International Journal of Economic Plants

https://ojs.pphouse.org/index.php/IJEP

Crossref

IJEP May 2026, 13(3): 01-06

Article IJEP6916

Full Research

Natural Resource Management

Doi: HTTPS://DOI.ORG/10.23910/2/2026.6916

Digital Twins in Agriculture: A Comprehensive Bibliometric Exploration of Applications and Future Trends

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Article History

Received on 07th January, 2026
Received in revised form on 04th April, 2026
Accepted in final form on 19th April, 2026
Published on 30th April, 2026

Abstract

This bibliometric study was conducted between September and December, 2025 using data retrieved from the Scopus database, focusing on global research publications related to Digital Twin applications in agriculture. Digital Twin technology has become a key component of Agriculture 4.0, enabling real-time simulation, prediction, and optimization of farming systems through virtual representations of physical environments. As agriculture faces rising food demand, climate variability, labour shortages, and resource constraints, Digital Twins offer significant potential to improve productivity, sustainability, and decision-making. However, research in this area remains fragmented across domains such as IoT, AI, robotics, precision agriculture, and climate-smart practices. Using a structured search strategy and PRISMA screening, 95 eligible articles published between 2019 and 2026 were identified. Bibliometric analysis was performed using the Bibliometrix R package and Biblioshiny interface, covering descriptive indicators, co-authorship and co-citation networks, keyword co-occurrence, and thematic evolution. Results show a fluctuating yet overall increasing publication trend, with a notable rise in 2025. Major publication sources include IEEE Access, Applied Sciences, Sensors, and Smart Agricultural Technology. China, the Netherlands, and the USA are leading contributors, with the Netherlands demonstrating the highest citation impact. Keyword analysis highlights strong emphasis on Digital Twins, IoT, machine learning, embedded systems, and agricultural robotics. Thematic mapping identifies core motor themes and emerging areas such as smart agriculture and climate resilience. Overall, the study consolidates fragmented knowledge, identifies research gaps, and outlines future directions to advance Digital Twin applications for sustainable, data-driven agriculture.

Keywords: Digital twin, agriculture 4.0, smart farming, bibliometric analysis

1. Introduction

In recent years, global agriculture has been undergoing a rapid transformation from traditional, labour - intensive farming toward digitized, smart-farming systems driven by data, automation, and intelligent decision-support technologies (Choudhary, 2023). This transition, often described as "Agriculture 4.0," reflects a paradigm shift comparable to the industrial revolutions that reshaped manufacturing (Batra et al., 2024; Zambon et al., 2019). Agriculture 4.0 integrates IoT sensors, artificial intelligence (AI), robotics, unmanned aerial systems, edge computing and big-data analytics to enable real-time monitoring, precision interventions and predictive management across the entire agri-food value chain (Ahmed and Shakoor, 2025, Misra et al., 2020). The pressures accelerating this transformation are significant. By 2050, global food demand is projected to increase by 59–98%, driven by population growth, urbanization, and rising income levels (Falcon et al., 2022). At the same time, farmers face unprecedented challenges: shrinking arable land, increasing labour shortages, volatile market conditions and mounting climate risks (Khatri et al., 2024). Conventional farming practices are increasingly inadequate to meet these demands, creating an urgent need for technologies that enhance productivity while minimizing environmental footprints (Misra and Ghosh, 2024). In this context, digital transformation is not merely a technological upgrade but a structural necessity for ensuring food security and long-term sustainability. Smart farming technologies help reduce input waste, improve traceability, and strengthen resilience against climate-induced uncertainties such as droughts, floods, and pest outbreaks. Furthermore, digital integration across the agri-food chain supports transparency, risk management, and adaptive responses to environmental and market fluctuations. Within this broader transformation, Digital Twin technology has emerged as a promising frontier for agriculture: Digital Twins are virtual replicas of real-world farming systems (crops, soils, greenhouse environments, livestock systems, etc.) that update dynamically with real-time data, enabling simulation, monitoring, prediction, and optimization of agricultural processes across the entire production lifecycle (Verdouw et al., 2021; Awais et al., 2025). Digital Twins facilitate a comprehensive understanding of field conditions and system behaviour. This capability allows stakeholders to test alternative scenarios, evaluate management strategies, and detect anomalies long before they manifest in the physical environment. Digital Twins can support precision irrigation, nutrient management, pest and disease forecasting, yield prediction, machinery scheduling and greenhouse climate control with unprecedented accuracy (Chauhan et al., 2025). They also enable farmers to reduce operational costs, enhance resource-use efficiency and increase overall resilience to environmental variability (Ametefe et al., 2024). Moreover, digital representations of farms create opportunities for automation and robotics integration, strengthening the shift toward autonomous or semi-autonomous farming ecosystems (Duckett et al., 2018). Beyond operational benefits, Digital Twins are increasingly being recognized for their potential to improve sustainability metrics by minimizing chemical use, optimizing energy inputs and supporting carbon-smart agriculture. Despite these advantages, the research landscape surrounding agricultural Digital Twins remains dispersed across engineering, computer science, environmental sciences, and agricultural disciplines. Variations in modeling approaches, data integration methods, and application contexts make it difficult to obtain a consolidated view of the field's intellectual structure. This study conducted a comprehensive bibliometric and scientometric analysis of Digital Twin research in agriculture to: (i) describe global publication trends, (ii) examine collaborative research patterns, (iii) uncover dominant and emerging themes. By mapping the knowledge structure of this rapidly expanding domain, the study provides valuable insights for researchers, technology developers, agribusiness leaders and policymakers seeking to advance the design, application and adoption of Digital Twin technologies within modern agriculture. The findings contribute to a clearer understanding of how technological innovation, interdisciplinary collaboration, and sustainability priorities are shaping the evolution of Digital Twin applications. Ultimately, this work supports the development of more integrated, intelligent, and resilient agricultural systems aligned with future food security and environmental goals.

2. Materials and Methods

The study was conducted between August, 2025 and December, 2025, during which data were retrieved from the Scopus database and analyzed using bibliometric tools. A quantitative bibliometric research design was adopted to analyze publication trends, influential journals, institutions, countries and thematic structures. Bibliometric provided objective indicators of scientific activity and allowed for the identification of relationships through citation, co-authorship and keyword networks. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework was used to guide the data identification and screening process (Moher et al., 2009). The Scopus database was selected as the primary source due to its extensive coverage of peer-reviewed journals, high-quality indexing and compatibility with bibliometric mapping tools. Scopus was widely recommended for bibliometric research because of its comprehensive metadata, including author affiliations, citations, abstracts and keywords.

A structured search string was developed using Boolean operators (OR, AND), synonyms and keyword combinations relevant to Digital Twin applications in agriculture. The final search strings were given in the Table 1.

Table 1: Combination of keywords

Database	Search strings	No. of articles
Scopus	"digital twin" OR "virtual twin" OR "cyber physical system" OR "CPS" OR "DT model" OR "digital replica" OR "virtual model" OR "digital simulati" OR "virtual farming system" AND agriculture OR "smart farm" OR "precision farm" OR "precision agriculture" OR "crop model" OR "livestock system" OR "farm management" OR "smart agriculture" OR "agri-food" OR "horticulture" OR "greenhouse"	2,551

2.1. Inclusion and exclusion criteria

To ensure relevance and consistency, specific inclusion and exclusion criteria were applied during the screening process. The inclusion and exclusion criteria were enclosed in Table 2. Only studies published between 2019 and 2026 were included, while those before 2019 were excluded. The review considered only peer-reviewed journal articles, eliminating book chapters, books, reviews, notes, and conference papers. Publications had to be in English, with non-English works removed. Additionally, only final published articles were included, excluding articles still in press. The study focused on open-access journal sources, while restricted-access documents and materials from books, conference proceedings, book series, and trade journals were excluded.

Table 2: Inclusion and exclusion criteria

Criteria	Inclusion criteria	Exclusion criteria
Timeline	2019–2026	<2019
Document type	Article	Book chapters, review, book, note, conference paper
Language	English	Non-English
Publishing type	Final	Article in Press
Access type	Open access	Restricted Access
Source type	Journal	Book, conference paper, book series, trade journal

These criteria ensured a high-quality, coherent dataset for bibliometric analysis.

2.2. Selection process and data analysis

The screening and selection process followed a structured and systematic approach aligned with the PRISMA guidelines and was illustrated in Figure 1. First, all records retrieved from the database were compiled and duplicate entries were removed to avoid redundancy. The eligible documents were then assessed against the predefined inclusion and exclusion criteria. The remaining articles were screened by title, abstract and keywords to determine their relevance to Digital Twin applications in agriculture. Finally, full-text verification was performed to confirm thematic relevance and the completeness of bibliometric metadata. Only studies that fully satisfied all criteria were included in the final dataset for bibliometric analysis.

Data analysis was conducted using the Bibliometrix R package and its Biblioshiny interface (Rashid et al., 2023). The cleaned dataset was imported to generate descriptive indicators such as annual publications, leading authors, journals and country contributions. Bibliometrix was also used to perform co-authorship, co-citation and keyword co-occurrence analyses, along with thematic mapping. These analytical outputs provided a clear understanding of research trends, collaboration patterns and thematic structures in Digital Twin research within agriculture.

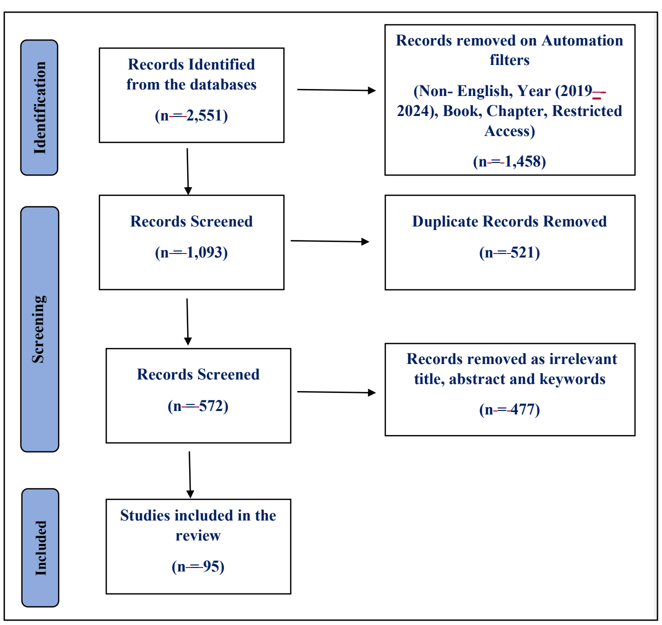

Figure 1: PRISMA flowchart

3. Results and Discussion

3.1. Annual scientific production

The annual scientific production showed a fluctuating but overall increasing trend over the years which was given in Figure 2. From 2019 to 2021, there was a steady rise in the number of publications, increasing from 7 to 10 articles, indicating growing research interest. In 2022, production slightly declined to 8 articles, but this was followed by a significant rebound in 2023, reaching 12 publications. The year 2024 again showed a drop to 7 articles, but 2025 marked a dramatic surge with 39 articles, the highest output in the dataset suggesting a strong expansion of research activity, possibly driven by new funding, emerging technologies or heightened academic focus. However, the sharp decline in 2026 to 3 articles might reflect incomplete data for the year, publication delays, or shifting priorities. Overall, the pattern highlighted a major peak in 2025 demonstrating intensified scientific engagement during that period. Trends in annual scholarly output are commonly interpreted as indicators of the maturity and momentum of a research field (Donthu et al., 2021; Zupic and Cater, 2015).

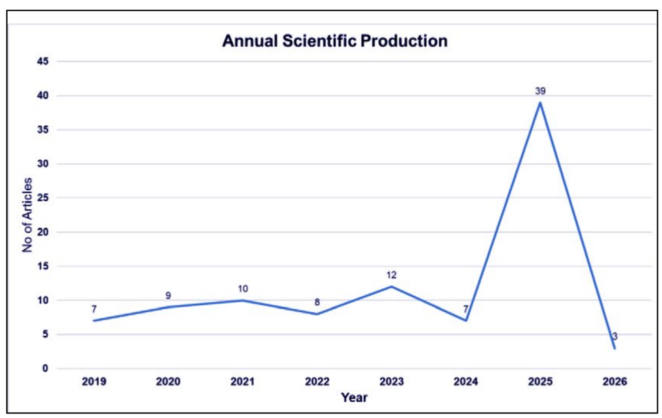

Figure 2: Annual Scientific Production of articles from the period of 2019 –2026

3.2. Most relevant sources

The analysis of the most relevant sources from Figure 3 revealed that research on the topic was published across a diverse range of high-impact journals, reflecting its interdisciplinary nature. IEEE Access emerged as the leading source with nine articles, highlighting strong contributions from engineering and technology-focused research. This

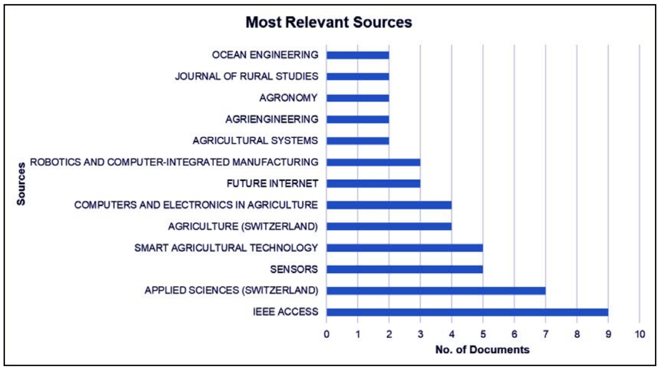

Figure 3: Most relevant sources

was followed by Applied Sciences (Switzerland) with seven articles and Sensors and Smart Agricultural Technology, each contributing five publications, indicating growing interest in sensor-based innovations and smart farming solutions. Journals such as Agriculture (Switzerland) and Computers and Electronics in Agriculture each account for four articles, underscoring the central role of agricultural technology applications. Additional contributions from Future Internet, Robotics and Computer-Integrated Manufacturing, and Agricultural Systems further demonstrated the integration of digitalization and automation in contemporary agricultural research. The presence of journals like Agri engineering, Agronomy, Journal of Rural Studies and Ocean Engineering each contributing two articles, highlighted the multi-domain engagement from agronomy and rural development to engineering fields supporting a comprehensive understanding of advancements in the sector.

3.3. Corresponding author countries

The distribution of corresponding authors across countries highlighted strong international participation in the research domain, with notable variations in both single-country publications (SCP) and multiple-country collaborations (MCP). The corresponding author countries was distributed in Figure 4. China leads with the highest number of contributions, dominated largely by SCPs, indicating strong domestic research productivity. The Netherlands followed with a substantial share of MCPs, reflecting its active involvement in international collaborative networks. The USA, Germany, Italy and Spain also showed significant contributions, combining both domestic and collaborative research efforts. Countries such as the United Kingdom, Australia, Denmark and Ireland demonstrated moderate but meaningful publication outputs, with Ireland showing a higher share of SCPs. Meanwhile, contributions from Canada, Colombia, Greece, India, Korea, Morocco, Portugal, Saudi Arabia and Austria, although fewer, illustrated the growing global interest in the field. Overall, the pattern underscored a geographically diverse research landscape, with both established and emerging countries actively contributing to knowledge production.

3.4. Most cited countries

The citation distribution highlighted the global landscape of

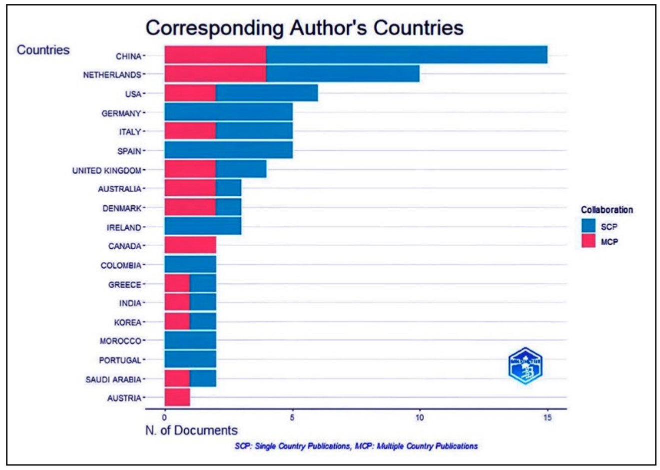

Figure 4: Corresponding author countries

influential research contributions to Digital Twin applications in agriculture which was given in Figure 5. The Netherlands leads with 1,422 citations, indicating its strong research leadership and high-impact scholarly output in digital agriculture and simulation technologies. The USA followed with 1,206 citations, reaffirming its critical role in advancing data-driven and computational farming systems. Among European countries, Spain (423 citations), Denmark (370), Italy (304) and the United Kingdom (234) form a strong mid-tier cluster, reflecting their growing engagement in precision agriculture and digital modeling research. China also showed substantial influence with 265 citations, driven by its rapid technological adoption in agricultural modernization. Emerging research contributors such as India (192 citations), Greece (185) and Austria (134) demonstrated increasing participation and recognition in the field. Additionally, the United Arab Emirates (114) and Germany (107) revealed expanding interest in Digital Twins, particularly in controlled-environment agriculture and smart farming systems. Overall, the citation pattern underscored a geographically diverse yet increasingly interconnected research landscape, with both established and emerging nations contributing significantly to the evolution of Digital Twin technologies in agriculture.

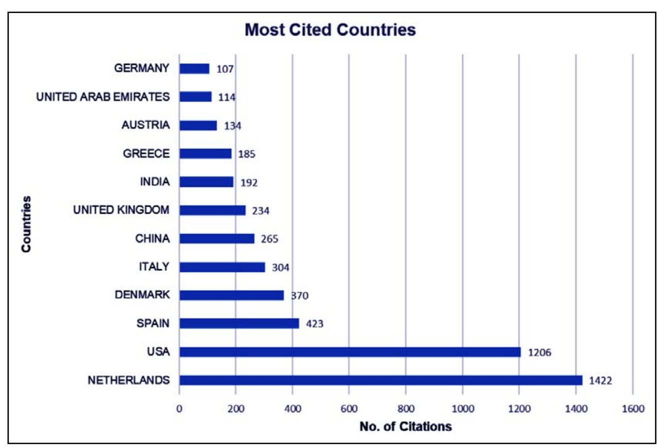

Figure 5: Most cited countries

3.5. Word cloud

The word cloud in Figure 6 highlighted the dominant thematic focus areas within the Digital Twin research landscape in agriculture. The most prominent terms digital twin, internet of things, agriculture, embedded systems and agricultural robots indicated that current research was strongly oriented toward integrating advanced digital technologies into farming systems. Keywords such as machine learning, artificial intelligence, cyber-physical systems and real-time systems reflected the increasing emphasis on intelligent automation and data-driven decision-making. Additionally, terms like precision agriculture, smart farming, climate change and sustainability demonstrated that much of the literature prioritized enhancing environmental efficiency and resilience in agricultural production. Emerging concepts such as blockchain, remote sensing, edge computing and data analytics further showed how interdisciplinary technologies were converging to build more responsive and efficient agricultural ecosystems. Overall, the keyword distribution illustrated a research field that was rapidly evolving through technological innovation with Digital Twin systems acting as a core integrator of smart, sustainable and automated agricultural practices.

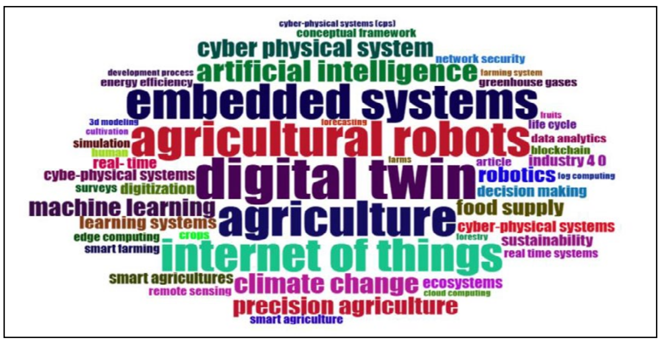

Figure 6: Word cloud

3.6. Thematic map

The thematic map in Figure 7 illustrated the conceptual structure of research on agricultural Digital Twins by categorizing themes based on their relevance (centrality) and degree of development (density). In the upper-right quadrant (Motor Themes), highly developed and central topics such as agricultural robots, embedded systems and internet of things dominated, indicating that these areas were driving scientific progress and formed the core technological backbone of Digital Twin applications in agriculture. Closely positioned were machine learning, learning systems, decision making, and edge computing, reflecting their growing role in enabling intelligent, real-time farm management solutions. In the upper-left quadrant (Niche Themes), specialized but less central topics such as industrial research and 3D printing appear, representing advanced but narrowly focused areas with strong internal development. The lower-right quadrant (Basic Themes) features foundational and widely relevant themes including digital twin, agriculture, and climate change, which served as essential building blocks for the research field despite moderate development. Finally, the lower-left quadrant (Emerging or Declining Themes) contained less mature or evolving topics such as smart agriculture, agricultural technology, and greenhouse gas resilience, indicating areas that were either developing or receiving declining attention.

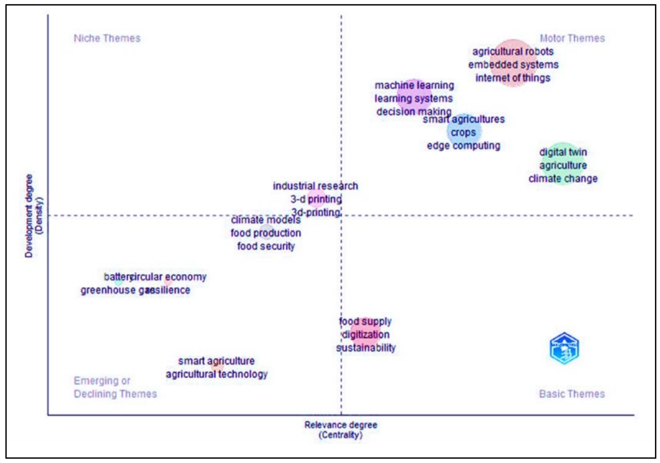

Figure 7: Thematic map

4. Conclusion

This bibliometric study demonstrated that research on Digital Twin technologies in agriculture had expanded steadily, with a major surge in 2025 driven by advances in IoT, AI, and smart farming. Global contributions were led by China, the Netherlands, and the USA, reflecting strong international engagement. The field was anchored in core technological themes while progressing toward smart agriculture and climate resilience. Overall, Digital Twins showed strong transformative potential, though further research was needed to address integration, scalability, and sustainability challenges.

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