Review

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Review

Application of Digital Twin Technology in Smart Agriculture: A Bibliometric Review

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Abstract

Digital twin technology is reshaping modern agriculture. Digital twins are the virtual replicas of real-world farming systems, which are continuously updated with real-time data, and are revolutionizing the monitoring, simulation, and optimization of agricultural processes. The literature on agricultural digital twins is multidisciplinary, growing rapidly, and often fragmented across disciplines, which lacks well-curated documentation. A bibliometric analysis includes thematic content analysis and science mapping, which provides research trends, gaps, thematic landscape, and key contributors in this continuously evolving and emerging field. Therefore, in this study, we conducted a bibliometric review that included collecting bibliometric data via keyword search strategies on popular scientific databases. The data was further screened, processed, analyzed, and visualized using bibliometric tools to map research trends, landscapes, collaborations, and themes. Key findings show that publications have grown exponentially since 2018, with an annual growth rate of 27.2%. The major contributing countries were China, the USA, the Netherlands, Germany, and India. We observed a collaboration network with distinct geographic clusters, with strong intra-European ties and more localized efforts in China and the USA. The analysis identified seven major research theme clusters revolving around precision farming, Internet of Things integration, artificial intelligence, cyber-physical systems, controlled-environment agriculture, sustainability, and food system applications. We observed that core technologies, such as sensors, artificial intelligence, and data analytics, have been extensively explored, while identifying gaps in research areas. The emerging interests include climate resilience, renewable-energy integration, and supply-chain optimization. The observed transition from task-specific tools to integrated, system-level approaches underline the growing need for adaptive, data-driven decision support. By outlining research trends and identifying strategic research gaps, this review offers insights into leveraging digital twins to improve productivity, sustainability, and resilience in global agriculture.

Keywords: digital twin; sensors; Internet of Things; artificial intelligence; smart farming; precision farming

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1. Introduction

Over the past few decades, global agriculture has been continuously transforming from conventional farming to digitized and smart farming [1,2]. Integrating the latest agricultural technologies boosts farm profitability through higher yields and lower input costs [3]. Recent advances in low-cost sensor technology, improved computational capability, and advanced data-driven predictive models are enabling the digitization of farming [4–6]. This transformation is driven by precision, smart, and sustainable agriculture technologies that leverage sensors, data, and models to increase production efficiency, reduce inputs (e.g., labor, fertilizer, water), and enhance environmental sustainability [3,7]. Digital farming employs advanced technologies, not limited to remote sensing, sensors, Internet of Things (IoT) devices, artificial intelligence (AI), data analytics, and computation tools, but also suggests a significant shift towards integrated sensors, devices, data-driven predictive models, and computation-intensive agriculture systems [8,9]. The current research and development remains more task-centric or system-specific, utilizing a single combination of tools or approaches to obtain task-specific solutions or objectives. However, there is a growing interest in developing whole-system-specific methods, suggesting a need for centralized and integrated solutions that collect, process, and analyze data on a broad system level and simulate, predict, and optimize the whole system operation in real-time. This framework sets an ideal foundation for the digital twin technology in agriculture, which is an emerging field that has the potential to redefine how agriculture systems are optimized for higher production with reduced inputs [10,11].

A digital twin is a virtual representation of a real-world object, system, process, or environment that is continuously updated with real-time data collected via multiple and interconnected sensors or devices, along with data-driven models [12]. The concept of the digital twin was first introduced by NASA in 2010. [11]. This concept outlines the foundational concept of digital twins, emphasizing their role in integrating modeling, simulation, and real-time data to enhance decision-making in complex aerospace systems [13]. The concept was later adopted across multiple fields, including manufacturing [14], healthcare [15], urban planning [16], and agriculture [17], for optimization, predictive maintenance, and data-driven decision-making. For example, in manufacturing, digital twins are used to monitor and optimize production lines, enabling predictive maintenance and improved operational efficiency [14]. The integration of IoT and cyber-physical systems in Industry 4.0 has significantly advanced the application of digital twins. In healthcare, digital twins enable personalized medicine, treatment planning, and hospital resource management by creating patient-specific virtual models [15]. These applications are revolutionizing diagnosis and predictive healthcare through real-time simulations and data analytics. In urban planning, digital twins of cities are used to model infrastructure, simulate urban growth, and support smart city development [16]. They provide a dynamic platform for urban governance, environmental monitoring, and transportation management.

Digital twins differ fundamentally from conventional AI models or simulation tools. Traditional simulation models are typically static, offline, and one-directional: they accept input parameters, run scenarios, and output results without further interaction with the physical system [18]. In contrast, digital twins continuously synchronize with live data streams, support bi-directional data exchange for both monitoring and actuation, and embed advanced diagnostic and prognostic analytics [19]. While traditional models excel at the design-stage, "what-if" analyses, digital twins extend their capabilities to real-time control with generative learning, enabling closed-loop optimization across the entire crop or livestock production cycle [20].

In recent years, digital twin technology has gained significant interest in agricultural systems [21]. Digital twins offer multiple advantages in modern farming [20]. For example, by fusing sensor-derived soil moisture data, weather forecasts, and crop growth models, digital twin-driven irrigation management can reduce water use by up to 25% and minimize fertilizer waste by 10-15%, lowering production costs and negative environmental impact [22]. Moreover, precise, data-informed interventions such as variable rate seeding or targeted pest control can improve yield uniformity and overall productivity, as demonstrated in pilots across Europe and North America [23]. The sustainability objectives are supported through optimized resource allocation and emissions monitoring, helping farms comply with regulatory standards and achieve climate-smart agriculture goals [22]. Finally and most importantly, scenario-based simulations enable proactive risk management by forecasting pest outbreaks, equipment failures, or extreme weather impacts, thus safeguarding both yields and profitability in a farm or greenhouse [24].

Overall, the digital twin technologies in agriculture have received significant momentum, with both research and practical applications accelerating rapidly. However, the existing literature is cross-disciplinary in scope, yet lacking a unified direction. This highlights the need for systematic documentation and quantitative assessment to better understand the field's development and research landscape. The dispersed and cross-disciplinary research landscape complicates efforts to assess the field's development, trends, and key contributors. It is essential to identify thematic trends and gaps, and understand key contributors, global hotspots, and emerging focus areas. The

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individual case studies focusing on technological development are available but lack a comprehensive, quantitative analysis that scientifically maps evolution, collaboration patterns, research hotspots, and underexplored gaps within this emerging domain. To systematically assess the development of this field, bibliometric analysis, using mathematical and statistical methods to examine bibliographic data, offers a quantitative approach to uncover research trends, scholarly influence, and thematic evolution [25].

Therefore, in this study, we conducted a bibliometric and science mapping analysis of global research on digital twin applications in agriculture. A large amount of bibliometric data was collected from major scientific databases, which are carefully filtered and systematically assessed via bibliometric analysis tools to understand publication trends, influential authors, institutions, collaboration networks, global hotspots, thematic clusters, and keyword evolution. The goal of this study is to provide a structured overview of the current research landscape, offer insights into emerging trends, and identify strategic directions for future research and innovation in agricultural digital technologies. The specific aims of this study are: (1) Quantify publication trends and research productivity by country, institution, author, and source; (2) Identify research hotspots, core technologies, and thematic areas through keyword co-occurrence and clustering; (3) Map collaboration networks among countries and institutions; and (4) Highlight emerging or underexplored topics and future research directions. This study will offer a structured synthesis of existing research, highlighting pathways for coordinated and impactful innovation in agricultural digitalization. This work contributes to the scholarly understanding of digital twins in agriculture while serving as a strategic resource for advancing digital transformation in food and farming systems.

2. Materials and Methods

In this study, we adopted a bibliometric review to provide a broader overview of research trends, hotspots, emerging themes, and patterns of knowledge production on specific research topics [26]. The primary reason for conducting a bibliometric review was that the initial volume of literature data was too large for manual review and inspection, while the scope of the study was broad and qualitative in nature.

2.1. Data Collection

The first step in a bibliometric review involves a collection of extensive and relevant documents for analysis. Figure 1 provides an overview of an employed literature review procedure for bibliometric analysis [27]. Although several scientific databases are available for literature search, Scopus and Web of Science were selected for data collection due to their comprehensiveness, popularity, and reliability [28]. A combination of keyword search strategies was employed using relevant keywords and Boolean operators to capture the most comprehensive dataset. The search was conducted in February 2025 and search queries were as follows: (i) Web of Science: TS = (“digital twin”) AND TS = (“agriculture” OR “farming systems”); (ii) Scopus: TITLE (“digital twin”) AND TITLE-ABS-KEY (“agriculture” OR “farming systems”). These queries resulted in 662 documents from Web of Science and 1,305 documents from Scopus, resulting in a total of 1,967 articles selected for further bibliometric analysis. The two data sources were combined using the Bibliometrix package in R, identifying and removing 332 duplicate records, resulting in a dataset of 1,635 unique documents. The document exclusion criteria were established to remove irrelevant records and ensure the accuracy of the dataset. The documents were excluded if they were non-English, contained incomplete metadata, or were irrelevant to the agricultural domain or digital twin systems. These criteria were applied to 1,635 documents, based on a careful review of their titles, abstracts, and, when necessary, full-text content. After applying these exclusion criteria, a final total of 597 articles were included for the bibliometric analysis. The bibliometric data contains descriptive records on published materials, not limited to authors, journals, publication title, abstract, year, place, keywords, source, publisher, affiliation, country, and citation.

Once the bibliometric data were collected, we selected widely recognized bibliometric tools that support comprehensive analysis and science mapping. Therefore, the data analysis and visualization were performed using the following most popular bibliometric software tools: (1) Biblioshiny, a web-based graphical interface for the Bibliometrix R package, which provides an interactive and user-friendly platform to import, process, and analyze bibliographic data [29]. This tool generated descriptive statistics, author metrics, and keyword trend analyses. (2) VOSviewer, a specialized software tool used to construct and visualize bibliometric networks, including keyword co-occurrence and thematic evolution for science mapping [30]. Both tools are widely used in bibliometric research [29,30], which allows quantitative analysis and visual exploration of patterns in the literature on digital twin applications in agriculture.

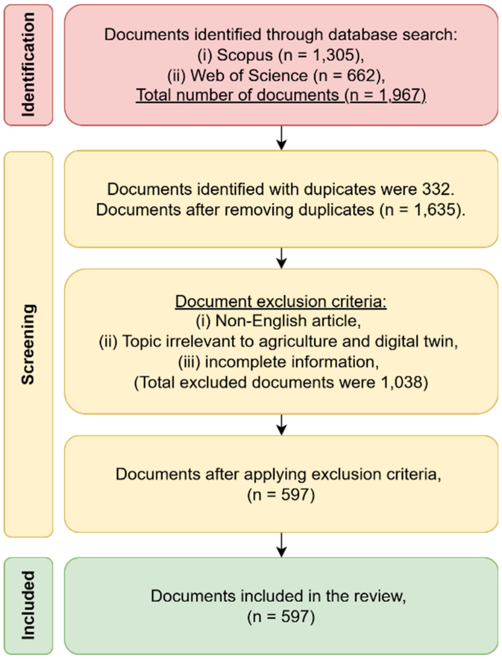

Figure 1. An overview of an employed literature selection procedure for bibliometric analysis.

2.2. Data Overview

A summary of the bibliometric dataset, which included a total of 597 documents, is presented in Table 1. These 597 documents were published across 424 sources, with an average document age of 2.09 years, reflecting a relatively new research domain. Authorship data show contributions from 2,244 authors, with an average of 4.88 co-authors per document, and 12.06% of all publications involved international collaboration. Collectively, these metrics highlight the field's emerging status and growing global engagement.

Table 1. Descriptive summary of the bibliometric dataset on digital twin applications in agriculture.

Category	Value
Timespan	2018 to 2025
Sources (Journals, Books, etc.)	424
Total number of documents	597
Document average age	2.09
Average citations per document	8.72
Keywords plus	2,910
Author's keywords	1,720
Number of authors	2,244

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Single-authored documents	23
Co-authors per document	4.88
International co-authorship %	12.06

3. Results and Discussion

The bibliometric results presented in this study are categorized into two major components: (a) Performance analysis, which identifies global publication trends, research hotspots, leading publication sources, and influential authors and institutions [31]; and (b) Science mapping, which focuses on unstructured textual data, particularly author-supplied keywords, to explore the thematic structure, research focus areas, and potential knowledge gaps within the field of agriculture [31].

3.1. Publication Trends and Document Types

The annual global scientific literature production on digital twin applications in agriculture has shown a significant increase in recent years (Figure 2a). The digital twin technology is a relatively new concept in agriculture [32], with the first document published in 2018 [33]. Thus, the number of published documents remained relatively low through 2020, with fewer than 30 documents published cumulatively (Figure 2a). However, a sharp upward trend began in 2021, with exponential growth observed through 2024, reaching a peak of 210 publications/year. This rapid rise suggests increasing research interest in digital twin technology in agriculture, likely driven by advances in AI and the proliferation of low-cost IoT systems [33]. The decline in documents in 2025 is attributed to incomplete indexing at the time of analysis, conducted in February 2025. Overall, the annual growth rate of 27.24% was observed in agricultural digital twin literature. The document type distribution reveals that journal articles and conference proceedings constitute the majority of the literature (Figure 2b). The high proportion of conference papers and articles suggests that the field is still in its infancy stages, with researchers favoring quicker dissemination routes for technology-oriented innovations. Review articles (8.4%), book chapters (5.5%), and other document types (1.5%) together form a small portion of the literature, highlighting both the emerging nature of digital twin applications in agriculture and the opportunity for more comprehensive syntheses and educational integration.

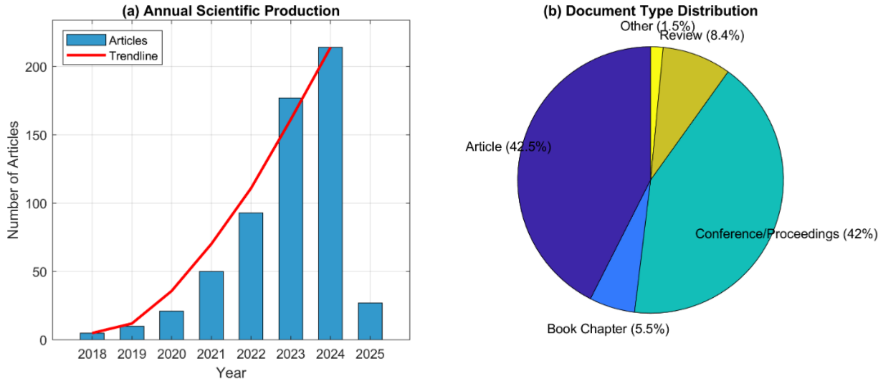

Figure 2. An overview of an employed literature selection procedure for bibliometric analysis.

3.2. Global Distribution of Scientific Literature

The global distribution of published documents on agricultural digital twin applications is presented in Figure 3. China leads with the highest number of documents (n > 180), followed by the USA, Italy, Germany, and India, indicating concentrated research activity in both developed and emerging economies. Unsurprisingly, China and the USA are at the forefront in agricultural production in multiple categories [34,35]. This likely reflects their early investments in smart agriculture, IoT infrastructure, and digital innovation policies. In contrast, European and Southeast

Asian countries show moderate engagement, while many regions in Africa, South America, and Central Asia appear underrepresented in this domain. This global distribution identifies research hotspots and underrepresented regions, further suggesting potential opportunities for international collaboration, capacity building, and technology transfer to expand the adoption of digital twin technologies.

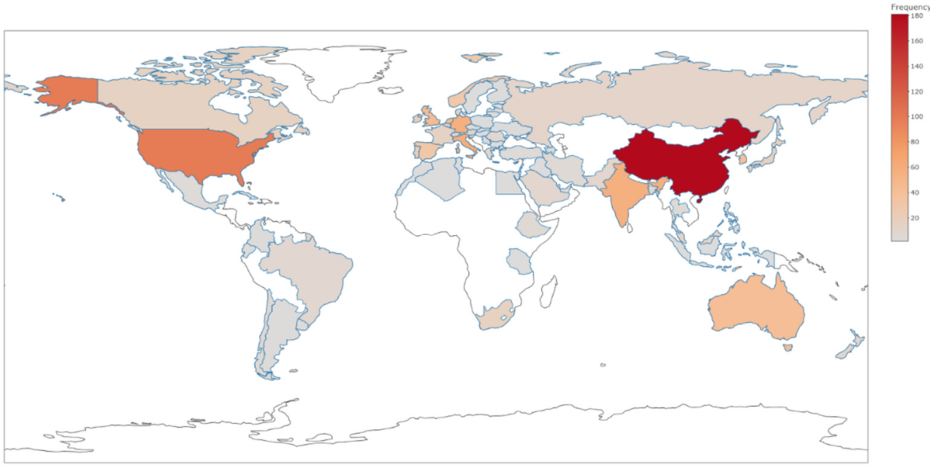

Figure 3. Global distribution of scientific literature on digital twin applications in agriculture.

3.3. Global Collaboration Trend and Network

Collaboration is critical when it comes to developing complex, novel, and emerging technologies, such as digital twins, since it would be efficient and effective if all the expertise, infrastructure, and resources from multiple institutions or countries could be integrated to develop a full-scale system. Collaboration can improve research quality, innovation, global relevance via information or resource sharing, as well as technology transfer [36]. The collaboration among the top 25 most productive countries is presented in Figure 4, which is broadly classified into single-country publications (SCP) and multi-country publications (MCP). The top five countries (i.e., China, USA, Italy, Germany, and India) lead in single-country efforts with a SCP percentage greater than 83%. On the other hand, several European countries (e.g., the United Kingdom, Norway, Switzerland, Greece, and Portugal) exhibit MCP above 20%, reflecting a strong tendency toward international collaboration. A few countries, including Denmark, Russia, Latvia, Belgium, and Austria, have limited to no international collaboration, as evidenced by their predominance of single-country publications and minimal contributions to multi-country efforts. Apart from the geographic distribution of research, Figure 4a presents collaborative dynamics, which could potentially provide insight into national capacity, dependence, and level of global engagement in advancing digital twin technologies for agriculture, which can be important for policymakers to outline future directions.

The subsequent visualization of the global collaboration network (Figure 4b) visualizes the collaboration landscape among the countries where the node represents the country, the line represents the collaborative link, and their respective size or thickness and position represent the collaboration frequency, strength, and relatedness, respectively. The collaboration landscape is organized into three distinct clusters, including Red (China, USA, Australia, etc.), Green (Canada, UK, Germany), and Blue (Norway, Denmark), each with a central hub. The network suggests key global hubs shaping digital twin research, while suggesting uneven participation with several countries situated at the network periphery.

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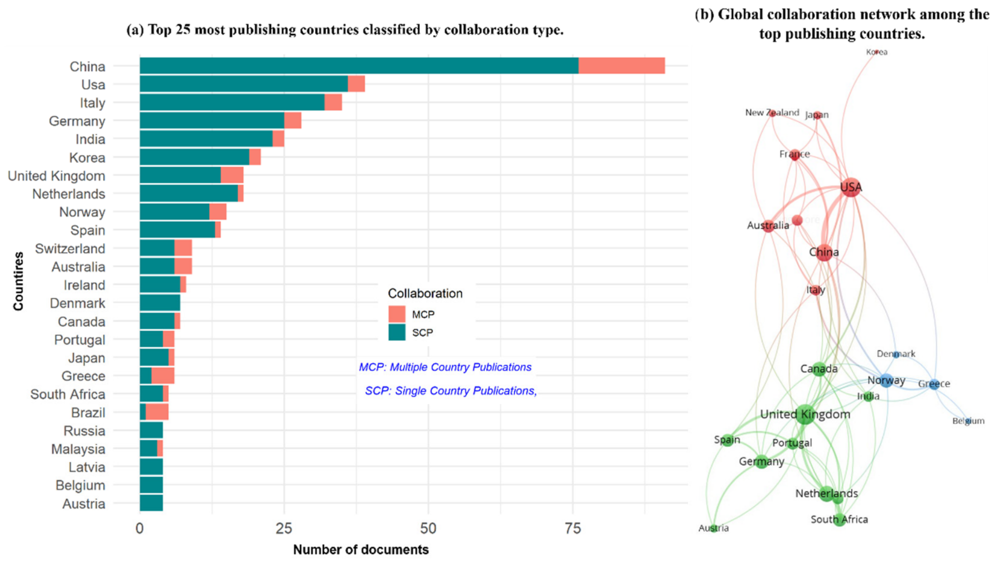

Figure 4. Top 25 most productive countries in digital twin research in agriculture: (a) collaboration type, (b) collaboration network.

3.4. Major Institutions, Authors Contribution, and Publishing Sources

Table 2 lists the global academic and research institutions driving innovation at the intersection of agriculture and digital twin technologies. While China and the USA rank highest in terms of total research output, the institutional analysis reveals that Wageningen University and Research, Netherlands, and the Norwegian University of Science and Technology, Norway, are the most prolific individual institutions. This suggests that the USA and China have a large number of small contributing institutions, each with relatively lower individual output, whereas, in some European and Asian countries, research efforts appear to be centralized within a few highly productive institutions.

Table 2. Institutions ranked by the number of published documents on digital twins in agriculture.

Institutions	Number of Articles
Wageningen University and Research, Netherlands.	30
Norwegian University of Science and Technology, Norway.	19
Samara State Technical University, Russia.	16
China Agricultural University, China.	15
Samara National Research University, Russia.	11
University of California System, United States.	11
National University of Singapore, Singapore,	10
Stellenbosch University, South Africa.	10
Zhejiang University, China.	9
Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia	8

Most productive authors were identified based on two key metrics: number of publications and h-index (Figure 5). The h-index is a well-accepted measure of consistent scholarly influence, which reflects both productivity and citation impact [37]. The study analyzed around 2,244 authors for a minimum of five articles and five h-index, and only seven authors met this condition. Skobelev P leads with 14 articles and a seven h-index, followed by Simonova E with 13 articles and a six h-index. This data suggests that digital twin in agriculture is still an emerging field; high-impact contributions are currently concentrated among a relatively small group of researchers, and immense opportunities exist for further scholarly influence and collaboration.

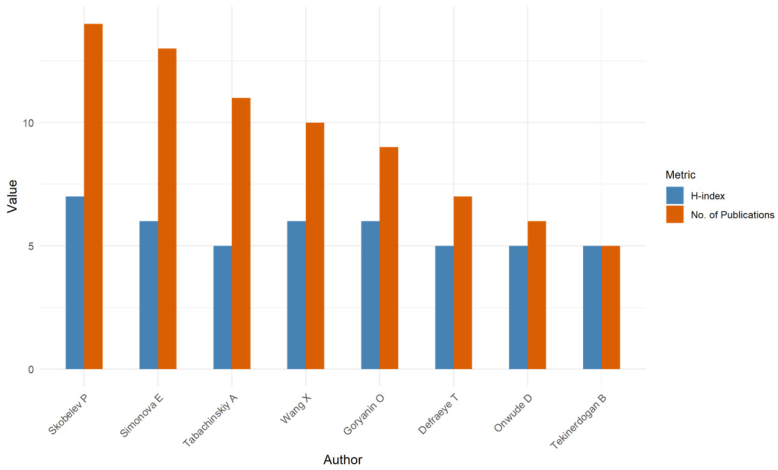

Figure 5. Top contributing authors in Digital Twin research in agriculture, based on a number of publications and h-index.

The study also reveals that authors disseminated their research across a wide range of platforms, with a total of 424 distinct sources utilized. The most frequently used publication venues are listed in Table 3. Given the multidisciplinary nature of digital twin technology, it is not surprising that many of the top sources fall within engineering and applied sciences journals, including "Computers and Electronics in Agriculture," "Sensors," "IEEE ACCESS," and "Applied Sciences". These platforms are highly relevant to the IoT, sensor networks, and real-time monitoring systems, which are the core components of digital twin frameworks and, hence, are well-suited for research that bridges digital systems, sensing technologies, and agricultural applications. Besides technical journals, several agriculture-specific journals were also utilized, such as "Agriculture" and "Frontiers in Plant Science," indicating the growing adoption of digital twin methodologies within the agronomic and plant sciences domain. The dataset also includes a notable number of conference proceedings, such as "Lecture Notes in Computer Science" and "Lecture Notes in Networks and Systems", which highlights the emerging and technical nature of digital twin research, where many innovations are first introduced in engineering or computer science venues before transitioning into applied agricultural contexts. Collectively, the data suggests the interdisciplinary nature of digital twin research in agriculture, spanning domains of engineering, computer science, agronomy, and environmental science.

Table 3. The most used publication sources for disseminating agricultural digital twin research.

Sources	No. of Articles
Computers and Electronics in Agriculture	20
Sensors	13
IEEE ACCESS	10
Applied Sciences	8
Agriculture	7
Energies	7
Frontiers in Plant Science	7
Lecture Notes in Computer Science	7
Digital Twins for Smart Cities and Villages	6
Lecture Notes in Networks and Systems	5

3.5. Keyword Analysis

In bibliometric studies, keyword analysis allows qualitative analysis on selected topics and helps understand the thematic structure, research focus, landscape, and evolution within the field [38]. It examines the keywords appearing in the article title, abstract, and author keywords to identify the most frequent concepts, tools, technologies, and disciplinary areas, as well as their inter-relationships [39]. In this study, we selected author keywords that are intentionally selected by authors to best describe their work. Thus, author keywords are the most accurate reflection of research priorities and specific focus. The study included a total of 1,720 authors' keywords. The keyword analysis is presented in Figure 6, with the help of a word cloud and keyword frequency. A word cloud is a visual text representation where word size correlates with its frequency in the dataset [40] As expected, the "digital twin" largely dominates the word cloud with the highest occurrence frequency, pointing to its central role. Other frequently occurring keywords include "internet of things," "smart agriculture," "artificial intelligence," "precision agriculture," "machine learning," and "cyber-physical system," reflecting the interdisciplinary integration of sensors, data, and data-driven methods or technologies within agricultural contexts. These terms highlight the foundational components of any digital twin architecture, including sensing systems, data acquisition, and modeling frameworks, which are well-represented as the most common keywords. In contrast, the word cloud also reveals less frequent but specific keywords directly related to agricultural applications, such as "remote sensing," "phenotyping," "real-time monitoring," "plant factory," "greenhouse," "climate change," "horticulture," "controlled-environment agriculture," "wind farms," "food industry," and "agriculture 4.0." These keywords provide valuable qualitative insights into the research scope and application areas, while also highlighting potential gaps or underexplored areas within the agricultural digital twin research landscape.

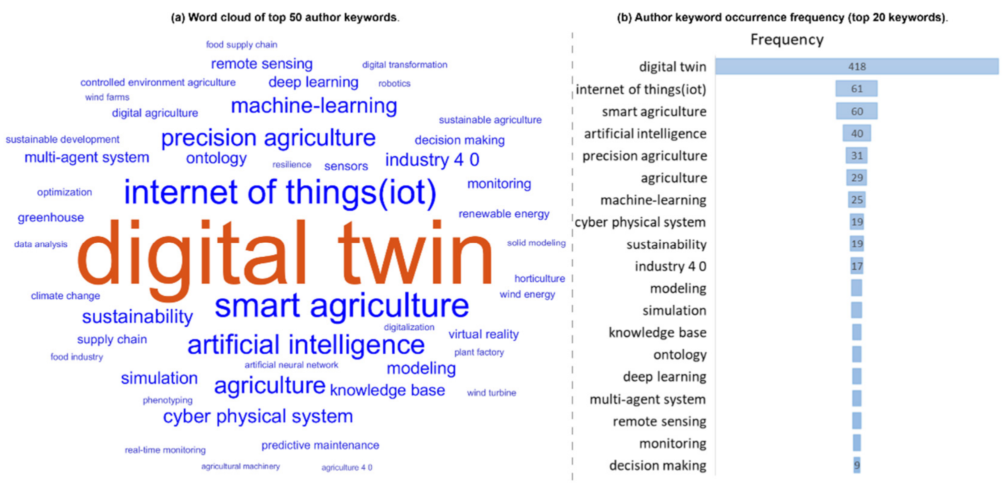

Figure 6. Analysis of author-provided keywords: (a) Word cloud and (b) Keyword occurrence frequency.

3.6. Keyword Trend

Cumulative growth trend analysis of the top four keywords reveals distinct trends in thematic evolution (Figure 7). "Digital Twin" shows the most significant and rapidly growing keyword, increasing from just three cumulative mentions in 2018 to over 400 by February 2025, indicating a sharp acceleration in research activity and the emerging dominance of the concept within the field. In contrast, the other three keywords (e.g., "Internet of Things," "Artificial Intelligence," and "Smart Agriculture") displayed a slower, more gradual upward trend, each remaining below 60 cumulative occurrences by February 2025. This pattern suggests that supporting technologies are steadily gaining traction, and research centered explicitly around digital twin systems is expanding at a significantly faster pace.

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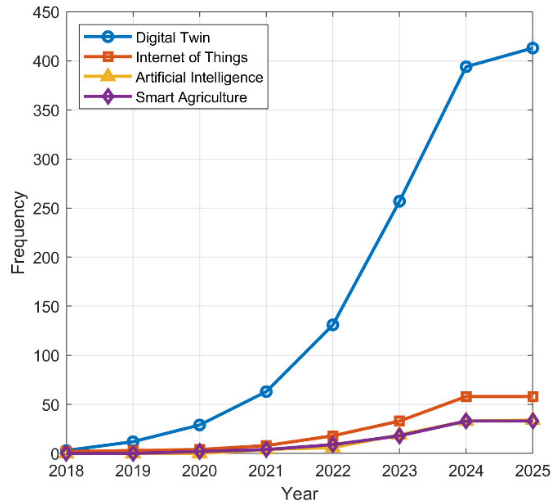

Figure 7. Cumulative trend of top four keywords over time.

3.7. Keyword Co-Occurrence Network

A keyword co-occurrence network is shown in Figure 8, which contain three major elements: (1) Nodes, which represent individual keywords, and their size indicates keyword frequency; (2) Link, which represents the strength of co-occurrence (i.e., thicker lines indicate a strong relationship and vice-versa); and (3) Layout where nodes are spatially arranged to show the keyword relatedness based on co-occurrence. The shorter distance between two keywords shows stronger relatedness and vice-versa [41].

The central and most dominant node, "digital twin", is linked to all keywords shown on the network but with varying link strength and spatial layout. Node size, link strength, and layout placement within the network provide qualitative insights into the structure and significance of each research area. Moreover, by tracking the presence, size, and connection strength of individual nodes, it is possible to infer the existence, prominence, or absence of specific literature themes within the field [41].

The co-occurrence network includes several broad-level thematic keywords that define the conceptual landscape of digital innovation in agriculture. For example, keywords such as "digital agriculture," "precision farming," "smart agriculture," "sustainable agriculture," and "agriculture 4.0" appear as distinct yet interconnected nodes with "digital twin" and other related keywords, often located at a certain distance from the central node. These keywords represent overlapping and interconnected methods to modernize agriculture, each focusing on different aspects to improve agricultural efficiency, productivity, and sustainability while reducing costs, inputs, and labor; ultimately leading to better outcomes than the conventional farming system [42,43]. The presence of these keywords suggests that digital twin technology will play a key role in modernizing and innovating current agricultural systems.

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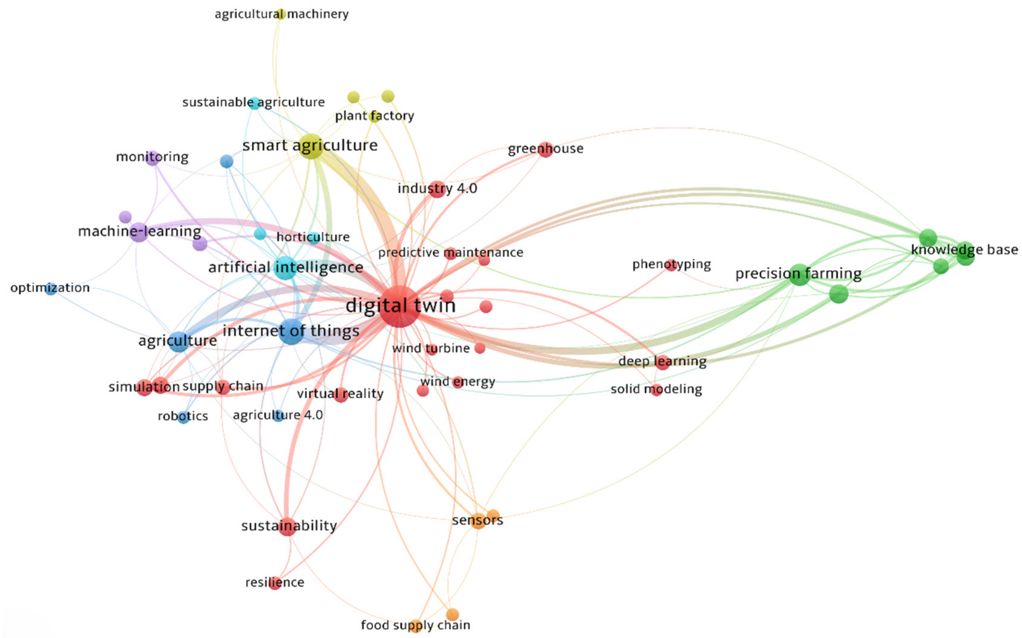

Figure 8. Keyword co-occurrence network based on keywords provided by authors of publications.

Digital twin technology is in the early stages of development and typically involves significant cost and infrastructure investment [**44**]. Therefore, the presence of keywords like "controlled environment agriculture," "greenhouse," "horticulture," and "plant factory" in the co-occurrence network is notable and expected. These domains are primarily associated with the production of high-value crops/produce, where the initial investment in advanced digital technologies is more economically justifiable due to the potential for higher returns [45,46]. This highlights a logical entry point for digital twin adoption, where capital-intensive systems can better absorb the cost of implementation while benefiting from the enhanced monitoring, prediction, and optimization capabilities that digital twin systems offer. Moreover, greenhouse and controlled environment agricultural systems are, in general, characterized by a higher level of automation and widespread sensor adoption than conventional farming, which are key prerequisites for digital twin implementation [**47**].

In the co-occurrence network, keywords such as "phenotyping," "remote sensing," "real-time monitoring," and "decision making" reflect the integration of sensors, data acquisition, and analytical technologies within agriculture. These terms are relevant to precision agriculture and smart farming, which aim to gather real-time data on plants and their environmental conditions. On the other hand, phenotyping allows the rapid collection of morphological and physiological crop traits, combined with remote sensing technologies, including drones, satellites, and field-based sensors, to provide the foundational data streams necessary for building and operating digital twin systems [48,49]. The real-time monitoring further emphasizes the importance of continuous data flow and system responsiveness, which are essential for dynamic simulation, forecasting, and anomaly detection in a digital twin framework [**50**]. Similarly, the keyword "decision making", suggests the role of digital twin in modeling and monitoring agricultural systems, but also in supporting data-driven management strategies that optimize productivity and sustainability. Collectively, these keywords highlight the sensor, data, and analytics-driven nature of today's agriculture, which can be further exploited with DT technologies.

The presence of keywords such as "machine learning," "deep learning," and "artificial intelligence" in the co-occurrence network reflects the dependence on advanced computational methods to analyze agricultural data for decision-making. These methods are key components of digital agriculture and digital twin systems, where large volumes of heterogeneous data collected from sensors and IoT devices must be interpreted in real-time. Machine learning performs pattern

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recognition and predictive modeling, while deep learning can process large, complex, unstructured data, not limited to images or time-series signals [51]. Overall, these methods can optimize resources and support intelligent decision-making in agricultural systems. Network keywords suggest that agriculture is shifting toward autonomous, data-informed farming systems, where digital twins can learn and adapt over time based on real-world inputs.

Keywords like “Internet of Things (IoT),” “sensor,” “robotics,” “cyber-physical system,” “multi-agent system,” and “agricultural machinery” suggest the technological tools or infrastructure needed for digital twin implementation. For example, sensors provide a primary data source, capturing environmental, biological, and mechanical information necessary for modeling and monitoring [52]. While IoT serves as the connecting layer, allowing real-time data transfer [53]. Robotics and agricultural machinery contribute to the automation and execution of physical tasks, often informed by digital models [54]. Cyber-physical systems integrate computational algorithms with physical processes, forming the structural core of digital twin systems [55]. Meanwhile, multi-agent systems facilitate decision-making among multiple autonomous components (e.g., drones, robotic platforms, or digital services) coordinated within a digital twin framework [56]. Together, these keywords represent the hardware-software ecosystem, which is an important component of the digital twins framework.

The keywords “climate change,” “sustainability,” and “resilience” are located at the network periphery, with few connecting links to digital twins, indicating active but underexplored research areas. However, in recent times, it has been believed that advances in sensors, IoT devices, robotics, automation, and digital twins may have the potential to solve critical global food production challenges, including climate change, sustainability, and resilience [57,58].

Notably, the network also includes keywords related to renewable energy sources, such as “wind energy,” “wind turbine,” and “wind farm,” suggesting active research in these areas as well. Wind turbines and wind farms include multiple sensors and require predictive maintenance and performance monitoring. Therefore, the use of digital twin technologies in this context can allow real-time monitoring, failure prediction, and optimization of renewable energy infrastructure [59,60]. Likewise, keywords such as “food supply chain” and “food industry” indicate an active and growing interest in applying digital twin approaches within the food systems domain.

The absence of primary agricultural-related keywords (e.g., irrigation, livestock farming, fruit harvesting, orchard farming from the co-occurrence network suggests that digital twin applications have not yet been explored to a greater extent in this domain. This notable gap highlights untapped research opportunities where digital twin technologies could offer significant value, particularly in optimizing resource use, improving animal health monitoring, and enhancing post-harvest logistics. The current focus on plant-based systems, controlled environments, and precision crop management may represent only the initial phase of digital twin integration in agriculture, indicating substantial potential for future expansion into diverse and traditionally underrepresented areas of the agri-food system.

The co-occurrence network contains seven clusters, with each node color representing a distinct and non-overlapping group (Table 4). A broad set of thematic patterns can be inferred from the grouping of related keywords; therefore, each cluster has been assigned a representative theme based on the common research focus shared by its keywords [61].

Table 4. Keyword co-occurrence cluster and associated keywords.

Clusters	Keywords	Common theme
Cluster 1 (Red)	“anomaly detection”, “data analysis”, “deep learning”, “digital agriculture”, “digital twin”, “digitalization”, “greenhouse”, “industry 4.0”, “modeling”, “phenotyping”, “predictive maintenance”, “renewable energy”, “resilience”, “simulation”, “solid modeling”, “supply chain”, “sustainability”, “virtual reality”, “wind energy”, “wind turbine”	Key digital twin technologies and applications

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Cluster 2 (Green)	"cyber-physical system", "decision making", "knowledge base", "multi-agent system", "ontology", "precision farming"	Intelligent systems and decision support
Cluster 3 (Blue)	"agriculture", "agriculture 4.0", "climate change", "internet of things", "optimization", "robotics"	Technological convergence and environmental integration
Cluster 4 (Yellow)	"agricultural machinery", "controlled environment", "plant factory", "real-time monitoring", "smart agriculture"	Controlled environment agriculture
Cluster 5 (Purple)	"digital transformation", "machine-learning", "monitoring", "remote sensing"	Remote sensing and data-driven monitoring
Cluster 6 (Cyan)	"artificial intelligence", "horticulture", "sustainable agriculture", "sustainable development"	Sustainability and policy-oriented research
Cluster 7 (Orange)	"food industry", "food supply chain", "sensors", "wind farms"	Food systems and infrastructure monitoring

This study offers valuable insights into the evolution and thematic structure, but it has some limitations that should be acknowledged. First, the analysis is limited to publications indexed in Scopus and Web of Science, which, although comprehensive, may exclude relevant literature from other databases, institutional repositories, or grey literature. Second, the keyword-based search strategy may not capture all relevant articles if authors used inconsistent or unconventional terminology to describe digital twin applications. However, the number of documents included in this study appears to be sufficient to support meaningful bibliometric analysis. Additionally, bibliometric indicators such as publication counts and h-index metrics may favor older publications and more established research groups, potentially underrepresenting newer or emerging contributions. Lastly, this review focuses primarily on quantitative and structural analysis that may limit qualitative review approaches such as systematic review, which provide a deeper contextual interpretation since they target specific research questions on a particular topic.

4. Conclusions

In this study, we conducted a bibliometric review of digital twin applications in agriculture. The review began with the collection of bibliometric data from major scientific databases. The data was then analyzed and visualized using specialized bibliometric software tools to help understand trends, patterns, and key insights within the research landscape. The following major conclusions can be drawn from this study:

- The research on digital twin applications in agriculture has accelerated significantly in recent years.
- Most active contributors are China, the US, the Netherlands, Russia, and Germany, with institutions like Wageningen University and China Agricultural University leading in publication output.
- The study reveals core research areas, including precision farming, smart agriculture, IoT, machine learning, and cyber-physical systems, while identifying unexplored areas.
- The study also reveals distinct thematic clusters and shows the growing convergence between the digital twin and agricultural technologies, including remote sensing, decision support systems, and sustainability frameworks.
- The present analysis provides a quantitative and thematic understanding of the digital twin-agriculture landscape, serving as a strategic roadmap for researchers, practitioners, and policymakers.

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In summary, the study offers critical insights into the evolution of the digital twin and the research structure in agriculture. The productivity trends, influential contributors, and thematic clusters identified in this study highlight current strengths and uncover critical gaps and emerging opportunities. These findings can guide future research, foster interdisciplinary collaboration, and support data-driven decision-making technologies for sustainable and resilient agricultural systems.

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