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DIGITAL TWINS AND INNOVATION IN SUSTAINABILITY MANAGEMENT: A BIBLIOMETRIC ANALYSIS, CHALLENGES AND FUTURE DIRECTIONS

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Abstract. This paper systematically explores the current research status and application potential of digital twin technologies (DTs) in sustainable development management, using bibliometric and segmented regression analyses to reveal the field's dynamic trends and research hotspots. Based on the analysis of 421 papers extracted from the Scopus database, this paper summarises the vital role of DTs in smart cities, circular economy, and Industry 4.0. It identifies the key challenges to their implementation, including the digital divide, high cost, data privacy protection, and technical complexity. The paper further suggests future research directions through case studies and theory: exploring the integration of DTs with AI, enhancing interdisciplinary collaboration, and developing low-cost implementations. The contribution of this paper is to provide comprehensive academic support and practical suggestions for the application and development of DTs.

Keywords: Digital twin; bibliometric analysis; management; SDGs

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JEL Classifications: O32, O36, Q01

1. Introduction

Sustainable development is a core concept currently widely used in many fields. Its goal is to improve human well-being while protecting the natural systems that support life on Earth. The idea of sustainable development can be traced back to ancient times and forestry practices in 18th-century Europe (Carlowitz, 1713; Grober, 2010), but the modern definition originated from the report “Our Common Future” published by the World Commission on Environment and Development in 1987 (World Commission on Environment and Development, 1987), which defined sustainable development as “meeting the needs of the present without compromising the ability of future generations to meet their own needs”. In 1992, the United Nations Conference on Environment and Development (Rio Summit) officially endorsed this concept and emphasised the vital role of academic institutions in addressing environmental and development issues. Today, sustainable innovation has become a leading principle of global development, and its application extends far beyond traditional areas such as energy and transportation to all aspects of society (De Oliveira et al., 2021).

In this context, Digital Twins (DTs) have emerged as a key tool to support sustainable development management due to their unique advantages in precise modelling, real-time monitoring and optimal management. In 2003, Professor Grieve first proposed the concept of DTs, defining them as a comprehensive

digital engineering view from product design to production planning, production engineering, manufacturing and related services, i.e. product lifecycle management (Semeraro et al., 2021). With the rapid development of technology, the application of DTs has expanded to transportation and logistics, smart cities, manufacturing, industrial product lifecycle management, and hybrid energy systems (Lu et al., 2020; Wang et al., 2024).

The core advantage of digital twin technology is that through an extensive sensor network, real-time processing of massive amounts of data, and efficient computing power, complex systems embedded in physical entities can be accurately modelled to predict system behaviour under different conditions and constraints (Tao & Qi, 2019; Niederer et al., 2021). Therefore, DTs are regarded as a significant breakthrough in digitalisation and represent the future trend of simulation technology. In an environment where enterprises innovate rapidly, digital twins can be used as both a technical tool and an innovative concept in stakeholder collaboration, business model optimisation, disruptive technology development, and customer interaction (Riascos et al., 2023).

Digital twins have demonstrated their potential in applications ranging from microscopic molecular modelling (Cannoodt et al., 2021) to macroscopic landscape management (Bauer, Dueben, Hoefler et al., 2021), from epidemic prevention and control in public health (Laubenbacher, Sluka, & Glazier, 2021) to planetary science and climate prediction (Bauer, Stevens, & Hazeleger, 2021; Voosen, 2020). In recent years, digital twins have begun to support social mitigation and adaptation measures to address climate change, such as flood prediction and monitoring, disaster-resilient community building, and supporting the achievement of the Sustainable Development Goals (SDGs) (Deren, Wenbo, & Zhenfeng, 2021). In the energy sector, efficient grid construction (Francisco, Mohammadi, & Taylor, 2020) and epidemic prevention and control modelling in public health (Deren, Wenbo, & Zhenfeng, 2021) are examples of their wide application across multiple fields. However, despite the breakthroughs that digital twins have achieved in many fields, they have not yet received sufficient attention in the global sustainable development agenda (Tzachor et al., 2022). Future research and policy need to explore further how to fully realise the potential of DTs in achieving the SDGs.

2. Theoretical background

Digital twin technology was first proposed by Grieve (2003), which refers to the synchronisation and simulation of physical entities through virtual modelling to achieve data-driven complete life cycle management (Grieves, 2003). The core of this technology is to use real-time data and virtual models to achieve complete life cycle management of physical entities (Grieves, 2014), and in practical applications, it has three distinct technical features: real-time data collection and transmission of physical systems through the Internet of Things (IoT) and sensors (Shehadeh et al., 2024); dynamic simulation using virtual models to predict the behaviour of systems under different conditions (Allam et al., 2021); and system integration to support cross-domain resource optimisation and management (He & Bai, 2020). In recent years, with the rapid development of the Internet of Things (IoT), artificial intelligence (AI), and big data technologies, this technology has been widely used in many fields, such as manufacturing, aerospace, urban planning, healthcare, and agriculture. It has demonstrated unique advantages in resource optimisation, energy efficiency improvement, and system prediction (Liu et al., 2021; Shehadeh et al., 2024). Digital twins are a vital tool for driving innovation in sustainable development management.

In sustainability, DTs support the optimisation and collaborative management of resources in complex systems through real-time monitoring and simulation (Zahedi et al., 2024). Digital twin technologies enhance spatial planning and management of urban and rural sustainability initiatives. Miszczak, Krivins, and Kaze (2024) emphasise that sustainable spatial development depends significantly on integrating economic, ecological, and social dimensions through advanced spatial planning and stakeholder engagement. Digital twins provide a robust technological framework to facilitate these integrations, offering data-driven simulations that align economic growth with environmental preservation. As a core innovative technology of Industry 4.0, DTs can optimise production processes, reduce resource waste, and achieve green manufacturing. (Liu et al., 2021). For example, in water-energy-food-environment (WEFE) management, digital twin technology supports the efficient use of resources and decision-making optimisation by integrating multi-source data (Jurgelane-Kaldava et al., 2024) and building dynamic models (Shehadeh et al.,

2024). In addition, the rise of urban digital twin (UDT) technology has further expanded the application of this field. In smart city planning, UDT can support low-carbon transportation and intelligent energy management through dynamic monitoring (Allam et al., 2022). Supporting the smart city planning and low-carbon infrastructure construction can help achieve sustainable development goals at the city level (Miehe et al., 2021). Similarly, in the field of circular economy, DTs can support waste reuse and closed-loop resource management (Verdouw et al., 2021).

Effective sustainability management through digital twins relies on technical capability but must also account for organisational capacities and humans - their values and behaviours that influence technology acceptance and application.

In this context, workforce characteristics profoundly influence organisational innovation and sustainability management through digital twins. Recent studies highlight that workforce diversity significantly enhances organisational performance through improved creativity, innovative solutions, and better responsiveness to environmental and operational challenges (Etalong et al., 2025). Such diversity can also enrich the implementation and use of digital twin technologies by incorporating varied perspectives and expertise into sustainability practices.

Earlier research demonstrated that aligning sustainability initiatives with regionally relevant human values enhances adoption and economic viability (Kaže et al., 2011). Additionally, recently adopted innovative image-based methodologies for measuring personal values significantly improve understanding of individual motivations (Kaže et al., 2022), thus being critical for designing targeted digital sustainability interventions. Similarly, consumer values directly influence economic behaviours, including willingness to participate in formal economic processes, which is crucial when planning digital interventions to mitigate grey economy practices (Kaže & Bolinskis, 2011).

The aforementioned suggests a significant area not limited to values and motivation only but also human factors such as digital literacy, resistance to change, sociocultural readiness, and even philosophical worldviews underlying these perceptions of experts in the field (Elsehrawy et al., 2023). For instance, successful implementation of DTs depends on alignment with human values and significantly on societal acceptance, digital literacy, and organisational cultures. Resistance to change, lack of technical knowledge, and sociocultural attitudes towards technology significantly influence adoption rates and effectiveness (Rasheed et al., 2020).

It might raise additional ethical questions, for instance, from a privacy perspective. While offering significant benefits, DT technologies also bring critical ethical and privacy challenges. Their dependence on extensive data collection, including sensitive and personally identifiable information, concerns about data security, user privacy, and surveillance have emerged. Organisations employing digital twins must navigate complex issues of informed consent, data ownership, transparency in data handling, and compliance with privacy regulations such as the General Data Protection Regulation (GDPR) in the European Union. Addressing these ethical implications requires robust governance frameworks and clear ethical guidelines to prevent data misuse and build public trust in digital twin deployments (De Kerckhove et al., 2022; Helbing & Sánchez-Vaquerizo, 2023; Naikwadi & Shrivastav, 2025).

Despite the great potential of digital twins in sustainable development, their implementation still faces many challenges, including environmental impact: high energy consumption and carbon footprint issues limit the long-term sustainability of DTs (He & Bai, 2020); insufficient data standardisation: the integration of multi-source heterogeneous data is complex and the level of standardisation is low (Zahedi et al., 2024); infrastructure constraints: developing countries lack the necessary technology and infrastructure (Allam & Jones, 2021; Muhamud et al., 2024). In addition, there may be risks of corruption, especially in developing countries (Krivins, 2014; Krivins et al., 2023). These challenges indicate that multifaceted technological, policy and societal efforts are still needed to achieve the large-scale application of technology and sustainable development goals.

Deploying digital twins can significantly aid regions heavily reliant on a single resource, such as oil, in achieving broader economic diversification. Okueweze et al. (2025) argue that diversifying away from oil dependency is essential for sustainable economic growth, reducing vulnerability to price volatility, and fostering resilience by expanding innovative sectors and value-added manufacturing. Digital twin technology could play a pivotal role in simulating and planning this transition, thus reinforcing sustainable economic development strategies for transforming economies towards more sustainable models. In the past, it has been particularly relevant to digital transformation and adopting new technologies and business practices. Such a transformation of economic sectors through digital technologies, as exemplified by digital banking, underscores the necessity of aligning technological innovations with customer needs and expectations. Kaže, Baumanė, Šumilo, and Škapars (2007) highlight that successfully integrating digital technologies within traditional sectors such as banking demands comprehensive adaptation strategies, considering both technological readiness and consumer behavioural shifts towards knowledge-intensive interactions. Digital twins, similarly, require businesses and industries to realign strategies towards more interactive and knowledge-intensive sustainability practices. Digital twins exemplify broader trends in digitalisation and e-environment tools crucial for sustainable business practices. For instance, an effective use of digital environments significantly accelerates sustainable business development, though many organisations remain at the preliminary stages of digital adoption. Effective digital twin implementation requires overcoming these initial barriers by enhancing digital literacy, aligning business models with digital innovation, and capitalising fully on available digital tools for sustainability.

Beyond these aspects, scholars emphasise several critical perspectives of digital twins, particularly concerning the practical adoption perspective. From an economic and financial perspective, despite clear benefits, digital twins' financial and economic feasibility remains challenging. High initial investment, complex integration processes, and uncertainty about return on investment can act as barriers, particularly for small and medium-sized enterprises, thus requiring careful financial planning and targeted policy support (Qi & Tao, 2018; Jones et al., 2020). From a regulatory and governance framework perspective, widespread adoption of digital twins is contingent upon supportive regulatory environments and robust governance frameworks. Clear standards and interoperability regulations are essential to facilitate integration across diverse systems and industries, particularly within cross-border contexts and international collaborations (Melesse et al., 2020; Mureddu et al., 2025). Scalability and interoperability perspectives pose additional technical challenges for DT implementation. Ensuring seamless communication and integration among heterogeneous systems, especially when scaling digital twin solutions across industries or geographical regions, requires standardised protocols and data formats (Cimino et al., 2019; Lu et al., 2020), which might be a challenge from the practical adoption perspective to many enterprises. Another perspective is lifecycle management, including end-of-life considerations for digital twins, which remains underexplored but critical for sustainability. As DTs involve significant technological resources, strategies for responsible disposal, recycling, or repurposing of digital assets and hardware infrastructure are essential components of comprehensive sustainability management (Parrott & Warshaw, 2017). One of the most topical perspectives is integrating artificial intelligence and machine learning algorithms, which significantly enhances digital twins' predictive power and adaptive capabilities. Advanced AI-driven analytics enable more accurate simulations, predictive maintenance, anomaly detection, and adaptive responses, thus increasing efficiency and reliability in complex systems management (Shao & Kibira, 2018; Fuller et al., 2020).

These perspectives show that digital twin technologies offer a multifaceted approach to sustainability management, integrating advanced technical capabilities with significant consideration of human, organisational, ethical, economic, regulatory, and technological challenges. As highlighted, successful deployment of DTs requires addressing these complex factors collectively rather than in isolation. Given these theoretical insights, it is essential to systematically examine how these aspects are currently discussed in practical contexts. The subsequent chapter employs a bibliometric analysis to map existing research trends, knowledge gaps, and future directions, providing empirical evidence to support strategic development and informed policymaking for the broader implementation of digital twins in sustainability management.

3. Methods

This study selected bibliometric analysis as the core research method, which is highly respected and widely used in academic research (Zupic & Cater, 2015). This method provides an objective and solid framework for systematically reviewing the literature. Its essence lies in a comprehensive, multidimensional, in-depth analysis of the conceptual framework and scope covered by digital twins and innovation in sustainable development management (Ramos-Rodríguez & Ruiz-Navarro, 2004). Bibliometric analysis can accurately analyse the complex paradigms of specific scientific topics in the key dimensions of quality and quantity using scientific statistical methods (De Bakker, Groenewegen, & Den Hond, 2005; Niu et al., 2016). In this review of the literature, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) standard process was strictly followed to ensure the scientific nature, reliability and standardisation of the research (Moher, Liberati, Tetzlaff, & Altman, 2009). The use of bibliometric analysis tools can accurately extract high-frequency keywords, keenly capture the dynamics of research hotspots, and carefully sort out the distribution of core academic journals in this research field, thus laying a solid foundation and providing key support for in-depth exploration of the theme of digital twins and sustainable development management innovation (Bornmann & Mutz, 2014).

This study also used a more advanced method called segmented regression analysis, which is used in the regression analysis of the data. Segmented Regression Analysis can better identify nonlinear changes and periodic characteristics in time series data. This method can effectively reveal turning points in trends and growth patterns in each period by dividing the data into multiple intervals and modelling each interval separately (Bornmann & Mutz, 2014).

Mathematically, the basic form of a segmented regression model is as follows:

$$y(t) = \begin{cases} b_0 + b_1 \cdot t + \epsilon, & \text{if } t \leq a_1 \\ b_0 + b_1 \cdot a_1 + b_2 \cdot (t - a_1) + \epsilon, & \text{if } a_1 < t \leq a_2 \\ b_0 + b_1 \cdot a_1 + b_2 \cdot (a_2 - a_1) + b_3 \cdot (t - a_2) + \epsilon, & \text{if } t > a_2 \end{cases}$$

Among them, a_1 , a_2 are turning points, b_1 , b_2 , b_3 are the growth rates of each stage, respectively, representing the error term. The model parameters are estimated by least squares, which can identify key turning points and their corresponding growth patterns (van Raan, 2000).

Segmented regression analysis has demonstrated critical value in studying scientific growth and technology diffusion. As Bornmann and Mutz (2014) discovered when investigating the growth of scientific literature, the trajectory of global scientific activity since the Industrial Revolution has been characterised by multiple stages, from slow growth to exponential growth. This finding provides conclusive evidence of the central role of segmented regression analysis in accurately revealing the process of long-term trend changes. Moreover, van Raan's (2000) research results clearly show that factors such as policy orientation, war conflicts, and technological changes significantly impact scientific development, which is characterised by significant differences in stages. In digital twin research, segmented regression analysis also plays a key role. It is widely used to explore the dynamic evolution model of technology diffusion and its internal influencing factors in detail. For example, by systematically analysing the growth of digital twin technology in different professional fields, researchers can accurately identify key nodes in the technology promotion process and deeply reveal the core mechanisms driving its development (Zahedi et al., 2024).

At present, the profound impact of digital twin technology in driving the innovation dimension of sustainable development management has aroused the interest and attention of scholars, policymakers, and industry experts. This situation urgently calls for a comprehensive bibliometric, in-depth exploration of the intersection of these fields. It is of great importance to comprehensively review the existing literature, gain insight into emerging research topics, accurately define the framework of the role of digital twins in sustainable innovation practices, and prospectively identify potential trends for future research.

Given this, this study innovatively uses bibliometric analysis to explore the research hotspots of digital twin technology (DTs) in sustainable development management. It organically integrates segmented regression analysis to discuss the dynamic evolution model of its technology diffusion intensely. Furthermore, through a comprehensive quantitative analysis and a case study paradigm, this study reveals research trends and practical challenges from multiple perspectives by profoundly analysing the following core issues to construct a systematic reference framework for academic research communities and practitioners:

RQ1. What is the growth of scientific publications concerning digital twins and sustainability management innovation? Does it have research potential?

RQ2. By segmenting and analysing the number of citations and high-frequency keywords in the literature, this study examines the hotspots in different time frames to explore the innovation vitality of this research field. What is the future development direction?

RQ3. In which journals do researchers mainly publish articles?

RQ4. Who are the top institutions involved in digital twins and sustainability management innovation?

RQ5. How is the literature geographically distributed? Is there a digital divide?

RQ6. Which authors have been the most prolific regarding digital twins and innovation in sustainability management? What challenges do DTs face from the perspective of innovation in sustainability management?

3. Data sources and search strategy

The data used in this study were obtained from the Scopus database, currently the largest abstract and citation database of peer-reviewed literature (Baas et al., 2020). Scopus indexes various elements of scientific publications obtained from external publishers, such as publication titles, abstracts, keywords, author names, linked affiliations, references, and drug terms (Berkvens, 2012). The data were obtained by executing a general search query. The database search was limited to one day, November 4, 2024, to prevent bias that could result from frequent routine updates. The research focused on literature related to digital twins and innovation management for sustainable development indexed in the Scopus database between 2014 and 2024 for review in bibliometric analysis (see Figure 1).



Figure 1. Outline of the data retrieval process

Search term: ('Digital twin' OR 'Digital twins' OR 'DT' OR 'DTs') AND ('Innovate' OR 'Innovation' OR 'Innovative' OR 'Innovativeness' OR 'Create' OR 'Creation' OR 'Creative' OR 'Creativity' OR 'Creativeness') AND ('manage' OR 'management') AND ('sustainable development' OR 'sustainability')

To combine many subtopics in a search query, we used Boolean operators OR and AND to accomplish this task and include all relevant information. Table 1 below illustrates the Boolean operators (OR, AND) search method in the Scopus database. Researchers obtained a sample document in *CSV format from Scopus to analyse key information. This information includes the year of publication, title, author name and affiliation, abstract, keywords, journal name, document type, and references. In addition, the search criteria were refined to include only Articles and exclude Reviews, Book chapters, Conference papers and Conference reviews. Finally, a dataset of 421 documents was obtained.

Table 1. The search strings

Database Search criteria	Search string strategy Boolean operators	No. Documents
Search string keyword	(‘Digital twin’OR ‘Digital twins’ OR ‘DT’OR ‘DTs’) AND (‘Innovate’ OR ‘Innovation’ OR ‘Innovative’ OR ‘Innovativeness’ OR ‘Create’ OR ‘Creation’ OR ‘Creative’ OR ‘Creativity’ OR ‘Creativeness’) AND (‘manage’ OR ‘management’) AND (‘sustainable development’ OR ‘sustainability’)	20,298
Documents Types	Articles only	11,164
Year Published	2017-2023	-
Language	English	-
Scopus Database	Total databases	421

After identifying the documents, the data is verified and cleaned manually. All entries in the columns are checked to ensure no important data is missed and to ensure standardisation. After sorting, the data is saved for analysis, and the author, title, ID, year, source, volume, issue, citation time, link, abstract, keywords and publisher information of the study are finalised. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart is as follows (see Figure 2). Publication trends ae

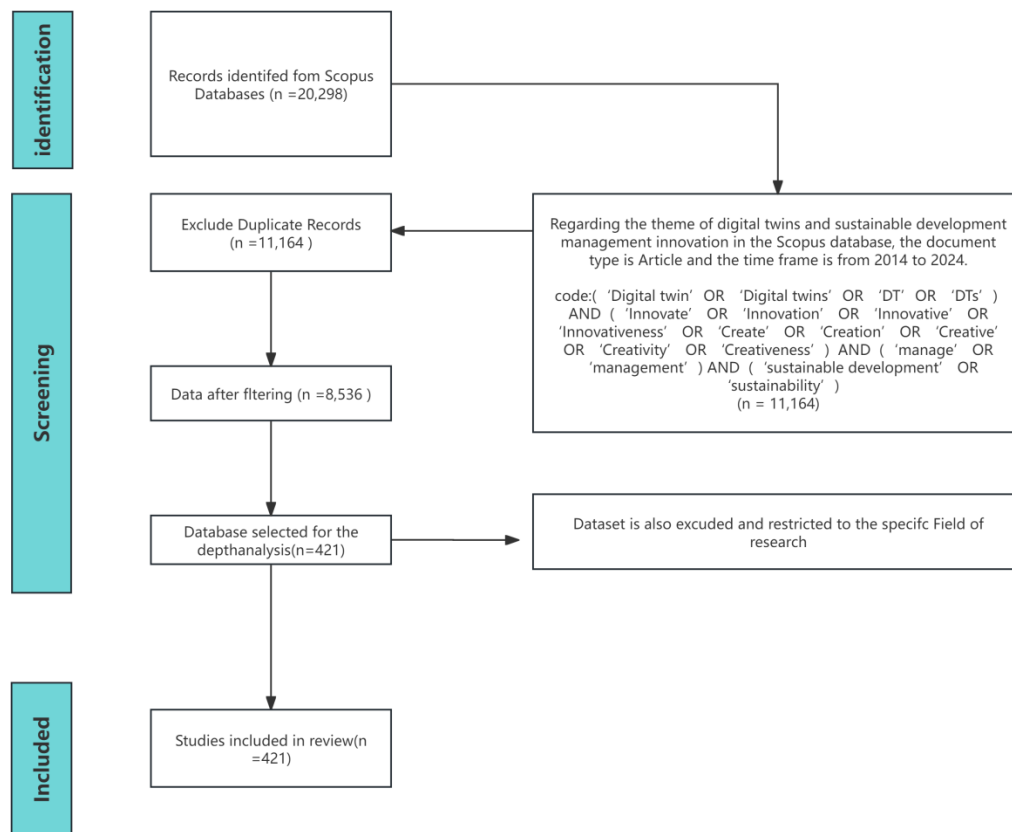
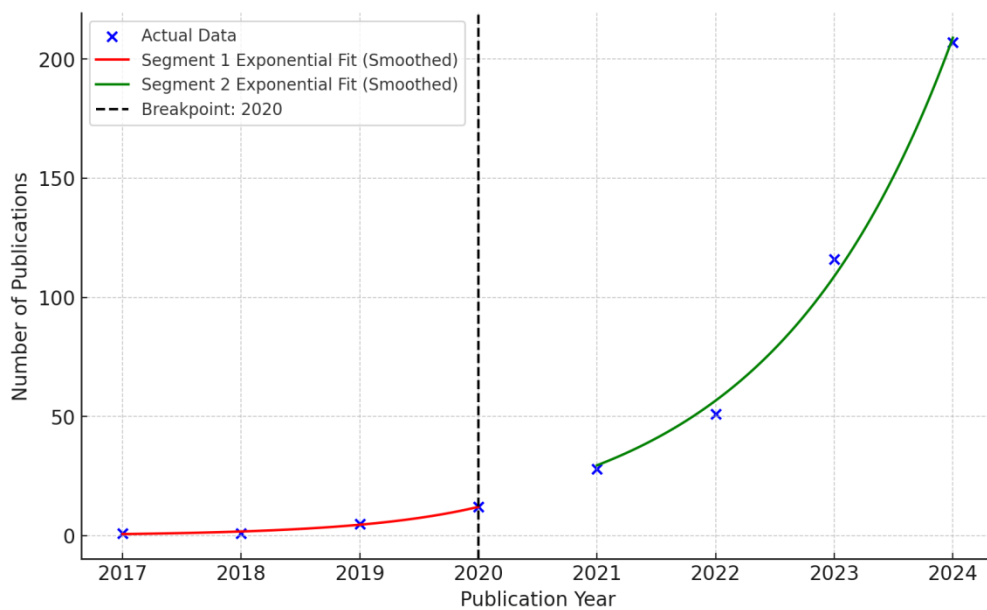


Figure 2. PRISMA Model

**Figure 3.** Publication Trend

Source: Scopus Database

3. Analysis and discussion

RQ1. What is the growth of scientific publications concerning digital twins and sustainability management innovation? Does it have research potential?

In this study, the intersection of digital twins and sustainable development is an emerging direction that is still in the early stages of discipline development. The time frame is significant, and we have used an advanced statistical technique, segmented regression analysis, to analyse and describe the relationship between the year of publication and the number of papers published in the field (Bornmann & Mutz, 2015).

We selected 2020 as the breakpoint and performed segmented exponential regression analysis on the relationship between the year of publication and the number of publications, which yielded the following results:

An exponential regression model was used for each segment:

$$y = a \cdot e^{b \cdot x}$$

y: Number of publications.

x: Publication year.

a: the number of publications in the base year, indicating the initial baseline level of academic output

b: the exponential growth rate of publications per year, indicating the rate at which the number of publications increases over time

Before 2020: For years $x \leq 2020$, $y = 0.6612 \cdot e^{0.9682 \cdot (x - 2017)}$

After 2020: For years $x > 2020$, $y = 29.5232 \cdot e^{0.6523 \cdot (x - 2020)}$

The analysis shows that before 2020, the number of publications started small but grew relatively quickly, almost doubling yearly. After 2020, the number of publications grew even more, but the growth rate slowed down. However, it still maintained an extremely high rate, showing the huge research potential in this field.

In addition, our model has a high degree of fit: Segment 1: $R^2=0.9896$, Segment 2: $R^2=0.9953$, Overall: $R^2=0.9976$. This statistical result shows that about 99.76% of the observed changes in the number of published papers can be attributed to changes in the year of publication. This substantial R-squared value emphasises the importance of the temporal trend, indicating that the year of publication is a strong predictor of the number of papers in our field of study. It is a strong testament to the evolving nature of the field and the key role that the passage of time plays in influencing research output. Overall, our analysis highlights the significant influence of the temporal factor on publication patterns and reveals essential trends in our field of study.

RQ2. By segmenting and analysing the number of citations and high-frequency keywords in the literature, this study examines the hotspots in different time frames to explore the innovation vitality of this research field. What is the future development direction?

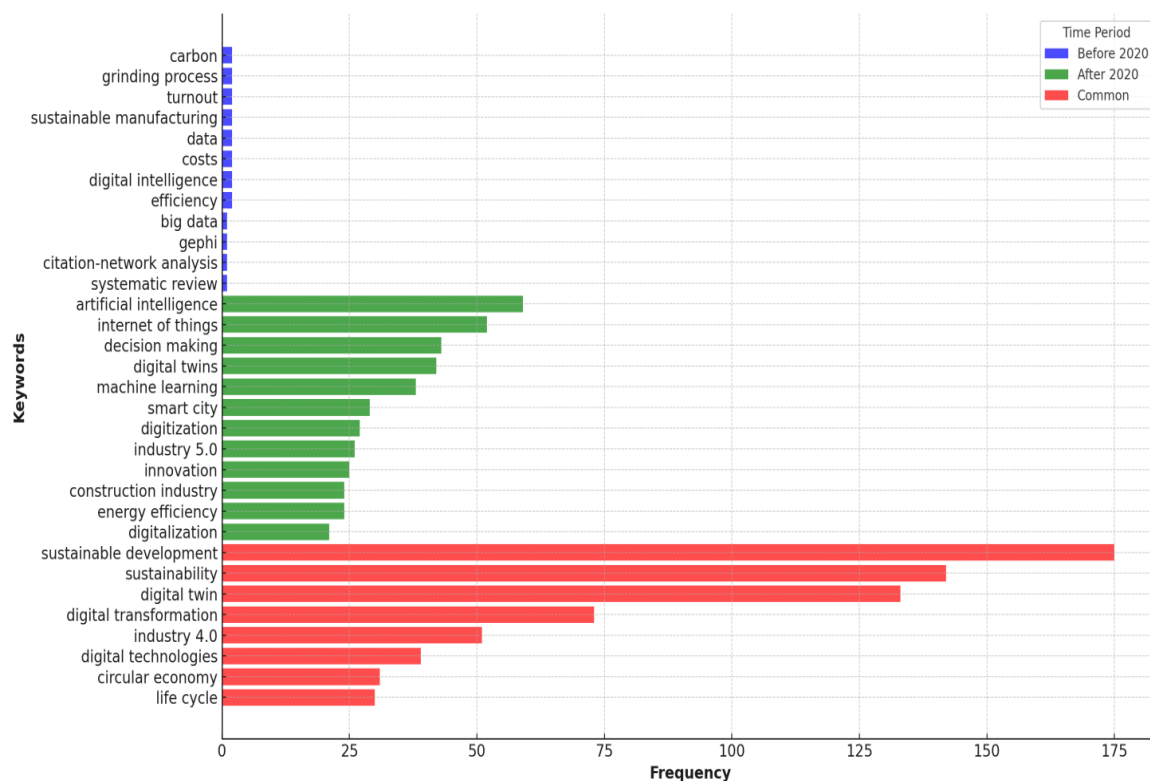


Figure 4. Quotation trends
Source: Scopus Database

This study analyses citation trends for datasets in our research field. The datasets reveal a dynamic pattern of academic recognition over time (see Figure 4 above). In the opening year of 2017, research articles were cited 13 times, indicating that the field has reached a benchmark level of academic recognition. Subsequently, citations increased significantly, peaking at 832 in 2020 and 2048 in 2021.

This significant spike highlights the increased influence and recognition within the research field. However, the number of citations in 2022 fell back to 1916, indicating a stabilisation in the recognition of research articles.

These fluctuations in the number of citations are evidence of the evolving nature of research influence, with 2020 again identified as a key turning point, reflecting the impact of the COVID-19 pandemic on DTs research promotion (Allam et al., 2021). We then used 2020 as a cut-off point to conduct a segmented analysis of the frequently appearing keywords in the dataset (Figure 5).

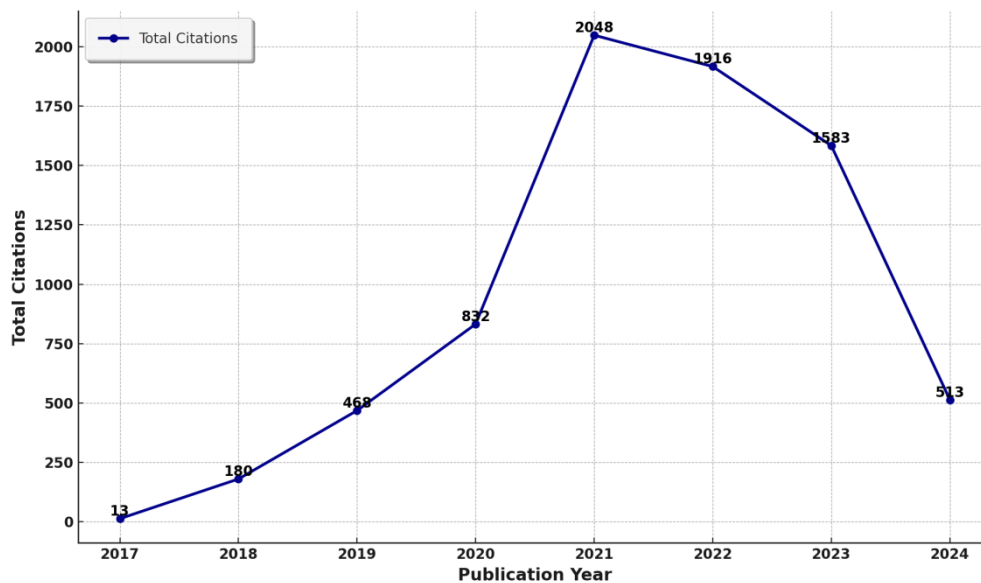


Figure 5. High-frequency keywords
Source: Scopus Database

The analysis showed that Industry 4.0, circular economy, digital transformation, and life cycle are research directions that continue to be active in this field. Before 2020, most research in this field focused on using big data to improve the sustainable development of the manufacturing industry. After 2020, it quickly expanded to multidisciplinary fields such as artificial intelligence, smart cities, energy efficiency, management decisions, and Industry 5.0. This significant change highlights the expanding interdisciplinary influence and continuously improving innovation activity of digital twin technology in the field of sustainable development management while also demonstrating some of the future research directions in this field: interdisciplinary research across engineering, management, and other disciplines, the use of DTs to replace humans in decision-making and management, and the combination of DTs with AI and machine learning.

Through the analysis of the corresponding data sets, we have determined the following future research directions in this field:

- (1) Cross-domain collaboration: Further explore the comprehensive application framework of DT technology in different fields (such as smart cities, smart agriculture, and manufacturing) to promote knowledge crossover and innovation among multiple disciplines.
- (2) Technology optimisation and standardisation: Research how to reduce the economic cost of DT system deployment and improve data standardisation methods to improve the applicability and scalability of the technology.
- (3) Social and ethical challenges: Strengthen research on the impact of DT technology on data privacy, ethical controversies, and social governance to address potential risks in the application of technology.
- (4) Integration of climate and ecological models: Explore the application of DTs in predicting global climate change and ecosystem sustainability and strengthen its role in natural resource management, risk prevention, and control.

(5) Integration of artificial intelligence: Deeply integrate DTs with artificial intelligence (AI) and machine learning technologies to enhance their predictive and decision-making capabilities and solve complex problems.

RQ3. In which journals do researchers mainly publish their articles?

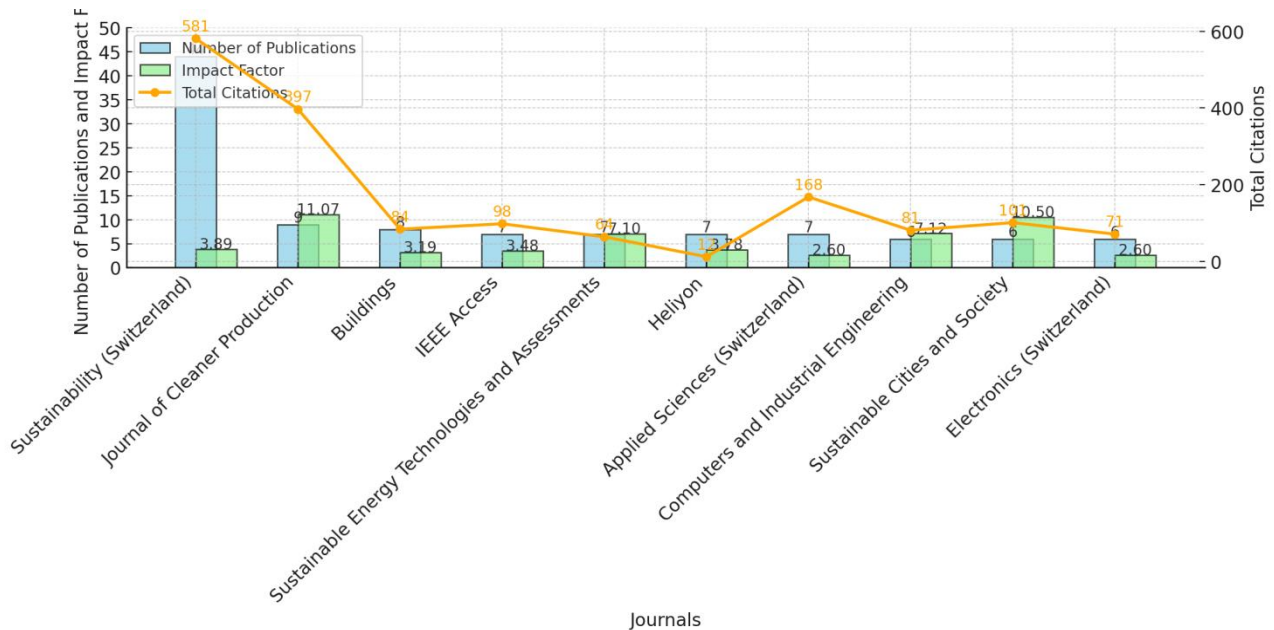


Figure 6. Influence and respectability of Top Ten Journals

Source: Scopus Database

The Scopus dataset provides a comprehensive overview of academic journals in a specific research field, revealing their respective contributions and impact on academia (Baas et al., 2020). Notably, “Sustainability” is the most prominent journal, with 44 publications and 581 citations. The aforementioned indicates that academia recognises the journal’s content highly. In addition, the impact factors, especially those of journals such as the “Journal of Cleaner Production” (impact factor 11.072) and “Sustainable Cities and Society” (impact factor 10.05), are also very prominent, highlighting the influence and respectability of these journals (see Figure 6 above). These indicators provide valuable insights for researchers to navigate the academic field and enable them to identify important and relevant journals to their research.

Table 2 below illustrates the search results in the Scopus database (search options: Search within / Article title; Search documents / ‘digital AND twin’; Year range ‘From 2025 to 2025’; Filter by subject area / Business, Management and Accounting). The search criteria were refined to include only Articles. Finally, a dataset of 40 documents was obtained:

Table 2. The search results: Business, Management and Accounting

	Journal	Authors, who published in year 2025
1.	Applied Stochastic Models in Business and Industry	Bleistein, T., Paulus, M., Gani, K., Becker, R., Werth, D. Oksuz Gurdal, B., Testik, O.M.
2.	Architectural Engineering and Design Management	Chen, W., Hu, C., Zou, R., Yang, Q., Chen, Y., Xing, J., Mou, C.
3.	Benchmarking	Srivastava, G., Bag, S.
4.	Business Strategy and the Environment	Kilinc, T., Sjödin, D., Parida, V.
5.	Cities	Luo, J., Liu, P., Xu, W., Zhao, T., Biljecki, F. Diaz-Sarachaga, J.M.
6.	Construction Management and Economics	Miraj, P., Wang, T., Koutamanis, A., Chan, P.

7.	Engineering, Construction and Architectural Management	Ohueri, C.C., Masrom, M.A.N., Habil, H., Ambashe, M.S.
8.	Global Business Review	Sharma, A.K., Srivastava, M.K., Sharma, R.
9.	Global Journal of Flexible Systems Management	Hossain, M.I., Talapatra, S., Saha, P., Belal, H.M.
10.	International Journal of Clothing Science and Technology	Moskvin, A., Moskvin, M., Kuzmichev, V.
11.	International Journal of Engineering Business Management	Al-Qirim, N., Majdalawieh, M., Bani-hani, A., Al Hamadi, H.
12.	International Journal of Logistics Management	Singh, R.K.
13.	International Journal of Logistics Research and Applications	Shoaib, M., Zhang, S., Ali, H., Ahmad, M.S., Khan, M.A
14.	International Journal of Pharmaceutical and Healthcare Marketing	Avinash, B., Joseph, G.
15.	International Journal of Precision Engineering and Manufacturing - Green Technology	Cho, H.-S., Sohn, J.-H., Han, J.-B., Yeu, T.-K.
16.	International Journal of Production Economics	Lee, J., Chua, P.C., Liu, B., Moon, S.K., Lopez, M.
17.	International Journal of Production Research	Cheng, Y., Liu, H., Qi, Q., Tao, F. Zhang, C., Tao, F., Qi, Q., Cheng, Y., Cheng, J., Wang, B., Nee, A.Y.C. Zhu, X., Liao, B., Shen, Y., Kong, M. Werner, A., Schusel, F., Hämmerle, M., Schaper, S., Hölzle, K.
18.	Internet of Things (The Netherlands)	Bozkaya-Aras, E., Onel, T., Eriskin, L., Karatas, M. Iqbal, M., Suhail, S., Matulevičius, R., Shah, F.A., Malik, S.U.R., McLaughlin, K. Suhail, S., Iqbal, M., McLaughlin, K., Lee, B., Imtiaz, B. Burattini, S., Mariani, S., Montagna, S., Picone, M., Ricci, A. Okegbile, S.D., Gambo, I.P. Özkan, E., Kök, İ., Özdemir, S.
19.	Journal of Advanced Manufacturing Systems	Love, A., Behseresht, S., Pastrana, O.A.V., Sakai, J., Park, Y.H.
20.	Journal of Cleaner Production	Piron, M., Bovo, E., Lucchetta, G., Manzardo, A.
21.	Journal of Construction Engineering and Management	Yan, H., Liu, C., Yang, X., Feng, K.
22.	Journal of Environmental Accounting and Management	Jia, R., Jia, L., Jiang, H., Wang, P., Deguchi, Y., Zhang, J.
23.	Journal of Innovation and Knowledge	Cao, J., Spulbar, C., Eti, S., Horobet, A., Yüksel, S., Dinçer, H.
24.	Journal of Management in Engineering	Yan, J., Lu, Q., Li, N., Pitt, M.
25.	Journal of Modelling in Management	Mharzi, R., Ben Kacem, A., Elouadi, A.
26.	Journal of Research in Marketing and Entrepreneurship	Nyquist, A.-M., Farshid, M., Brown, T.
27.	Logistics	Roman, E.-A., Stere, A.-S., Roşca, E., Radu, A.-V., Codroiu, D., Anamaria, I. Rinaldi, M., Caterino, M., Riemma, S., Macchiaroli, R., Fera, M.
28.	Production Engineering Archives	Elqabli, Z., Kamach, O., Chater, Y.
29.	TQM Journal	Chalipour, A., Noorzai, E., Golabchi, M., Hosseini Nourzad, S.H.

RQ4.What are the top institutions involved in digital twins and innovations in sustainability management?

The dataset reveals significant differences in the research output and impact of institutions, as measured by the number of citations and the average number of citations per article. King Saud University leads the way with 15 papers published, achieving an impressive total of 179 citations and an average of 11.93 citations per paper. LUT University and The Hong Kong Polytechnic University followed closely behind, with 13 and 12 publications, total citations of 117 and 89, and average citations of 9 and 7.42, respectively. This observation indicates that these institutions have produced numerous research results that have powerfully impacted their respective academic circles.

Although the University of Cambridge has only published seven papers, its educational influence is unique. Their papers have been cited 242 times, with an average of 34.57 citations each, which indicates the institution's important position in academia. The University of Johannesburg and Zhejiang University also have seven publications each, with 151 and 71 citations, respectively, and an average of 21.57 and 10.14, respectively. Figure 7 highlights the contribution of these two universities as leading institutions conducting

research and generating resonance within their academic fields. The University of Chinese Academy of Sciences published six paper. Although the average number of citations per paper was 7.5, indicating a medium level of impact, it demonstrates the global reach of its research. The Norwegian University of Science and Technology achieved an impressive 730 citations from just five publications, with an average of 146 citations per paper, demonstrating the institution's excellence in this field of research.

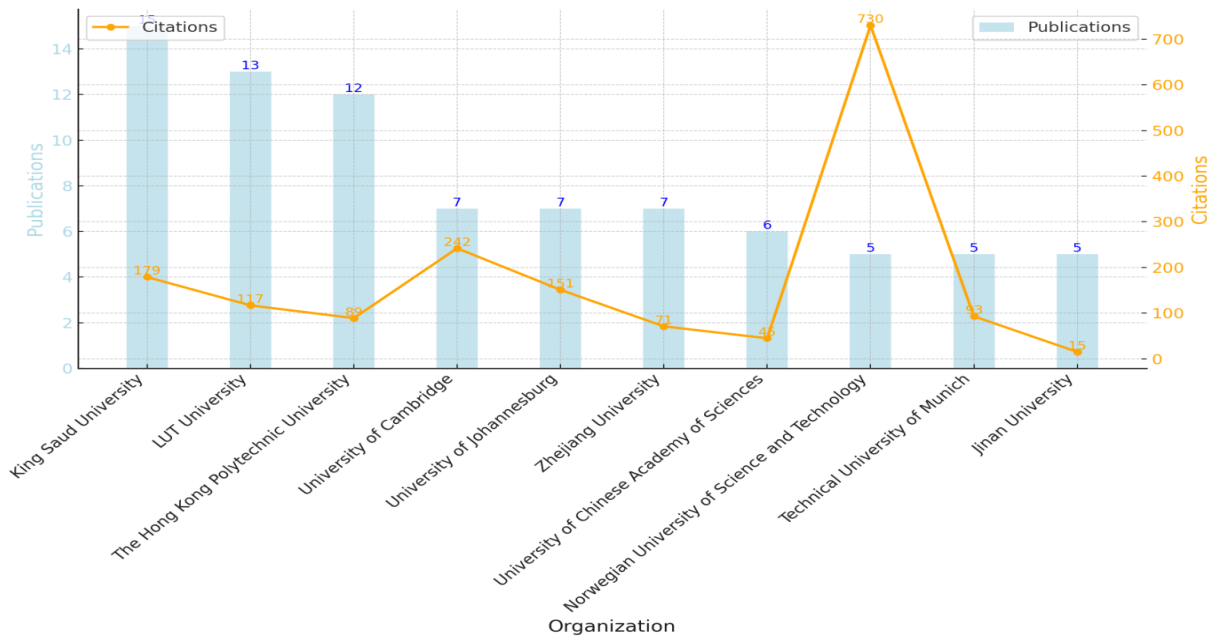


Figure 7. Top Ten Institutions

Source: Scopus Database

Similarly, the Technical University of Munich, with five papers published, also has a respectable average of 18.6 citations. Finally, with an average of just three citations, Jinan University still has five publications that indicate significant contributions to academic research.

RQ5. How is literature distributed geographically? Is there a digital divide?

This dataset reflects the diversity and richness of research results in various countries. China ranks first with 218 papers and 1,610 total citations, highlighting its essential position in the global research community.

Notably, India and the United Kingdom follow closely, with 96 and 89 papers published, respectively. Still, their total citations reach 1,003 and 1,145, respectively, further demonstrating the significant influence of both countries in academic research. The United States ranked fourth with 77 papers published. Research activities in European countries such as Italy,

Spain, Germany and Portugal were also active, with the number of papers published ranging from 27 to 68. Germany is particularly noteworthy, with 887 citations, reflecting its essential contribution to related research fields. In addition, Saudi Arabia is the only non-European or non-American country (excluding China) in the top ten, with 27 papers demonstrating its potential as an emerging research force (Figure 8).

When examining the distribution of relevant data in depth, it is not difficult to notice that there is a significant digital divide between different countries within the academic research fields of digital twins and sustainable development. Specifically, China, the United States, and many European countries have played a significant role in digital twin technologies (DTs) research. With their strong technical capabilities, abundant resource reserves, and relatively complete scientific research systems, they have produced many influential research results in this field. In contrast, many developing countries have relatively weak technological conditions and lack resources; therefore, they have not invested enough in research on digital twins and sustainable development.

This imbalance in the quantity and impact of research results between different countries, i.e., the digital divide, has, to a certain extent, constrained the widespread popularisation and practical application of digital twin technology (DTs) at the global level (Allam & Jones, 2021).

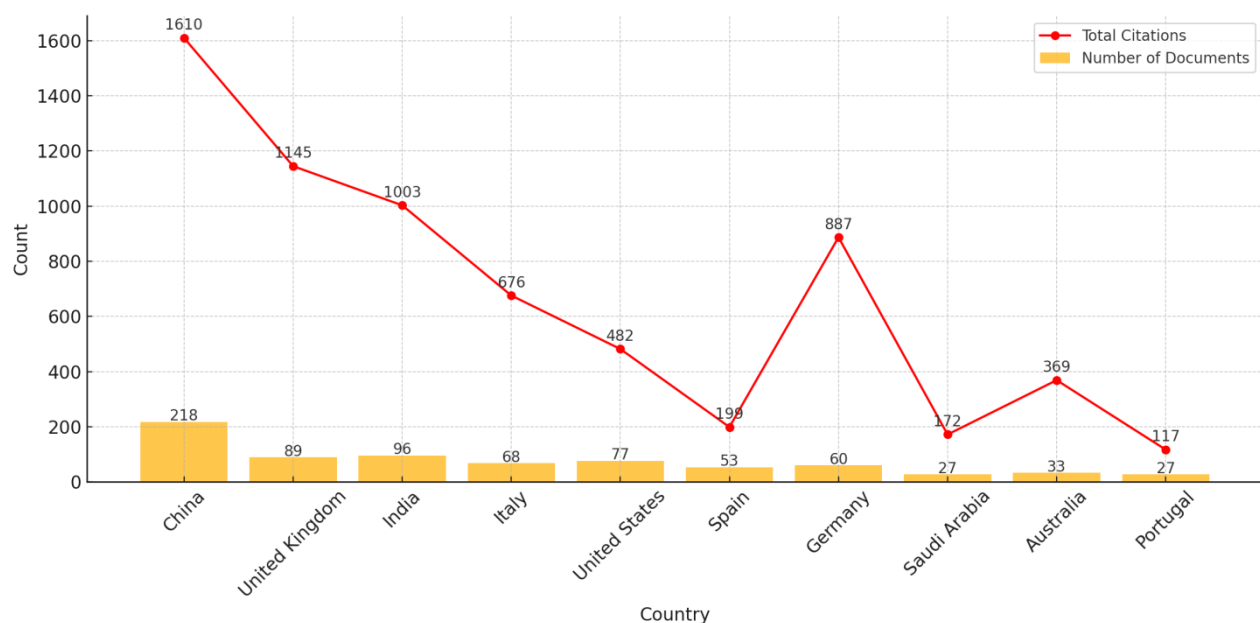


Figure 8. Top Ten Countries
Source: Scopus Database

Further analysis of the data presented in the dataset shows that countries with low publications in this field are often relatively economically underdeveloped. The above shows that the dataset not only clearly shows the significant gap in research impact between countries worldwide in digital twins and sustainable development but also reveals that the digital divide has become a serious challenge to applying digital twin technology in achieving the Sustainable Development Goals.

RQ6. Which authors have been most productive in the field of digital twins and sustainability management innovation? What challenges do DTs face from the perspective of sustainability management innovation?

We extracted the 10 most influential authors in digital twins and sustainability management innovation from the dataset. While studying the authors' contributions to the field, we explored the challenges DTs face from the perspective of sustainability management innovation by conducting an in-depth reading of the literature of these 10 authors (see Table 3).

Table 3. Top Ten Authors

Individual Authors	Total_Publications	Total_Citations
Jones, D.S.	2	491
Allam, Z.	2	491
Li, J.	5	437
Mikalef, P.	1	413
Kristoffersen, E.	1	413
Blomsma, F.	1	413
He, B.	2	411
Bai, K.-J.	1	398
Bibri, S.E.	2	381
Verdouw, C.	2	317

Source: Scopus Database

This study focuses on the relevant literature of ten authors. After careful screening, some documents that are highly relevant to the topic are selected for in-depth analysis. The study found that digital twin technology (DTs) faces a series of challenges that need to be urgently addressed in the process of practical application of innovation in sustainable development management:

(1) Data management and technical complexity: The core of digital twin technology lies in its ability to accurately obtain, efficiently process, and deeply analyse real-time data. However, when faced with complex systems, integrating data from multiple sources with heterogeneous characteristics poses a significant challenge (Verdouw et al., 2021). At the same time, data integrity and accuracy play a critical role in digital twin technology's predictive and decision-making functions. However, under specific resource-constrained conditions, existing data collection and transmission technologies often cannot fully meet these stringent requirements for data quality (Allam & Jones, 2021).

(2) Infrastructure and resource constraints: The effective deployment of digital twin technology depends on powerful computing capabilities and sufficient storage capacity, which undoubtedly sets high standards and requirements for infrastructure construction. Unfortunately, many developing countries and regions with relatively limited resources generally lack the technical support and economic guarantees (Kastratovic et al., 2024) necessary to implement digital twin technology. This situation seriously restricts the widespread promotion and popular application of digital twin technology worldwide (Wang et al., 2023; Vilks et al., 2024). Especially in the era of Industry 4.0, the manufacturing industry's implementation cost of digital twin systems has increased significantly, further exacerbating the application difficulties caused by infrastructure and resource constraints (He & Bai, 2020).

(3) Environmental and economic sustainability: Although digital twin technology can theoretically help improve resource utilisation efficiency, the high cost associated with its development and operation stages poses a severe test for sustainable economic development. In addition, since digital twin systems usually require high-performance computing resources to maintain their operations, the resulting energy consumption and corresponding carbon footprint have become significant challenges regarding environmental sustainability that cannot be ignored (Tian, 2022; He & Bai, 2020).

(4) Social and governance issues: The widespread application of digital twin technology inevitably involves many complex social issues and governance challenges. Data privacy protection issues, ethical controversies, and the need for cross-organisational collaboration are particularly prominent among them. These issues significantly affect the social acceptance of digital twin technology and put forward new requirements and challenges for existing governance models (Allam et al., 2022). Therefore, striking a reasonable balance

between the development process of digital twin technology and actual social needs remains a core issue that researchers and practitioners must focus on and explore in depth in the current and future periods.

(5) Specific challenge areas in application scenarios: The demand characteristics and challenges faced by digital twin technology in different professional fields are significantly different. For example, in the specific field of smart agriculture, the ability to accurately simulate complex and ever-changing ecosystems using digital twins has become a key bottleneck restricting the practical application of this technology. In smart manufacturing, the sustainable management of the entire product life cycle has become the current research focus (Verdouw et al., 2021; He & Bai, 2020).

Conclusions and recommendations for future research

Through a bibliometric analysis, this study explored the current research status and application potential of digital twin (DT) technologies in sustainable development management. The study shows that DTs play an important innovative role in sustainable development fields such as smart cities, circular economies, and Industry 4.0. Still, they face implementation challenges such as the digital divide, high costs, data privacy protection, and technical complexity. By analysing 421 papers, we have summarised the key challenges of digital twin technology and proposed future research directions, including integration with artificial intelligence, cross-domain collaboration, technology optimisation and standardisation, social and ethical challenges, and integration of climate and ecological models. Deepening these studies will promote the application of DT technology in sustainable development management and provide new ideas and paths for the global realisation of sustainable development goals. The research also revealed that the research results of digital twin technology in different countries are unevenly distributed, highlighting the digital divide. The literature suggests that despite the breakthroughs in digital twin technology in multiple fields, it has not yet received sufficient attention in the global sustainable development agenda. Future research and policy must explore how to use digital twins to achieve sustainable development goals fully.

In summary, this research is a stepping stone for future research. It encourages scholars to delve into all aspects of DTs' applications and their impact on the SDGs. By addressing these key issues, researchers can play a key role in shaping a more sustainable environment.

References

- Allam, Z., & Jones, D. S. (2021). *Future (post-COVID) digital, smart and sustainable cities in the wake of 6G: Digital twins, immersive realities and new urban economies*. *Land Use Policy*, 101, 105201. <https://doi.org/10.1016/j.landusepol.2020.105201>
- Allam, Z., Sharifi, A., Bibri, S. E., Jones, D. S., & Krogstie, J. (2022). The Metaverse as a virtual form of smart cities: Opportunities and challenges for environmental, economic, and social sustainability in urban futures. *Smart Cities*, 5(3), 771-801. <https://doi.org/10.3390/smartcities5030040>
- Al-Qirim, N., Majdalawieh, M., Bani-hani, A., & Al Hamadi, H. (2025). Cyber threat intelligence for smart grids using knowledge graphs, digital twins, and hybrid machine learning in SCADA networks. *International Journal of Engineering Business Management*, 17. <https://doi.org/10.1177/18479790251328183>
- Avinash, B., & Joseph, G. (2025). Embracing resilience in pharmaceutical manufacturing: "digital twins" – forging a resilient path in the VUCA maze. *International Journal of Pharmaceutical and Healthcare Marketing*, <https://doi.org/10.1108/IJPHM-03-2024-0024>
- Baas, J., Schotten, M., Plume, A., Côté, G., & Karimi, R. (2020). Scopus as a curated, high-quality bibliometric data source for academic research in quantitative science studies. *Quantitative science studies*, 1(1), 377-386. <https://doi.org/10.1007/s40436-020.00302-5>
- Bauer, P., Dueben, P.D., Hoefler, T. et al. (2021). The digital revolution of Earth-system science. *Nat Comput Sci*, 1, 104-113. <https://doi.org/10.1038/s43588-021-00023-0>
- Bauer, P., Stevens, B. & Hazeleger, W. (2021). A digital twin of Earth for the green transition. *Nat. Clim. Chang.* 11, 80-83. <https://doi.org/10.1038/s41558-021-00986-y>
- Berkvens, P. (2012). Scopus custom data documentation. Retrieved from https://p.widencdn.net/mrbekb/Scopus_Custom_Data_Documentation_Version9

Bleistein, T., Paulus, M., Gani, K., Becker, R., & Werth, D. (2025). IIoT and Digital Twin: A Systematic Literature Review and Looking Beyond the State. *Applied Stochastic Models in Business and Industry*, 41(1), art. no. e2923. <https://doi.org/10.1002/asmb.2923>

Bornmann, L., & Mutz, R. (2014). Growth rates of modern science: A bibliometric analysis based on the number of publications and cited references. *Journal of the Association for Information Science and Technology*, 65(4), 857-863. <https://doi.org/10.1002/asi.23329>

Bornmann, L., & Mutz, R. (2015). Growth rates of modern science: A bibliometric analysis based on the number of publications and cited references. *Journal of the Association for Information Science and Technology*, 66(11), 2215-2222. <https://doi.org/10.1002/asi.23329>

Bozkaya-Aras, E., Onel, T., Eriskin, L., & Karatas, M. (2025). Intelligent human activity recognition for healthcare digital twin. *Internet of Things (The Netherlands)*, 30, art. no. 101497. <https://doi.org/10.1016/j.iot.2025.101497>

Burattini, S., Mariani, S., Montagna, S., Picone, M., & Ricci, A. (2025). Distributing intelligent functionalities in the Internet of Things with agents and Digital Twins. *Internet of Things (The Netherlands)*, 31, art. no. 101560. <https://doi.org/10.1016/j.iot.2025.101560>

Cannoodt, R., Saelens, W., Deconinck, L., & Saeys, Y. (2021). Spearheading future omics analyses using dyngen, a multi-modal simulator of single cells. *Nat. Commun.*, 12, 3942. <https://www.nature.com/articles/s41467-021-24152-2>

Cao, J., Spulbar, C., Eti, S., Horobet, A., Yüksel, S., & Dinçer, H. (2025). Innovative approaches to green digital twin technologies of sustainable smart cities using a novel hybrid decision-making system. *Journal of Innovation and Knowledge*, 10(1), art. no. 100651. <https://doi.org/10.1016/j.jik.2025.100651>

Carlowitz, H.C. (1713). *Sylvicultura Oeconomica oder haußwirthliche Nachricht und Naturgemäße Anweisung zur Wilden BaumZucht*. Leipzig: Johann Friedrich Braun. [https://books.google.com.hk/books?hl=zh-CN&lr=&id=4exeAAAAcAAJ&oi=fnd&pg=PP20&dq=Carlowitz,+H.+C.,+\(1713\).+Sylvicultura+Oeconomica+oder+hau%C3%9Fwirthliche+Nachricht+und+Naturgem%C3%A4%C3%9Fige+Anweisung+zur+Wilden+BaumZucht.+Leipzig:+Johann+Friedrich+Braun.&ots=jmiWwqL3E0&sig=PIlltf-HXgLY5DxuHAp6gvaKdFI&redir_esc=y#v=onepage&q&f=false](https://books.google.com.hk/books?hl=zh-CN&lr=&id=4exeAAAAcAAJ&oi=fnd&pg=PP20&dq=Carlowitz,+H.+C.,+(1713).+Sylvicultura+Oeconomica+oder+hau%C3%9Fwirthliche+Nachricht+und+Naturgem%C3%A4%C3%9Fige+Anweisung+zur+Wilden+BaumZucht.+Leipzig:+Johann+Friedrich+Braun.&ots=jmiWwqL3E0&sig=PIlltf-HXgLY5DxuHAp6gvaKdFI&redir_esc=y#v=onepage&q&f=false)

Chalipour, A., Noorzai, E., Golabchi, M., & Hosseini Nourzad, S.H. (2025). Uncovering key success factors for enhanced office-site communication through digital twins. *TQM Journal*. <https://doi.org/10.1108/TQM-04-2024-0146>

Chen, W., Hu, C., Zou, R., Yang, Q., Chen, Y., Xing, J., & Mou, C. (2025). Evolutionary method of digital twin model for building physics mechanism. *Architectural Engineering and Design Management*, 21(2), 356-378. <https://doi.org/10.1080/17452007.2024.2389305>

Cheng, Y., Liu, H., Qi, Q., & Tao, F. (2025). Consensus strategies of manufacturing service collaboration in digital twin shop-floor. *International Journal of Production Research* <https://doi.org/10.1080/00207543.2025.2464158>

Cho, H.-S., Sohn, J.-H., Han, J.-B., & Yeu, T.-K. (2025). Development of a Real-Time Track Solver for Digital Twin of the Underwater Tracked Vehicle. *International Journal of Precision Engineering and Manufacturing - Green Technology*, art. no. 113480. <https://doi.org/10.1007/s40684-025-00716-1>

Cimino, C., Negri, E., & Fumagalli, L. (2019). Review of digital twin applications in manufacturing. *Computers in Industry*, 113, 103130. <https://doi.org/10.1016/j.compind.2019.103130>

De Bakker, F. G. A., Groenewegen, P., & Den Hond, F. (2005). A bibliometric analysis of 30 years of research and theory on corporate social responsibility and corporate social performance. *Journal of Business Ethics*, 62(3), 283-299. <https://doi.org/10.1177/0007650305278086>

De Kerckhove, D., Henz, P., & Saracco, R. (2022). Digital Twins: Ethical and Societal Impacts. Ebook of Digital Reality Initiative (DRI) webinar, 29 Spetember 2021. IEEE. <https://digitalreality.ieee.org/images/files/pdf/2022jan-ebook-digitaltwins-ethical-and-societal-implicationsfinal41822.pdf>

De Oliveira, M. M., Andreatta, L. G., Stjepandić, J., & Cancigliieri Junior, O. (2021). Product lifecycle management and sustainable development in the context of industry 4.0: A systematic literature review. *Advances in Transdisciplinary Engineering*, 16, 213-222. <https://ebooks.iospress.nl/doi/10.3233/ATDE210100>

Deren, Li, Wenbo, Y., & Zhenfeng, Sh. (2021). Smart city based on digital twins. *Computational Urban Science* 1(2021), 1-11. <https://link.springer.com/article/10.1007/s43762-021-00005-y>

Diaz-Sarachaga, J.M. (2025). Developing an assessment governance framework for urban digital twins: Insights from smart cities. *Cities*, 156, art. no. 105558. <https://doi.org/10.1016/j.cities.2024.105558>

Elqabli, Z., Kamach, O., & Chater, Y. (2025). Multimode approach using Reinforcement Learning and Digital Twin for operating mode management. *Production Engineering Archives*, 31 (1), 116-128. <https://doi.org/10.30657/pea.2025.31.11>

Elsehrawy, R., Kumar, B., & Watson, R. (2024). Critical realism as an underpinning philosophy for the implementation of digital twins for urban management. *Journal of Critical Realism*, 23(2), 187-223. <https://doi.org/10.1080/14767430.2023.2301277>

- Etalong, T. A., Chikeleze, F. O., Kaze, V., & Krivins, A. (2025). The impact of workforce diversity on job performance in Public Sector Organisations. *Entrepreneurship and Sustainability Issues*, 12(3), 169-179. <https://doi.org/10.9770/y7495453227>
- Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: Enabling technologies, challenges, and open research. *IEEE Access*, 8, 108952-108971. <https://doi.org/10.1109/ACCESS.2020.2998358>
- Grieves, M. (2014). Digital Twin: Manufacturing Excellence through Virtual Factory Replication. White Paper, 1–7. https://www.3ds.com/fileadmin/PRODUCTS-SERVICES/DELMIA/PDF/Whitepaper/DELMIA-APRISO-Digital-Twin-Whitepaper.pdf?utm_source=chatgpt.com
- Grober, U. (2010). Die Entdeckung der Nachhaltigkeit: Kulturgeschichte eines Begriffs (3rd ed.). München: Kunstmann. https://www.berlin.de/ba-treptow-koepenick/ueber-den-bezirk/lokale-agenda-21/vortrag_k_penick.pdf
- Haefner, N., Wincent, J., Parida, V., & Gassmann, O. (2021). Artificial Intelligence and Innovation Management: A Review, Framework, and Research Agenda. *Technological Forecasting and Social Change*, 162(1), 1-10. <https://doi.org/10.1016/j.techfore.2021.01.001>
- He, B., & Bai, K.-J. (2020). Digital twin-based sustainable intelligent manufacturing: A review. *Advances in Manufacturing*, 8(2), 1-15. <https://doi.org/10.1007/s40436-020.00302-5>
- Helbing, D., & Sánchez-Vaquerizo, J.A. (2023). Digital twins: potentials, ethical issues and limitations. In Zwitter, A., & Gstrein, O. Handbook on the Politics and Governance of Big Data and Artificial Intelligence. ElgarOnline, pp. 64-104. <https://doi.org/10.4337/9781800887374.00013>
- Hossain, M.I., Talapatra, S., Saha, P., & Belal, H.M. (2025). From Theory to Practice: Leveraging Digital Twin Technologies and Supply Chain Disruption Mitigation Strategies for Enhanced Supply Chain Resilience with Strategic Fit in Focus. *Global Journal of Flexible Systems Management*, 26(1), art. no. 102412, 87-109. <https://doi.org/10.1007/s40171-024-00424-w>
- Iqbal, M., Suhail, S., Matulevičius, R., Shah, F.A., Malik, S.U.R., & McLaughlin, K. (2025). IoV-TwinChain: Predictive maintenance of vehicles in internet of vehicles through digital twin and blockchain. *Internet of Things (The Netherlands)*, 30, art. no. 101514. <https://doi.org/10.1016/j.iot.2025.101514>
- Jia, R., Jia, L., Jiang, H., Wang, P., Deguchi, Y., & Zhang, J. (2025). Establishment of a Digital Twin Model to Predict and Analyse Greenhouse Gas Emission and Transport in Turbulent Flames from Lagrangian Viewpoint. *Journal of Environmental Accounting and Management*, 13(2), 191-218. <https://doi.org/10.5890/JEAM.2025.06.005>
- Jones, D., Snider, C., Nassehi, A., Yon, J., & Hicks, B. (2020). Characterising the digital twin: A systematic literature review. *CIRP Journal of Manufacturing Science and Technology*, 29, 36-52. <https://doi.org/10.1016/j.cirpj.2020.02.002>
- Jurgelane-Kaldava, I., Batenko, A., Krivins, A., Durguti, E., & Garškaitė-Milvydienė, K. (2024). Data security risks and their prevention: Latvian enterprises in the context of selected countries. *Entrepreneurship and Sustainability Issues*, 11(4), 78-90. [http://doi.org/10.9770/jesi.2024.11.4\(5\)](http://doi.org/10.9770/jesi.2024.11.4(5))
- Kastratović, R., Krivins, A., & Veikša, I. (2024). Economic and legal aspects of foreign direct investment patterns in Serbia and Latvia. Access to science, business, innovation in the digital economy, *ACCESS Press*, 5(3), 440-458, [https://doi.org/10.46656/access.2024.5.3\(4\)](https://doi.org/10.46656/access.2024.5.3(4))
- Kaže, V., Baumane, I., Sumilo, E., & Skapars, R. (2007). Trends and priorities in the development of the Latvian banking services in the context of emerging knowledge based economy: Case of e-banking. *TRAMES-Journal of the Humanities and Social Sciences*, 11 (61/56), 2, 173-188. <https://doi.org/10.3176/tr.2007.2.06>
- Kaže, V., & Bolinskis, G. (2011). Consumer Values Behind the Grey Economy. Proceedings of the International Conference on New Socio-Economic Challenges of Development in Europe 2010, Riga: University of Latvia, 70-79.
- Kaže, V., Bolinskis, G., & Kurovs, J. (2022). An image-based approach to measuring human values. *Societies*, 12(6), 191. <https://doi.org/10.3390/soc12060191>
- Kilinc, T., Sjödin, D., & Parida, V. (2025). Navigating Digital Servitization for the Twin Transition: How Manufacturers Can Support Customers With Digitalization and Sustainability. *Business Strategy and the Environment*, <https://doi.org/10.1002/bse.4255>
- Krivins A., Vilks A., & Kipane A. (2023). Corruption perception trends: European Union countries. *Access Journal (Access to Science, Business. Innovation in the Digital Economy)*, 5(1), 58-67. [http://doi.org/10.46656/access.2024.5.1\(4\)](http://doi.org/10.46656/access.2024.5.1(4))
- Krivins, A. (2014). Prevention of corruption in the sphere of public purchases: Interviews with experts. 4th International Interdisciplinary Scientific Conference SOCIETY, HEALTH, WELFARE. SHS Web of Conferences, 10, 00018, 1-6. <http://dx.doi.org/10.1051/shsconf/20141000018>
- Laubenbacher, R., Sluka, J.P., & Glazier, J.A. (2021). Using digital twins in viral infection. *Science*, 371, 1105-1106. <https://www.science.org/doi/abs/10.1126/science.abf3370>
- Lee, J., Chua, P.C., Liu, B., Moon, S.K., & Lopez, M.A. (2025). A hybrid data-driven optimisation and decision-making approach for a digital twin environment: Towards customising production platforms. *International Journal of Production Economics*, 279, art. no. 109447. <https://doi.org/10.1016/j.ijpe.2024.109447>

- Liu, S. M., Bao, J. S., Lu, Y. Q., Li, J., Lu, S. Y., & Sun, X. M. (2021). DTS Modeling Method Based on Biomimicry for Machining Aerospace Components. *Journal of Manufacturing Systems*, 58(1), 180-195. <https://doi.org/10.1016/j.jmsy.2021.01.001>
- Love, A., Behresht, S., Pastrana, O.A.V., Sakai, J., & Park, Y.H. (2025). Hybrid Physical-Virtual Digital Twin System for Additive Manufacturing. *Journal of Advanced Manufacturing Systems*, 24(1), 1-20. <https://doi.org/10.1142/S0219686725500015>
- Lu, Y. Q., Liu, C., Wang, K. I. K., Huang, H. Y., & Xu, X. (2020). DTS-Driven Smart Manufacturing: Connotation, Reference Model, Applications and Research Issues. *Robotics and Computer-Integrated Manufacturing*, 61(1), 1-27. <https://doi.org/10.1016/j.rcim.2020.01.001>
- Luo, J., Liu, P., Xu, W., Zhao, T., & Biljecki, F.A. (2025). Perception-powered urban digital twin to support human-centered urban planning and sustainable city development. *Cities*, 156, art. no. 105473. <https://doi.org/10.1016/j.cities.2024.105473>
- Melesse, T.Y., Di Pasquale, V., & Riemma, S. (2020). Digital twin models in industrial operations: A systematic literature review. *Proc. Manuf.*, 42(2020), 267-272. <https://doi.org/10.1016/j.promfg.2020.02.084>
- Mharzi, R., Ben Kacem, A., Elouadi, A. Catastrophe-related disruptions' preparedness and emergency management in Morocco: a proactive risks and resilience digital twin-based analysis. *Journal of Modelling in Management*, 20(3), 825-845. <https://doi.org/10.1108/JM2-02-2024-0050>
- Miehe, R., Waltersmann, L., Sauer, A., & Bauernhansl, T. (2021). Sustainable production and the role of digital twins: Basic reflections and perspectives. *Journal of Advanced Manufacturing and Processing*, 3, e10078. <https://doi.org/10.1002/amp2.10078>
- Miraj, P., Wang, T., Koutamanis, A., & Chan, P. (2025). Organising digital twin in the built environment: a systematic review and research directions on the missing links of use and user perspectives of digital twin in Architecture, Engineering and Construction (AEC) sector. *Construction Management and Economics* <https://doi.org/10.1080/01446193.2025.2451631>
- Miszczak, K., Kriviņš, A., & Kaze, V. (2024). Challenges and drivers of green and sustainable spatial development: a case study of Lower Silesia and Latvia. *Entrepreneurship and Sustainability Issues*, 12(2), 85-98. <https://doi.org/10.9770/b7283449476>
- Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2029). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Medicine*, 6(7), e1000097. <https://doi.org/10.1371/journal.pmed.1000097>
- Moskvin, A., Moskvina, M., & Kuzmichev, V. (2025). Development of a reference database on historical body sizing and digital twins. *International Journal of Clothing Science and Technology*. <https://doi.org/10.1108/IJCST-04-2024-0086>
- Muhamud, A., Etalong, T. A., Krivins, A., & Kaze, V. (2024). Point of sale and cashless policy in selected market. *Entrepreneurship and Sustainability Issues*, 12(1), 169-178. [http://doi.org/10.9770/jesi.2024.12.1\(12\)](http://doi.org/10.9770/jesi.2024.12.1(12))
- Mureddu, F., Paciaroni, A., Pavelka, T., Pemberton, A., & Remotti, L.A. (2025). Rights and Responsibilities: Legal and Ethical Considerations in Adopting Local Digital Twin Technology. In: Raes, L., Ruston McAleer, S., Croket, I., Kogut, P., Brynskov, M., Lefever, S. (eds) *Decide Better*. Springer, Cham. https://doi.org/10.1007/978-3-031-81451-8_11
- Naikwadi, A. S., & Shrivastav, S. J. (2025). Privacy and Ethical Issues in Digital Twins. *International Research Journal of Modernization in Engineering Technology and Science*, 7(02). https://www.irjmets.com/uploadedfiles/paper/issue_2_february_2025/67559/final/fin_irjmets1739855171.pdf
- Niederer, S. A., Sacks, M. S., Girolami, M., & Willcox, K. (2021). Scaling digital twins from the artisanal to the industrial. *Nat. Comput. Sci.*, 1, 313-320. <https://doi.org/10.1038/s43588-021-00072-5>
- Nyquist, A.-M., Farshid, M., & Brown, T. (2025). Employing digital twin technology in the pursuit to avert sustainable marketing myopia. *Journal of Research in Marketing and Entrepreneurship*, 27(2), 277-293. <https://doi.org/10.1108/JRME-01-2024-0007>
- Ohueri, C.C., Masrom, M.A.N., Habil, H., & Ambashe, M.S. (2025). IoT-based digital twin best practices for reducing operational carbon in building retrofitting: a mixed-method approach. *Engineering, Construction and Architectural Management*, 32(3), 2044-2065. <https://doi.org/10.1108/ECAM-08-2023-0827>
- Okegbile, S.D., & Gambo, I.P. (2025). Artificial intelligence-driven security framework for internet of things-enhanced digital twin networks. *Internet of Things (The Netherlands)*, 31, art. no. 101564. <https://doi.org/10.1016/j.iot.2025.101564>
- Oksuz Gurdal, B., & Testik, O.M.A. (2025). Framework for Product Life Cycle Management Based Digital Twin Implementation in the Aerospace Industry. *Applied Stochastic Models in Business and Industry*, 41(2), art. no. e70001. <https://doi.org/10.1002/asmb.70001>
- Okwueze, F.O., Gueh D., Kaze V., Krivins, A., & Etalong, T. (2025). Oil Revenue Dependency: economic and legal challenges. Access to science, business, innovation in the digital economy, *ACCESS Press*, 6(2), 270-286, [https://doi.org/10.46656/access.2025.6.2\(2\)](https://doi.org/10.46656/access.2025.6.2(2))
- Özkan, E., Kök, İ., & Özdemir, S. (2025). System Development Lifecycle Assisted Digital Twin Development Model for Smart Micro-grids. *Internet of Things (The Netherlands)*, 31, art. no. 101580. <https://doi.org/10.1016/j.iot.2025.101580>

- Parrott, A., & Warshaw, L. (2017). Industry 4.0 and the Digital Twin: Manufacturing Meets Its Match. New York: Deloitte University Press. https://www2.deloitte.com/content/dam/insights/us/articles/3833_Industry4-0_digital-twin-technology/DUP_Industry-4.0_digital-twin-technology.pdf
- Piron, M., Bovo, E., Lucchetta, G., & Manzardo, A. (2025). Soft-sensors to drive manufacturing toward clean production: LCA based on Digital Twin. *Journal of Cleaner Production*, 498, art. no. 145192. <https://doi.org/10.1016/j.jclepro.2025.145192>
- Qi, Q., & Tao, F. (2018). Digital twin and big data towards smart manufacturing and Industry 4.0: 360-degree comparison. *IEEE Access*, 6, 3585–3593. <https://doi.org/10.1109/ACCESS.2018.2793265>
- Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital twin: Values, challenges and enablers from a modeling perspective. *IEEE Access*, 8, 21980–22012. <https://doi.org/10.1109/ACCESS.2020.2970143>
- Riascos, R., Majić, T., Ostrosi, E., Sagot, J. C., & Stjepandić, J. (2023). Digital Twin as Enabler of Sustainability and Risk Management of Medical Devices. In *Leveraging Transdisciplinary Engineering in a Changing and Connected World* (pp. 453-462). IOS Press. <https://ebooks.iospress.nl/doi/10.3233/ATDE230639>
- Rinaldi, M., Caterino, M., Riemma, S., Macchiaroli, R., & Fera, M. (2025). Emergency Supply Chain Resilience Enhanced Through Blockchain and Digital Twin Technology. *Logistics*, 9(1), art. no. 43. <https://doi.org/10.3390/logistics9010043>
- Roman, E.-A., Stere, A.-S., Roșca, E., Radu, A.-V., Codroiu, D., & Anamaria, I. (2025). State of the Art of Digital Twins in Improving Supply Chain Resilience. *Logistics*, 9(1), art. no. 22. <https://doi.org/10.3390/logistics9010022>
- Ščeuļovs, D., Gaile-Sarkane, E., & Kaže, V. (2011). E-environment benefits for Latvian sustainable business development. *Management Theory and Studies for Rural Business and Infrastructure Development*, 26, 234-240.
- Semeraro, C., Lezoche, M., Panetto, H., & Dassisti, M. (2021). DTS Paradigm: A Systematic Literature Review. *Computers in Industry*, 130(7), 1–23. <https://doi.org/10.1016/j.compind.2021.07.001>
- Shao, G., & Kibira, D. (2018). Digital manufacturing: Requirements and challenges for implementing digital surrogates. *Proceedings of the 2018 Winter Simulation Conference*, 1226-1237. <https://doi.org/10.1109/WSC.2018.8632242>
- Sharma, A.K., Srivastava, M.K., & Sharma, R. (2025). Barriers and Challenges for Digital Twin Adoption in Healthcare Supply Chain and Operations Management. *Global Business Review*, <https://doi.org/10.1177/09721509251314795>
- Shehadeh, A., Alshboul, O., & Arar, M. (2024). Enhancing urban sustainability and resilience: Employing digital twin technologies for integrated WEFE nexus management to achieve SDGs. *Sustainability*, 16, 7398. <https://doi.org/10.3390/su16177398>
- Shoib, M., Zhang, S., Ali, H., Ahmad, M.S., & Khan, M.A. (2025). Integrating circular economy while adopting digital twin for enhancing logistics efficiency: a hybrid Fuzzy Delphi-FUCOM based approach. *International Journal of Logistics Research and Applications*, <https://doi.org/10.1080/13675567.2025.2451750>
- Singh, R. K. (2025). Transforming humanitarian supply chains with digital twin technology: a study on resilience and agility. *International Journal of Logistics Management*. <https://doi.org/10.1108/IJLM-08-2024-0504>
- Srivastava, G., & Bag, S. (2025). Harnessing digital twin technology to enhance resilience in humanitarian supply chains: an empirical study. *Benchmarking*, <https://doi.org/10.1108/BIJ-12-2024-1143>
- Suhail, S., Iqbal, M., McLaughlin, K., Lee, B., & Imtiaz, B.A. (2025). framework for enhancing cyber incident response with Security-Enhancing Digital Twins in Cyber-Physical Systems. *Internet of Things (The Netherlands)*, 31, art. no. 101547.: <https://doi.org/10.1016/j.iot.2025.101547>
- Tao, F., & Qi, Q. (2019). Make more digital twins. *Nature*, 573, 490-491. <https://doi.org/10.1038/d41586-019-02849-1>
- Tian, Z. (2022). Application of computer 3D modeling technology in the simulation design of modern garden ecological landscape. *Mathematical Problems in Engineering*, 7033261. <https://doi.org/10.1155/2022/7033261>
- Tzachor, A., Sabri, S., & Richards, C.E. et al. (2022). Potential and limitations of digital twins to achieve the Sustainable Development Goals. *Nat Sustain*, 5, 822-829. <https://doi.org/10.1038/s41893-022-00923-7>
- van Raan, A. F. J. (2000). The impact of science indicators: The Leiden Perspective. *Scientometrics*, 47(3), 347–362. <https://doi.org/10.1023/A:1005647906878>
- Verdouw, C., Tekinerdogan, B., Beulens, A. J. M., & Wolfert, S. (2013). Digital twins in smart farming. *Agricultural Systems*, 189, 103046. <https://doi.org/10.1016/j.agry.2020.103046>
- Vilks, A., Kipane, A., & Krivins, A. (2024). Preventing international threats in the context of improving the legal framework for national and regional security. *Social & Legal Studies*, 7(1), 97-105. <https://doi.org/10.32518/sals1.2024.97>
- Voosen, P. (2020). Europe is building a 'digital twin' of Earth to revolutionise climate forecasts. *Science*. <https://doi.org/10.1126/science.abf0687>

Wang, S., Zhang, S., Xi, G., & Wong, M. C. (2024). Analysis of innovation efficiency and influencing factors of listed companies in Beijing-Tianjin-Hebei economic zone based on improved DEA. *Insights into Regional Development*, 6(2), 24-47. [https://doi.org/10.9770/IRD.2024.6.2\(2\)](https://doi.org/10.9770/IRD.2024.6.2(2))

Wang, Y., Kang, M., Liu, Y., Li, J., Xue, K., Wang, X., Du, J., & Tian, Y. (2023). Can digital intelligence and cyber-physical-social systems achieve global food security and sustainability? *IEEE/CAA Journal of Automatica Sinica*, 10(5), 123951. <https://doi.org/10.1109/JAS.2023.123951>

Werner, A., Schuseil, F., Hämmerle, M., Schaper, S., & Hölzle, K. (2025). Modular Digital Twin—an approach for generating and exploiting product sustainability information towards service-oriented business models. *International Journal of Production Research*, 63(3), 992-1010. <https://doi.org/10.1080/00207543.2024.2366997>

World Commission on Environment and Development (Ed.). (1987). Our Common Future: Report of the World Commission on Environment and Development. United Nations. Available: www.un-documents.net/our-common-future.pdf

Yan, H., Liu, C., Yang, X., & Feng, K. (2025). Real-Time Digital Twin-Driven 3D Near-Miss Detection System at Construction Sites. *Journal of Construction Engineering and Management*, 151(4), art. no. 04025021. <https://doi.org/10.1061/JCEMD4.COENG-15583>

Yan, J., Lu, Q., Li, N., & Pitt, M. (2025). Developing Data Requirements for City-Level Digital Twins: Stakeholder Perspective. *Journal of Management in Engineering*, 41(2), art. no. 04024068. <https://doi.org/10.1061/JMENE4.MEENG-6434>

Zahedi, F., Alavi, H., Sardroud, J. M., & Dang, H. (2024). Digital twins in the sustainable construction industry: A systematic literature review. *Buildings*, 14(3613). <https://doi.org/10.3390/buildings14113613>

Zhang, C., Tao, F., Qi, Q., Cheng, Y., Cheng, J., Wang, B., & Nee, A.Y.C. (2025). Digital twin-based shop-floor reconfiguration design for uncertainty management. *International Journal of Production Research* <https://doi.org/10.1080/00207543.2024.2448605>

Zhu, X., Liao, B., Shen, Y., & Kong, M. (2025). Towards Industry 5.0: digital twin-enhanced approach for dynamic supply chain rescheduling with real-time order arrival and acceptance. *International Journal of Production Research*, <https://doi.org/10.1080/00207543.2025.2481184>

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