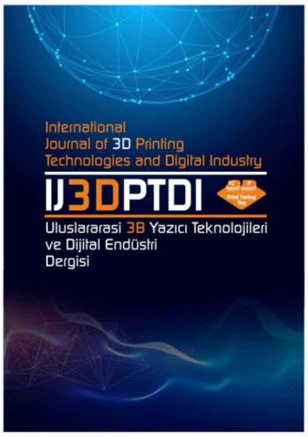

ULUSLARARASI 3B YAZICI TEKNOLOJİLERİ
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INTERNATIONAL JOURNAL OF 3D PRINTING
TECHNOLOGIES AND DIGITAL INDUSTRY

ISSN:2602-3350 (Online)

URL: https://dergipark.org.tr/ij3dptdi

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Bu makaleye şu şekilde atıfta bulunabilirsiniz (To cite to this article): *Zadeh S. N., Sati Z. E., "A Bibliometric Evaluation of Smart Agriculture Research" Int. J. of 3D Printing Tech. Dig. Ind., 9(2): 194-206, (2025).*

DOI: 10.46519/ij3dptdi.1648618

Araştırma Makale/ Research Article

Erişim Linki: (To link to this article): https://dergipark.org.tr/en/pub/ij3dptdi/archive

A BIBLIOMETRIC EVALUATION OF SMART AGRICULTURE RESEARCH

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(**Received:** 28.02.25; **Revised:** 26.05.25; **Accepted:** 25.07.25)

ABSTRACT

Smart agriculture, leveraging technologies such as the Internet of Things, machine learning, and artificial intelligence, offers innovative solutions to enhance productivity, minimize environmental impact, and support data-driven decision-making. This study aimed to perform a bibliometric analysis of research published in the field of smart agriculture from 2014 to 2024. Data were collected from two major databases, Web of Science and Scopus, and analyzed using VOSviewer software. Key indicators examined included annual publication trends, citation metrics, researcher co-authorship networks, and keyword co-occurrence patterns. The results reveal that the number of publications in this field has increased more than twelvefold over the past decade, with emerging technologies forming the core of the main conceptual clusters. Countries such as China, the United States, and India have been leading contributors to scientific output. Six major thematic clusters were identified: technology, resource management, sustainability, data analytics, policymaking, and economics. However, the involvement of social sciences and humanities remains relatively limited. Despite significant advances, challenges persist, including a lack of indigenous research from developing countries and insufficient integration of interdisciplinary data. The findings of this study provide valuable insights to inform innovative policymaking, guide investment in technological infrastructure, and shape future research directions in smart agriculture.

Keywords: Agriculture, Farming, Smart Agriculture, Smart Farming, Bibliometric Analysis

1. INTRODUCTION

The Food and Agriculture Organization (FAO) estimates that the global population will reach approximately 9.73 billion by 2050, leading to a significant increase in the demand for food, water, and natural resources. In response to this challenge, smart agriculture is emerging as a complementary or alternative approach to traditional farming systems [1]. This approach utilizes innovative technologies in the production and management of agricultural products with the aim of increasing productivity, reducing costs, and minimizing environmental impacts [2,3].

Smart agriculture leverages a range of advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), smart sensors, drones, and robotics to enable precise monitoring and management of agricultural operations [1]. The evolution of agriculture can be historically categorized into four main stages:

• Agriculture 1.0, based on manual labor and animal power;
• Agriculture 2.0, characterized by the introduction of machinery and mechanization [4];
• Agriculture 3.0, marked by the integration of environmental sensing, data analytics, and digital monitoring systems [5,6];
• Agriculture 4.0 (smart agriculture), which incorporates sensor networks, robotics, cloud computing, and AI to optimize decision-making and improve crop performance [7,8].

Within this context, precision agriculture, as a subset of smart agriculture, focuses on the efficient use of resources through spatial management supported by information technologies. Agriculture 4.0 goes beyond operational precision by intelligently integrating technologies to enhance the resilience and sustainability of agricultural systems [9,10].

Understanding the research developments in this domain requires the application of methods such as bibliometric analysis—a quantitative approach to examining and evaluating the structure, evolution, and trends in a research field using indicators such as publication trends, citation rates, frequent keywords, and patterns of international collaboration [11–13]. The key advantage of bibliometric analysis lies in its ability to structure complex literature and identify gaps and opportunities for further research [14].

This study conducts a bibliometric analysis of smart agriculture research within the time frame of 2014 to 2024. This period was selected due to the rapid growth in scholarly publications, increased investment in digital agricultural technologies, and significant shifts in global agricultural policy.

The primary innovation of this study lies in its comprehensive and structured bibliometric evaluation of the smart agriculture research landscape. Unlike most previous studies that rely solely on either the Web of Science or Scopus database, this research integrates both sources, enhancing the accuracy and completeness of the data. Additionally, by focusing on a contemporary period (2014–2024), it provides a forward-looking perspective on scientific progress in this field. Another noteworthy contribution is the application of the VOSviewer software to generate visual science maps, illustrating the relationships between concepts, keywords, and authors and revealing hidden structures within the literature. The study also categorizes key concepts into major thematic clusters such as technology, management, sustainability, and agricultural economics, offering a clear framework for guiding future research. Finally, the analysis of contributing countries and academic disciplines provides a realistic depiction of global and interdisciplinary collaboration in advancing smart agriculture.

The main objectives of this research are as follows:

- To analyze research trends and patterns in smart agriculture using data from the Web of Science and Scopus databases.
- To identify and classify the main keywords, concepts, and emerging technologies such as IoT and machine learning within smart agriculture.
- To examine the relationships among key concepts and terms to reveal dominant patterns in smart agriculture research.
- To map the strategic development of smart agriculture research based on publication trends, geographic distribution, and citation metrics.
- To discover and categorize the major themes and concepts in smart agriculture research, with an emphasis on technological advancements and innovations.

2. MATERIAL AND METHOD

There are several sources available for collecting data on scientific publications, the most common of which include Web of Science (WoS), Scopus, Dimensions, Crossref, Microsoft Academic, and Google Scholar. Among these, WoS and Scopus are the two most widely used databases in bibliometric studies [15]. Historically, they were the only accessible options for publication analysis [16]. Due to their high data quality and comprehensive coverage across multiple dimensions, these two databases remain the primary choices for bibliometric research. Choosing between these databases can significantly influence the outcomes of the analysis (Wang & Waltman, 2016). Although Scopus offers broader coverage than WoS, it faces several issues, such as the lack of pre-processed reference lists, which leads to inconsistencies in citations and necessitates more complex bibliometric matching techniques. Additionally, Scopus provides more fragmented coverage, includes a higher number of duplicate citations, varies in source quality, has a shorter historical record, and its classification and indexing systems are less standardized. These factors can affect bibliometric analyses' accuracy and comprehensiveness [16,17].

In this study, both Web of Science and Scopus were used separately to collect data. Each database was considered an independent source, and no merging or matching of records between them was performed. To extract relevant publications, a combination of keywords and commonly used terms in the field of smart agriculture was employed. Keywords such as "smart agriculture," "precision agriculture," "digital farming," "agriculture 4.0," and "smart farming" were selected using the OR operator. These keywords were further combined using the AND operator with thematic phrases such as “Smart agriculture” and “Climate change,” “Smart agriculture” and “Smart farming,” “Smart agriculture” and “Governance,” “Smart agriculture” and “Technologies,” “Smart agriculture” and “Agricultural policies,” “Smart agriculture” and “Decision making,” “Smart agriculture” and “Machine learning,” and “Smart agriculture” and “Internet of Things.” The search was conducted across all sections of the articles, including titles, abstracts, keywords, and full text.

A time filter was applied to include studies published between 2014 and 2024, ensuring the inclusion of research relevant to recent developments and emerging technologies in smart agriculture. Only English-language articles were included in the final analysis. However, this language restriction may introduce a bias by excluding research from non-English-speaking countries, particularly in regions such as Latin America, China, Russia, and the Middle East, which could influence the geographical and thematic diversity of the data. In the Web of Science database, the search was conducted across a broad range of indexes, including SCI-EXPANDED, SSCI, A&HCI, CPCI, and BKCI, to capture interdisciplinary dimensions. This approach ensured that articles addressing the social, technological, policy-related, and conceptual aspects of smart agriculture were also included in the analysis.

3. EXPERIMENTAL FINDINGS

3.1. The Analysis of Published Articles in Smart Agriculture

To conduct a more precise analysis of scientific publications in the field of smart agriculture, criteria were established to evaluate and select relevant keyword combinations. The data were extracted from the Web of Science database covering the period from 2014 to 2024. According to Table 1, keyword combinations with at least 1,000 articles and an average citation count above 25 were considered eligible for in-depth analysis, while those with fewer than 500 articles or an average citation count below 20 were excluded. Additionally, the diversity of publication types—such as reviews, conference papers, and book chapters—was used as a supplementary criterion to ensure a more comprehensive evaluation.

As shown in Table 2, over the past decade, research in the field of smart agriculture has experienced significant growth. According to data extracted from the Web of Science database, more than 17,000 scientific articles containing the keyword "smart agriculture" were published between 2014 and 2024. This considerable volume of academic output reflects the growing global interest in technology- and data-driven solutions in agriculture. Among these, 2,277 are review articles (approximately 13.1% of the total), indicating a relative conceptual maturity of the field. Additionally, 3,570 are conference papers (about 20.5%), which highlights the dynamic nature of emerging technologies and their active dissemination through scientific forums.

In the keyword combination analysis, the pairing of “smart agriculture” and “technologies” yielded the highest number of publications, with 5,000 articles (around 28.8% of the sample). This reflects a strong research focus on modern technologies such as the Internet of Things (IoT), machine learning (ML), robotics, and remote sensing. The average citation per article in this category is approximately 26.3, underscoring its notable scientific impact.
The combination “smart agriculture” and “climate change” ranks second, with 2,962 articles (roughly 17%). This pairing underscores global environmental concerns and the need for climate-resilient agricultural systems. Notably, this category has the highest average citation count (approximately 29.7) among all combinations, indicating its high scientific relevance and interdisciplinary influence across agriculture, environmental science, and sustainable development.

The combination “smart agriculture” and “precision/smart farming”, with 4,005 articles, also represents a significant portion of the literature. This co-occurrence reflects a conceptual overlap between the two terms, emphasizing technology-driven precision in agricultural management. However, the average citation rate in this group (21.2) is slightly lower than that of other technology-focused categories.

One noteworthy finding is the relatively low representation of governance and policy-related topics. The combination “smart agriculture” and “governance” appears in only 345 articles (around 1.9%) and has a comparatively lower citation average (17.4 citations per article), suggesting a research gap in institutional, legal, and ethical dimensions. In contrast, the combination “smart agriculture” and “agricultural policies” shows a better presence with 1,246 articles, yet remains underrepresented compared to the more dominant technology-oriented themes.

Combinations related to data-driven decision-making and artificial intelligence, such as “decision making” (1,127 articles) and “machine learning” (1,416 articles), account for a substantial share of the research and report relatively high average citation rates (24.1 and 32.8, respectively). This highlights their crucial role in guiding modern agricultural processes. Similarly, the combination “Internet of Things”, with 1,858 articles and an average citation rate of 28.9, underscores its foundational role in enabling real-time communication and automation in smart farming.

In conclusion, the analysis reveals that research in smart agriculture is predominantly oriented toward technological innovation, data-centric approaches, and environmental sustainability, especially through themes such as “technologies,” “precision agriculture,” and “IoT.” However, the relatively limited focus on governance, policy, and equity-driven development points to a significant gap. Future research must adopt a more interdisciplinary perspective, with greater attention to the human, institutional, and social dimensions of smart agriculture. Moreover, the rapid growth in studies focused on “decision making” and “machine learning” reflects the increasing importance of data-driven strategies and advanced algorithms in optimizing agricultural systems, marking the evolution of this field into a multifaceted and intelligent discipline.

Table 1. Inclusion and Exclusion Criteria for Keyword Combinations in the Bibliometric Study of Smart Agriculture Research (2014–2024).

Criterion	Eligibility	Elimination
Total Articles	More than 1,000 articles	Fewer than 500 articles
Average Citations (Impact)	Citation average above 25	Citation average below 20
Tech Orientation	Use of emerging technologies (e.g., IoT, ML, AI)	Lack of technological relevance
Article Type Diversity	Includes reviews, conferences, book chapters	Limited to one type of publication
Social/Policy Relevance	Relevant to governance or policy-making	Low attention in policy-related research
Growth/Dynamism	Active in conferences and dynamic publications	Low growth or limited development
Environmental Relevance	Interdisciplinary topics like “Climate change” considered	Weak connection to global environmental issues

Table 2. Distribution of Publications in Smart Agriculture Based on Keyword Combinations (Web of Science, 2014–2024).

Keyword Combination	Total Articles	Review Article	Proceeding Paper	Book Chapter
“Smart agriculture”	17,356	2277	3570	369
“Smart agriculture” and “Climate change”	2,962	582	224	120
“Smart agriculture” and “Smart farming”	4,005	605	1,032	94
“Smart agriculture” and “Governance”	345	38	63	15
“Smart agriculture” and “Technologies”	5000	1199	1799	173
“Smart agriculture” and “Agricultural policies”	1,246	192	102	48
“Smart agriculture” and “Decision making”	1,127	151	289	19
“Smart agriculture” and “Machine learning”	1,416	235	359	12
“Smart agriculture” and “Internet of things”	1,858	368	921	47

3.2. Analysis of Published Articles in Smart Agriculture: Role and Impact of Various Scientific Disciplines

Based on data extracted from the Web of Science database, Figure 1 illustrates the distribution of published articles in the field of smart agriculture across various scientific disciplines between 2014 and 2024. The search was conducted using the keywords "smart agriculture" OR "precision agriculture" OR "digital farming" OR "agriculture 4.0" OR "smart farming," and included only publications in the English language.

As expected, the field of agriculture ranks first, with 5,652 published articles, underscoring its central role as the foundational domain of smart agriculture. However, what distinguishes smart agriculture from traditional farming is the strong presence and complementary contributions of interdisciplinary and technology-oriented fields. In second place is engineering, with 4,777 articles, highlighting the importance of engineering tools, systems, and equipment in advancing modern agricultural technologies. This includes subfields such as electrical, mechanical, mechatronics, and control engineering, which play essential roles in the development of agricultural robots, drones, automated irrigation systems, and smart harvesting equipment.

Computer science follows in third place with 4,520 articles. This field plays a key role in developing machine learning algorithms, big data processing, computer vision, and predictive analytics. Many decision-support systems, soil and crop monitoring platforms, and pest detection systems are built on algorithms derived from computer science. Environmental sciences and ecology, with 3,423 articles, rank fourth. These disciplines focus on monitoring climatic conditions, assessing environmental sustainability, and modeling the environmental impacts of agricultural technologies. Their connection with smart agriculture is particularly relevant in the context of climate-smart agriculture. Multidisciplinary science and technology fields, with 2,665 articles, reflect the increasing integration of research efforts across basic sciences, engineering, and the humanities. These areas contribute to the development of sensors, agricultural bioinformatics, and multi-purpose analytical tools.

The field of chemistry, with 2,090 articles, has contributed to the design and production of nanofertilizers, smart pesticides, and environmentally friendly compounds—especially relevant in precision agriculture and efforts to reduce ecological harm. Plant sciences, with 1,637 articles, have explored the impact of smart technologies on crop growth, productivity, and resilience. This field is closely linked to genomics, phenotyping, and genetic improvement, which are being significantly enhanced by data-driven technologies. Telecommunications and information technologies, with 1,534 articles, have played a key role in implementing Internet of Things (IoT) infrastructure, wireless sensor networks, and 5G-enabled systems in smart farm management. Additionally, materials science (1,293 articles) and food science and technology (1,354 articles) have contributed to innovations in agricultural equipment materials, smart packaging, cold chain logistics, and extending the shelf life of products.

This analysis clearly highlights the deeply interdisciplinary nature of smart agriculture. Its continued and sustainable development requires close collaboration between technical, biological, environmental, and social sciences. These insights can help researchers, policymakers, and investors better understand existing gaps and capacities, enabling more targeted investments and the formulation of forward-looking policies.

Figure 1. The spread of articles published in the domain of smart agriculture from 2014 to 2024 among different scientific field.

3.3. Analysis of Global Trends in Published Articles on Smart Agriculture (2014-2024)

The data analyzed in this section were extracted from the Web of Science (WoS) database, covering the period from 2014 to 2024. The search was conducted using the keywords "smart agriculture" OR "precision agriculture" OR "digital farming" OR "agriculture 4.0" OR "smart farming." Only English-language documents were included, comprising various types such as Articles, Proceeding Papers, Book Chapters, Review Articles, and Editorial Materials. The purpose of this analysis is to examine the annual growth trend of global publications in the field of smart agriculture and to identify shifts in scientific attention over the past decade.

According to Table 3, titled "Global Publication Trends in Smart Agriculture: Annual Growth and Statistics (2014–2024)," the number of publications increased from 380 in 2014 to 4,914 in 2024, indicating a more than twelvefold rise during this period. This remarkable growth reflects the increasing role of smart agriculture in addressing major global challenges such as food security, climate change, and resource efficiency. In certain years, such as 2016, the annual growth rate peaked at 57.08%, likely driven by technological breakthroughs and increased investment in research. However, in more recent years—specifically 2023 and 2024—the growth rate declined to 9.92% and 15.46%, respectively, which may suggest a saturation in some research areas or a shift in research priorities.

Overall, despite a slight decline in the growth rate in the later years, the general trend highlights the continuous dynamism and relevance of the smart agriculture domain. The high number of publications in 2024 further confirms its established and growing importance in scientific studies. This analysis indicates that smart agriculture remains not only a thriving area of research but also holds great potential for innovation and delivering sustainable solutions to global challenges.

Table 3. Global Publication Trends in Smart Agriculture: Annual Growth and Statistics (**2014-2024**).

Final Publication Year	Record Count	annual growth quantity of publications
2014	380	35%
2015	438	15.26٪
2016	688	57.08٪
2017	881	28.05٪
2018	1,173	33.14٪
2019	1,622	38.28٪
2020	2,256	39.09٪
2021	3013	33.55٪
2022	3,872	28.51٪
2023	4,256	9.92٪
2024	4,914	15.46٪

3.4. Analysis of Article Distribution by Countries and Regions in the Area of Smart Agriculture

Based on data extracted from the Web of Science database, Figure 2 illustrates the distribution of scientific publications in the field of smart agriculture across various countries during the period 2014–2024. As shown in the chart, China leads by a significant margin, having published over 600 articles. This dominance is the result of multiple factors, including substantial government investments, technology-driven policies, advanced research infrastructure, and the high economic importance of agriculture within the country. Furthermore, through strategic initiatives such as the “Digital Agriculture 2035” program, China is actively pursuing a structural transformation of its agricultural production and supply chains[18].

In second place is the United States, with more than 350 publications, playing a crucial role in the advancement of agricultural technologies. Leveraging the capabilities of leading universities and research institutions, as well as strong industry collaboration, the U.S. has significantly contributed to the development of machine learning algorithms, land management systems, and agricultural robotics.

India ranks third, with approximately 270 articles. Its position is rooted in a vast agricultural market, a growing demand for efficient technologies, and government-led digital agriculture initiatives. Given challenges such as droughts, resource constraints, and population growth, smart agriculture research in India primarily focuses on productivity enhancement, optimized water usage, and intelligent crop monitoring.

South Korea and Italy occupy the fourth and fifth positions, respectively. These countries have made notable contributions to the scientific literature by capitalizing on advanced technologies and successful experiences in implementing precision agriculture. South Korea, in particular, has emphasized the development of environmental sensors, farm robots, and communication networks (e.g., 5G), playing a key role in enabling IoT-based agriculture.

Other notable contributors include Spain, Germany, Brazil, and Japan, each of which has conducted impactful research based on their unique economic, climatic, and technological contexts. These countries have made advances in areas such as sustainable agriculture, artificial intelligence, supply chain optimization, and climate modeling.

This geographical distribution highlights that scientific output in smart agriculture is closely linked to a country’s technological development level, supportive policies, and the economic significance of its agricultural sector. Countries with robust research infrastructures or persistent agricultural challenges tend to show greater interest in innovation and the adoption of advanced technologies. Moreover, regional differences reflect localized priorities within the domain of smart agriculture. For example, North America and East Asia focus more on automation and data mining, while Europe prioritizes environmental sustainability, and South Asia emphasizes resource efficiency and food security.

This analysis can assist researchers, policymakers, and investors in identifying successful global models and designing appropriate research and development pathways tailored to their specific regional needs and conditions.

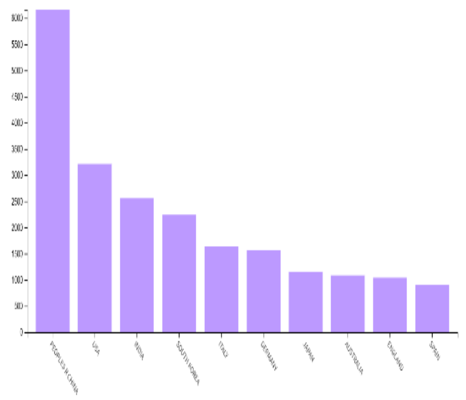

Figure 2. Article distribution across countries and region in the area of smart agriculture.

3.5. Evaluation of Web of Science Citation Indexes in Smart Agriculture

Figure 3 presents an analysis of the Web of Science citation indexes in the field of smart agriculture from 2014 to 2024. The data indicate that a substantial portion of research in this domain has been published in reputable scientific and technological journals. The SCI-Expanded index, with 16,258 records, holds the largest share among the Web of Science indexes. This dominance suggests that research on smart agriculture is primarily disseminated through high-impact journals in the fields of basic science and technology, underscoring the scientific and technological orientation of the discipline.

Furthermore, the CPCI-S index, with 3,460 records, highlights the significant role of conferences in the dissemination of innovative research in this field. The ESCI index, with 2,799 records, reflects the growing presence of emerging studies in newly established journals, signaling an increasing interest in smart agriculture among newer scientific publications. Similarly, the SSCI index, with 1,965 records, addresses the social, policy-related, economic, and sociological aspects of smart agriculture.

On the other hand, the publication of books and humanities-related research in the area of smart agriculture has remained relatively limited. The BKCI-S and BKCI-SSH indexes, with 323 and 160 records respectively, along with the CPCI-SSH index (308 records), indicate that books and the humanities have been less utilized as platforms for disseminating research in this field. This highlights an opportunity to expand interdisciplinary studies, particularly by integrating the humanities and social sciences with technological approaches in smart agriculture.

Overall, the analysis of citation indexes indicates that research in the field of smart agriculture is predominantly scientific and technological in nature, with the majority of publications appearing in high-impact journals indexed in SCI-Expanded. In addition, conferences and emerging journals—reflected through indexes such as CPCI-S and ESCI—have played a significant role in disseminating innovative research in this domain. However, the relatively low representation of books and humanities-related studies, as indicated by the BKCI and CPCI-SSH indexes, highlights a gap in interdisciplinary engagement. To fully harness the transformative potential of smart agriculture, future research should emphasize the integration of humanities and social sciences with scientific and technological approaches, paving the way for more balanced and sustainable development.

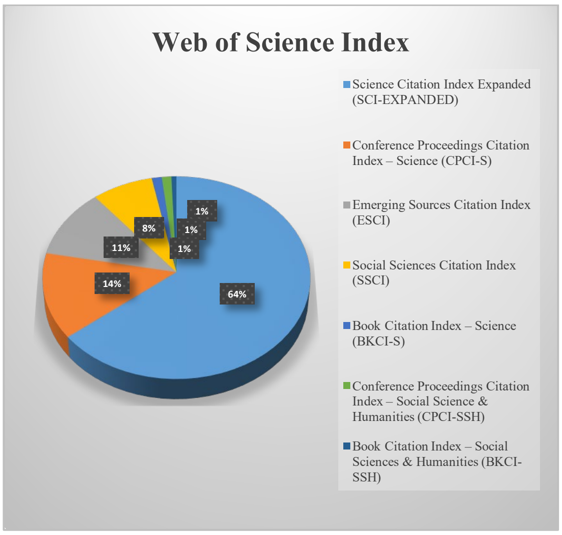

Figure 3. Analysis of Citation Indexes in the Field of Smart Agriculture.

3.6. Citation Analysis and Key Trends in Smart Agriculture Research

In a bibliometric analysis of leading research in the field of smart agriculture from 2014 to 2024, some highly cited articles were identified, focusing on emerging technologies such as the Internet of Things (IoT), machine learning, nanotechnology, and blockchain. Data were collected from the Web of Science database using the keywords: "smart agriculture," "precision agriculture," "digital farming," "agriculture 4.0," and "smart farming," combined with the OR operator and limited to the years 2014 to 2024. From the search results, articles were selected based on two criteria: publication in reputable journals under the publishers IEEE and Springer Nature, and receiving more than 400 citations.The selection of articles from the reputable publishers IEEE, Springer Nature, and Elsevier is based on their prominent role in disseminating high-quality research in the field of emerging agricultural technologies. These publishers contribute significantly to the most influential publications in areas such as the Internet of Things, machine learning, and smart agriculture, and their articles are widely cited in the academic community. Focusing on these sources ensures the scientific credibility of the analysis and enables the accurate identification of key research trends. Details of these influential publications are presented in Table 4.

One of the most prominent articles is a study published by Springer Nature in Nature Climate Change, titled “Climate-Smart Agriculture for Food Security”. This work presents a conceptual framework for adapting agriculture to climate change and highlights the role of smart technologies in enhancing the resilience of farming systems against environmental variability.

In addition, articles published by IEEE emphasize the pivotal role of IoT in developing smart infrastructure for environmental monitoring, precision irrigation, and real-time data collection in agriculture. For instance, studies such as “IoT and Data Analytics in Agriculture” and “Survey on IoT in Smart Farming”, featured in IEEE Access and the IEEE Internet of Things Journal, explore both the opportunities and challenges of implementing IoT in agricultural environments. These publications underline the benefits of sensor integration, real-time communication, and data analytics, while also addressing barriers such as infrastructure limitations and data security that must be overcome for successful digital agriculture deployment.

Beyond technology, several articles also investigate the social dimensions of smart agriculture. One notable example discusses interdisciplinary approaches to ethical concerns, data ownership, and farmer participation. These types of studies, often published in Springer Nature journals, stress that technological advancement must be accompanied by consideration of human, social, and policy factors to ensure sustainable adoption within farming communities.

Finally, innovations such as blockchain and nanotechnology are also featured in the most cited articles. Blockchain is presented as a tool for improving transparency and traceability in agricultural supply chains, while nanoformulations are explored for their potential to reduce pesticide usage and enhance pest control efficiency. Overall, this analysis reveals that the convergence of digital technologies with agriculture outlines a promising path toward a more sustainable, data-driven, and climate-resilient agricultural future.

Table 4. Most Cited Articles on Smart Agriculture Technologies (2014–2024) Published by IEEE, Springer Nature, and Elsevier (Source: Web of Science).

Title	Citations	Year	Journal	Key Topics	Conceptual Contribution
Climate-smart Agriculture for Food Security [19]	960	2014	Nature Climate Change (Springer Nature)	Climate Change	Establishes a framework linking food security, climate change, and smart agricultural technologies.
An Overview of Internet of Things (IoT) and Data Analytics in Agriculture: Benefits and Challenges [20]	646	2018	IEEE Internet of Things Journal	IoT, Data Analytics	Explores early applications of the Internet of Things in agriculture, highlighting benefits and infrastructure challenges.
IoT and Agricultural UAVs: Comprehensive Review[21]	370	2022	Internet of Things Journal (IEEE)	UAV, IoT	Reviews the combined applications of UAVs and sensors in advancing smart agriculture.
IoT-Based Smart Agriculture: Making the Fields Talk [22]	368	2019	IEEE Access	IoT	Focuses on developing communication infrastructure for smart agriculture through IoT.
A Survey on the Role of IoT in Agriculture for the Implementation of Smart Farming [23]	333	2019	IEEE Access	IoT	Offers a broad examination of the role of IoT in smart farming practices.
IoT for Smart Precision Agriculture in Rural Areas [24]	285	2018	IEEE Internet of Things Journal	IoT, Precision Agriculture	Discusses how IoT can enhance agricultural development in remote and rural regions.
UAVs in Smart Agriculture: Applications and Challenges [25]	283	2021	IEEE Sensors Journal	UAVs, Automation	Reviews the technical requirements and challenges of integrating UAVs in smart agriculture.
Internet of Things for the Future of Smart Agriculture: A Comprehensive Survey of Emerging Technologies [26]	236	2021	IEEE/CAA Journal of Automatica Sinica	IoT, Technology	Provides a comprehensive review of emerging IoT technologies for the future of smart agriculture.
Recent advancements and challenges of Internet of Things in smart agriculture: A survey [27]	212	2022	Future Generation Computer Systems (Elsevier)	IoT, Challenges	Surveys current and future challenges associated with implementing IoT in agricultural systems.

3.7. Visualizing Bibliometric Networks in Smart Agriculture Research Using Vosviewer

Information visualization is an essential technique for understanding the structure and relationships within large sets of documents. To support this, specialized tools have been developed that allow for dynamic and intuitive representation of vast amounts of information. One such tool is **VOSviewer**, an open-source software designed specifically for creating and visualizing bibliometric networks. VOSviewer allows researchers to generate network maps and explore complex relationships in a visual format [28]. In this study, VOSviewer was also used to construct and display networks of co-authorship and country collaboration.

This study employed VOSviewer software to generate a strategic coordination map, enabling an in-depth analysis of the complex interconnections among keywords and thematic areas within smart agriculture research. The selection of VOSviewer was based on its powerful capabilities in producing bibliometric maps and its user-friendly interface, which enhances clarity and accessibility for a broad range of users. Figure 4 presents a network diagram created using VOSviewer, visualizing the most influential publications on smart agriculture indexed in the Scopus database between 2014 and 2024. In this visualization, author-assigned keywords appear as nodes, where the size of each node indicates the frequency of the keyword's occurrence, and the links between nodes represent the co-occurrence relationships between keywords [45]. Only keywords appearing at least five times were included in the analysis, resulting in a total of 3,474 keywords, with 277 meeting the minimum threshold. After constructing the co-occurrence network, we analyzed the nodes and identified the most frequently co-occurring keywords. Based on a review of relevant literature in smart agriculture, we then classified the keywords into thematic clusters. Each cluster was labeled with a parent category reflecting its overarching research domain. Table 5 presents the most frequently used keywords in smart agriculture, organized into categories according to the primary themes that emerged from the network analysis.

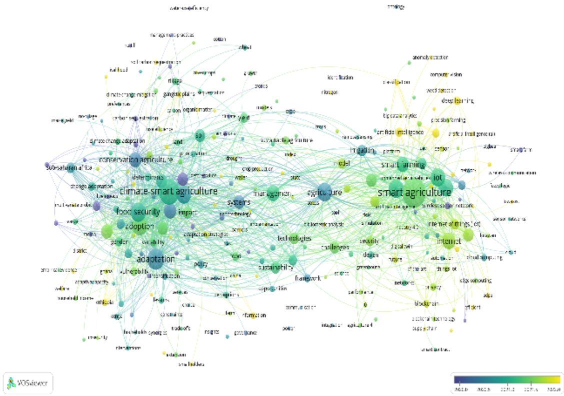

Figure 4. Keyword Co-occurrence networks.

Table 5. The key terms in the domain of smart agriculture, separated by the main branches.

Primary Branches	Key Words
General Keywords	Smart Agriculture, Precision Agriculture, Agricultural Technology, Sustainable Agriculture, Agricultural Innovation
Technology and Applications	IoT Applications in Agriculture, Big Data Utilization in Agriculture, Artificial Intelligence in Agricultural Practices, Machine Learning in Agriculture, Agricultural Drones, Remote Sensing in Agriculture, Crop Monitoring, Soil Monitoring, Smart Irrigation, Variable Rate Technology (VRT), GPS Agriculture
Agricultural Management and Strategies	Farm Management Information Systems (FMIS), Decision Support System, (DSS) in Agriculture, Agricultural Supply Chain Management, Yield Mapping, Site-Specific Farming
Sustainability and Environment	Climate-Smart Agriculture, Carbon Sequestration in Agriculture, Water-Efficient Farming, Organic Farming Technology
Data and Analysis	Data Analytics in Agriculture, Sensor Networks in Agriculture, Agricultural Robotics, Geospatial Analysis in Agriculture
Research and Education	Agricultural Research, Agri-Tech Education, E-agriculture, Digital Farming
Economic and Social	Agricultural Economics, Rural Development Technology, Agri-Business Innovation

Table 5 presents a review of key terms in the field of smart agriculture, categorizing them according to major thematic branches. General terms such as smart agriculture, precision agriculture, agricultural technology, and sustainable agriculture are introduced as foundational concepts. The technology and applications branch encompasses the use of technologies such as the Internet of Things (IoT), big data, artificial intelligence, machine learning, drones, sensors, smart irrigation, and other related tools in agricultural settings. The agricultural management and strategy branch includes terms such as farm management information systems, decision support systems, agricultural supply chain management, and localized agricultural technologies. The sustainability and environment branch addresses concepts like climate-resilient agriculture, water optimization, and organic farming, emphasizing environmental adaptation and resource conservation. The data and analytics branch focuses on areas such as data analysis, sensor networks, agricultural robotics, and geospatial analytics.

The research and education branch covers terms related to agricultural research, agricultural technology education, and digital agriculture. Lastly, the economic and social aspects branch includes themes such as agricultural economics, rural development technologies, and innovation in agribusiness. This categorization offers a comprehensive overview of the core domains and terminology within smart agriculture.

Table 6 further introduces and defines key concepts in smart agriculture and illustrates the relationships among them. It explains terms such as climate-resilient agriculture, food security, water efficiency, and smart agriculture, highlighting their roles in improving agricultural productivity and sustainability. For each concept, the table provides a description of its function and interconnections. For instance, smart agriculture refers to the application of technologies like IoT and sensors to enhance efficiency and output, while water efficiency involves improved water management aimed at reducing environmental impacts. The table also identifies key conceptual linkages, such as the connection between food security and climate change, or between soil management and sustainability. This structure enables readers to grasp the multidimensional implications of each concept and understand their importance in driving forward smart agriculture.

4. RESULTS

This bibliometric study offers a comprehensive assessment of the evolution, conceptual structure, and scientific landscape of smart agriculture research from 2014 to 2024. Drawing on data from two reputable databases—Web of Science and Scopus—and utilizing visual analytical tools such as VOSviewer, the study presents a detailed overview of publication trends, core research themes, and key technological developments in the field. The rapid increase in scholarly output, particularly in areas related to data-driven approaches and climate-resilient agriculture, reflects the growing global interest in leveraging advanced technologies to address agricultural challenges. Further analysis revealed that scientific publications in smart agriculture grew more than twelvefold during the study period. The highest annual growth occurred in 2016, while the publication volume peaked in 2024, highlighting the dynamic nature and rising prominence of the field. Geographically, China, the United States, and India lead in scientific output, underlining the influence of national policies and investments in agricultural technology. Moreover, disciplinary analysis shows that smart agriculture lies at the intersection of agricultural sciences, engineering, information technology, and environmental studies, demonstrating its inherently interdisciplinary character.

The conceptual analysis using VOSviewer identified six major thematic clusters centered on technologies such as the Internet of Things (IoT), big data, intelligent decision-making, and environmental sustainability. While these technologies dominate the current literature, citation analysis reveals limited engagement from the social sciences, humanities, and policy-related fields. This gap underscores the need for broader, more inclusive research perspectives that integrate human, institutional, and ethical dimensions alongside technical innovations.

In conclusion, the findings of this study suggest that the future of smart agriculture should focus on enhancing interdisciplinary collaboration, empowering smallholder farmers, advancing digital equity, and employing more sophisticated analytical tools. Additionally, developing open, data-driven infrastructures and evidence-based policymaking will help guide the research and application of smart agriculture more effectively. Ultimately, smart agriculture represents not only a technological imperative but also a critical pathway toward achieving global sustainability goals.

Table 6. Key terms and related concepts in smart agriculture.

Key Words	Definition	Links
Climate-smart Agriculture	Agricultural methods designed to adjust to climate variations and optimize the utilization of climate-related resources.	Entails strong connections with food security, adaptation, water management.
Smart Agriculture	It aims to increase agricultural efficiency by using technological innovations (IoT, sensors).	Data-based decision making is linked to drive systems and automation.
Adaptation	Changing farming methods to respond to the effects of climate change.	Climate smart agriculture is associated with environmental sustainability; various strategies (e.g., plant species change).
Food Security	Ensuring that all have access to sufficient, safe and nutritious food.	Climate change interacts directly with agricultural productivity and social justice.
Water Efficiency	Better use of water resources and savings.	Irrigation is related to groundwater management and environmental impacts
Sustainability	Conserving resources by balancing economic, environmental and social conditions.	Linked to sustainable agricultural practices, renewable energy and natural resource management.
IoT (Internet of Things)	A system in which objects are connected to each other to collect data in agriculture.	Smart agriculture involves many connections with data analytics and automation.
Agricultural Practices	Methods of conducting agriculture; sustainable, traditional or modern practices.	Related to agricultural policies, food production impacts and environmental sustainability.
Technology Adoption	Incorporating new technologies into agricultural processes.	Links to education, policy development and financing.
Climate Resilience	Increasing resilience to climate change.	Adaptation approaches are related to environmental protection and healthy ecosystems.
Crop Management	Optimization of the growth processes of agricultural products.	Productivity is directly linked to adaptation strategies to climatic conditions.
Soil Health	Preservation of soil structure and fertility.	Water management has an important relationship with agricultural practices and sustainability.

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