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Digital Twins for Sustainable and Low-Carbon Supply Chains in Industry X.0: Crossing the Fragmented Bridge Between Academic Research and Industrial Adoption

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ABSTRACT

Digital twins (DTs) offer transformative potential for shaping low-carbon, resilient, and circular supply chains by providing real-time virtual monitoring and decision-support capabilities. However, despite growing theoretical interest in technology-driven frameworks, translations into scalable, standards-aligned industrial implementations remain limited. To address this gap, we conducted a comprehensive bibliometric and thematic analysis of 229 DT-related research articles published between late 2019 and mid-2025, focusing on sustainability outcomes. The dataset was systematically compiled from three major academic databases, Scopus, ScienceDirect, and Web of Science, which ensured both consistency and robustness of the review. We mapped trends across research themes, geographies, and journal outlets and identified key clusters spanning AI-powered optimization, circular-economy frameworks, and built-environment lifecycle modeling. Our findings reveal that, although nearly 40% of studies are conceptual, only one-third present practical deployment and fewer than 30% adopt a mixed approach. Critically, interoperability standards (for example, ISO 23247 and OPC UA) and lifecycle metrics (Scope 3 emissions, LCA, Digital Product Passports) are seldom fully integrated within empirical work. This fragmentation underscores a bridge in progress between academic innovation and industrial practice. We conclude by highlighting opportunities to accelerate adoption, namely, designing DTs that are empirically validated, multi-objective, and grounded in stakeholder ecosystems, which would enable DTs to evolve from theoretical promise to operational tools for sustainable supply network transformation.

Keywords: ***carbon intelligence, circular economy, digital twins, industry X.0, industry 5.0. low-carbon design sustainable supply chains, supply chain 4.0***

1. INTRODUCTION

The increasing urgency of climate change and environmental degradation has driven the exploration of tools like digital twins (DTs), virtual replicas of physical systems that continuously absorb real-time data, enabling proactive simulation, enhanced visibility, and strategic decision-making across supply chains (Grieves & Vickers, 2016; Guo & Mantravadi, 2025; Sajadieh & Noh, 2025). Concurrently, the evolution of industrial paradigms toward Industry X.0, which emphasizes sustainability, resilience, and human-centric systems, positions DTs as central to transforming how products, processes, and infrastructures are designed, operated, and optimized (Martini et al., 2024; Onu et al., 2023). Despite this promise, there remains a pronounced gap between DT theory and large-scale industrial application, particularly in sectors critical to sustainability, such as energy, construction, logistics, and manufacturing. Systematic reviews reveal that, while frameworks have become increasingly sophisticated, they often fall short in accounting for real-world conditions, such as fragmented system architectures, data privacy issues, and governance complexities that hinder scalable implementation (Kuštelega *et al*., 2024; Perno *et al*., 2022; Soledispa-Canarte *et al*., 2023).

RQ1: What are the dominant research themes and contributions regarding digital twins within sustainable supply chain discourse during 2019-mid-2025?

RQ2: To what extent do current DT studies incorporate elements of practical adoption, such as interoperability standards, carbon lifecycle integration (e.g., Scope 3, LCA), and cross-sector collaborations (e.g., DPP, circular economy models)?

RQ3: Where are the remaining gaps that hinder effective bridge-building between academic innovation and industry-scale adoption, and how can future research meaningfully address these misalignments?

By leveraging a bibliometric analysis spanning late-2019 to mid-2025 and grounded in sustainability discourse, this work offers a comprehensive and forward-looking perspective that aligns technical innovation with systemic sustainability imperatives.

2. BACKGROUND AND FUNDAMENTALS

2.1 Digital Twins in the Industry X.0 Era

Digital twins (DTs) are defined as dynamic, data-driven virtual representations of physical systems, continuously synchronized through bidirectional data flows to enable monitoring, simulation, and predictive decision-making across asset lifecycles (Bucci *et al.*, 2024; Tao *et al.*, 2018). As industrial paradigms evolve from Industry 4.0 toward human-centric, sustainable, and resilient Industry X.0/Industry 5.0 models, DTs emerge as core enablers of decarbonization, resource efficiency, and operator-in-the-loop decision support (Ivanov, 2023; Tao *et al.*, 2018; Van Erp *et al.*, 2024). In this transition, DTs integrate operational technologies (OT) with IT, edge, and AI services, so that insights generated at the virtual level can be enacted rapidly in the physical environment, a capability that has been reported as critical for energy-aware and low-carbon manufacturing (Abdessadak *et al.*, 2025; Bibri & Huang, 2025; Tao *et al.*, 2018). Anchoring DT-enabled decisions in sustainability requires balancing economic, environmental, and social objectives within multi-objective optimization frameworks so that cost, emissions, and circular-value indicators can be assessed jointly rather than in isolation (Mujkic *et al.*, 2018). For instance, in smart manufacturing, Industry X.0 integrates DTs with edge computing and AI to optimize resource use, reduce environmental burdens, and support real-time reconfiguration of production lines (Bibri & Huang, 2025; Rojek *et al.*, 2025).

2.2 Enhancing Supply Chain Resilience and Visibility

In supply chain management, DTs are leveraged for real-time system modeling and stress testing across disruption scenarios, from pandemics to geopolitical crises, which supports contingency planning and risk mitigation (Ivanov, 2023; Wasi *et al.*, 2025). Recent resilience-oriented studies show that DTs can reproduce multi-echelon material and information flows and then inject disturbance events, such as port closures, supplier shutdowns, or transport capacity losses, to evaluate recovery options and service-level impacts (Ivanov & Gusikhin, 2025; Longo *et al.*, 2023; Roman *et al.*, 2025). Digital-first simulation approaches are increasingly used to design virtual systems that guide physical implementations, improving efficiency and reducing waste (Resman *et al.*, 2025; Salis *et al.*, 2023). Simulation-based digital supply chain twins couple discrete-event or agent-based models with live data so that planners can compare alternative sourcing, routing, or inventory policies before execution, which shortens design-to-operate cycles and lowers experimentation costs (Longo *et al.*, 2023). By integrating simulation, AI, and data analytics, DTs augment end-to-end visibility and agility, moving supply chains toward more autonomous and resilient ecosystems (Espinosa-Jaramillo *et al.*, 2024; Roman *et al.*, 2025). AI-powered twins, in particular, can run large batches of what-if scenarios and Monte Carlo experiments to prioritize risk-mitigation strategies under high-volatility, as documented in recent reviews on DT-driven supply chain resilience (Ivanov & Gusikhin, 2025; Liu *et al.*, 2024). Port and logistics applications reinforce this trajectory, with DTs supporting berth allocation, cargo-handling safety, and emergency response, and showing that operational data can be fed back into the twin to improve future disruption handling (Klar, 2024; K. Wang *et al.*, 2024).

2.3 Enabling Sustainability: LCA, Circular Economy, and Lifecycle Awareness

Two converging bodies of literature, life cycle assessment (LCA) and the circular economy (CE), frame the sustainability potential of DTs. LCA-integrated DTs leverage Scope 3 carbon accounting under the GHG Protocol and the ISO 14040/14044 standards, enabling real-time footprint tracking and targeted interventions (Ghose & Pizzol, 2024; Yang *et al.*, 2023). Meanwhile, DTs are increasingly recognized as foundational tools for CE, supporting reuse, remanufacturing, and closed-loop strategies by providing granular, lifecycle-wide data across product histories (Ali *et al.*, 2025; Mügge *et al.*, 2024; Preut *et al.*, 2021). Recent work shows that LCA can be digitally enabled through data pipelines and analytics that couple IoT, AI, and big data with LCA inventories, which improves timeliness and decision relevance (Popowicz *et al.*, 2025). In parallel, DT-supported product carbon foot-printing demonstrates how Scope 3 estimates can be operationalized at scale by linking process twins to supplier data and logistics events (Winter *et al.*, 2025). From a standards perspective, ISO 23247 provides a manufacturing DT framework that structures data exchange between physical assets and their virtual counterparts, which facilitates LCA–DT interoperability in practice (for Standardization, 2021). On the CE side, EU Digital Product Passports under the Ecodesign for Sustainable Products Regulation are accelerating requirements for traceable, lifecycle-wide information, a policy driver that DT architectures are well positioned to support (Barkhausen *et al.*, 2022). Together, these developments indicate a pathway in which DTs feed LCAs with near real-time inventories and CE objectives are supported by trustworthy product histories, which strengthens emissions management and circular design decisions (Mügge *et al.*, 2024; Piron *et al.*, 2024).

2.4 DTs in Urban and Building Environments

Urban and built-environment applications of digital twins (DTs) are expanding, particularly for energy performance, in-door environmental quality (IEQ), and climate resilience. A systematic review highlights the role of DTs in improving indoor air quality and energy efficiency by integrating building information modeling (BIM), Internet of Things (IoT) sensing, and big-data analytics for real-time monitoring (Sayed *et al*., 2025). City-scale implementations, such as metropolitan digital twins in Sydney and “twin-of-twins” frameworks for urban planning, support data-driven design, risk forecasting, flood resilience, and sustainable resource allocation (Barrile *et al*., 2025; Kaynak *et al*., 2025; Sohail *et al*., 2025). Beyond monitoring, building DTs are increasingly used to optimize HVAC control and demand response, with reviews reporting measurable gains in energy efficiency while maintaining indoor environmental quality (Arsecularatne *et al*., 2024). At the city scale, flood-focused urban DTs couple hydrodynamic models with transportation networks to anticipate service disruptions and evaluate adaptation options, as demonstrated in a Waterloo (Iowa) case framework (Kaynak *et al*., 2025). The Sydney urban digital twin illustrates multi-source data fusion for sustainability planning, integrating real-time and historical feeds (for example, weather, emissions, and mobility) to support scenario analysis and policy evaluation (Sohail *et al.*, 2025). Complementary studies link urban DTs to critical-infrastructure resilience, showing how data-driven twins strengthen interdependency analysis for energy, transport, and water systems under climate stress (Kaynak *et al.*, 2025). Within buildings, AI-driven DTs for IEQ show how sensor-rich twins inform ventilation and thermal strategies, aligning occupant comfort with energy objectives (Yitmen *et al.,* 2025).

2.5 Interoperability and Standards as Enablers

Digital twins' scalability depends on technical interoperability. The ISO 23247 standard provides a DT reference frame- work for manufacturing (Shao & Helu, 2020), while OPC UA enables secure, semantic data interoperability (Van Bocxlaer, 2024), both of which are essential to support accelerated DT adoption. Concretely, ISO 23247 defines a common vocabulary and reference architecture for observable manufacturing elements, guiding connectivity between physical assets and their virtual counterparts and aligning data flows across the lifecycle (for Standardization, 2021). Recent drafts in the series ex- tend guidance on composition and digital threads, indicating how multiple twins can interoperate and how product-lifecycle data can remain synchronized (for Standardization, 2021). OPC UA complements this by providing a secure transport and information-modelling stack, with security properties and common misconfigurations empirically analyzed in peer-reviewed studies, and with address-space and information-model layers that enable domain semantics for cross-vendor interoperability (Busboom, 2024; Cavalieri & Salafia, 2020; Diemunsch *et al.*, 2025; Erba *et al.*, n.d.; Girbea *et al.*, 2012). At the semantic layer, standardized asset models such as the Asset Administration Shell and, in some ecosystems, DTDL model definitions, structure machine-readable vocabularies that DT platforms can exchange consistently (Karabulut *et al.*, 2024; Quadrini *et al.*, 2023; Schmidt *et al.*, 2023; Shi *et al.*, 2024).

2.6 Market Dynamics and Industrial Uptake

Recent academic surveys on digital twin research report that the global DT market is expected to grow by an order of magnitude over the next decade, with consolidated industry figures for the early 2030s situated in the 200-250 billion USD range, which confirms rapid and multi-sector adoption (Soori *et al.*, 2023; Sun *et al.*, 2024; Zhou *et al.*, 2025). These reviews, which synthesize multiple market outlooks, consistently identify manufacturing, energy and utilities, and smart-city programmes as the three dominant demand drivers of this expansion (Mazzetto, 2024; Pronost *et al.*, 2024). In parallel, DT literature on smart manufacturing notes a shift from physical-first to digital-first engineering, in which virtual models are used to design, validate, and de-risk systems before physical roll-out (Pronost *et al.*, 2024; Soori *et al.*, 2023). In this configuration, the twin effectively becomes the primary experimentation space, so CAPEX- or OPEX-intensive choices, such as line reconfiguration, buffer-capacity extensions, or layout changes in logistics facilities, are first evaluated in silico and only then implemented in the real system, which has been shown to reduce rework and time-to-value (Ivanov & Dolgui, 2021; Roman *et al.*, 2025).

2.7 Summary and Research Gaps

Synthesizing the literature indicates that, although digital twins (DTs) are well conceptualized and broadly theorized, real-world deployment still faces friction caused by data-governance challenges, interoperability gaps, inconsistent LCA methodologies, and scalability constraints. Despite emerging standards and promising urban pilots, a segmented landscape persists that hinders seamless translation between research and practice. Our bibliometric analysis corroborates this fragmentation and positions the present study to advance scholarship by proposing interoperability-aligned, lifecycle-focused, and data-grounded DT adaptation models that are both theoretically robust and empirically demonstrable.

3. MATERIALS AND METHODS

The rapid proliferation of digital twin (DT) applications across smart manufacturing, supply chains, and sustainable systems has generated a substantial and dynamic body of literature. However, comprehensive synthesis, particularly regarding DTs' role in advancing sustainability, resilience, and transparency in supply chains, remains limited. To address this gap, our study applies bibliometric analysis, a validated methodological approach for uncovering structural dimensions, developmental trajectories, and knowledge clusters within scientific domains (Bhaskar *et al.*, 2025; Galkin *et al.*, 2025).

By systematically mapping publication patterns, including temporal growth, geographical and institutional contributions, influential journals, evolving keyword networks, and thematic clusters, we provide an evidence-based framework. This framework mirrors the structure of our results and highlights intersections between DT research and sustainability imperatives, as well as areas where significant gaps remain.

3.1 Research Framework

This study employs bibliometric analysis to systematically chart the evolving landscape of DT research in sustainable and low-carbon supply chains within the broader context of Industry X.0. Bibliometric methods provide a quantitative and replicable lens for examining the intellectual structure and developmental contours of a research domain, enabling detailed exploration of publication dynamics, research impact, thematic evolution, and knowledge diffusion (Galkin *et al.*, 2025; Öztürk *et al.*, 2024).

Our analytical design is structured along five complementary dimensions:

(i) **Publication trajectories**: mapping growth patterns and emergent waves of research interest;
(ii) **Geographic and institutional contributors**: profiling regional strengths and potential imbalances in knowledge production;
(iii) **Journal outlets and citation influence**: identifying authoritative voices and trending discourse models;
(iv) **Keyword co-occurrence and trend analysis**: detecting shifting research foci and interconnected themes;
(v) **Clustering and network mapping**: exposing latent thematic structures and bridges between conceptual and applied research streams.

Grounded in these dimensions, the methodology provides a comprehensive, multi-scalar perspective on DT scholarship. It reveals not only the maturity level of existing academic constructs but also the pipeline toward sustainable and scalable deployment in real-world supply chains.

3.2 Data Sources and Search Strategy

To construct a comprehensive and relevant dataset, this study draws on three major scholarly sources: *Scopus*, *Web of Science (WoS)*, and *ScienceDirect*. Scopus and WoS are multidisciplinary abstract-and-citation indexes with broad coverage across technology, management, and environmental sciences, whereas ScienceDirect is a full-text platform that hosts Elsevier journals and books (Pranckute˙, 2021; Tober, 2011). To manage overlap rigorously, we used **Scopus** as the *primary indexing and export source*, consulted **WoS** to *cross-check coverage and citation consistency*, and accessed **ScienceDirect** strictly for *full-text retrieval and metadata completion* (for example, Articles in Press). All records were *deduplicated by DOI* (or by title-author-year when the DOI was unavailable), so ScienceDirect entries did not generate additional counted items. This staged approach leverages the complementary strengths of Scopus and WoS for discovery and analytics, while relying on ScienceDirect only to obtain authoritative PDFs and fill metadata gaps (Singh *et al.*, 2021). For **Scopus**, the refined search query was as follows:

```
TITLE("digital twin")
AND TITLE-ABS-KEY("sustainable supply
chain" OR "green supply chain" OR "low
carbon" OR "net zero" OR "circular
economy"
OR "carbon footprint" OR "carbon
intelligence")
```

The strategy for **Web of Science (WoS)** was conceptually aligned, employing topic searches (TS):

```
TS = ("digital twin")
AND TS=("supply chain" OR "logistics")
AND TS=("sustainable" OR "circular
economy" OR "low carbon" OR "net zero"
OR "carbon footprint" OR "carbon
intelligence")
```

For **ScienceDirect**, searches focused on:

```
TITLE("digital twin")
AND TITLE-ABS-
KEY("sustainable supply
chain" OR "green supply
chain" OR "low carbon"
OR "net zero" OR
"circular economy"
```

This trio of carefully calibrated queries enabled the compilation of a robust collection of documents that directly address the intersection of digital twin technology, sustainable or low-carbon supply chains, and the broader Industry X.0 paradigm. The resulting dataset reflects both *breadth*, across disciplines and publication venues, and *specificity*, toward practical and theoretical developments that clarify the fragmented bridge between academic innovation and industrial adoption.

3.3 Inclusion and Exclusion Criteria

To curate a precise and relevant corpus for our bibliometric analysis on digital twins (DTs) for sustainable and low-carbon supply chains in Industry X.0, we established clear inclusion parameters. Publications were retained only when the term *digital twin* appeared in the title and at least one sustainability-related phrase, such as *sustainable supply chain*, *green supply chain*, *low carbon*, *net zero*, *circular economy*, *carbon footprint*, or *carbon intelligence*, appeared in the title, abstract, or keywords. The dataset was restricted to peer-reviewed journal articles published in English between 2019 and 2025, spanning disciplines such as engineering, computing, energy, environmental sciences, business, economics, and mathematics.

Conversely, exclusion criteria filtered out non-article formats (for example, conference papers, book chapters, and edito- rials), non-English works, and entries outside the specified timeframe or subject domains. Following database extraction, we conducted rigorous deduplication across all sources (Scopus, Web of Science, and ScienceDirect) to maintain dataset accuracy. Recognizing that some highly relevant studies might not surface through keyword-based searches, we also applied the *snowballing technique* via citation chaining, identifying additional pertinent articles from the reference lists of already selected publications. This manual inclusion, grounded in academic judgment, added three key articles that enriched the dataset and ensured a more comprehensive representation of the field. Snowballing is a widely accepted bibliometric enhancement method, particularly when database coverage is incomplete or terminologies vary (Wohlin, 2014; Wohlin *et al.*, 2022).

Through this combination of structured search strategies and targeted snowballing, we assembled a focused and robust foundational dataset for subsequent bibliometric mapping and analysis.

As shown in Figure 1, the article selection process was conducted in a structured and sequential manner to ensure both scientific rigor and relevance. A total of 274 records were retrieved from Scopus, 183 from ScienceDirect, and 137 from Web of Science. After the initial screening, 173 Scopus, 77 ScienceDirect, and 42 Web of Science records were excluded, leaving 101, 106, and 95 eligible documents from the respective databases.

Merging these records produced a combined dataset of 302 documents. A subsequent deduplication step eliminated 76 redundant entries, resulting in 226 unique articles. To further enhance coverage, three additional studies were incorporated through snowballing, which yielded a final dataset of 229 articles

This multi-stage selection process ensured transparency, reproducibility, and the elimination of potential biases, which provided a comprehensive and representative foundation for the bibliometric analysis. The rigor of the procedure strengthens the reliability of the findings and supports the validity of the subsequent network and trend analyses.

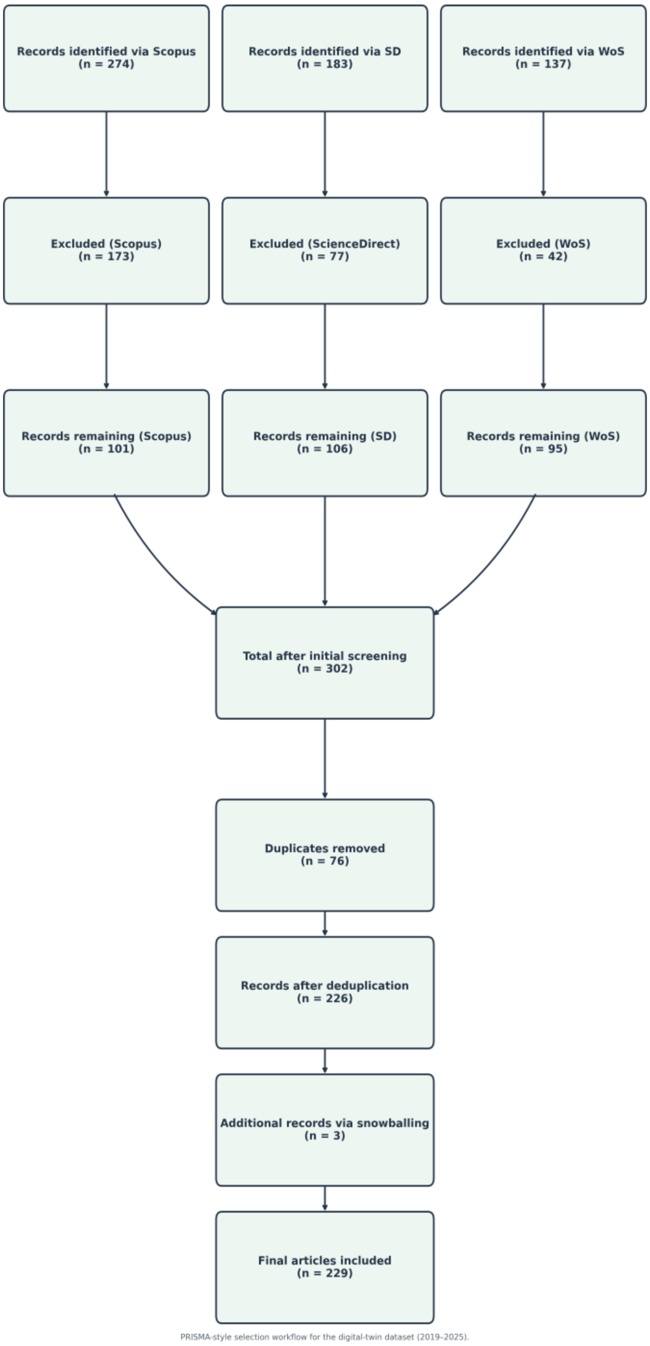

Figure 1 Workflow for sustainability in supply chain management.

4. RESULTS

4.1 Growth of Research Output on Digital Twins and Sustainable Supply Chains (2019-2025)

The temporal evolution of scientific output from 2019 to 2025, as illustrated in Figure 2, demonstrates a pronounced upward trajectory, reflecting the growing recognition of sustainable and digitally enabled supply chains as a core research frontier. In the early phase (2019-2021), contributions were limited, with fewer than 15 publications over three years. This modest output corresponds to the exploratory stage of the field, in which studies were predominantly conceptual or method- ological, laying the groundwork for integrating digital twins, Industry 4.0/5.0, and circular-economy frameworks into supply chain research.

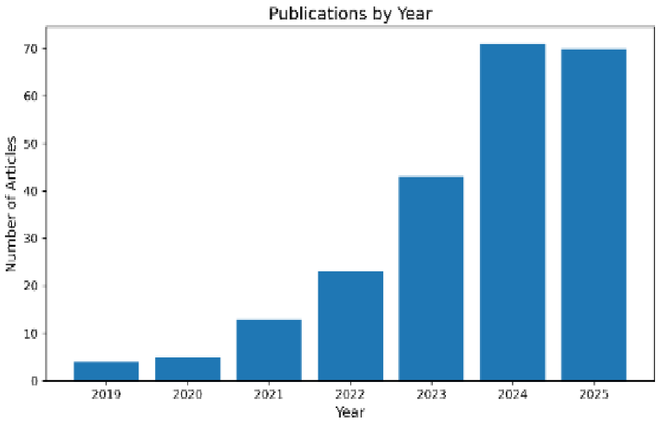

Figure 2 Annual publications on digital twins for sustainable and low-carbon supply chains (2019-2025)

From 2022 onward, a consolidation phase is observed, with publication volumes rising sharply to 23 articles in 2022 and nearly doubling to 43 in 2023. This inflection point signals a transition from fragmented conceptual discussions to more empirical and application-oriented contributions. The timing of this growth aligns with global initiatives such as the European Green Deal, the United Nations Sustainable Development Goals (SDGs), and intensified industrial commitments to net-zero emissions, which collectively stimulated academic engagement with low-carbon and resilient supply chains.

The acceleration became most evident in 2024, when output surged to 71 articles, followed by 70 articles in 2025. It should be noted, however, that the 2025 figure is based on partial-year data and does not capture the complete publication cycle. Consequently, the true volume for 2025 is likely to exceed the reported value, suggesting that the upward trajectory observed in previous years will continue. The steep rise from 2022 onward underscores the mainstreaming of sustainability and carbon-intelligent approaches within supply chain management, supported by digital innovations such as cyber-physical systems and digital twins. The apparent plateau at a high level in 2024-2025 reflects not stagnation, but consolidation of the field into a mature research stream that is now attracting sustained scholarly attention across disciplines. Overall, the trend indicates a decisive shift from theoretical exploration to widespread adoption and integration, which helps to bridge the gap between academic research and industrial practice in sustainable supply chain innovation.

4.2 Country Contributions and Cross-Border Collaboration

As shown in Figure 3, the bibliometric mapping of country contributions reveals a diverse, although uneven, global distribution of research on digital twins and sustainable supply chains. China leads with 32 documents, followed by the United Kingdom (19) and Italy (9). Other notable contributors include Germany (7), South Korea (6), Singapore (5), the United States (4), and the Netherlands (4). Several countries, including Australia, Spain, Sweden, France, and Finland, exhibit modest but increasing participation, which indicates the widening international relevance of this domain.

The country-level evidence reflects both the *globalization* and the *regionalization* of sustainable supply chain scholarship. Established scientific hubs, such as China, the United Kingdom, and the United States, shape the intellectual agenda, while emerging economies (for example, Turkey, Morocco, and Romania) are beginning to engage, which suggests a gradual broadening of participation. This dual pattern, characterized by concentration in a few leading nations alongside expanding collaborative ties, facilitates the diffusion of methods and practices across regions. For journals such as *Sustainability*, these dynamics highlight that the interaction between leading hubs and emerging participants is central to building an inclusive, global research landscape on sustainable and low-carbon supply chains.

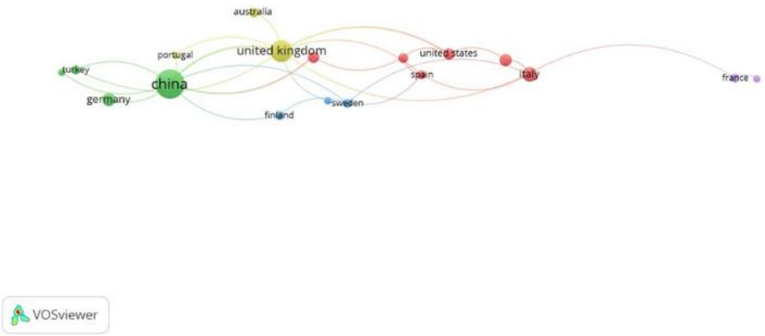

Figure 3 Country co-authorship network for digital twins in sustainable/low-carbon supply chains (2019-2025)

4.3 Leading Publication Venues: Top 10 Journals and their Scope

The analysis of publication sources highlights the ten most active journals publishing on digital twins, Industry X.0, and sustainable or low-carbon supply chains. These outlets reflect the methodological, sectoral, and interdisciplinary character of the field, with contributions spanning computer science, engineering, construction, energy, and sustainability.

A closer examination of the outlets in Table 1 reveals distinct patterns. On the one hand, engineering and computational journals, such as Procedia Computer Science and Computers & Industrial Engineering, dominate the ranking, reflecting the technical orientation of digital-twin research. These venues typically emphasize algorithms, modeling, and optimization methods that underpin digital-twin development and their integration into supply chain systems.

Table 1 Top 10 journals publishing on digital twins and sustainable supply chains (2019-2025).

Rank	Journal	Documents	Main Focus / Relevance
1	Procedia Computer Science	15	Computational methods, algorithms, and data-driven modeling for digital twins.
2	Energy and Buildings	12	Energy efficiency, sustainable construction, and Carbon-reduction strategies.
3	Automation in Construction	10	Industry 4.0/5.0 technologies applied to the construction and built environment.
4	Computers & Industrial Engineering	10	Optimization, industrial systems engineering, and supply-chain analytics.
5	Sustainable Energy Technologies & Assessments	9	Renewable energy, low-carbon technologies, and sustainability assessments.
6	Journal of Building Engineering	9	Sustainable building practices, resilience, and digital applications in construction.
7	Sustainability (Switzerland)	8	Interdisciplinary sustainability research bridging technology, policy, and practice.
8	Applied Sciences (Switzerland)	6	Applied engineering and environmental science with digital and sustainability focus.
9	Buildings	6	Sustainable architecture, building performance, and Industry 4.0 adoption.
10	Cleaner Logistics and Supply Chain	4	Logistics, green supply-chain management, and circular-economy transitions.

On the other hand, the presence of energy- and construction-oriented journals*, Energy and Buildings, Automation in Construction,* and *the Journal of Building Engineering,* signals the adoption of digital-twin concepts in the built environment, where energy efficiency, carbon reduction, and infrastructure resilience are critical priorities. This crossover illustrates how sustainability-focused supply chain research is increasingly being tested and validated through case studies in construction, building operations, and energy-intensive sectors energy-related DT applications, several case-oriented reviews show that operational twins can feed near real-time energy or emissions data to monitoring dashboards, which aligns with emerging requirements on Scope 3 visibility and lifecycle transparency, particularly in circular and low-carbon supply chains (Ivanov & Dolgui, 2021; Zhu & Jin, 2025).

Another key insight is the strong representation of MDPI journals in the ranking, namely *Sustainability, Applied Sciences,* and *Buildings*. These outlets act as interdisciplinary platforms, bringing together contributions from engineering, environ- mental sciences, and policy studies. Their prominence highlights the importance of accessible, cross-disciplinary venues in diffusing digital-twin research beyond traditional engineering communities and embedding it within broader sustainability debates. The inclusion *of Cleaner Logistics and Supply Chain,* the only explicitly supply chain-oriented journal in the top ten, further indicates a shift toward direct applications of digital technologies in logistics, green supply chains, and circular-economy transitions.

These findings suggest that the journal distribution reflects three interrelated dynamics. *First*, the field retains a strong technical and methodological base, anchored in computer science and industrial engineering outlets. *Second*, it demonstrates significant application in sectoral contexts such as construction, buildings, and energy, which serve as proving grounds for sustainability-oriented digital-twin solutions. *Third*, it is increasingly supported by interdisciplinary sustainability journals, which provide visibility and bridge academic research with industrial practice and policy. This triad of methodological, sectoral, and interdisciplinary contributions helps explain the rapid growth and consolidation of digital-twin research in the sustainability domain, as evidenced by the strong representation of outlets aligned with low-carbon design, carbon intelligence, and Industry X.0.

4.4 Evolving Keyword Landscape: From technical Foundations to Managerial Adoption

The temporal overlay (Figure 4) shows how the agenda around digital twins and sustainable supply chains evolved from 2020 to 2025, shifting from technological exploration to sustainability frameworks and, more recently, to industrial adoption and managerial applications.

- **Early Phase-Technological Foundations (2020-2021):** Dominant terms: *Industry 4.0*, *Internet of Things (IoT)*, *big data*, *machine learning*, *artificial intelligence*. Focus on building the technological backbone of DTs, optimization, simulation, and predictive maintenance, mainly as proofs of concept rather than at scale.
- **Transitional Phase-Sustainability Integration (2022):** Growing presence of *energy efficiency*, *carbon emissions/footprint*, *renewable energy*, *energy utilization*. Broadening toward environmental impact and decarbonization, aligned with the Euro- pean Green Deal and UN SDGs; DTs framed as tools for low-carbon operations in construction, energy, and manufacturing supply chains.
- **Expansion Phase-Holistic Sustainability Frameworks (2023):** Emergence of *circular economy*, *sustainable development*, *life cycle analysis*, *environmental management*, *waste management*. Conceptual maturation toward systemic strategies, closed-loop supply chains, resource circulation, zero-waste transitions, signaling convergence of sustainability science and industrial engineering.
- **Recent Phase-Industrial Adoption and Managerial Integration (2024-2025):** Uptick in *supply chain management*, *logistics*, *resilience*, *decision making*, *management*. Emphasis on real-world deployment, scalability, disruption readiness, and alignment with corporate sustainability strategies, shifting from technological feasibility to strategic adoption

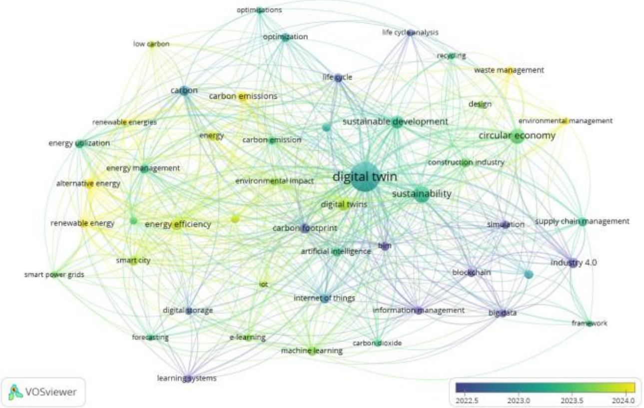

Figure 4 Keyword overlap visualization for digital twins and sustainable supply chains (2019-2025).

4.5 Keyword Cluster Analysis: Thematic Structure (2019-2025)

To better understand the evolving contours of the digital-twin and sustainability literature, we conducted a keyword co-occurrence analysis, which is visualized in Figure 5 and categorized thematically in Table 2.

Below, we interpret these clusters by considering both their methodological importance and their real-world relevance, showing how research has shifted from technical, energy-centric themes (Cluster 1) and sustainability-oriented applications of digital twins (Cluster 2) toward broader discussions of lifecycle impacts (Cluster 3) and AI-driven optimization (Cluster 4). Figure 5 facilitates visual recognition of density and proximity among keywords, while Table 2 provides granular detail on the composition and thematic labeling of each cluster. Taken together, this pairing offers both a macro-level overview and a precise breakdown, consistent with recommended practices for effective figure-table integration.

Table 2 Keyword clusters derived from co-occurrence analysis.

Cluster	Items	Label
Green cluster	algorithm; alternative energy; carbon; decision making; digital storage; digital twins; e-learning; energy; energy efficiency; energy management; energy utilization; forecasting; IoT; learning systems; machine learning; renewable energies; renewable energy; smart city; smart power grids	Technological and Energy Foundations
Red cluster	big data; blockchain; circular economy; construction industry; design; digital twin; environmental management; framework; Industry 4.0; life cycle analysis; management; recycling; simulation; supply chain management; sustainability; waste management	Digital Twin Applications in Sustainability and Supply Chains
Blue cluster	BIM; building information modelling; carbon dioxide; carbon emission; carbon emissions; carbon footprint; environmental impact; information management; internet of things; life cycle; low carbon; sustainable development	Carbon, Lifecycle, and Built Environment
Yellow cluster	artificial intelligence; optimizations; optimization; *deep learning*; *reinforcement learning*; *genetic algorithms*; *metaheuristics*; *swarm intelligence*; *predictive maintenance*	AI and Optimization Techniques

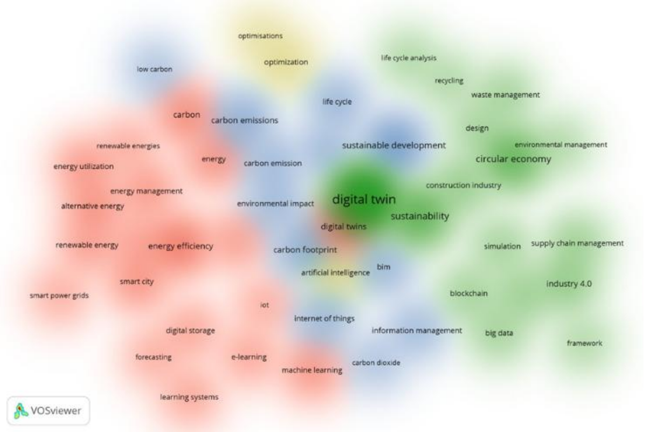

Figure 5 Keyword cluster density map (VOSviewer) for digital twins and sustainable supply chains (2019-2025).

4.5.1 *Cluster 1: Technological and Energy Foundations*

Cluster 1 encompasses 19 items, including *algorithm*, *digital twins*, *energy efficiency*, *energy management*, *IoT*, *machine learning*, *renewable energy*, and *smart city*. This cluster highlights the technological backbone of the field, in which digital twins are conceptualized as advanced cyber-physical systems underpinned by Industry 4.0 enablers such as IoT, machine learning, and big-data analytics. Early research examined how these technologies enhance real-time monitoring, predictive analytics, and decision-making within supply chains (Fuller *et al.*, 2020; Sharma *et al.*, 2022).

A strong emphasis is placed on energy-oriented applications, including energy efficiency, energy utilization, and renewable energy. This reflects how digital twins are increasingly leveraged to optimize energy flows in manufacturing, logistics, and urban systems, which contributes to low-carbon and smart-city transitions (Kajba, Obrecht, & Ojsteršek, 2023; Ni *et al.*, 2023;

O'Dwyer *et al.*, 2020; Omar, 2025). For example, smart power grids and renewable integration are often modeled through digital twins to forecast demand, enhance reliability, and reduce carbon emissions (Cao & Zhou, 2024; Mchirgui *et al.*, 2024).

The inclusion of *algorithms*, *learning systems*, and *forecasting* underscores reliance on artificial intelligence and advanced optimization techniques to process large-scale data streams generated by IoT-enabled devices. These technologies not only enable greater operational efficiency, they also facilitate the integration of renewable-energy systems into supply chains, aligning with global decarbonization goals (You *et al.*, 2022).

While Cluster 1 demonstrates a solid technological foundation, this technology-centric focus also reveals limitations. Much of the early work was conducted in controlled experimental or simulation environments, often neglecting institutional, economic, and social dimensions that determine whether these solutions can scale in real supply chains. Although IoT and AI-driven optimization show clear promise for improving energy efficiency, adoption remains uneven across regions and industries because of issues related to data availability, interoperability, cybersecurity, and high implementation costs. In addition, the strong emphasis on energy efficiency and smart systems risks a techno-optimistic bias if rebound effects and lifecycle impacts, such as the carbon footprint of building and operating large-scale IoT infrastructures, are not addressed. Thus, while Cluster 1 lays the necessary technological groundwork, its contribution to sustainability depends on embedding these tools within strategies for governance, equity, and long-term carbon reduction.

4.5.2 *Cluster 2: Digital Twin Applications in Sustainability and Supply Chains*

This cluster evidences the field's shift from enabling technologies to applied decision support. Digital twins (DTs) are used for supply chain stress testing, scenario planning, and resilience analytics, operationalized through simulation models and big-data pipelines (Ivanov, 2023). Managerial terms (for example, *supply chain management* and *management*) reflect the pivot from proofs of concept to decision-oriented visibility, agility, and policy testing across sourcing, production, and distribution (Roman *et al.*, 2025).

A core strand links DTs with environmental accounting, most notably life cycle assessment (LCA) and environmental management, by connecting twins to inventory and impact models that are consistent with ISO 14040/14044 principles and practice (Petri *et al.*, 2025; S. Yang *et al.*, 2023). In the built-environment and construction vertical, DTs are coupled with building information modeling (BIM) to perform energy and lifecycle analyses for low-carbon design and site logistics (Boje *et al.*, 2023; Pathak, 2023). The presence of *circular economy*, *recycling*, and *waste management* indicates an upstream move toward eco-design and closed-loop strategies, in which DTs provide product and asset histories and material passports (Ali *et al.*, 2025; Mügge *et al.*, 2024). Blockchain appears as a complementary tool for traceability and accountability across multi-tier networks, although adoption patterns remain uneven and largely theory-driven (Kouhizadeh *et al.*, 2021).

Several frictions still limit scale-up and external validity:

- **Interoperability and data governance.** Binding constraints persist across ERP/PLM/IoT stacks and between firms, and recent reviews emphasize the need for multi-level interoperability (syntax, semantics, protocols, ownership) (Acharya *et al.*, 2024; David *et al.*, 2024).
- **Scope-3 data gaps.** DT-driven footprinting and supplier engagement are hindered by incomplete upstream data and weak data contracts, which makes carbon and circularity metrics noisy (Ströher *et al.*, 2025).
- **Objective realism.** Although multi-objective formulations are emerging, many studies still optimize single goals on stylized datasets, which underscores the need for richer industrial evidence (Kamble *et al.*, 2022).
- **Blockchain trade-offs.** ESG-oriented ledgers can introduce environmental and operational burdens (for example, PoW energy and system complexity), so energy-aware architectures and careful value-case design are essential (Tayebi & Amini, 2024).
- **Sectoral capability gaps.** Construction shows strong potential, yet it faces skills shortages, integration costs, and organizational resistance that fragment lifecycle use of BIM-DT-LCA stacks (Jahangir *et al.*, 2024).
- **Standards and ontologies.** Progress hinges on reference architectures and semantic standards (for example, ISO 23247 for manufacturing DTs and OPC UA for interoperable messaging) to make DTs composable across partners and platforms (Cavalieri & Gambadoro, 2023; Ferko *et al.*, 2023; Shao & Helu, 2020; Talasila *et al.*, 2025).

4.5.3 Cluster 2: Digital Twin Applications in Sustainability and Supply Chains

This cluster emphasizes the integration of lifecycle-oriented sustainability into the built environment, driven by building information modeling (BIM) and digital-twin (DT) technologies. BIM provides the foundational digital representation and decision support across design, construction, and operation, which enables lifecycle assessment (LCA). A notable advance- ment is the *Building Life Cycle Digital Twin* (BLDT) framework, which combines real-time IoT data, machine learning, and semantic interoperability to enable dynamic, high-fidelity LCA of both embodied and operational carbon. A case study at the Port of Grimsby reported that BLDT achieved a 25% reduction in energy consumption while improving operational efficiency, which underscores its potential for predictive interventions and optimized carbon accounting (Petri *et al.*, 2025; W. Yu *et al.*, 2022).

Buildings and construction remain substantial contributors to global energy use and CO_2 emissions, accounting for ap- proximately 30-34% of final energy consumption and about 26-33% of energy-related CO_2 emissions. The manufacture of materials such as cement and steel represents an additional 14-16% of global emissions, which highlights the environmental impact of construction supply chains (Fennell *et al.*, 2021; Hamilton *et al.*, 2020). Many studies align with established stan- dards such as ISO 14040/14044 (LCA), ISO 14067 (product carbon footprint), and EN 15978 (whole-building LCA), which support methodological transparency and comparability.

In design applications, BIM-enabled LCA is used to evaluate embodied-carbon trade-offs across structural systems, ma- terial choices, and façade designs, while broader frameworks that advocate BIM–DT integration into industrial infrastructure emphasize optimizing environmental footprints through enhanced resource management (Badenko *et al.*, 2024; Heydari & Heravi, 2023).

Despite these advances, practical deployment faces significant challenges. *Data interoperability* remains a persistent hur- dle, because BIM-to-LCA pipelines often suffer from inconsistent formats, manual mapping, and fragmented semantics, which introduce uncertainty and limit scalability. Methodological choices, such as system boundaries or impact-category selection under ISO and EN standards, can substantially alter LCA outcomes, reinforcing the need for transparent and harmonized as- sumptions. While dynamic LCA via digital twins is promising, adoption is still largely limited to pilots, constrained by access to and governance of operational data. In addition, because the sector continues to rely heavily on high-carbon materials (for example, cement and steel), lifecycle modeling alone will not deliver deep decarbonization, so material innovation, policy action, and supply chain collaboration are equally essential.

4.5.4 Cluster 4: AI and Optimization Techniques

Cluster 4 emphasizes the instrumental role of artificial intelligence (AI) and optimization techniques in transforming digital-twin (DT) systems from static models into dynamic, decision-oriented tools. Recent studies show how AI integration enables DTs to act as predictive engines, simulating future disruptions and optimizing operations across supply chains for enhanced responsiveness and efficiency (Espinosa-Jaramillo *et al.*, 2024; Roman *et al.*, 2025; Wasi *et al.*, 2025). Likewise, frameworks in which DTs are augmented with real-time data streams support continuous operational optimization, dynamically adjusting product flows and system behavior in response to changing conditions (Kušic´ *et al.*, 2023; L. Yang *et al.*, 2025). These capabilities underscore a shift toward real-time, adaptive, and resilient supply chain management.

Despite this promise, AI-optimization systems face several deployment challenges:

- **Data quality and latency.** High-fidelity performance depends on clean, timely sensor data, and noisy IoT environments and data lag can degrade model reliability.
- **Computational burden.** Large-scale, multi-echelon

optimization under disruption scenarios can be computationally intensive, which limits real-time use.

- **Interoperability.** Without standard architectures and protocols, such as ISO 23247 and OPC UA, AI components risk remaining siloed, which hinders integration and scalability (**ISO23247**; **OPCUA_Core**).
- **Explainability and trust.** Black-box models reduce stakeholder confidence, so interpretable AI is needed for auditing and governance.
- **Sustainability integration.** Many routines optimize throughput or cost while omitting carbon-intensity and circularity metrics, so sustainability-aware objective functions and constraints are required.

Closing these gaps, through robust real-time data frameworks, scalable computing, interoperable platforms, transparent AI, and sustainability-aware algorithms, is essential for AI-powered digital twins to operate as practical and trusted agents in low-carbon, resilient supply chains.

5. BRIDGING THE FRAGMENTED DIVIDE BETWEEN ACADEMIC RESEARCH ACADEMIC RESEAHC AND INDUSTRIAL ADOPTION

Based on a careful analysis of 229 article titles, we observe that roughly 39.3% focus on theoretical contributions, 32.8% emphasize practical implementations, and the remaining 27.9% adopt a mixed approach. This distribution reflects a field in conceptual maturation, in which theory still delineates most contours of digital-twin possibilities, while real-world applica- tion is only beginning to gain traction. Theoretical work, including frameworks, conceptual analyses, and literature reviews, remains essential for shaping research frontiers. For instance, the comprehensive review by Sharma *et al.* underscores how digital-twin models articulate potential roles in enabling real-time simulation, forecasting, and decision support, yet acknowl- edges that implementation details are sparse, which hinders reproducibility and evaluation (Ma *et al.*, 2024; Sharma *et al.*, 2022). In parallel, IoDT (Internet of Digital Twins) surveys outline enabling architectures but also surface urgent challenges of privacy, security, and ethical compliance, particularly given the data-rich nature of DT environments (Y. Wang *et al.*, 2023). Nevertheless, practical implementations are emerging. Research has begun to deliver conceptual-implementation ap- proaches for deploying digital twins in supply chain processes (Abouzid & Saidi, 2023; Freese & Ludwig, 2025), and other work is proposing frameworks for planning and introducing digital twins operationally (Ogunsoto *et al.*, 2025). In maritime logistics, a peer-reviewed port case develops and evaluates a port digital twin that coordinates port-vessel scheduling, improves ETA prediction, and estimates voyage emissions for decarbonization (Eom *et al.*, 2023). In warehouse operations, an IFAC- indexed case study reports a large-scale automated fresh-food facility in which a logistics digital twin supports order-picking and fulfillment control under real constraints (Ashrafian & Pedersen, 2023).In engineer-to-order manufacturing, an *Applied Sciences* case documents a warehouse digital twin that integrates IoT, BIM, and AI for prefabricated components, reducing handling complexity and supporting throughput gains (Pracucci, 2024). For energy systems, an *Energies* implementation study presents a digital twin for grid-integrated electric vehicles that coordinates EVs, charging infrastructure, and operators, demonstrating an interoperable architecture in pilot operation (J.-U. Yu *et al.*, 2024). Taken together, these indexed cases point to a gradual shift from pilots to targeted operational deployments across ports, warehouses, engineer-to-order factories, and EV-grid integration, where digital twins support planning, coordination, and low-carbon decision-making (Ashrafian & Pedersen, 2023; Eom *et al.*, 2023; Pracucci, 2024; J.-U. Yu *et al.*, 2024).

Yet, the limited prevalence of mixed papers, those that combine theory and application, suggests an ongoing knowledge-design gap. Even when drivers such as interoperability are identified as key requirements, their practical enablement is often lacking. NIST analyses, for example, clearly note interoperability challenges, since digital twins developed in isolation fail to scale and integrate, which jeopardizes speed, agility, and composability (David *et al.*, 2024; Lin *et al.*, 2023). The challenge deepens when considering digital-twin adoption in smart grids and manufacturing, because comprehensive reviews such as Mchirgui's catalogue both the promise of operational optimization and the persistent barriers, including limited data trust, cost constraints, and unclear value metrics (Mchirgui *et al.*, 2024). Field evidence now shows factory-level and network-level twins closing feedback loops to reduce downtime and coordinate distributed assets, for example EV charging fleets interacting with the grid through an implemented digital-twin platform (J.-U. Yu *et al.*, 2024). Many industrial implementations remain modular and pilot-scale, without integration into broader enterprise systems such as ERP or PLM, which highlights that interoperability, data governance, and financial or business-case alignment still lag behind theoretical clarity (Conde *et al.*, 2021; Lanzini *et al.*, 2024; Seeharit *et al.*, 2024; Wynn & Irizar, 2023).

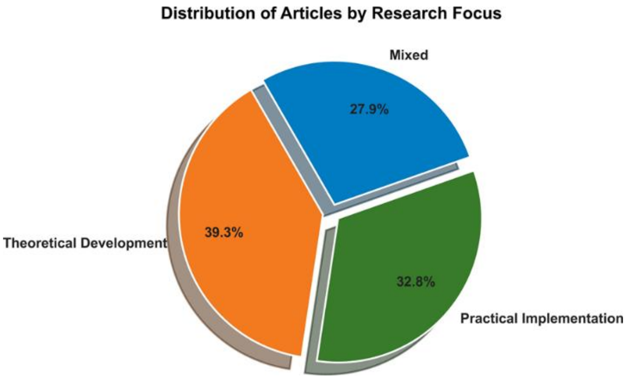

Figure 6 Distribution of articles by research focus

Further complicating translation to practice, healthcare-based case studies using CFIR reveal how stakeholder perspectives introduce nuanced ethical, regulatory, technical, and socio-organizational barriers that theory often overlooks

(Xames & Topcu, 2024). Similarly, ethnographic studies of digital-twin deployment in construction settings surface discrepancies between imagined design scopes and the iterative evolution of deployment, often resulting in misalignment with organizational processes and limited ability to evaluate impact (Agrawal *et al.*, 2022). Thus, the 39%/33%/28% split is telling, the field is richly conceptualized, but practical utility still lags, even though some mixed initiatives offer compelling glimpses of scalable application. Progress is occurring, but it is gradual, constrained by compartmentalized development, missing infrastructure for interoperability, fragmented stakeholder perspectives, and the absence of shared implementation roadmaps.

To bridge the fragmented research-industrial divide, future work must adopt realistic, multidimensional research designs, grounded in interoperability standards such as ISO 23247 and OPC UA for structural composability (Shao *et al.*, 2024; Zhang, 2019), while also embedding real stakeholder contexts, governance requirements, and operational constraints. Recent indexed implementations in ports, warehouses, and EV-grid systems suggest that aligning digital-twin architectures with open interfaces and clear operational governance accelerates scale-up and measurable impact (Ashrafian & Pedersen, 2023; Eom *et al.*, 2023; Pracucci, 2024; J.-U. Yu *et al.*, 2024). Only by anchoring models in living systems can digital twins serve as both epistemic tools and action enablers, accelerating the shift from design to deployment across circular supply chains, smart energy systems, and low-carbon infrastructure.

6. PRACTICAL IMPLICATIONS AND FUTURE RESEARCH DIMENSIONS

Across logistics, urban planning, and manufacturing domains, digital twins (DTs) have demonstrated tangible sustainability benefits. In manufacturing, agile supply chain systems empowered by DTs have achieved real-time resource optimization, reduced warehousing times, and lowered environmental footprints, which highlights DTs' potential to align operational efficiency with ecological outcomes (Ivanov *et al.*, 2019; Kaplan, 2023; Roman *et al.*, 2025). In logistics and transportation, recognized as energy-intensive sectors, DT applications have enabled fuel-consumption optimization, offering reduction path-ways for greenhouse gas emissions through virtual scenario testing (Kajba, Jereb, & Cvahte Ojsteršek, 2023; Kajba, Obrecht, & Ojsteršek, 2023). The built environment is also undergoing transformation through DT-enabled interventions. Recent findings show that DTs, combined with IoT and predictive algorithms, significantly advance indoor environmental quality and energy efficiency, directly contributing to Sustainable Development Goals such as clean energy (SDG 7), health (SDG 3), and sustainable infrastructure (SDG 11) (Venkateswarlu & Sathiyamoorthy, 2025; Yitmen *et al.*, 2025). Meanwhile, urban digital twins are being deployed across more than 500 cities to manage complex systems, from waste collection to flood resilience, delivering both environmental benefits and more organized city planning (Rolnick *et al.*, 2022).

Despite these successes, critical gaps hinder the mainstreaming of DTs for sustainability. A primary challenge lies in the inconsistency and quality of real-world data, because reliable, timely, and interoperable datasets remain rare within supply chains and urban systems (Xiros *et al.*, 2025). This weakens the ability of DTs to generate effective circularity outcomes across material flows. Also pressing is the shortage of longitudinal impact studies that validate DT benefits over time across multiple lifecycle stages. Sustainability outcomes such as net carbon reduction, lifecycle energy use, or social equity have rarely been tracked consistently beyond pilot implementations. From a methodological perspective, digital twins often lack integrated frameworks to balance multiple objectives, such as cost, emissions, resource use, and resilience. Their maximal performance remains theoretical unless they are co-designed with stakeholders within standards-aligned architectures (for example, ISO 23247 for industrial DT frameworks) (Shao *et al.*, 2023). Cross-sector collaboration stands as another vital frontier. Urban digital twin (DT) scalability demands synchronized data infrastructures, participatory governance, and regulatory trust, which requires concerted engagement from academia, industry, and public stakeholders to develop inclusive, transparent DT ecosystems that move beyond technical modeling and support equitable, resilient urban transformation. (Deng *et al.*, 2021) Lastly, extending digital twins into underserved domains such as agriculture, renewable infrastructure, and regional energy systems offers high sustainability potential. Emerging research on reinforcement-learning-augmented DTs in agriculture shows how DTs can optimize resource use even under dynamic field conditions (Goldenits *et al.*, 2024). Collectively, these insights suggest a path toward a theoretically grounded, interoperable, multi-objective, and socially embedded DT ecosystem, one that is capable of elevating both sustainability performance and stakeholder confidence in its deployment.

7. CONCLUSIONS

This bibliometric investigation has illuminated the evolving contours of digital-twin (DT) research in the context of sustainable supply chains. Over the analyzed period, theoretical maturity has advanced significantly, with scholars developing robust conceptual frameworks grounded in AI, IoT integration, lifecycle approaches, and circular-economy principles, thereby establishing DTs as vital enablers of operational visibility, environmental monitoring, and decision support.

Despite this intellectual progress, the transition from theory to scalable, cross-sector implementation remains partial. Our keyword and cluster analyses show growing interest in interoperability standards such as ISO 23247 and OPC UA and in traceability mechanisms such as Digital Product Passports. Yet these critical components are conspicuously absent from many empirical studies, which indicates an integration gap that impedes systemic adoption.

Our geographic and disciplinary mapping further reveals that DT sustainability research is predominantly concentrated within engineering and computer-science domains. This suggests untapped potential for broader involvement from logistics experts, policymakers, and urban-governance practitioners, sectors in which sustainability outcomes are most critically needed.

Encouragingly, momentum is gathering toward mixed-methods approaches that combine conceptual sophistication with real-world pilot implementations. Notably, digital twins deployed in urban infrastructure, logistics networks, and manufacturing systems are beginning to demonstrate how interoperability, lifecycle awareness, and stakeholder alignment can converge to support decarbonization, waste reduction, and operational resilience.

Indeed, complex real-world challenges, such as climate-induced disruptions, evolving regulations, and supply-chain fragilities, are catalyzing a shift from static prototypes toward dynamic, integrated DT ecosystems. A current industrial case study in the manufacturing sector, for example, illustrates how DTs infused with AI enable firms to adapt production networks in real time in response to climate risks, which enhances both operational resilience and supply-chain transparency. Nonetheless, the landscape remains fragmented. While theoretical innovation is abundant, connectivity between academic constructs and industrial exploitation is still tentative. By charting where theory intersects, and diverges, from practical reality, this study lays the groundwork for future research that is deeply operational, standards-aligned, and impact-driven.

Building on this foundation, the next wave of research must:

- Develop multi-objective frameworks capable of balancing cost, emissions, resource use, and resilience, with stakeholder co-design and standards alignment as essential enablers;
- Foster cross-sector collaboration, integrating synchronized data infrastructures, participatory governance, and regulatory trust to ensure equitable and sustainable urban DT ecosystems;
- Expand into underserved domains, including agriculture, renewable infrastructure, and regional energy systems, where reinforcement-learning-augmented DTs show promise for dynamic resource optimization.

Such a trajectory holds the promise of elevating digital twins from promising models to transformative engines of low- carbon, circular, and resilient supply systems

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest in connection with this manuscript. The research was conducted independently, without any financial or personal relationships that could be interpreted as influencing the study's findings or interpretations.

DATA AVAILABILITY STATEMENTS

The datasets used for the bibliometric analysis in this study were retrieved from Scopus, Web of Science, and ScienceDirect, all of which require subscription-based access. As a result, the raw data cannot be made openly available. However, the derived and processed datasets on which the findings are based can be provided by the corresponding author upon reasonable request.

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