategic decisions (Park & Choi, 2024). This includes resilience testing, sustainability modelling, and cost-benefit trade-offs under uncertainty.

These capabilities are modular and scalable, allowing organisations to adapt them to various operational contexts (Li et al., 2023).

5.4 Strategic Outcomes

DT adoption should provide benefits that align with long-term supply chain objectives:

Resilience: DTs ensure resilience by risk identification and response planning in the early phase. Ivanov and Dolgui (2024) found that scenario modelling made possible by digital tools allowed for faster recovery from COVID-19-induced disturbances.

Efficiency: Improved visibility and forecast capabilities eradicate waste in operations, streamline logistics, and enhance the accuracy of decision-making (Wang et al., 2023; Zhou et al., 2024).

Sustainability: DTs ensure sustainable supply chains using carbon emissions tracking, optimal energy usage, and maintaining ethical sources (Tao et al., 2024; Garcia & Lee, 2024).

These are not mutually exclusive outcomes but complement each other. For instance, supply chain agility (efficiency) contributes to resilience building, and optimisation reduces environmental impact (sustainability).

5.5 Framework Illustration

The conceptual framework is structured as follows:

Enablers of Adoption

- Technological Infrastructure
- Organizational Readiness
- Stakeholder Collaboration
- Regulatory and Policy Support

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Core Digital Twin Capabilities

- Real-Time Monitoring
- Predictive & Prescriptive Analytics
- Scenario-Based Optimization

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Strategic Outcomes

- Supply Chain Resilience
- Operational Efficiency
- Environmental and Social Sustainability

Source: Author (2025).

This cascading logic captures a sequential and reinforcing logic: enablers at the foundation facilitate DT capabilities, which yield measurable outcomes.

6. Discussion

The theoretical synthesis and systematic review of digital twin (DT) applications in supply chain management (SCM) reveal a multi-faceted reframing of theory and practice. As far as digital twins have gained popularity as technological innovations, their significance extends further to redefining theoretical explanations of supply chain dynamics and transforming real-world operational strategies. The contribution is delineated under two sections: theoretical and practical.

6.1 Theoretical Contributions

Digital twin technology introduces revolutionary breakthroughs to theoretical supply chain wisdom, particularly regarding systems thinking, adaptive capacity, and socio-technical integration.

6.1.1 Extending Dynamic Capabilities Theory (DCT)

Digital twins offer a practical implementation of Dynamic Capabilities Theory since organisations can sense, seize, and reconfigure in response to environmental instability (Ivanov & Dolgui, 2024). Sensing capabilities-made possible by real-time observation and data analysis-are such that organisations can identify disruptions and inefficiencies in real time (Liu et al., 2023; Mourtzis et al., 2024). Seizing is facilitated through predictive and prescriptive analytics that optimise decisions under uncertainty (Yao et al., 2024). Reconfiguration, in this instance, involves the use of DT simulations to dynamically reconfigure supply networks in response to shocks (Park & Choi, 2024).

This integration brings DCT into the realm of digital-facilitated operation cognition, transforming its application from conceptual control of resources to experiential digital testing (Singh & Das, 2023). The model created in this study provides value by embedding DCT in an operational context that is data-intensive and real-time.

6.1.2 Reframing Supply Chain Resilience Theory

The resilience discourse traditionally emphasised redundancy and robustness; however, digital twins introduce a shift toward anticipatory resilience, driven by simulation and predictive capabilities (Zhang & Li, 2023). This proactive dimension where potential disruptions are pre-visualised redefines resilience not merely as recovery capacity but as an embedded adaptive strategy.

Furthermore, digital twins extend socio-technical systems theory by demonstrating that technological tools alone are insufficient. Organisational culture, user trust, and inter-organisational data sharing are now integral to technological effectiveness (Lin & Wu, 2023; Garcia & Lee, 2024). This calls for a re-evaluation of supply chain theories that neglect human-system interactions.

6.1.3 Bridging Sustainability and Digitalisation

The integration of ESG (Environmental, Social, Governance) indicators into digital twin performance frameworks (Singh & Narayan, 2023) underscores the growing alignment between sustainability theory and digital innovation. Digital twins offer a pathway for operationalising sustainability goals by embedding ethical sourcing, carbon tracking, and circular economy principles within routine decision-making (Tao et al., 2024; Kumar et al., 2023). This represents a paradigm shift from aspirational sustainability to measurable and actionable strategies.

6.2 Practical Contributions

From a practical point of view, digital twins pose transformational consequences on supply chain design, operations, and risk management. Such considerations are particularly timely as companies seek agility and resilience in the face of global disruptions.

6.2.1 Enabling Intelligent Supply Chain Operations

Operators increasingly rely on digital twins for timely visibility into operations, particularly in logistics and inventory (Wang et al., 2023). Predictive analytics enable supply chain chokepoints to be identified ahead of time, and prescriptive models optimise transport routes, production plans, and inventory (Yao et al., 2024).

Zhou et al. (2024) demonstrate evidence from food supply chains where blockchain-enabled digital twins improve traceability, reduce food loss, and maximise quality standard compliance. These applications are indicative of a shift towards smart, autonomous supply chains with digital back-loop feedback integrated into business-as-usual operations.

6.2.2 Enhancing Risk Preparedness and Response

The capability to simulate disruptive scenarios-anything from pandemics to geopolitical shocks-allows supply chain leaders to construct robust contingency plans. Ivanov and Dolgui (2024) and Park & Choi (2024) observe how DTs allow businesses to switch from reactive risk management to proactive resilience planning.

In addition, predictive maintenance supported by digital twins significantly reduces unplanned downtime and operational loss in asset-heavy sectors like manufacturing and energy (Patel & Verma, 2024). That efficiency converts to actual ROI, essential for gaining buy-in from executives.

6.2.3 Driving Sustainable and Ethical Supply Chains

Digital twins allow organisations to monitor carbon emissions, simulate low-impact supply chain practices, and verify supplier compliance with ethical methods (Garcia & Lee, 2024; Tao et al., 2024). These capabilities align supply chains with mounting regulatory and consumer pressure for sustainability.

Particularly, SMEs benefit from modular and cloud-based DT solutions, which enable them to drive digital transformation at non-scarce infrastructure costs (Kumar et al., 2023; Tiwari et al., 2024). This democratisation of next-generation technology gives rise to inclusive innovation in the supply chain ecosystem.

6.2.4 Supporting Strategic Decision-Making

AI-driven DT dashboards provide real-time decision aid, putting strategic measures together with key performance indicators (KPIs). Yao et al. (2024) show how such dashboards complement scenario planning to help managers view the effects of different decisions instantly.

But Singh & Narayan (2023) caution that the success of these types of tools relies on user training and interface design. This emphasises human-cantered design for digital twin interfaces (Mourtzis et al., 2024), especially in high-risk environments like healthcare or critical infrastructure supply chains.

6.3 Integrative Summary

By and large, digital twins represent a confluence of technology and strategy, theory and application. In theory, they push and reinterpret dominant supply chain paradigms, whereas practically they enable adaptive, real-time, and sustainable operation. The proposed framework offers a roadmap for companies that aim to bridge digital innovation with competitive and sustainable outcomes. Future research must continue bridging these fields to push digital twins from experimentation into mass supply chain transformation.

7. Future Research Agenda

Despite growing academic interest and technological prowess, certain critical research gaps at the intersection of digital twin (DT) and supply chain management (SCM) remain to be thoroughly investigated. These gaps represent key avenues for future investigation that can refine theoretical frameworks, enrich empirical insights, and guide the design of scalable, equitable, and sustainable DT solutions.

7.1 Digital Twin Energy Efficiency and Environmental Trade-Offs

While digital twins allow for sustainability by means of logistics optimalisation and waste reduction (Tao et al., 2024), few studies calculate the environmental cost of operating high-performance digital ecosystems. Digital twins rely on continuous data flows, cloud storage, and AI computation, all of which consume substantial energy (Dasgupta et al., 2023). Future research should quantify the carbon footprint of DT infrastructure and explore energy-efficient architectures, including edge computing and green data centres.

Moreover, comparative studies are needed to assess whether DT-enabled sustainability outcomes (e.g., reduced waste, optimised routing) outweigh their environmental costs, especially across different industries and geographic contexts (Tiwari et al., 2024).

7.2 Cybersecurity and Data Governance Frameworks

The increasing connectivity of digital twin ecosystems introduces new cybersecurity vulnerabilities, including data breaches, simulation tampering, and misinformation attacks (Schroeder & Haider, 2023). Current literature tends to treat cybersecurity as a technical add-on rather than a core design element of DTs.

Future studies should explore blockchain-enabled security, AI-driven threat detection, and zero-trust architectures to protect DT data streams (Zhou et al., 2024). There is also a need for integrated governance models that balance privacy, data ownership, and interoperability across multi-stakeholder supply chains (Nguyen & Bui, 2023).

7.3 Human–Digital Twin Interaction

While the technological functionality of digital twins has advanced rapidly, human interaction with DT systems remains under-researched. Studies have noted cognitive overload and low user trust, especially in high-risk environments like healthcare and food supply chains (Mourtzis et al., 2024).

Future research should focus on user-centred design, incorporating behavioural science to develop intuitive interfaces and adaptive feedback systems. Experimental studies examining augmented and virtual reality integration in DTs could offer insights into immersive decision-making and improved user trust (Zhang et al., 2023).

7.4 Global Scalability and Contextual Adaptation

Much of the current research focuses on DT adoption in large, technologically mature firms. However, global supply chains involve diverse stakeholders, including SMEs in developing economies that face constraints in infrastructure, funding, and digital skills (Ghobakhloo et al., 2023).

Further research should address contextual scalability, including cloud-native DT solutions, low-cost IoT configurations, and public-private partnerships to support digital infrastructure. Comparative case studies across regions can help develop adaptable frameworks for inclusive adoption (Kumar et al., 2023).

7.5 Standardisation and Interoperability

Despite calls for open standards, lack of interoperability remains a major bottleneck in integrating DTs with legacy systems (Ivanov & Dolgui, 2024). There is a growing need for research into industry-wide standards, including common data models, APIs, and certification protocols.

Interdisciplinary collaboration with inputs from information systems, engineering, law, and supply chain scholars is essential to advance governance mechanisms and compliance models that facilitate smooth integration across industries and national boundaries (Smith et al., 2023).

7.6 Integration of Ethical and Social Performance Metrics

Most DT evaluations remain focused on cost, time, and efficiency metrics. However, DTs also offer the potential to monitor labour practices, promote ethical sourcing, and assess social impact (Garcia & Lee, 2024).

Future studies should investigate how to embed social performance indicators such as labour equity, fair trade compliance, and community impacts within DT dashboards. Doing so would align SCM strategies with emerging supply chain due diligence legislation in regions such as the EU and North America.

Future research should move beyond proof-of-concept studies and address real-world implementation complexities. Through the exploration of energy efficiency, cybersecurity, human-system interaction, inclusive scalability, and ethical issues, researchers can enable the achievement of the full transformative capability of digital twins in global supply chain networks.

8. Conclusion and Implications

8.1 Summary of Contributions

This study offers a deep integration of emerging trends in digital twin (DT) technology for supply chain management (SCM) with theoretical contribution and managerial relevance. Drawing on a systematic literature review (SLR) and thematic analysis of 45 peer-reviewed journal articles (2023–2025), six broad thematic clusters emerged: evolution of DT applications, real-time monitoring, risk and resilience, interoperability, performance frameworks, and future trends. These concepts were integrated into a conceptual framework that mapped out the linkage of enabling factors, essential DT capabilities, and strategic performance.

The study makes several new contributions. It first redefines DTs as socio-technical systems through the identification of the synergy between technological capability and organisational readiness. Second, it broadens existing models by incorporating sustainability and ethical governance dimensions, thereby aligning digital innovation with ESG-driven supply chain practices. Third, it introduces contextual scalability as a core consideration, recognising the uneven digital maturity across industries and regions, particularly in developing economies.

Furthermore, by embedding the Dynamic Capabilities Theory (DCT) within a digital SCM environment, the study bridges conceptual gaps in understanding how real-time sensing, predictive analytics, and simulation-based optimisation contribute to adaptive and resilient supply chain strategies. It thus advances both academic discourse and managerial practice in the digital transformation of global logistics networks.

8.2 Limitations

Despite its contributions, this study has several limitations that must be acknowledged. The systematic review focused solely on peer-reviewed journal articles published between 2023 and 2025, which may have excluded valuable insights from grey literature, white papers, and practitioner reports. Additionally, while the thematic synthesis offers

conceptual depth, it does not include empirical testing or case-based validation of the proposed framework. As such, the generalisability of the framework may be limited without further empirical substantiation.
Geographic and industry-specific diversity in DT adoption was not fully explored. The predominance of studies from technologically advanced economies could bias findings and limit applicability in emerging or under-resourced regions. Finally, the fast-paced evolution of digital technologies means that insights presented here may require periodic updating to remain current and relevant.

8.3 Final Remarks

Digital twin technology holds transformative potential for supply chain management by enhancing visibility, agility, and sustainability. This study underscores the importance of viewing DTs not simply as technical add-ons but as strategic enablers that require cultural, infrastructural, and regulatory alignment. For researchers, the conceptual framework offers a structured pathway for future empirical exploration. For practitioners, it provides a decision-making tool to guide technology adoption aligned with organisational objectives and global sustainability mandates. Moving forward, further research should investigate real-world implementations of the framework across diverse sectors and geographies, with particular attention to low-resource contexts. Moreover, interdisciplinary collaboration among engineers, data scientists, and supply chain managers will be critical in refining DT solutions that are scalable, ethical, and impactful.

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