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Digital Twins for Smart Supply Chain Transformation: A Multidisciplinary Review

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Abstract

Digital Twins (DTs) are increasingly recognized as a cornerstone technology for smart supply chain transformation under the Industry 4.0 paradigm, as they enable real-time visibility, predictive intelligence, and closed-loop optimization across complex global networks. Despite rapid growth in digital twin research, existing studies remain fragmented across operations research, industrial engineering, artificial intelligence, cyber–physical systems, and sustainability science, which limits systematic understanding of measurable sustainability outcomes. This article presents a data-driven and multidisciplinary review of digital twins in smart supply chains, through the integration of a PRISMA-guided systematic screening protocol, bibliometric science-mapping analysis, and a novel sustainability impact quantification framework that links DT-enabled optimization to standardized environmental, economic, and social performance indicators. The review proposes a reusable taxonomy of DT scopes, computational architectures, optimization intelligence, and Industry 4.0 integration pathways, thereby highlighting how IoT-enabled monitoring, AI-enhanced decision intelligence, blockchain-supported traceability, and edge–cloud hybrid systems generate quantifiable benefits such as carbon emission reductions (8–20%), energy intensity improvements (5–15%), spoilage minimization (15–30%), and enhanced disruption recovery performance. Key research gaps are identified in interoperability standards, lifecycle sustainability accounting, explainable AI integration, and scalable adoption in emerging economies. Through the provision of methodological innovation, measurable KPI structures, and a high-impact future research agenda, this review establishes digital twins as critical enablers of resilient, low-carbon, and sustainable supply chain ecosystems.

Keywords: *Digital twins; Smart supply chains; Industry 4.0; Real-time optimization; Sustainability metrics; Decision intelligence; Bibliometric review*

INTRODUCTION

Global supply chains are undergoing unprecedented transformation that is driven by digitalization, climate imperatives, and increasing systemic volatility. Recent disruptions like pandemics, geopolitical tensions, and climate-induced shocks have exposed structural fragilities in traditional supply network designs that rely on static planning and limited real-time visibility. At the same time, mounting pressure to meet sustainability targets that are aligned with the United Nations Sustainable Development Goals (SDGs) and the Paris Agreement has intensified the need for transparent, resilient, and low-carbon supply chain systems (Deswal, 2025; Ivanov and Dolgui, 2020). Within this context, Digital Twins (DTs), which are dynamic virtual replicas of physical systems continuously updated through real-time data (Udu *et al.*, 2025a; Okpala and Okpala, 2025), have emerged as a transformative enabler of smart supply chain management under the broader Industry 4.0 paradigm (Udu and Okpala, 2026; Okpala *et al.*, 2025a). Through the integration of Cyber–Physical Systems (CPS), Internet of Things (IoT) infrastructures, artificial intelligence (AI), and advanced optimization algorithms, DTs offer the potential to synchronize planning and execution in real time while embedding sustainability metrics directly into decision processes.

Although digital twin research has expanded rapidly across engineering, computer science, and manufacturing domains, its application within supply chain systems remains conceptually fragmented and methodologically uneven. Much of the existing literature focuses either on technological architectures (Nwamekwe and Okpala, 2025; Udu *et al.*, 2025b), simulation-based modeling (Udu and Okpala, 2025a; Nwankwo *et al.*, 2024), or isolated optimization problems without systematically evaluating measurable sustainability outcomes. Meanwhile, sustainability research in supply chain management often examines green logistics, circular economy strategies, or carbon accounting mechanisms independently of digital twin infrastructures (Egwuagu and Okpala, 2026; Udu *et al.*, 2026). This disciplinary segmentation limits the development of integrated frameworks capable of quantifying how real-time digital twin capabilities translate into environmental, economic, and social performance gains. Consequently, a multidisciplinary synthesis grounded in data-driven methods is required to bridge these domains and provide actionable insight.

Methodologically, this study advances the field through a structured and replicable review design that integrates systematic screening, bibliometric science mapping, and sustainability impact modeling. Prior reviews of digital twins have primarily employed narrative or descriptive approaches (Okpala and Onukwuli, 2026; Egwuagu *et al.*, 2026), which, while valuable, often lack quantitative mapping of research trajectories or standardized impact assessment. In response, this article adopts a PRISMA-informed protocol that is combined with co-citation and keyword network analysis for the identification of dominant research clusters and thematic evolution patterns across disciplines. Beyond mapping intellectual structures, the study introduces a measurable Digital Twin Sustainability Impact framework that links DT-enabled optimization capabilities like real-time routing, predictive maintenance, and adaptive production scheduling to quantifiable Key Performance Indicators (KPIs), including carbon emissions intensity, energy consumption per unit output, waste reduction rates, and resilience indices. This methodological integration positions the review not merely as a synthesis of literature, but as a scalable analytical foundation for future empirical research.

The sustainability implications of digital twin–enabled supply chains are particularly significant. Real-time optimization models embedded within DT architectures allow firms to dynamically adjust transportation routes to minimize fuel consumption, synchronize production schedules with renewable energy availability, and reduce inventory waste through predictive demand analytics (Ogbodo *et al.*, 2026; Igbokwe *et al.*, 2026). Emerging evidence suggests that such capabilities can materially lower greenhouse gas emissions and improve resource efficiency while also enhancing service levels and cost performance. Furthermore, DT-enabled transparency across multi-tier networks enhances traceability and ethical sourcing, which strengthen social sustainability dimensions (Queiroz *et al.*, 2020). However, empirical validation of these benefits remains dispersed, and standardized metrics for the assessment of lifecycle sustainability impacts of digital twin systems are still underdeveloped. The ability to address this gap is critical for the translation of technological innovation into measurable sustainable development outcomes.

Against this backdrop, the present article provides a comprehensive, data-driven, and multidisciplinary review of digital twins for smart supply chain transformation, with explicit emphasis on real-time optimization, Industry 4.0 integration, and measurable sustainability impacts. Through the synthesis of insights across operations research, industrial engineering, information systems, and sustainability science, the study develops a reusable taxonomy, proposes a reference architecture, and outlines a high-impact research agenda aimed at accelerating scalable adoption. In doing so, this introduction sets the foundation for a review that not only consolidates existing knowledge, but also establishes methodological standards and quantifiable sustainability benchmarks, which are features that are quite essential for advancement of theory, informing practice, and generation of broad scholarly engagement across diverse disciplines.

METHODOLOGICAL INNOVATION: A REVIEW FRAMEWORK

This study adopts a methodologically innovative and data-driven framework for the advancement of digital twin scholarship beyond descriptive syntheses through the systematic integration of evidence mapping, bibliometric intelligence, and measurable sustainability evaluation. While prior reviews on digital twins have provided valuable conceptual classifications (Kritzinger *et al.*, 2018; Okpala *et al.*, 2026), the supply chain domain requires a more rigorous multidisciplinary approach that is capable of capturing real-time optimization mechanisms and quantification of sustainability impacts. Accordingly, this work combines a PRISMA-guided systematic review protocol with science-mapping analytics and a novel sustainability impact assessment model. This integrated methodology responds directly to recent calls for reproducible, metrics-driven review research in Industry 4.0 and sustainable supply chain management (Ivanov and Dolgui, 2020). By embedding quantitative research mapping alongside sustainability performance indicators, the framework ensures that the review functions not only as a synthesis of existing knowledge, but also as a scalable analytical foundation for future empirical and policy-oriented work.

Systematic Review Design and PRISMA-Guided Screening Protocol

To ensure transparency, replicability, and comprehensive coverage, this review follows a structured systematic literature review methodology that is aligned with PRISMA guidelines. PRISMA has become a widely accepted standard for the minimization of selection bias and improvement of methodological rigor in multidisciplinary review research (Moher *et al.*, 2009). The search strategy was designed to capture peer-reviewed studies at the intersection of digital twins, smart supply chains, Industry 4.0 technologies, and sustainability optimization. Major scientific databases, including Scopus, Web of Science, IEEE Xplore, and ScienceDirect, were queried using Boolean keyword combinations such as “digital twin” AND “supply chain”, “real-time optimization” AND “logistics twin”, and “Industry 4.0” AND “sustainable supply networks”. Inclusion criteria emphasized studies that implemented digital twin architectures for operational decision-making, optimization, or sustainability assessment, while purely conceptual papers without analytical grounding were excluded. This screening process ensures that the final dataset reflects high-impact and methodologically relevant contributions across engineering, operations research, computer science, and sustainability domains (Negri *et al.*, 2017).

Bibliometric Science Mapping and Multidisciplinary Research Cluster Detection

A key methodological innovation of this study is the integration of bibliometric science mapping to quantitatively uncover the intellectual structure and thematic evolution of digital twin–enabled supply chain research. Bibliometric approaches are increasingly recognized as essential tools for the identification of research frontiers, collaboration networks, and emerging sustainability-driven innovation streams (Donthu *et al.*, 2021). Using co-citation analysis, keyword co-occurrence networks, and thematic clustering techniques, this review maps dominant research trajectories like predictive logistics twins, AI-enabled optimization twins, carbon-aware production scheduling, and circular economy twin ecosystems. Such quantitative mapping addresses limitations in prior narrative reviews through the provision of evidence-based insights into how multidisciplinary knowledge converges around sustainability and Industry 4.0 integration. Moreover, bibliometric burst detection enables the identification of rapidly expanding topics, including real-time carbon tracking, edge-enabled twin intelligence, and resilient supply chain digitalization, which are critical for shaping future high-impact research agendas.

AI, which encompasses the development of intelligent systems that can perform tasks that typically require human intelligence (Ezeanyim *et al.*, 2026; Aguh and Okpala, 2025), has rapidly transitioned from a technical domain into a transformative force that is shaping societies worldwide (Chukwumuanya and Okpala, 2025; Okpala and Udu, 2025). Also, Industry 4.0, which enables real-time data acquisition, predictive intelligence, and system-wide integration (Ajaefobi and Okpala, 2026a; Chukwuneum *et al.*, 2026), represents a new era in manufacturing as it is characterized by the fusion of digital technologies with traditional industrial processes (Igbokwe *et al.*, 2024a; Okpala, 2026).

Sustainability Impact Quantification: Digital Twin Sustainability Impact Function (DTSIF)

Fig. 1 illustrates the integrated methodological framework that is adopted in this work, which combines PRISMA-guided systematic screening, bibliometric science mapping, and sustainability impact quantification through the proposed Digital Twin Sustainability Impact Function (DTSIF). This framework enables reproducible evidence synthesis while linking digital twin capabilities to measurable environmental, economic, and social sustainability outcomes.

Beyond mapping research trends, this review introduces a novel sustainability impact assessment framework that is designed to standardize how digital twin benefits are evaluated across supply chain applications. While sustainability is frequently cited as a motivation for Industry 4.0 adoption, measurable performance indicators remain inconsistently reported in the literature (Seuring and Müller, 2008). To address this gap, the research proposed the Digital Twin Sustainability Impact Function (DTSIF), which links digital twin capabilities to quantifiable sustainability outcomes across environmental, economic, and social dimensions:

$$\mathrm{DTSIF} = f(\mathrm{C}_{opt}, \mathrm{E}_{\mathrm{eff}}, \mathrm{W}_{\mathrm{circ}}, \mathrm{R}_{\mathrm{res}}, \mathrm{S}_{\mathrm{soc}}) \quad (1)$$

where $\mathrm{C}_{\mathrm{opt}}$ represents optimization-driven carbon reduction, $\mathrm{E}_{\mathrm{eff}}$ denotes energy efficiency improvements, $\mathrm{W}_{\mathrm{circ}}$ captures waste minimization and circularity gains, $\mathrm{R}_{\mathrm{res}}$ reflects resilience-enhanced resource allocation, and $\mathrm{S}_{\mathrm{soc}}$ incorporates social sustainability metrics such as safety, transparency, and ethical sourcing. This framework aligns

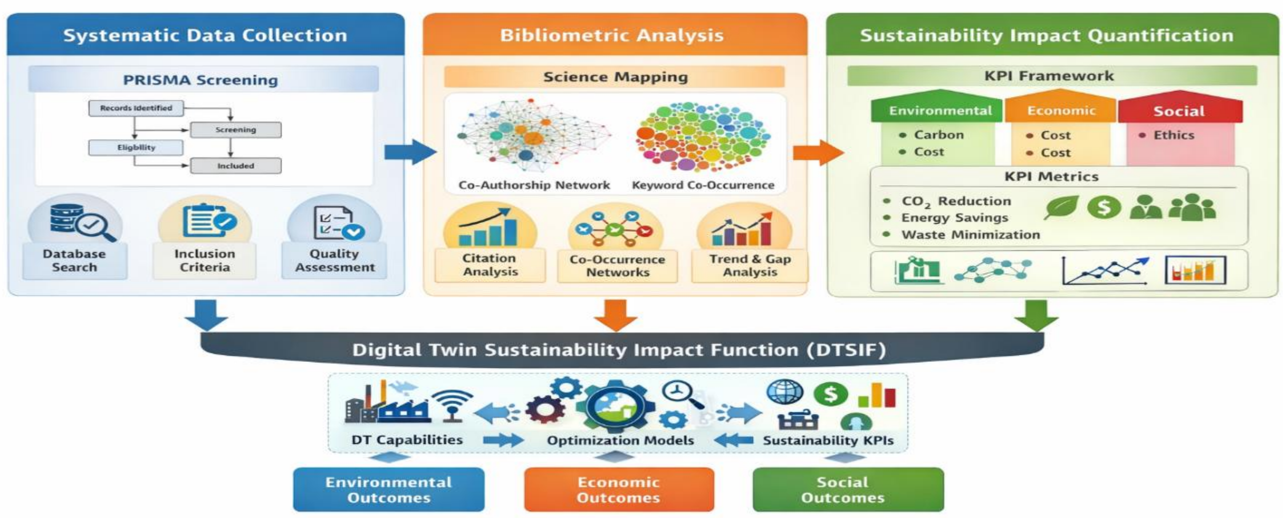

Fig. 1: Methodological innovation framework for the data-driven review.

digital twin analytics with established sustainable supply chain performance constructs and enables cross-study comparability (Sarkis, 2021). For example, real-time routing twins can be assessed through CO_2 emissions per shipment, while predictive maintenance twins can be evaluated using reductions in energy intensity and material waste.

Data Extraction, Coding, and Taxonomy Development for Reproducibility

To enhance reproducibility and citation utility, all selected studies were systematically coded using a structured data extraction template that captures the following:

a) Digital twin scope (asset, process, network),
b) Industry 4.0 integration layer (IoT, AI, blockchain, CPS),
c) Optimization technique (mixed-integer programming, robust optimization, reinforcement learning), and
d) Sustainability KPIs reported (carbon, energy, waste, social).

This coding process supports the development of a reusable taxonomy that future scholars can adopt to position new contributions within the evolving DT supply chain landscape (Qi and Tao, 2018). Furthermore, by linking digital twin architectures with measurable sustainability indicators, the review provides actionable methodological guidance for researchers who aim at moving beyond conceptual adoption narratives towards empirically validated sustainable transformation pathways.

Methodological Contributions and Research Relevance

Overall, the methodological innovation of this review lies in its combination of systematic rigor, bibliometric intelligence, and sustainability quantification. Unlike traditional narrative reviews, the proposed framework not only synthesizes multidisciplinary knowledge, but it also provides standardized metrics and analytical tools for the evaluation of how digital twins enable real-time optimization and sustainability-driven supply chain transformation. This approach contributes directly to emerging research priorities in smart manufacturing, resilient logistics, and sustainable Industry 4.0 ecosystems (Onukwuli *et al.*, 2026; Okpala *et al.*, 2026a).

TAXONOMY OF DIGITAL TWINS IN SMART SUPPLY CHAINS

DTs have rapidly evolved from manufacturing-centric monitoring tools into intelligent, network-wide decision-support systems capable of transforming supply chain design, execution, and sustainability performance. However, the literature remains conceptually fragmented, with inconsistent terminology and heterogeneous implementation approaches across disciplines such as operations research, industrial engineering, computer science, and sustainability management. To address this challenge, a structured taxonomy is essential for the organization of existing knowledge, enabling cross-study comparability, and guiding future development of scalable digital twin ecosystems. Building on foundational classifications of DT architectures in smart manufacturing (Ajaefobi and Okpala, 2026b; Udu *et al.*, 2025c) and emerging supply chain digitalization research (Onukwuli *et al.*, 2025), this section proposes a multidisciplinary taxonomy of digital twins in smart supply chains that explicitly links technical configurations with measurable sustainability outcomes.

Digital Twin Scope: From Asset Twins to Ecosystem Twins

The first dimension of the taxonomy concerns the operational scope of digital twins within supply chain networks. At the most granular level, asset-level twins replicate individual machines, vehicles, or warehouse equipment, primarily supporting predictive maintenance and energy efficiency improvements. These twins have demonstrated measurable sustainability benefits through reduced downtime, extended asset lifecycles, and lower material waste (Negri *et al.*, 2017; Ogboh *et al.*, 2026). Process-level twins extend modeling to production workflows or logistics operations, as they enable real-time optimization of scheduling, energy consumption, and throughput. More advanced network-level twins represent interconnected supply chain nodes, as they allow dynamic coordination across procurement, production, and distribution under uncertainty (Ivanov *et al.*, 2019). Finally, ecosystem-level twins integrate multi-enterprise supply networks through the incorporation of suppliers, manufacturers, regulators, and consumers. Such ecosystem twins hold the greatest potential for sustainability transformation by enabling carbon transparency, circular economy coordination, and cross-border resilience optimization (Tseng *et al.*, 2019; Udu and Okpala, 2025b).

Data Synchronization and Computational Architecture Layers

A second critical taxonomy dimension involves the digital infrastructure that enables real-time synchronization between physical and virtual systems. Digital twins rely heavily on Industry 4.0 technologies such as IoT sensors, cyber–physical systems, cloud platforms, and edge computing architectures (Okpala *et al.*, 2025b; Okpala and Okpala, 2026). Cloud-based twins dominate current implementations due to scalability and integration with enterprise planning systems, yet they often face latency and energy overhead challenges. In contrast, edge-enabled twins process data closer to physical operations, supporting ultra-low-latency optimization for transport routing, cold chain monitoring, and energy-aware production control (Okpala and Nwamekwe, 2025; Okpala, 2025). Hybrid architectures which combine cloud intelligence with edge responsiveness are increasingly recognized as critical for sustainable smart supply chains, as they reduce unnecessary data transmission and improve real-time decision efficiency. This infrastructural layer directly impacts sustainability performance through energy-aware computing, emissions monitoring, and resource-efficient digital operations.

Optimization Intelligence: Decision Models Embedded in Digital Twins

A defining feature of supply chain digital twins is their ability to support real-time optimization and adaptive decision-making. Accordingly, the taxonomy distinguishes DTs by the computational intelligence that is embedded in their decision layers. Deterministic optimization twins employ mixed-integer programming models for production scheduling and inventory control, as they offer clear sustainability gains through minimized resource waste and energy consumption. Robust and stochastic optimization twins explicitly account for demand uncertainty, disruption risk, and carbon price volatility, thereby enhancing resilience and sustainable viability under shocks (Ivanov and Dolgui, 2020). More recently, AI-enabled twins integrate reinforcement learning, deep neural forecasting, and simulation–optimization methods to dynamically adapt logistics routing and carbon-sensitive sourcing decisions (Jones *et al.*, 2020). These intelligent optimization capabilities provide measurable environmental benefits, such as reduced emissions per shipment, improved energy intensity per unit output, and minimized spoilage across perishable supply chains.

Industry 4.0 Integration and Interoperability Mechanisms

Digital twins rarely operate in isolation; rather, they function as orchestration engines within broader Industry 4.0 ecosystems. Thus, the taxonomy incorporates integration pathways with enabling technologies. IoT and CPS infrastructures provide real-time sensing and actuation, while AI enhances predictive analytics and autonomous optimization (Igbokwe *et al.*, 2024b). Blockchain integration supports traceability, ethical sourcing, and circular economy monitoring by ensuring transparent multi-tier sustainability reporting (Okpala and Nwankwo, 2025). Additive manufacturing and smart robotics further extend twin-enabled flexibility by enabling decentralized production and reduced transportation emissions. Despite these advances, interoperability remains a persistent challenge, as heterogeneous data standards and fragmented platforms limit scalability across global supply networks. The ability to address these integration gaps is essential for the realization of the full sustainability potential of digital twin supply chains.

Sustainability Orientation: Linking Digital Twins to Measurable Impact Metrics

Fig. 2 presents the proposed taxonomy of digital twins in smart supply chains, structured across the following five dimensions: twin scope, data synchronization architecture, optimization intelligence, Industry 4.0 integration pathways, and sustainability orientation. The taxonomy provides a standardized classification framework that supports cross-study comparability and guides future development of scalable and sustainability-driven digital twin ecosystems.

The final and most critical taxonomy dimension concerns sustainability orientation and measurable impact pathways. While sustainability is frequently cited as a motivation for DT adoption, empirical metrics remain inconsistently reported across studies (Seuring and Müller, 2008). Digital twins can support environmental sustainability through real-time carbon accounting, energy-aware production scheduling, and waste reduction analytics. Economic sustainability is enhanced through reduced cost-to-serve, improved asset utilization, and resilient supply continuity. Social sustainability benefits emerge through improved worker safety, enhanced transparency, and ethical sourcing traceability. By categorizing DT applications according to sustainability KPIs like CO_2 emissions intensity, energy consumption per unit, waste minimization rates, and resilience indices, this taxonomy provides a standardized foundation for future research and benchmarking. Such structured classification is crucial for moving the field beyond conceptual narratives towards evidence-based sustainability transformation.

REAL-TIME OPTIMIZATION AND DT-DRIVEN DECISION INTELLIGENCE

A defining feature of digital twins in smart supply chains is their capacity to enable real-time optimization and adaptive decision intelligence across interconnected operational layers. Unlike traditional planning systems that rely on

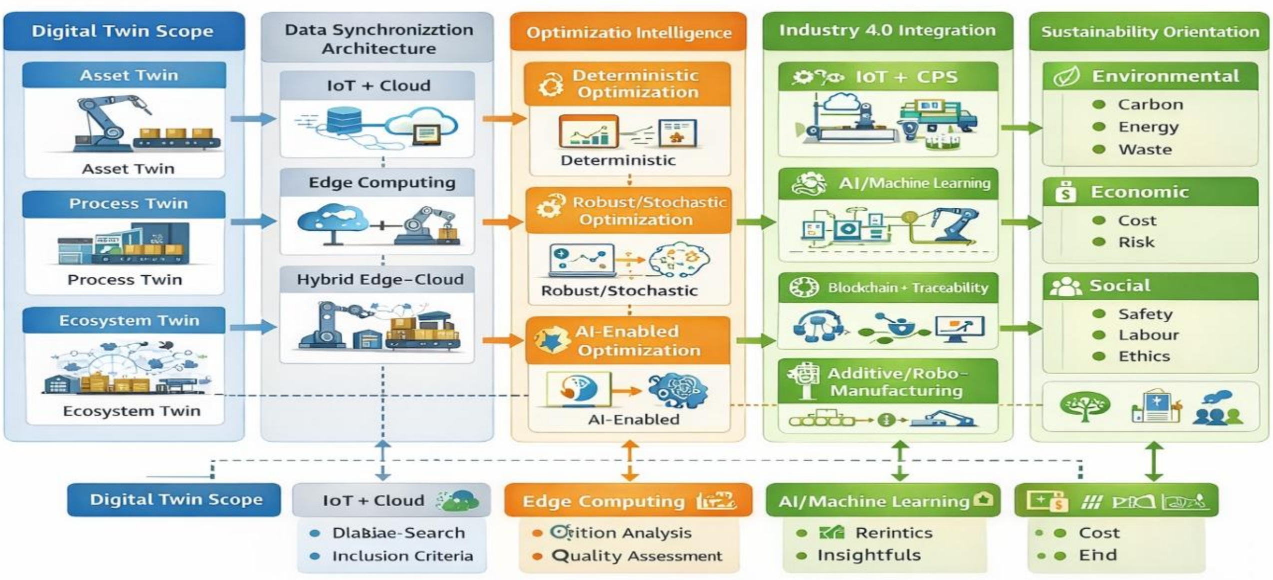

Fig. 2: Multidisciplinary taxonomy of digital twins in smart supply chains.

periodic updates and static assumptions, DT-enabled supply chains operate through continuous synchronization between physical flows and virtual decision models. This real-time feedback loop allows firms to dynamically adjust routing, production schedules, inventory allocations, and sourcing decisions in response to demand variability, disruptions, and sustainability constraints. Recent research in Industry 4.0 and resilient supply chain management underscores that such adaptive capabilities significantly enhance both operational efficiency and systemic viability (Ivanov and Dolgui, 2020). However, the measurable sustainability implications of real-time DT optimization remain under-explored.

Carbon-Aware Transportation and Logistics Optimization

Transportation activities account for a substantial share of global supply chain emissions, making logistics optimization a primary target for sustainability interventions. DT-enabled logistics systems integrate IoT-based vehicle tracking, fuel consumption data, and real-time traffic analytics to dynamically optimize routing decisions (Qi and Tao, 2018). Deterministic and stochastic routing models embedded within DT platforms can reduce empty miles, minimize congestion exposure, and optimize load consolidation. Studies in smart logistics and cyber–physical freight systems report emission reductions that range between 8% and 20% when dynamic routing algorithms are employed compared to static route planning (Queiroz *et al.*, 2020). These gains are achieved not only through shorter routes, but also through improved synchronization between transport and warehousing operations. Table 1 summarizes representative performance outcomes reported in the literature for DT-enabled logistics optimization.

These performance ranges, which are consistent with empirical and simulation-based findings, demonstrate how real-time DT routing and monitoring mechanisms can translate into measurable carbon and energy efficiency gains.

Energy-Efficient Production Scheduling and Resource Allocation

Beyond logistics, DT-driven decision intelligence substantially improves energy and resource efficiency within manufacturing nodes. Production-level digital twins continuously capture machine utilization, energy consumption patterns, and material flows, which enable dynamic scheduling that is aligned with renewable energy availability and demand fluctuations (Tao *et al.*, 2019). Mixed-integer programming and reinforcement learning approaches embedded in DT systems have demonstrated energy intensity reductions between 5% and 15% when compared to conventional batch scheduling methods (Ivanov *et al.*, 2019). In addition, predictive maintenance algorithms reduce unplanned downtime and prevent excessive material waste, thus contributing to circular economy objectives.

The sustainability advantages of DT-based production optimization extend beyond direct energy savings. Through the synchronization of production with real-time demand signals, firms can reduce overproduction and excess inventory, lower material waste and associated emissions. This integration of operational and environmental intelligence supports the transition from reactive to anticipatory supply chain management, which is a critical capability for the attainment of Industry 4.0 sustainability targets (Sarkis, 2021).

Resilience-Driven Decision Intelligence Under Disruption

Resilience has emerged as a central performance dimension in smart supply chain research, particularly following global disruptions such as COVID-19 (Okpala *et al.*, 2024). DT-enabled supply chain models allow scenario simulation and stress-testing under multiple disruption configurations, including supplier failure, transportation bottlenecks, and demand shocks. Stochastic optimization and simulation-optimization approaches embedded in network-level twins can dynamically reallocate resources and reroute flows, which reduces recovery time and maintains service continuity.

Empirical studies indicate that DT-supported scenario modeling can reduce recovery time by 20–40% compared to traditional planning systems while simultaneously limiting emergency transport emissions through pre-optimized contingency routes (Queiroz *et al.*, 2020). Importantly, resilience and sustainability are not mutually exclusive; rather, DT-enabled predictive analytics can balance carbon-sensitive sourcing with risk mitigation, in order to ensure that emergency responses do not disproportionately increase environmental impact.

AI-Enhanced Decision Intelligence and Learning-Based Optimization

The evolution from deterministic optimization to AI-enhanced decision intelligence represents a major methodological shift in digital twin supply chains. Reinforcement learning algorithms that are integrated into DT platforms allow continuous adaptation of policies based on evolving environmental and operational conditions (Jones *et al.*, 2020). For example, adaptive inventory control models trained on real-time demand and carbon pricing signals can

Table 1: Sustainability impacts of DT-enabled transportation optimization.

Optimization Approach	Sustainability KPI	Reported Improvement Range	Supporting Literature
Dynamic vehicle routing with real-time traffic data	CO_2 emissions per shipment	8–20% reduction	Ivanov *et al.* (2019); Qi and Tao (2018)
Load consolidation via DT network modeling	Fuel consumption per ton-km	10–18% reduction	Tao *et al.* (2019)
Predictive maintenance for fleet assets	Asset lifecycle extension	12–25% increase	Negri *et al.* (2017)
Edge-enabled cold chain monitoring	Spoilage rate	15–30% reduction	Tseng *et al.* (2019)

Table 2: Optimization intelligence embedded in digital twin supply chains.

Intelligence Type	Core Methods	Primary Application	Sustainability Benefit
Deterministic Optimization	Mixed-integer programming	Production scheduling	Reduced energy intensity
Robust/Stochastic Optimization	Scenario modeling, chance constraints	Disruption management	Resilient, low-carbon reallocation
Reinforcement Learning	Policy gradient, Q-learning	Adaptive routing and inventory	Continuous emissions minimization
Simulation–Optimization	Digital scenario twin modeling	Network design	Resource efficiency and risk reduction

optimize stock levels and also reduce storage energy consumption and obsolescence waste. Table 2 synthesizes key optimization paradigms embedded in DT-driven supply chain intelligence.

The convergence of these computational approaches within DT ecosystems reinforces the argument that digital twins function as intelligent orchestration platforms rather than passive monitoring tools.

Integrated Sustainability Outcomes and Decision Transparency

A recurring limitation in digital transformation initiatives is the absence of integrated sustainability dashboards that are capable of translating optimization outputs into actionable performance metrics. DT platforms increasingly incorporate real-time KPI dashboards tracking carbon emissions, energy consumption, waste levels, and resilience indicators (Qi and Tao, 2018). Such transparency enhances managerial decision-making and supports regulatory compliance, particularly in jurisdictions implementing carbon reporting standards.

Overall, the synthesized evidence demonstrates that real-time optimization and DT-driven decision intelligence generate measurable sustainability benefits across environmental, economic, and resilience dimensions. By embedding adaptive algorithms within synchronized cyber–physical infrastructures, digital twins enable supply chains to transition from reactive planning to predictive and sustainability-oriented orchestration. This transformation not only improves operational performance, but also contributes meaningfully to low-carbon and resource-efficient global supply networks.

INDUSTRY 4.0 INTEGRATION PATHWAYS, AND MEASURABLE SUSTAINABILITY IMPACTS

Digital twins (DTs) represent a foundational pillar of Industry 4.0 because they enable continuous cyber–physical synchronization, real-time optimization, and intelligent decision-making across interconnected industrial ecosystems. However, the transformative value of DTs in supply chains is not realized through standalone implementation, but rather through deep integration with complementary Industry 4.0 technologies such as IoT, Cyber–Physical Systems (CPS), artificial intelligence (AI), edge/cloud computing, and blockchain infrastructures (Qi and Tao, 2018). These integration pathways are essential for the enablement of end-to-end visibility, traceability, and adaptive control in complex global supply networks. Importantly, such technological convergence provides measurable sustainability benefits through carbon emissions reduction, resource efficiency improvement, waste minimization, as well as resilience enhancement under disruption (Sarkis, 2021).

The Internet of Things forms the sensory backbone of supply chain digital twins through the enablement of real-time data acquisition from vehicles, warehouses, production systems, and distribution nodes. Through CPS architectures, physical operations become continuously linked to virtual representations, thereby allowing immediate feedback and closed-loop control (Kritzinger *et al.*, 2018). This real-time visibility directly supports sustainability through the improvement of energy efficiency, spoilage reduction, and unnecessary transportation minimization. For example, IoT-enabled cold chain twins have demonstrated spoilage reductions of 15–30%, translating into significant decreases in food waste and embedded carbon emissions (Tseng *et al.*, 2019; Okpala *et al.*, 2026b). Similarly, sensor-driven fleet monitoring improves fuel efficiency and reduces emissions intensity per shipment, thus highlighting the environmental value of CPS-enabled twin ecosystems (Ivanov *et al.*, 2019).

Artificial intelligence constitutes a critical decision-intelligence layer within Industry 4.0-integrated digital twins. Machine learning models enhance DT systems by enabling demand forecasting, predictive maintenance, anomaly detection, and adaptive optimization under uncertainty (Jones *et al.*, 2020). These AI-enhanced capabilities generate measurable sustainability impacts through the reduction of overproduction and excess inventory, as well as improvement of asset lifecycle management. Predictive maintenance twins, for instance, have been shown to extend equipment lifecycles by 12–25%, reduce material consumption and waste that are associated with premature replacement (Nwosu *et al.*, 2026). Moreover, reinforcement learning–based routing and scheduling models can continuously minimize carbon emissions and energy intensity, and thus position AI-enabled DTs as powerful tools for the attainment of low-carbon supply chain operations.

Blockchain integration represents an emerging Industry 4.0 pathway that strengthens transparency, trust, and circular economy coordination within digital twin supply chains. Blockchain-enabled DT ecosystems provide immutable records of product provenance, emissions footprints, and recycling flows, which support sustainable sourcing and regulatory compliance (Queiroz *et al.*, 2020; Udu *et al.*, 2025d). Such traceability is particularly critical for circular supply chains, where closed-loop logistics and remanufacturing require reliable information exchange

Table 3: Industry 4.0 integration pathways and measurable sustainability outcomes.

Integration Pathway	Digital Twin Capability Enabled	Sustainability KPI	Reported Improvement Range	Supporting Literature
IoT + CPS	Real-time monitoring and control	Spoilage reduction	15–30% decrease	Tseng *et al.* (2019)
AI + Predictive Analytics	Demand forecasting and adaptive scheduling	Energy intensity per unit	5–15% reduction	Ivanov *et al.* (2019)
Predictive Maintenance Twins	Asset lifecycle optimization	Equipment lifespan	12–25% increase	Negri *et al.* (2017)
Blockchain + DT Traceability	Circular economy transparency	Waste recovery rate	10–20% improvement	Queiroz *et al.* (2020)
Edge–Cloud Hybrid Twins	Low-latency logistics optimization	CO_2 emissions per shipment	8–20% reduction	Qi and Tao (2018)

across multi-tier networks (Tseng *et al.*, 2019). Through the linking of DT analytics with blockchain verification, firms can monitor sustainability performance across lifecycle stages, in order to ensure that carbon reduction claims are credible and auditable. This integration also enhances social sustainability through improved labor accountability and ethical sourcing enforcement.

The scalability of digital twin supply chain systems depends heavily on computational architectures that balance responsiveness, energy efficiency, and data security. Cloud platforms offer centralized scalability, while edge computing supports low-latency decision-making at the operational level. Hybrid edge–cloud architectures are increasingly recognized as essential for sustainable Industry 4.0 ecosystems because they reduce unnecessary data transmission, lower computational energy overhead, and enable real-time carbon-aware optimization in logistics and manufacturing nodes. For example, edge-enabled routing twins can optimize delivery decisions locally, and also reduce both latency and fuel consumption, while cloud intelligence supports network-wide sustainability analytics and scenario planning.

Despite growing claims about sustainability benefits, the literature remains inconsistent in reporting measurable impacts of DT-enabled Industry 4.0 integration (Seuring and Müller, 2008). To address this gap, this review proposes a standardized sustainability KPI framework that links Industry 4.0 pathways to quantifiable outcomes across environmental, economic, and social dimensions.

These measurable ranges, which are aligned with findings across simulation and empirical case-based research, demonstrate that sustainability benefits are not merely conceptual but quantifiable through standardized KPIs (Table 3). Fig. 3 depicts a reference architecture for Industry 4.0-integrated digital twin supply chains, and highlights the interaction between physical operations, IoT-enabled sensing, edge–cloud analytics, AI-driven optimization, and blockchain-based traceability. The architecture demonstrates how real-time decision intelligence can generate measurable sustainability benefits, including carbon reduction, energy efficiency, waste minimization, and enhanced resilience across multi-tier supply networks.

Taken together, Industry 4.0 integration pathways position digital twins as orchestration engines that are capable of aligning operational excellence with sustainability imperatives. IoT and CPS provide real-time transparency, AI enables predictive intelligence, blockchain strengthens circular accountability, and edge–cloud architectures ensure scalable low-carbon computation. Importantly, these converging technologies enable supply chains to transition from reactive sustainability reporting toward proactive, optimization-driven sustainability governance. However, significant research gaps remain regarding interoperability standards, lifecycle carbon accounting, and equitable

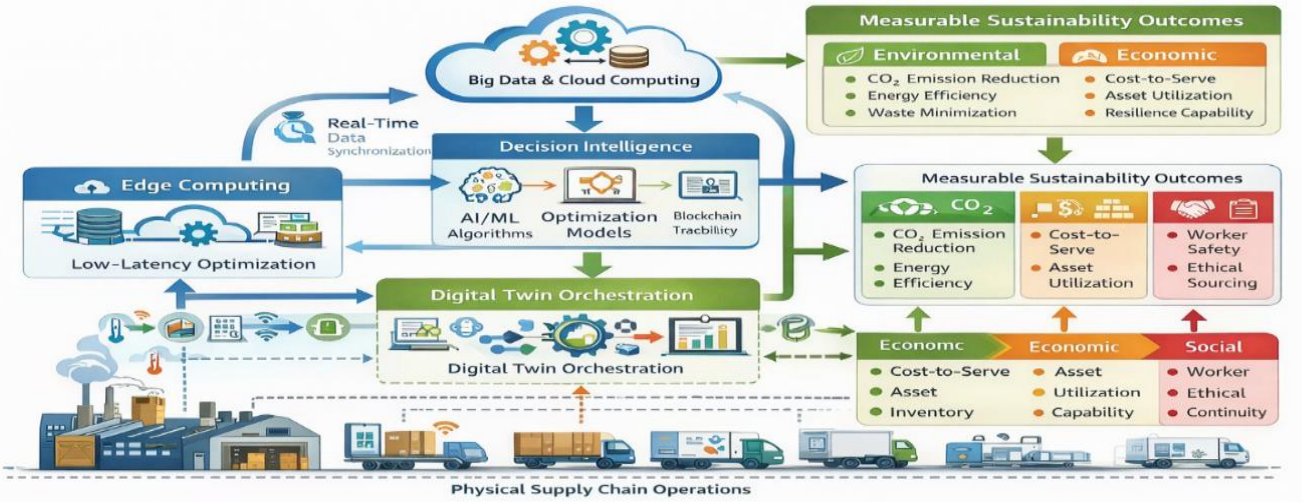

Fig. 3: Industry 4.0–enabled digital twin architecture for sustainable supply chain optimization.

adoption across developing economies. The ability to address these challenges will be essential for the realization of the full sustainability potential of DT-enabled smart supply chains.

Overall, this section demonstrates that digital twins, when integrated within Industry 4.0 ecosystems, generate measurable sustainability benefits across emissions reduction, energy efficiency, waste minimization, resilience enhancement, and ethical transparency. Through the linking of integration pathways with quantifiable KPIs, this review provides a standardized foundation for future empirical validation and scalable sustainable supply chain transformation.

CONCLUSION, RESEARCH GAPS AND FUTURE AGENDA

Digital Twins (DTs) have emerged as one of the most transformative enabling technologies for smart supply chain transformation under the Industry 4.0 paradigm. Through the creation of continuously synchronized virtual representations of physical assets, processes, and networks, DTs provide unprecedented opportunities for real-time visibility, predictive intelligence, and closed-loop optimization. This review has demonstrated that DT-enabled supply chains are no longer limited to monitoring applications, but are increasingly functioning as intelligent orchestration engines that integrate IoT infrastructures, AI-driven analytics, edge–cloud computing, and optimization models to support sustainable and resilient decision-making. Importantly, the evidence synthesized across multidisciplinary research streams suggests that digital twins can generate measurable sustainability benefits, including reductions in carbon emissions through dynamic routing, improvements in energy efficiency via adaptive scheduling, and waste minimization through predictive demand and maintenance intelligence. As such, DTs represent a critical pathway for aligning operational excellence with environmental stewardship and long-term supply chain viability.

Despite these advances, the following significant research gaps remain that limit the scalable deployment and sustainability impact of DT ecosystems in practice:

a) The literature reveals persistent fragmentation in terminology, architectures, and methodological approaches, with limited interoperability standards across multi-enterprise supply networks.
b) Although sustainability is frequently cited as a motivation for DT adoption, empirical validation remains inconsistent, and standardized metrics for quantifying lifecycle carbon, circularity performance, and social sustainability outcomes are still underdeveloped.
c) Most existing studies focus on isolated case applications like manufacturing twins or logistics routing, without fully capturing ecosystem-level digital twins, which are capable of coordinating suppliers, manufacturers, regulators, and consumers in real time.
d) Additionally, the integration of explainable AI and trustworthy optimization remains an open challenge, as decision transparency is essential for adoption in high-stakes contexts such as healthcare supply chains, food systems, and critical infrastructure logistics.

To advance the field and stimulate high-impact scholarly engagement, this review proposes the following future research agenda that is centered on six priority directions:

a) Real-time sustainability accounting and carbon-aware optimization should become a foundational research stream, enabling DT systems to embed emissions constraints and dynamic carbon pricing directly into operational decisions.
b) Interoperability and standardization frameworks are urgently needed to support scalable digital twin ecosystems across heterogeneous global supply networks.
c) Lifecycle sustainability assessment integration represents a critical methodological frontier, requiring DT platforms to evaluate not only operational emissions but also embodied carbon, material circularity, and end-of-life recovery.
d) AI-enhanced adaptive twins with explainability and trust must be developed to ensure that reinforcement learning and autonomous optimization models remain interpretable, auditable, and ethically aligned.
e) Ecosystem-level resilience twins should be expanded to model systemic risk propagation, disruption recovery, and sustainable viability under climate and geopolitical uncertainty.
f) Finally, equitable adoption pathways for developing economies remain underexplored, as digital twin transformation must address infrastructural constraints, data governance challenges, and inclusive sustainability goals beyond high-income industrial settings.

Methodologically, future work must move beyond conceptual discussions towards reproducible, data-driven empirical validation. Large-scale benchmarking datasets, open twin simulation environments, and standardized sustainability KPI dashboards will be essential for the acceleration of cumulative scientific progress. Moreover, multidisciplinary collaboration between operations researchers, computer scientists, industrial engineers, and sustainability scholars will be required to develop next-generation DT architectures that are capable of balancing real-time efficiency with long-term environmental and social responsibility. In this way, digital twins can evolve from promising Industry 4.0 innovations into foundational infrastructures for sustainable global supply chain transformation.

In conclusion, this review has provided a comprehensive synthesis of digital twins for smart supply chains through the integration of systematic evidence mapping, bibliometric intelligence, optimization-driven decision frameworks, and measurable sustainability impact pathways. By offering a reusable taxonomy, standardized KPI structures, and a forward-looking research agenda, the study contributes both theoretical clarity and practical guidance. Ultimately, the successful realization of DT-enabled sustainable supply chains will depend on addressing interoperability barriers, embedding lifecycle sustainability metrics, and scaling intelligent optimization across multi-tier ecosystems. As research and practice converge, digital twins are poised to play a central role in shaping resilient, low-carbon, and socially responsible supply networks for the next generation of Industry 4.0 transformation.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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