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Digital Twins in Supply Chains: Research Hotspots and Future Trajectories

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Abstract

Digital twins (DT) transform supply chain management by enabling real-time monitoring, simulation, and enhanced decision-making capabilities. However, the research landscape in this domain remains nascent and fragmented. This study conducts a bibliometric analysis to identify research hotspots and future trajectories in applying DT technology within supply chains, utilising 1,700 scholarly publications indexed in the Web of Science database from 2020 to 2024. The analysis was performed using R programming and the Bibliometrix package, complemented by the Biblioshiny graphical interface. The findings reveal that DT research is primarily concentrated in developed economies, with five critical themes emerging: predictive analytics, supply chain resilience, sustainability, operational efficiency, and integration with emerging technologies. The convergence with AI, blockchain, and the Internet of Things positions DT as a pivotal tool for enhancing transparency, traceability, and dynamic modelling of supply chain networks. This study underscores DT's

transformative potential in creating resilient, efficient, and sustainable supply chains. Furthermore, the study maps the current research landscape, identifies knowledge gaps, and highlights The study further maps the current research landscape, identifies knowledge gaps, and underscores the importance of policy support to drive DT adoption. This analysis provides a robust foundation for academics, practitioners, and policymakers to innovate within this critical field.

Keywords: *Digital twins, Supply chain, Bibliometric analysis, Resilience, Innovation.*

Introduction and background

Initially conceptualised in the context of manufacturing and aerospace, digital twins (DT) have rapidly expanded their applications to various fields including healthcare, urban planning, and supply chain management (Le & Fan, 2024; Wang et al., 2020a; 2022b; Schwarz & Wang, 2022; Yang et al., 2020). DT technology holds strong potential in logistics and supply chain management due to its highly dynamic and closed interaction features, which align well with its inherent strengths (Le et al., 2024; Mihai et al., 2022). Global supply chains' increasing complexity and dynamism necessitate innovative approaches to enhance operational efficiency, resilience, and sustainability. Despite its transformative potential, the adoption of DT in supply chains is still in its nascent stages (Xames &Topcu, 2024; Sadri et al., 2023), and extant literature exploring this technology remains fragmented and scattered across various disciplines with little consensus on best practices or standard frameworks for implementation (Zrelli & Rejeb, 2024; Wang, 2020).

Current research has primarily focused on specific use cases, such as predictive maintenance and logistics optimisation (Chauhan et al., 2022; Zrelli & Rejeb, 2024), while broader applications remain underexplored. This gap is evident in the absence of comprehensive bibliometric analyses that synthesize contributions, identify prevalent research themes, outline the current state of knowledge, and highlight the evolution of topics within the field of digital twins in supply chains. By addressing these issues, this analysis aims to provide a structured and evidence-based overview of current research on digital twins in supply chains, offering valuable insights for researchers, practitioners, and policymakers. The findings will contribute to a deeper understanding of the subject and highlight the opportunities and challenges in integrating digital twins'

technology in supply chain practices. Premised on the gaps in literature, the study seeks to address the following questions:

- What is the current level of research on digital twins in supply chains?
- Who are the most productive authors of digital twins in supply chains?
- Who are the most cited authors of digital twins in supply chains?
- Which are the most productive institutions, journals and countries on digital twins in supply chain research?
- What are the potential future research directions emerging from the current literature on digital twins in supply chain management?

The rest of the paper is structured as follows: Section 2 presents the literature review, while the research methodology is outlined in Section 3. The results and findings of the study are discussed in Section 4. Sections 5 and 6 present the implications, conclusions, limitations, and future research, respectively, while acknowledgements are provided in Section 7.

Literature Review

Digital twins

Digital twins (DT), a relatively recent concept originating from product lifecycle management (PLM), is still characterised by some terminological ambiguity. The National Aeronautics and Space Administration (NASA) initiated the Digital Twin (DT) concept in 2010 within the aerospace domain; it later expanded to other disciplines. For instance, NASA (2010) first introduced it as "an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or systems that uses the best available physical models, sensor updates, and fleet history to mirror the life of its flying twin." Wang (2020, p. 7) describes DT as "the processes and methods for describing and modelling the characteristics, behaviour, formation process, and performance of physical objects using digital

technology, and can also be referred to as digital twin technology." On the other hand, a more universally adopted definition by IBM (2022, p. 3) describes a digital twin as "a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning, and reasoning to help decision-making. Therefore, digital twins are a virtual representation of a physical object, a processor system that enables real-time monitoring, analysis, and optimisation of supply chain operations (Tao, Cheng et al., 2018).

Srai and Settanni (2019) emphasise that notwithstanding the specific definitions applied, the DT concept typically involves three aspects - a physical object, a digital or 'virtual' representation and the nature of the connection between the two and between DTs. The physical layer entails all the accurate information, such as data, decisions, and actions. In addition, the communication layer comprises the data transmission tools and processes for converting accurate information to machine-readable information and vice versa (Zheng et al., 2022; Far & Rad, 2022; Wang, 2020). On the other hand, Le and Fan (2024) submit that the digital layer contains computational and simulation techniques to process information, analysis, calculation, and predictions. The DT is at the core of the Fourth Industrial Revolution/Industry 4.0/4IR, enabled through advanced data analytics, artificial intelligence (AI) and the Internet of Things (IoT) connectivity.

DT adoption in the supply chain

From a supply chain perspective, interest in digital innovation and improved information deployment relates to comprehending how demand variability can be detected and production capacity modified without sacrificing time-to-serve and preventing excessive inventory (Liotine, 2020). The logistics and supply chain system is becoming more complex because it is a highly connected and inter-operated system of systems. Consequently, Wang (2020) contends that in pursuit of supply chain optimisation and efficiency, digital twin technology provides new ideas and tools for current manufacturing innovation and development.
The Centre for Digital Built Britain (2022) advocates that adopting a DT holds several potential benefits for society, the economy, business, and the environment. Studies establish that DTs provide opportunities to improve logistics and supply chain systems, simulating, modelling, operating, and managing tools by allowing more significant interactions between various data sources, models, and stakeholders (Marmolejo-

Saucedo, 2020). As supply chain interactions become more frequent and intimate, communications among stakeholders will grow more efficient. Consequently, research contends that the operational efficiency in supply chains will increase, enabling end-users to receive products quickly and promptly. The virtual supply chains emerging from DT provide an opportunity to test and experiment with various scenarios, enhancing each decision's theoretical and practical basis and minimising disruption to the actual system (van der Valk et al., 2022).

IoT has increased the volume of data usable across supply chains; its rich environment and data analytics provide an essential resource for predictive maintenance and fault detection (Mandolla et al., 2019; Bilberg & Malik, 2019). The DTs can tackle the challenge of seamless integration between IoT and data analytics by creating a connected physical and virtual twin (digital twin). A DT environment allows for rapid analysis and real-time supply chain decisions through accurate analytics. DTs has the potential to give real-time status on machines' performance as well as production line feedback. It provides the manufacturer with the ability to predict issues sooner. Digital Twin use increases connectivity and feedback between devices, improving reliability and performance. AI algorithms coupled with digital twins have the potential for greater accuracy, as the machine can hold large amounts of data needed for performance and prediction analysis. The digital twin is creating an environment to test products and a system that acts on real-time data; within a manufacturing setting, this can be a hugely valuable asset (Mawson & Hughes, 2019).

DT techniques also enhance the understanding of analytical results, facilitate tracking, and enable accurate tracing of the origins of products and materials (Busse et al., 2021) by end-users. Moreover, when embedded within integrated business planning platforms, digital twins can improve supply chain planning, encompassing operational and tactical planning through to strategic decision-making. Digital twins enhance visibility by utilising multiple data sources, connecting trading partners, and leveraging static data from enterprise resource planning platforms. Therefore, adopting DT implies that supply chains become more transparent, the credibility of the systems is increased, and a foundation for further development is established.

Most importantly, the primary value of DTs in supply chain planning lies in long-term decision-making. Digital twins simulate thousands of what-if scenarios that reflect the long-term outcomes of strategic decisions (Barykin et al., 2020). With this prescriptive analytics capability,

Zaidi et al. (2024) argue that digital twins can analyse scenarios to evaluate demand and supply, better assess risks, and prepare mitigation plans for potential disruptions. Furthermore, DT technology can optimise supply chain trade-offs between resilience and efficiency and analyse the return on investment (ROI) of significant investments over multiple time horizons, thereby strengthening its ability to accurately forecast, identify, and minimise disruption and damage (Tozanli & Saénz, 2022). Scholars contend that the creation of digital twins enables organisations to gain intelligence and a competitive advantage that enhances the responsiveness of their supply chains (Burgos & Ivanov, 2021; Ivanov, 2023). The COVID-19 pandemic exposed companies' vulnerabilities within complex supply chains, such as fluctuations in supply and demand, unpredictable productivity levels, and issues with inventory placement. Ivanov and Dolgui (2020) underscore the necessity for DTs to map supply networks and ensure visibility to manage such shocks.

Again, adopting DT boosts the operational and human excellence in logistics and supply chains. Le and Fan (2024, p. 4) define operational excellence as "the systems' capacity to maintain consistent and resilient operations in the face of unforeseen risks, fluctuations, and challenges." This implies that DT systems ensure competitive and productive procedures within dynamic and uncertain environments (Sandberg, 2021; Mishra et al., 2022). On the other hand, Rahman et al. (2022) view human excellence as the stakeholders and managers in logistics and supply chain sectors who can develop deliberate policies and utilise human resources to allocate responsibilities so that the systems operate efficiently. Thus, studies posit that operational and human excellence have a close symbiotic connection, as human excellence is the basis of operational excellence, and in turn, operational excellence enhances human excellence development (Cebir & Akkartal, 2024; Le & Fan, 2024).

Digital twins are also utilised in supply chain transportation management and last-mile delivery. In this case, a transporter deploys hundreds of sensors in its trucks, hubs, and packages. It collects inputs from drivers, employees, and customers to continuously gather the operational data generated by every entity in its extensive logistics network (Marmolejo-Saucedo et al., 2020). The data points feed an organisation's advanced analytics programmes, helping to optimise the transporter's logistics network for increased efficiency and flexibility. Digital twins support this effort by tracking packages moving through

the system in real time, from shipping label creation to final delivery (Guo & Mantravadi, 2025).

Research Methodology

This study employed a bibliometric analysis to identify research hotspots and future trajectories in applying digital twins in supply chain management. The bibliometric approach was chosen for its robustness and ability to systematically process and synthesise vast amounts of data. This allowed researchers to uncover trends, relationships, knowledge structures, and objective insights into the field's development (Donthu et al., 2021; Alsharif et al., 2020). Its quantitative nature ensures reproducibility and transparency, making it a reliable tool for evaluating the evolution of DTs in supply chain research and their impact on supply chain management by mapping key themes, influential authors, and emerging trends for mapping research hotspots and future trajectories.

Data Collection

The initial phase involved data collection from the *Web of Science*, a reputable interdisciplinary scientific database, of comprehensive coverage of high-quality data, robust citation and analysis (Zhu & Liu, 2020; AlRyalat, 2019). To avoid incorrect results, search strings were applied comprehensively across the entire article record, including titles, abstracts, keywords, and cited references. On 2 November 2024, a search was performed with an open timeline, employing the following combination of keywords as the search string: "digital twins," "digital twin system", "supply chain," "digital twin supply chain", "logistics," "predictive analytics," and "resilience." The study also incorporated articles published during 2024 due to their relevance, even though it was not yet year-end.

Only peer-reviewed articles, book chapters, and conference papers that provide empirical or theoretical insights related to the application of digital twins in supply chain management and published in English were included. Non-peer-reviewed materials such as non-scientific articles, editorials, grey literature, opinion pieces, news articles, and editorials that do not specifically address the application of digital twins in supply chains were excluded. Articles were screened based on their abstracts and keywords to refine the dataset further to verify their focus on DT and supply chain management as recommended by Passas (2024). The

collected dataset was then filtered for duplicates, incomplete records, and unrelated studies. Metadata was compiled for analysis, including titles, abstracts, keywords, authors, institutions, publication years, and citation counts. Duplicate records and irrelevant entries were removed during pre-processing to maintain data integrity. Metadata fields were standardised to ensure consistency in the analysis. The search yielded 1700 relevant publications from 2020 to 2024, capturing DT's historical evolution and contemporary developments in supply chains. These documents were selected for further analysis using the command-based software Bibliometrix package in R (Aria & Cuccurullo, 2017).

The study employed the *R* programming language and its *Bibliometrix* package, including its graphical user interface, *Biblioshiny*. *R* programming is a versatile statistical computing environment well-suited for handling large datasets and implementing advanced analytical techniques. The use of *R* is justified by its capabilities for customising analyses, replicability, and its active support community to enable the pre-processing of bibliographic data - removing duplicates, standardising metadata, performing statistical computations, and generating detailed visualisations (Derviş, 2019; Ab Rashid, 2023). The *Bibliometrix* R package identifies prolific authors, institutions, and publication trends. It also facilitates network analysis, including co-authorship networks, citation relationships, and keyword co-occurrence, and enables the tracking of thematic evolution and collaboration patterns (inter-institutional and international)

Biblioshiny is a user-friendly web-based application for bibliometric analysis that integrates seamlessly with *Bibliometri*cs. It allows researchers to interact with bibliographic datasets through an intuitive graphical interface, eliminating the need for extensive coding (Thangavel & Chandra, 2023). The bibliometric analysis encompassed four primary techniques: descriptive, performance analysis, co-citation analysis and visualisation. The descriptive analysis focused on publication trends, while the performance analysis technique evaluated productivity and the impact of research in the field. Also included were the metrics such as the number of publications per year, most cited articles, and influential authors, which were analysed to identify leading contributors and assess the growth trajectory of DT research in supply chain management. Performance analysis justified the selection of key studies and highlighted their relevance to the research topic. On the other hand, consistent with Torres-Pruñonosa et al. (2021) and Delagado-Alemany et al. (2022), co-citation analysis examined how frequently pairs of articles were cited,

revealing relationships between seminal works and identifying clusters of related research themes. This technique provided insights into the intellectual structure of the field, identifying foundational theories and frameworks underpinning DT in supply chain applications.

Visualisation tools, such as network maps and density plots, were employed to present the results of the analysis in a transparent and interpretable manner. Consistent with Moral-Muñoz et al. (2020), network maps highlighted the relationships between authors, institutions, and keywords, providing a holistic view of the research landscape. The analysis was structured into the network (co-authorship, co-citation) and content analysis (keyword co-occurrence) to derive insights into research hotspots and collaboration patterns (Gaviria-Marin, 2019). Keywords were analysed to identify recurring themes, emerging trends, and gaps in the literature. Co-occurrence mapping highlighted connections between key concepts, such as Digital Twin (DT) integration with artificial intelligence (AI) and blockchain technologies. This justifies focusing on emerging technological synergies and their potential for future research.

Results

Main documents in WoS

Table 1 displays the primary information about the dataset extracted from *WoS*on digital twins in supply chains. Table 1 shows the 1700 publications spanning from 2020 to 2024 with an annual growth rate of -5.18%, indicating a decline in output over time from 48 sources and 5738 authors across the globe. Furthermore, 96.88% (1647) of the identified publications are articles (798 articles, one book chapter article and 55 early access articles).

Table 1: *Main information about documents published in WoS*

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2020:2024
Sources (Journals, Books)	48
Documents	1700
Annual Growth Rate %	-5.18
Document Average Age	2.13
Average citations per doc	12.43
References	93896
DOCUMENT CONTENTS	
Keywords Plus (ID)	2519
Author's Keywords (DE)	5032
AUTHORS	
Authors	5738
Authors of single-authored docs	159
AUTHORS COLLABORATION	
Single-authored docs	166
Co-Authors per Doc	3.74
International co-authorships %	29.71
DOCUMENT TYPES	
Article	1647
Article: Early Access	47
Article; proceedings paper	2
Review: Early Access	4

Source: *Bibliometrix output on 2 November 2024*

Annual scientific production

Figure 1 shows the observed output of annual scientific publications in the digital twins and supply chains domain. The distribution of studies spanned from 1995 to 2024, albeit with a decline in research after the peak of 416 articles recorded in 2021. However, it is important to note that the number of scientific publications in 2024 needs to be completed (270), as the study's total publication analysis only covers the period up to 2 November - hence, the 2024 total is subject to change.

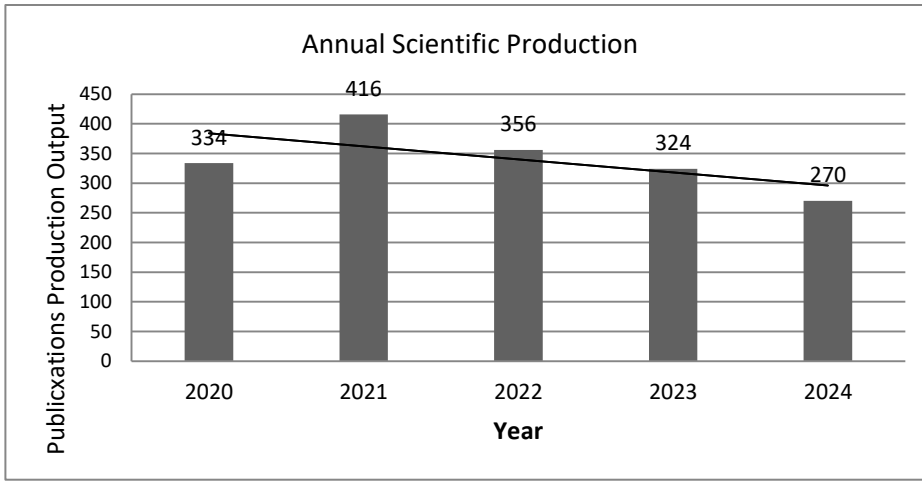


Figure 1: *Annual scientific production*
Source: *Bibliometrix output on 2 November 2024*

Most relevant sources

Figure 2 illustrates the distribution of the top ten most relevant sources of digital twins in the supply chain from the *WoS* database. As expected, sustainability leads with 1104 publications, given its prime focus on environmental, cultural, economic, and social sustainability issues. Second is the Journal of Cleaner Production, which comes with 131 documents, followed by the International Journal of Sustainability in Higher Education (91), Environment Development and Sustainability (78), Sustainability Science (42), Sustainability Accounting Management and Policy Journal (38), Sustainable Production and Consumption (31), Frontiers in Sustainability (20), and Discover Sustainability (18). At the same time, sustainable development is ranked tenth with 17 publications.

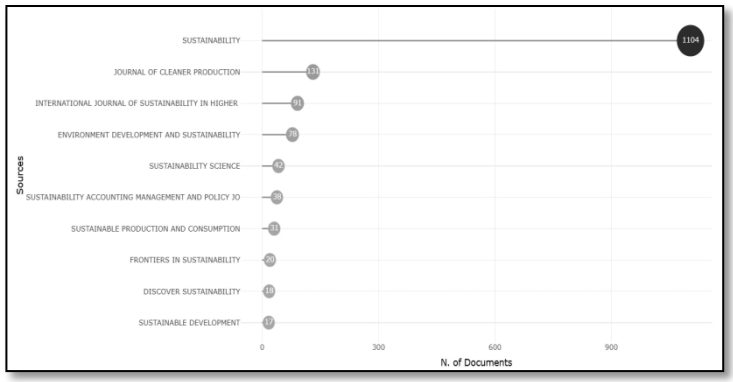


***Figure 2**: Most relevant sources*
***Source:** Bibliometrix output on 2 November 2024*

Source growth dynamics

The source growth of digital twins in the supply chain is shown in Table 2. The Sustainability Journal, Journal of Cleaner Production, International Journal of Sustainability in Higher Education, Environment Development and Sustainability Science are the five journals with the most substantial annual increase from 2020 to 2024. As of 2 November 2024, these journals had published 85.05% (1446) of 1700 articles (article, book chapter, and early access). The Sustainability had 1104 publications (64.94%), followed by the Journal of Cleaner Production with 131 articles (7.70%); the International Journal of Sustainability in Higher Education had 91 publications (5.35%), while Environment Development and Sustainability and the Sustainability Science Journal had 78 (4.59%) and 42 articles (2.47%), respectively.

***Table 2:** Journal source growth dynamics*

Year	Sustainability	Journal of Cleaner Production	International Journal of Sustainability in Higher Education	Environment Development and Sustainability	Sustainability Science
2020	243	34	16	7	5
2021	528	71	31	22	19
2022	762	100	47	27	27
2023	977	121	64	43	32
2024	1104	131	91	78	42
%	64.94	7.70	5.35	4.59	2.47

***Source:** Bibliometrix output on 2 November 2024*

Top 10 most relevant authors

The top 10 authors based on the number of articles published in the WoS database are listed in Table 3. The list indicates that the top three authors each published at least seven articles, whereas authors ranked fifth through tenth published six or fewer. The table of the relevant authors shows that Leal is 1st with ten publications, followed by Li with eight articles, while Kuma and Missimer are jointly in the third position with seven articles each. The fifth and eighth positions had three authors, with 6 and 5 publications, respectively.

Table 3: *Top 10 relevant authors*

Authors	Articles	Articles Fractionalised
Leal, F. W.	10	1.10
Li, W.	8	2.39
Kuma, A	7	1.68
Missimer, M.	7	2.75
Garsa-Reyes, J.A.	6	1.22
Kumar, K.	6	1.23
Yi, P.	6	1.92
Ayers, J.	5	2.25
Caeiro, S.	5	1.03
Liu, Y.	5	0.85

Source: *Bibliometrix output on 2 November 2024*

Most globally cited documents

The rankings of the top 10 globally cited documents based on digital twins in the supply chain in the WoS database are shown in Table 4. It indicates that in the lead was a study by Yadav et al. (2020) with a total of 330 citations, followed by Brundiers et al. (2021) with 253 citations, while Alsayegh et al. (2020) were in third position with 234 citations.

Table 4: *Most globally cited documents*

Rank	Author	Title	Source	Total Citations
1	Yadav et al. (2020)	A framework to overcome sustainable supply chain challenges th rough solution measures of Industry 4 .0 and circular economy: An automotive case.	Journal of Cleaner Production	330
2	Brundiers et al. (2021)	Key competencies in sustainability in higher education—toward an agreed-upon reference framework.	Sustainability Science,	253
3	Alsayegh et al.(202 0)	Corporate economic, environmental, and social sustainability performance transformation through ESG disclosure.	Sustainability	234
4	Kumar et al. (2020)	Application of industry 4.0 technologi es in SMEs for ethical and sustainable operations: Analysis of challenges	Journal of Cleaner Production	225
5	Kumar et al. (2021)	To identify industry 4.0 and circular economy adoption barriers in the agriculture supply chain by using ISM-ANP	Journal of Cleaner Production	214
6	Bag et al. (2021)	Key resources for industry 4.0 adoption and its effect on sustainable production and circular economy: An empirical study	Journal of Cleaner Production	211
7	Li & Yi (2020)	Assessment of city sustainability—Coupling coordinated development among economy, society and environment.	Journal of Cleaner Production	192
8	Gupta, Kumar & Wasan (2021)	Industry 4.0, cleaner production and circular economy: An integrative framework for evaluating ethical and sustainable business performance of manufacturing organisations.	Journal of Cleaner Production	185
9	Hussain & Malik (2020)	Organisational enablers for circular economy in the context of sustainable supply chain management	Journal of Cleaner Production	158
10	Nasrollahi et al. (2020)	Environmental pollution, economic growth, population, industrialisation, and technology in weak and strong sustainability: using the STIRPAT model	Environmen t, Developmen t and Sustainability	150

Source: *Bibliometrix output on 2 November 2024*

Relevant affiliations

The top ten institutions in the field of digital twins in the supply chain are presented in Table 5. The University of Helsinki ranks first with 51 articles, followed by the University of Lisbon (35 articles) and the

University of Maribor (28 publications), while the Technical University of Valencia is fourth with 27 articles. It can be observed that from the list of the ten most relevant affiliations on digital twins in supply chain studies as they appear in the WoS database, only the University of Johannesburg emerges from a developing country with a total of 26 articles.

Table 5: *Most relevant affiliations*

Rank	Affiliation	Articles
1	University of Helsinki	51
2	University of Lisbon	35
3	University of Maribor	28
4	The Technical University of Valencia	27
5	Leuphana University of Lüneburg	26
6	Ohio State University	26
7	University of Johannesburg	26
8	University of Minho	26
9	Arizona State University	24
10	Lund University	24

Bibliometrix output on 2 November 2024 Most cited country and scientific production

Table 6 illustrates the ten prolific country citations on digital twins in supply chain research published in the WoS database. This indicates that China has the highest total citation count (2410), followed by India, which has 1879 citations, while Spain ranks third with 1550 citations. All the remaining countries on this top 10 cited country list have a total citation count of less than 1500.

Table 6: *Country Scientific Production*

Rank	Country	Total Citations
1	China	2410
2	India	1879
3	Spain	1550
4	Italy	1386
5	Germany	1331
6	USA	1144
7	Portugal	766
8	United Kingdom	740
9	Brazil	670
10	Australia	654

Source: *Bibliometrix output on 2 November 2024*

In addition, a bibliometric coupling was performed to determine the top 10 countries' scientific production. Figure 3 shows that the most productive country was China, with 525 articles, followed by the United States of America (USA) and Spain, with 520 and 447 publications, respectively. Germany was ranked fourth with 304 articles. All the remaining countries on the list had produced less than 300 publications each: Portugal (298), Italy (273), the United Kingdom (UK, 264), Brazil (246), India (237), and Australia (203).

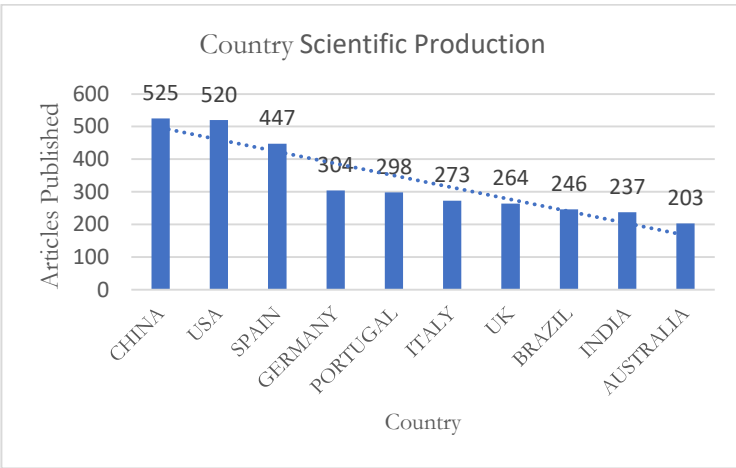


Figure 3: *Most cited countries' scientific production/////////*

Source: Bibliometrix output on 2 November 2024 Most frequent words and Wordcloud

The most frequent words used by authors and the Wordcloud related to digital twins and supply chain studies are displayed in Table 7 and Figure 4. DT have the highest number of occurrences (250), followed by "innovation" with 241 occurrences, "simulation" with 217 occurrences, and "optimisation" with 158 occurrences, while "Industry 4.0" is ranked fifth with 117 occurrences, all highlighting their critical roles in supply chain management (Gunal & Karatas, 2019; Luo et al., 2023; Raska et al., 2021). The top five keywords reveal their critical importance to contemporary academic research in supply chain management, reflecting the field's technological and strategic advancements. Digital twins enable predictive analytics to foresee supply chain disruptions or inefficiencies and facilitate real-time decision-making by integrating data from IoT devices and sensors, enhancing resilience by simulating "what-if" scenarios to test responses to potential risks, including supplier delays or transportation disruptions. Surprisingly, the words "supply chain" are ranked 11th with 85 occurrences from the reviewed publications, clearly highlighting the current scarcity and fragmentation of research in the digital twins-supply chain domain.

Table 7: *Most frequent words*

Rank	Words	Occurrences
1	Digital twin	250
2	Innovation	241
3	Simulation	217
4	Optimisation	158
5	Industry 4.0	117
6	Sustainability	114
7	Inter of Things (IoT)	103
8	Big Data	99
9	Artificial Intelligence	92
10	Blockchain	89
11	Supply Chain	85
12	Predictive Analytics	83
13	Resilience	68
14	Logistics	59
15	Smart Manufacturing	58
16	Cyber-Physical Systems	57
17	Cloud Computing	56
17	Machine Learning	51
19	Collaboration	48
20	Disruption Management	45

Source: *Bibliometrix output on 2 November 2024*

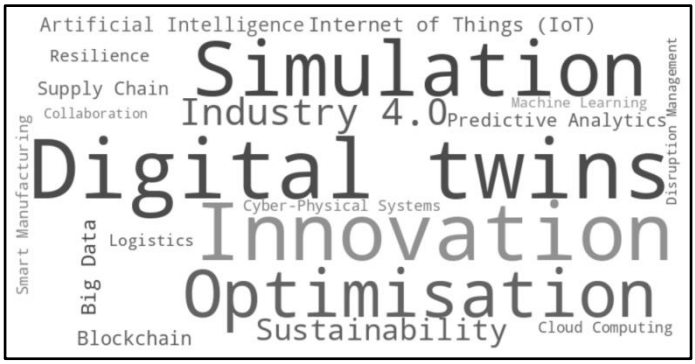


Figure 5: *Wordcloud*
Source: *Bibliometrix output on 2 November 2024*

Co-citation network

Table 8 and Figure 6 present the co-citation network analysis, a measure of the connections between documents (Zhang et al., 2020). Co-citation of two documents occurs when both are cited in a third publication (Aria & Cuccurullo, 2017) and is considered a useful measure to reflect the state of intellectual production in a given field and the evolution of schools of thought. Consistent with Robledo-Giraldo et al. (2023), the study employed co-citation analysis to provide an overview of the evolution of key concepts in DT and the supply chain. The co-citation analysis yielded two clusters (Table 8, Figure 6). Within Cluster 1, World Commission (2018) exerted the most prominent influence, evidenced by a betweenness centrality of 280.014.

Table 8: *Co-citation network parameters*

Node	Cluster	Betweenness Centrality
World Commission (2018)	1	280.014
Purvis (2019)	1	39.016
Jeurissen (2000)	1	25.205
UN Desa 2030	1	22.717
Rockström (2009)	1	6.499
Dyllick (2002)	1	54.541
Elkington (1997)	1	86.971
Steffen (2015)	1	2.405
Freeman (1984)	1	80.665
Hahn (2013)	1	6.646
Bocken (2014)	1	119.888
Eisenhardt (1989)	1	8.169
Braun Virginia (2006)	1	3.36
Sala (2015)	1	0.482
United Nations	1	0
Dimaggio (2000)	1	4.997
Engert (2016)	1	10.419
Van Marrewijk (2003)	1	0.384
Donaldson (1995)	1	0.332
Jensen Mc (1976)	1	0
KatesRw (2001)	1	0.701

Source: *Bibliometrix output on 2 November 2024*

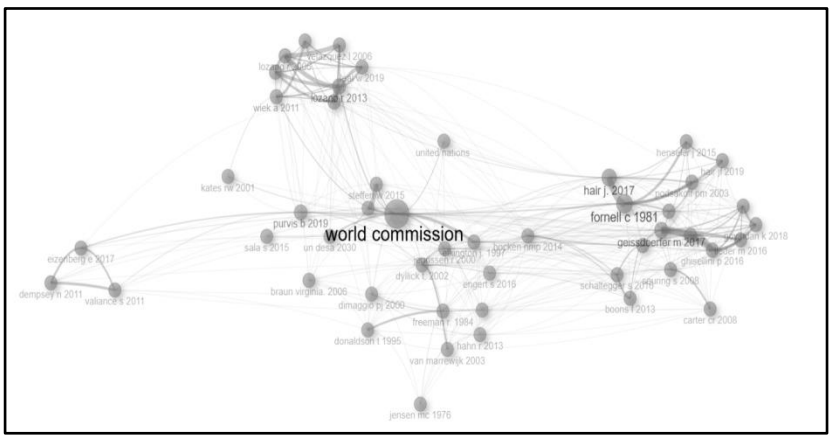


Figure 6: *Co-citation network*
Source: *Bibliometrix output on 2 November 2024*

Co-occurrence network

A co-occurrence network is a graphical representation that highlights the relationships and connections between items based on their simultaneous appearance in a specific context (Klarin, 2024). It is widely used to

analyse and visualise the structure and trends within a research domain. Table 9 and Figure 7 present the co-occurrence network. Table 9 shows that there are 50 items distributed into three clusters: cluster 1 with 28 items, cluster 2 with 10 items and cluster 3 with 12 items. The clusters refer to groups of closely related nodes formed based on their connectivity. Clustering reveals underlying themes or subfields within the dataset. The nodes represent the entities of interest in the network, such as keywords, authors, institutions, or cited references. Furthermore, the edges are the links which illustrate the strength of the relationship between nodes, typically based on how often two entities co-occur in the analysed data (Tan et al., 2023). Cluster one is predominantly characterised by the framework, supply chain management, and indicators, as revealed by their high betweenness centrality. This suggests these elements are crucial bridges for information flow within the network, assuming communication follows the shortest paths (Fosso Wamba, 2020) In cluster two, betweenness centrality highlights governance and corporate social responsibility as the leading themes, whereas cluster three centres on management, performance, and impact.

Table 9: *Co-occurrence network parameters*

Node	Cluster	Betweenness
Framework	1	104.696
Indicators	1	13.459
Systems	1	10.144
Supply Chain Management	1	18.119
Challenges	1	12.397
Design	1	1.357
Implementation	1	6.85
Strategies	1	3.344
Education	1	0.393
Barriers	1	3.558
Science	1	1.348
Energy	1	2.962
Knowledge	1	4.11
Climate Change	1	2.091
Circular Economy	1	2.236
Higher-Education	1	0.208
Consumption	1	1.489
Drivers	1	1.413
Future	1	3.113
System	1	0.521
Cities	1	1.759
Decision-Making	1	0.756
Integration	1	2.131
Life-Cycle Assessment	1	0.666
Perspective	1	0.664
Policy	1	1.183
Sustainability	1	0.957
Economy	1	0.928
Corporate Social Responsibility	2	12.723
Governance	2	19.614
CSR	2	3.317
Quality	2	2.049
Social Responsibility	2	2.374
Determinants	2	1.497
Disclosure	2	0.553
Information	2	0.835
Financial Performance	2	0.615
Strategy	2	0.521
Management	3	104.056
Performance	3	71.756
Impact	3	31.429
Model	3	18.562
Innovation	3	14.997
Industry	3	5.957
Green	3	2.913
Business	3	2.488
Corporate Sustainability	3	2.89
Environmental Sustainability	3	0.535
Behaviour	3	1.393
Smart	3	1.038

Source: *Bibliometrix output on 2 November 2024*

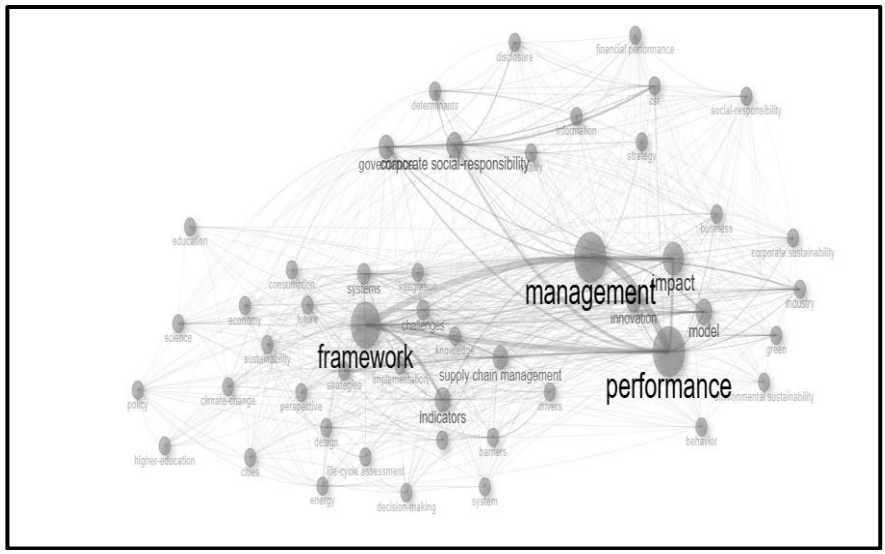


Figure 7: *Co-occurrence network*
Source: *Bibliometrix output on 2 November 2024 Country collaborations*

Figure 8 and Table 10 depict the primary collaborative research between countries from the WoS database. The 20 strongest collaborations are being nurtured by scholars from China, the United Kingdom, Pakistan, Australia, India, Germany, Spain, the USA, Saudi Arabia, Italy, Brazil and Portugal. The study also observes that countries from Africa have few international and intra-continental collaborations, for instance, the UK and Egypt (4), Brazil and South Africa (3), South Africa and Ghana (3), as well as Ghana and Zimbabwe (1).

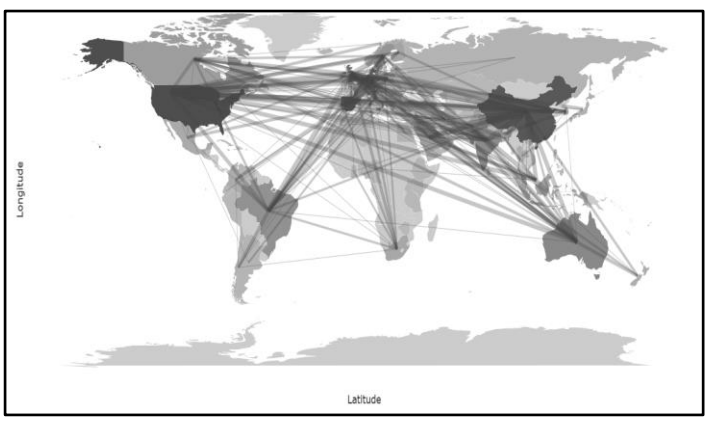


Figure 8: *Country collaboration map*
Source: *Bibliometrix output on 2 November 2024*

Table 9: Country collaborations

From	To	Frequency
China	Pakistan	18
China	United Kingdom	17
United Kingdom	Brazil	16
United Kingdom	India	15
USA	Germany	15
USA	United Kingdom	15
Germany	United Kingdom	14
Saudi Arabia	Pakistan	13
Spain	United Kingdom	13
United Kingdom	Netherlands	12
China	Malaysia	11
China	USA	11
Germany	Brazil	11
Italy	United Kingdom	11
China	Australia	10
Portugal	United Kingdom	10
Spain	Italy	10
Spain	Portugal	10
United Kingdom	Australia	10
United Kingdom	Sweden	10
China	India	9

Source: Authors compilation from Bibliometrix output on 2 November 2024

Conclusions, Limitations And Future Research

The study analysed the current research progress, hotspots, and future trajectories for DT and supply chains and has important theoretical, managerial and policy implications. The study comprehensively maps the digital twins' research landscape by identifying the most influential publications, authors, and trends. It also sparks academic discussions on how emerging technologies like DT can influence or reshape traditional supply chain concepts. A bibliometric analysis was employed on data on digital twins' research within supply chains extracted from the Web of Science (WoS) database to accomplish this.

Regarding the first research question, which sought to assess the current level of research on digital twins in supply chains, the study found that despite the growing recognition of digital twins as a transformative tool in supply chain management, the academic literature exploring this technology remains fragmented and scattered across various disciplines (Zrelli & Rejeb, 2024; Wang, 2020). Moreover, analysis of the most frequent keywords used by authors in their publications and Wordcloud related to DT and supply chain research in the WoS database revealed that DT has the highest number of occurrences (250). The results highlight its crucial role in supply chain management, consistent with previous studies by Joel et al. (2024) and Khadem et al. (2023). Therefore, consistent with Bhandal et al. (2022), it can be concluded that the applications of DT improve supply chain operational efficiency. Specific applications of DT in predictive maintenance, inventory management, sustainability, and supply chain resilience have also been highlighted as key areas of focus in the research landscape, consistent with van der Valk et al. (2022). In response to the second to fourth research questions, the literature review highlighted that as supply chains continue to grow in complexity and the demand for digital transformation intensifies, digital twins offer a powerful tool for achieving greater supply chain efficiency, agility, and sustainability.

Therefore, the field's evolution reflects the growing recognition of the potential of DT to revolutionise supply chain processes by enabling real-time monitoring, predictive analytics, and enhanced decision-making capabilities. However, for organisations and researchers to fully realise the potential of this technology, continued academic inquiry, interdisciplinary collaboration, and practical innovation will be essential. This finding corroborates extant literature (Tozanli & Saénz, 2022; Sandberg, 2021; Mishra et al., 2022). In addition, the study submits that supply chain managers can adopt DT technologies to improve supply chain efficiency by following a structured and phased approach that integrates digital tools, data analytics, real-time decision-making, and strategic foresight.

Despite using a broad keyword search for digital twin articles in the supply chain, this study is not without limitations; some articles may have been unintentionally overlooked due to database choice, selected search filters and inclusion criteria. Notwithstanding, the large sample size of 1700 peer-reviewed articles assures that the findings fairly reflect the research conducted around the topic. The study relies exclusively on the Web of Science (WoS) database for data extraction. Also, while WoS is a

highly reputable database, it may have excluded relevant information found in other databases, potentially limiting interdisciplinary breadth. Future reputable multi-database bibliometric studies incorporating Organisation Source Premier, Scopus and Science Citation Index together with non-traditional outlets such as industry reports could broaden the scope and reduce bias in DT supply chain research. Furthermore, the study was conducted on a specific timeframe, as of 2 November 2024, and ongoing developments may alter the identified trends in a fast-evolving field of digital twins. Consequently, future studies can adopt a longitudinal approach which captures the fast-emerging trends, tool adoptions, or policy shifts and reflects the real-time evolution of digital twins in supply chains.

In addition, future research could explore the challenges of scaling DT solutions in large, complex supply chains. Future research should investigate the under-researched scalability of Digital Twin (DT) solutions within large, complex global supply chains, addressing challenges such as data integration, infrastructure costs, and deployment complexity. Furthermore, as DT relies heavily on data, future research might address the growing concerns over data privacy and security, particularly in supply chains that handle sensitive information. Lastly, investigating the ethical implications of DT applications and developing secure frameworks for data management, examining how DTs synergise with other 4IR technologies, including blockchain for provenance and the Internet of Things (IoT)for real-time supply chain feedback, could be important areas for future studies.

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