

Review

Wireless Sensor Networks in Agriculture: Insights from Bibliometric Analysis

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Abstract: This study investigates how wireless sensor network (WSN) applications in agriculture are discussed in the current academic literature. On the basis of bibliometric techniques, 2444 publications were extracted from the Scopus database and analyzed to identify the temporal distribution of WSN research, the most productive journals, the most cited authors, the most influential studies, and the most relevant keywords. The computer program VOSviewer was used to generate the keyword co-occurrence network and partition the pertinent literature. Findings show the remarkable growth of WSN research in recent years. The most relevant journals, cited countries, and influential studies were also identified. The main results from the keyword co-occurrence clustering and the detailed analysis illustrate that WSN is a key enabler for precision agriculture. WSN research also focuses on the role of other technologies such as the Internet of Things, cloud computing, artificial intelligence, and unmanned aerial vehicles in supporting several agriculture activities, including smart irrigation and soil management. This study illuminates researchers' and practitioners' views of what has been researched and identifies possible opportunities for future studies. To the authors' best knowledge, this bibliometric study represents the first attempt to map global WSN research using a comprehensive sample of documents published over nearly three decades.

Keywords: wireless sensor networks; agriculture; precision agriculture; Internet of Things; bibliometrics



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1. Introduction

The global population has witnessed considerable growth from 2.5 billion in 1950 to 7.8 billion today. It is estimated that the world population will reach 9.7 billion by 2050 [1]. As the most prominent food source, agriculture has played a major role in human civilization [2,3]. However, the exponential increase in food demand due to population growth creates several pressing problems: water and air pollution, greenhouse gas emissions, and global warming. These issues, coupled with resource scarcity, accentuate the urgent need for adopting novel and sustainable solutions [3–5]. Several researchers have incorporated cutting-edge technologies to address these problems, including wireless sensor networks (WSN) [6,7], the Internet of Things (IoT) [8–10], artificial intelligence (AI) techniques [11–13], spatial technologies [14], remote sensing [15,16], computing technologies [17–19], blockchain technology [20,21], big data [8,22], and radio frequency identification (RFID) [23]. These technologies gave birth to smart and precision agriculture, which is estimated to reach \$15.3 billion in worth by 2025 [24].

As a collection of sensor nodes [25], WSN is of vital importance due to its enabling role in providing data for other layers and technologies. Conceptually, WSN consists

of numerous smart battery-powered nodes connecting through a wireless network. Enhancements in micro electromechanical systems (MEMS) make these nodes smaller, less expensive, and energy-efficient. These nodes are distributed across the field and are responsible for collecting data from the farm and environment. These various data include soil moisture, temperature, humidity, and crop conditions, to name a few. Furthermore, minor processing is enabled by the microcontrollers built in these nodes. Data and information are transmitted directly or indirectly to a base station or a hub. This results in considerable improvements in the decision-making process [2,26,27]. The significant benefits and capabilities WSN offer (e.g., monitoring, automation, optimization, etc.) have prompted several scholars to investigate the potential of this technology for agriculture. For example, [28] highlighted the vital importance of WSN in precision agriculture. The authors discuss the use of different sensors in sensing different parameters and the application of various communication technologies for data transmission. Thakur et al. [29] investigated the extant literature and summarized the different WSN technologies for implementing precision agriculture. The role of WSN in monitoring fields, optimizing irrigation, and measuring temperature and soil property is also illustrated. Similarly, Refs. [30,31] explored agricultural challenges and WSN solutions, including resources optimization, decision-making support, land monitoring, and energy efficiency. Ruiz-Garcia et al. [32] investigated the developments and applications of WSN and RFID in agriculture. Aznoli and Navimipour [33] explored the enabling strategies as one of the most challenging aspects of incorporating WSN in agriculture. Moreover, Refs. [2,26,34] were among a plethora of researchers who synthesized WSN research in the agricultural literature. Although these studies contribute to the WSN field from different perspectives, a structured systematic review based on a quantitative approach such as bibliometrics is still missing. Therefore, guided by the study of [35], we aim to fill this gap and examine the extant literature surrounding WSN applications in the agriculture sector. More specifically, in this investigation we attempt to seek answers to the following questions:

1. What are the publication dynamics on the interplay between WSN and agriculture?
2. How is WSN being used in agriculture?
3. What are the main research gaps regarding WSN applications in agriculture?

By answering these questions, our study provides significant insights, exploring the entire field of WSN applications and its journey in the agriculture domain. The current study offers academicians and practitioners a significant understanding of the potential for WSN in agriculture, the current state of the literature, research hotspots, and future research directions. This could advance their knowledge in the field, identify research gaps, and inform them of successful practices necessary to implement WSN in agriculture.

The article proceeds as follows. Bibliometric approach and protocols are discussed in Section 2. The main findings, including descriptive analysis, keywords analysis, clustering analysis, are explained in Section 3. Section 4 discusses in detail the results of the keyword co-occurrence network. The last section briefly concludes the paper.

2. Methodology

Among literature review methodologies, bibliometric analysis is a powerful quantitative tool using different measures to extract the behavior and dynamics of a knowledge domain [36–39]. We drew on best practices [38,40–42] to investigate in a comprehensive and objective way the entire field of WSN in agriculture. Scopus was selected to conduct this study because it is regarded as one of the most reliable and trustworthy databases with the largest abstract and citation database of peer-reviewed research utilized by many scholars [43–45]. Figure 1 illustrates the research process. Keywords including “wireless sensor network”, “WSN”, “agriculture”, “farming”, “farmer*”, and “agricultural” were searched in titles, abstracts, and keywords. The keywords were connected with the logical connectors OR and AND. We carried out a truncated search for one keyword by including one asterisk (*). For instance, “farmer*” can represent “farmers”. The timespan was set from 2002 to 2021. All types of documents were included in the analysis. Table 1 shows the

main information about the data. Moreover, the science mapping tool VOSviewer [46,47] and the web-based data analysis framework Biblioshiny [48] were adopted for the text mining and quantitative analysis of the findings.

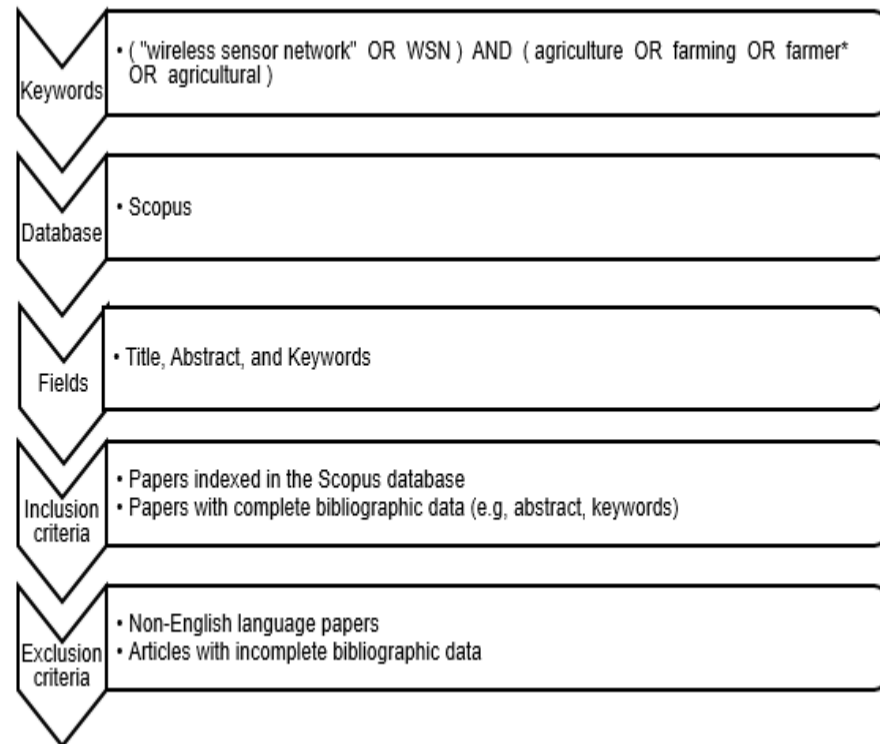


Figure 1. Research process.

Table 1. Main information regarding data collection.

Description	Results
Main information about data	
Timespan	2002:2021
Sources (Journals, Books, etc.)	1195
Documents	2444
Average years from publication	4.91
Average citations per documents	11.25
Average citations per year per doc	1.861
References	57,672
Document contents	
Keywords Plus (ID)	10,880
Author's Keywords (DE)	4671
Authors	
Authors	6460
Author Appearances	9044
Authors of single-authored documents	108
Authors of multi-authored documents	6352
Authors collaboration	
Single-authored documents	114
Documents per Author	0.378
Authors per Document	2.64
Co-Authors per Documents	3.7
Collaboration Index	2.73

3. Descriptive Analysis

3.1. Annual Distribution of Papers

Figure 2 portrays the evolution of publications that addressed WSN applications in agriculture. After the first publication in 2002, research on WSN experienced slow and gradual growth. This trend continued until 2006, when the number of publications increased threefold compared to the previous year. Later, we observed a significant increase between 2006 and 2010. This could be explained by advancements in computing technologies, wireless network services, and the miniaturization of sensor systems. From 2011 to 2016, it appears that the literature witnessed considerable growth. There was also an exponential growth rate in the use of WSN in agriculture between 2017 and 2020; the publication count soared remarkably. The incorporation of novel complementary technologies, specifically IoT with WSN in agriculture, is important in this stage. The latest year, 2021, is still not finished at the time of this analysis, and we expect that the number of publications will continue to rise and reach a new peak.

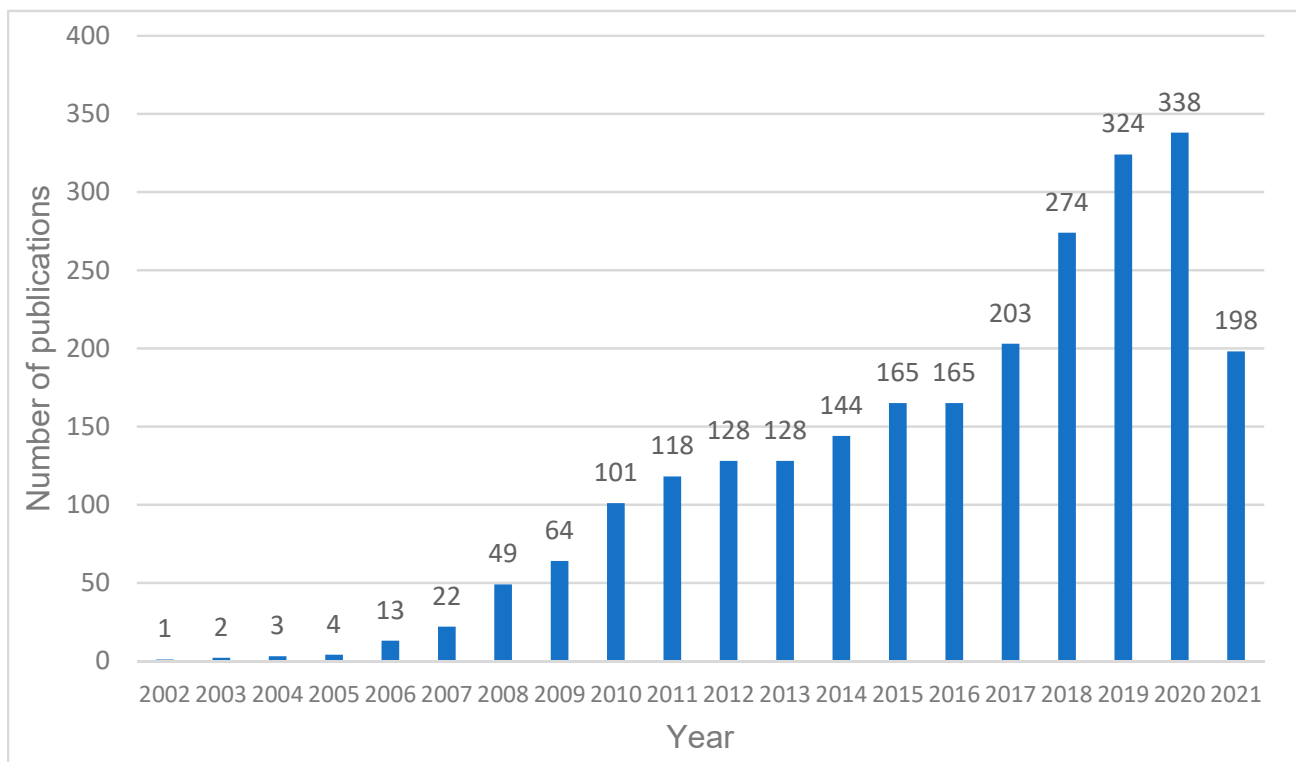


Figure 2. Annual distribution of papers.

3.2. Top 10 Most Relevant Journals

Regarding the most relevant journals based on the number of publications, Table 2 lists the top 10 and shows that Sensors was the only one to surpass the 100 papers mark. Moreover, we can observe that the journals devoted to computer science and engineering dominate the list. Moreover, no journals in fields as operations research, agronomy, environmental sciences appear among the top 10.

Table 2. Top 10 most relevant journals.

Rank	Source Title	Number of Articles
1	<i>Sensors</i>	101
2	<i>Computers and Electronics in Agriculture</i>	68
3	<i>Wireless Personal Communications</i>	32
4	<i>IEEE Sensors Journal</i>	21
5	<i>International Journal of Applied Engineering Research</i>	19
6	<i>IEEE Access</i>	18
7	<i>International Journal of Recent Technology and Engineering</i>	15
8	<i>IEEE Internet of Things Journal</i>	14
9	<i>Journal of Advanced Research in Dynamical and Control Systems</i>	13
10	<i>International Journal of Innovative Technology and Exploring Engineering</i>	12

3.3. Top 20 Most Cited Countries

Regarding the top 20 most-cited countries, Table 3 shows that China comes first with the highest total citations count (2892), followed by India with 2628 total citations, and Spain with 2472 total citations. In addition, the USA held the fourth position in the list, receiving a total of 2015 citations. The table indicates that Asian and European countries dominate the list. Moreover, Oceania (represented by Australia) contributed significantly to the WSN literature. Nations from Africa and the Middle East did not appear on the list. According to the average number of citations per article, North Macedonia was ranked first (270), followed by Mexico (59), Denmark (48.17), Greece (37.61), and Spain (36.90).

Table 3. Top 20 most cited countries.

Country	Total Citations	Average Article Citations per Year
China	2892	7.40
India	2628	9.63
Korea	840	11.35
Malaysia	729	14.88
Japan	382	15.28
Italy	744	17.30
Thailand	268	20.62
United Kingdom	538	23.39
USA	2015	26.17
Brazil	644	26.83
Germany	559	29.42
Portugal	447	29.80
South Africa	245	30.62
Australia	625	32.89
Pakistan	474	36.46
Spain	2472	36.90
Greece	865	37.61
Denmark	289	48.17
Mexico	531	59.00
North Macedonia	270	270.00

3.4. Top 20 Most Cited Papers

The top 20 most cited papers are illustrated in Table 4. Furthermore, the sources, titles, citations, and citations per year are also provided. The domination of review methodology and the total citation of the top 20 papers point to a mature field. The few papers with high citations per year reveal the emerging trends in the field. These trends include the integration of complementary technologies, specifically IoT with WSN [4,5,49], and the incorporation of energy efficiency in WSN [50,51]. Overall, the top 20 publications highlighted the role of WSN in improving automation and monitoring capabilities [52–54] enhancing

irrigation efficiency [52,55], and achieving precision agriculture [51,54,56]. Studies also addressed the architecture and design of sensor node communication and network [50,57].

Table 4. Most globally cited articles.

Rank	Study	Source	Total Citations	Total Citations per Year
1	[58]	<i>Ad Hoc Networks</i>	471	29.4375
2	[32]	<i>Sensors (Switzerland)</i>	465	35.7692
3	[27]	<i>Computers and Electronics in Agriculture</i>	425	60.7143
4	[2]	<i>Computer Standards and Interfaces</i>	406	50.75
5	[52]	<i>IEEE Transactions on Instrumentation and Measurement</i>	390	48.75
6	[4]	<i>IEEE Internet of Things Journal</i>	301	75.25
7	[54]	<i>Journal of Cleaner Production</i>	270	38.5714
8	[55]	<i>Computers and Electronics in Agriculture</i>	249	17.7857
9	[53]	<i>Procedia Engineering</i>	237	23.7
10	[5]	<i>Biosystems Engineering</i>	235	47
11	[59]	<i>Computers and Electronics in Agriculture</i>	216	15.4286
12	[60]	<i>Computers and Electronics in Agriculture</i>	201	18.2727
13	[51]	<i>Sensors (Switzerland)</i>	200	40
14	[56]	<i>Computers and Electronics in Agriculture</i>	198	15.2308
15	[61]	<i>Computers and Electronics in Agriculture</i>	192	13.7143
16	[57]	<i>Computer Networks</i>	180	12
17	[50]	<i>Ad Hoc Networks</i>	175	29.1667
18	[62]	<i>Computers and Electronics in Agriculture</i>	174	14.5
19	[49]	<i>Computers and Electronics in Agriculture</i>	169	56.3333
20	[63]	<i>IEEE Internet of Things Journal</i>	145	36.25

Four papers have received more than 400 citations. The top-ranked paper, [58], investigated the applications and design challenges for wireless underground sensor networks (WUSNs), including soil and environmental monitoring, problems of the underground communication channel, and challenges at each layer of the communication protocol stack. The second-most cited paper explored the role of WSN and RFID in agriculture and the food supply chain [32]. The paper's findings suggest that the agrifood industry could benefit from integrating these technologies in several ways, such as early warning in emergencies and maintenance, energy efficiency, and cost efficiency. Furthermore, [27] provided a comprehensive review accompanied by global and Indian cases about WSN potentials, applications, architectures, different sensors, and challenges in agriculture. Likewise, [2] explored the WSN and wireless sensor actor network (WSAN) applications in agriculture and brought significant insights. These applications include irrigation, fertilization, pest control, animal and pasture monitoring, greenhouse, and viticulture.

Furthermore, four papers have achieved more than 50 citations per year. In the paper with the most citations per year, [4] argued that the enabling role of IoT in integrating several technologies, including WSN, might represent a paradigm shift in the smart agriculture domain and could contribute to resource efficiency, food security, and productivity. The third publication in terms of citations per year [49] emphasized the importance of IoT in WSN and agriculture. Muangprathub et al. [49] developed a system to optimize crop watering based on WSN. The proposed system consisted of three components: physical, web application, and mobile application. The authors also used data-mining techniques to enhance watering efficiency and efficacy for crop growth optimization.

3.5. Keywords Dynamics—Authors versus Keywords Plus

Authors' keywords and keywords plus are presented in Table 5. Authors' keywords, or the most frequent keywords provided by authors, are on the left side, and the keywords plus or the most frequent keywords in selected articles' references are on the right side. Keywords plus are not provided by authors and are not necessarily in article titles. Instead, they were found by a computer algorithm [64,65]. Authors' keywords and keywords plus could complement each other and deepen scholarly understanding of the field. The former

is more concerned with research trends of researchers' interests. The latter, however, could add more in-depth insight into a study domain and reveal research directions [66].

Table 5. Top 20 most frequent keywords (authors keywords vs. keywords plus).

Authors Keywords	Occurrences	Keywords Plus	Occurrences
WSN	1688	wireless sensor networks	1557
IoT	482	agriculture	819
Precision Agriculture	332	sensor nodes	695
Zigbee	170	Internet of Things	421
Agriculture	162	precision agriculture	411
Sensor	142	agricultural robots	366
Smart Agriculture	84	monitoring	302
Sensor Network	77	crops	283
Greenhouse	63	soil moisture	273
Clustering	61	sensors	265
Energy Efficiency	60	irrigation	236
Smart Farming	60	energy efficiency	232
RFID	56	energy utilization	222
Irrigation	52	wireless telecommunication systems	203
UAV	50	Zigbee	194
Routing Protocol	48	sensor networks	193
Soil Moisture	47	wireless sensor network	185
Cloud Computing	44	Internet of Things	179
Environment Monitoring	43	wireless sensor	170
LoRa	43	environmental monitoring	147

From the table, the keywords used in the search algorithm are among the top ranks on both sides. Considering the authors' side, researchers have studied the importance of different aspects of WSN in smart agriculture and greenhouse. For instance, the primary applications of WSN in agriculture comprise environmental monitoring, irrigation, and soil moisture sensing. In addition, energy efficiency is one of the most critical factors in designing WSN applications, and it can be achieved by several mechanisms such as clustering and routing protocols. WSN telecommunication protocols and methods such as long range radio "LoRa" and "Zigbee" are among the top ranks. Furthermore, the combination of WSN, unmanned aerial vehicles "UAV", and RFID is beneficial for agriculture monitoring and tracking of agricultural goods from farm to market [23,67–71]. The keyword "IoT" is ranked second, indicating the vital role of IoT in enhancing precision agriculture and smart farming by integrating several technologies, including WSN and cloud computing. The keywords plus mostly reinforce the authors' keywords with the various insights it provided. Besides common keywords, the keywords "monitoring", "energy utilization", and "wireless telecommunication systems" fortify the insights extracted from the authors' side. Keywords plus also highlight the increasing importance of agricultural robots and their integration with WSN.

3.6. Treemap Dynamics

To complement our keywords analysis, we conducted an analysis of abstract keywords. Abstract keywords with high frequency are illustrated in the treemap (see Figure 3). The size of rectangles is proportional to the frequency of the keywords. The larger the rectangle, the more frequently the keyword is used in the abstracts. Abstract keywords can provide more detailed information to authors' keywords and keywords plus analyses. Analyzing the three forms of keywords allows scholars to study keywords dynamics more comprehensively and precisely [72]. From the figure, on the left side, "sensor", "wireless", "data", "network", "system", "agriculture", "monitoring", "WSN", "paper", "networks", and "nodes" are the most popular abstract keywords. The current analysis shows consistency with previous analyses and provides more details. For instance, the primary

goal of WSN implementations in agriculture is to capture, monitor, and control data and information from fields and surrounding environments. WSN can be used to sense soil moisture, temperature, conductivity, and acidity. Furthermore, irrigation can be supported by the use of WSN due to its ability to facilitate water quality monitoring and soil moisture sensing. The critical importance of energy and power consumption and management, paired with cutting-edge technologies such as IoT, is highlighted as a driving force toward precision and smart agriculture development. Moreover, the architecture, algorithm, and communication protocols for connecting sensor nodes such as IEEE are also emphasized. Overall, abstract keywords analysis adds to our insights by underscoring the importance of designing WSN applications and systems to improve crop yields, maximize operational efficiencies, and increase sustainability in agriculture.

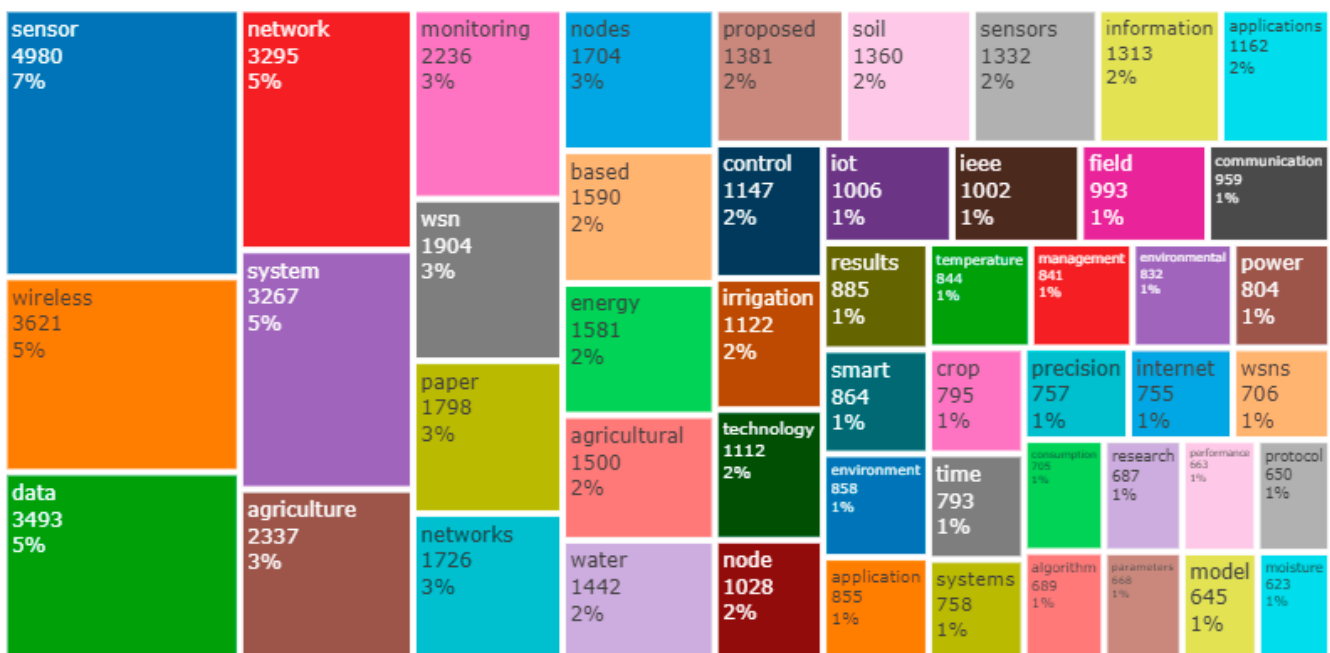


Figure 3. Treemap based on abstracts.

3.7. Trending Topics Analysis

To enrich previous analyses, we conducted trending topics analysis. We considered authors' keywords as the unit of analysis. The map was generated based on log frequency. By carrying out trending topics analysis, we depicted the evolution of WSN applications in agriculture and their related emerging and hotspot topics, as portrayed by Figure 4. WSN gained the most significant attention in 2017 as one of the most important enablers of precision agriculture. In 2018, the energy efficiency and security of WSN applications became a mainstream topic, followed by developments in clustering and computing techniques for improvements in energy efficiency and performance in 2019. The most critical keyword appearing more frequently as a trending topic in 2019 was IoT due to its capability to integrate multiple technologies with high efficiency and efficacy. Various technologies have become popular topics in this field. We expect that the evolution and utilization of complementary cutting-edge technologies will occur alongside WSN in agriculture as time passes.

At the starting point of the analysis in 2010, ubiquitous computing and information technologies (U-IT) became popular, followed by the proliferation of open-source lightweight operation systems (tinyOS) operating in 2011 and geospatial technologies, including GIS in 2011 and GPS in 2016. Moreover, RFID for products, livestock, and agriculture monitoring attracted attention in 2014, while remote sensing technologies (e.g., UAVs or drones) started trending in 2016 and accelerated thereafter. In recent years, AI techniques

only a few keywords being clustered, which reduces the representativeness and reliability of the clustering outcomes [78]. Therefore, to obtain a meaningful visualization, a cutoff value of five recommended by prior studies [79–81] was applied in our review to obtain a manageable number of clusters for the analysis [78]. Accordingly, a network with five clusters was generated (see Figure 5). In the figure, each node represents a keyword, and the size of the node is proportional to its frequency. The color of nodes indicates cluster membership for the keywords. Table 7 presents the top ten most frequent keywords in each cluster. In the subsequent sections, we support our bibliometric analysis with a qualitative review of WSN-related studies to provide in-depth details to the results of the keyword co-occurrence network. More specifically, we discuss the studies addressing the content of identified clusters. The analysis of each cluster offers valuable insights into existing and emerging themes within WSN research in the agriculture context.

Table 6. Keyword clustering parameters.

Type of Analysis	Keyword Co-Occurrence
Unit of analysis	Author keywords
Counting method	Full counting
Minimum number of a keyword	5
Threshold	280
Number of clusters	5

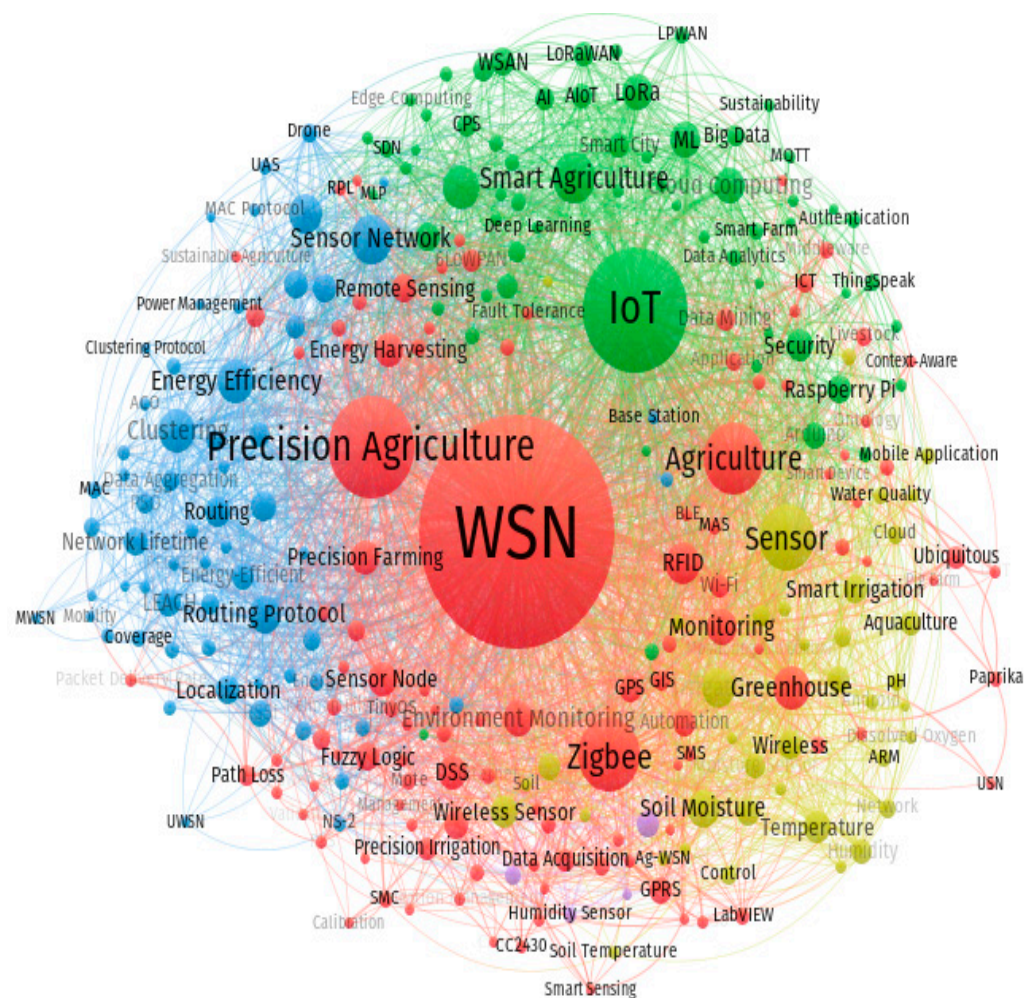


Figure 5. Keyword co-occurrence network.

Table 7. Top 10 most frequent keywords in each cluster.

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
WSN	IoT	Sensor Network	Sensor	Soil Moisture Sensor
Precision Agriculture	Smart Agriculture	Clustering	Irrigation	Temperature Sensor
Zigbee	Smart Farming	Energy Efficiency	Soil Moisture	Humidity Sensor
Agriculture	Cloud Computing	UAV	Wireless Sensor	pH Sensor
Greenhouse	LoRa	Routing Protocol	Temperature	
RFID	ML	Routing	Wireless	
Environment Monitoring	Security	Energy Consumption	Smart Irrigation	
Monitoring	ANN	Localization	Microcontroller	
Energy Harvesting	Raspberry Pi	Network Lifetime	GSM	
Sensor Node	WSAN	LEACH	Monitoring System	

4.1. Potentials of WSN for Precision Agriculture

Table 7 reveals that cluster 1 revolves around the critical role of WSN in precision agriculture. The most important keywords in this cluster are “WSN”, “Precision Agriculture”, “Zigbee”, and “Agriculture”. As a promising technology in precision agriculture, WSN is expected to modernize data collection in the agricultural field and support the automation of agriculture systems, which necessitate intensive sensing of environmental circumstances at the ground level [82]. The increasing use of WSN applications in precision agriculture enhances the efficiency and productivity of different agricultural production systems. According to [83], farmers could gain additional insights about their fields and identify their best solution by utilizing WSN. Elijah et al. [4] posit that the ability of WSN to self-organize, self-configure, self-diagnose, and self-heal has made the technology an excellent alternative for smart agriculture. WSN can be used to collect data related to soil moisture, weather temperature, control irrigation processes, and support farming decision-making [51]. Therefore, the basic aim of WSN adoption in agriculture is data collection, environmental monitoring, and data analysis [28,29].

Scholars have developed several protocols for sensor nodes communication and WSN implementation, including Zigbee, Bluetooth, and Wi-Fi. As one of the most suitable tools for precision agriculture applications, Zigbee facilitates irrigation supervision, water quality management, and fertilizer and pesticide monitoring, all of which need a cyclic information update [51]. Because of its energy-efficient, flexible, reliable, and affordable wireless protocol, Zigbee simplifies the monitoring of a wide variety of environmental conditions, including soil health, weed-disease detection, crop growth, and agricultural product quality [84]. Precision agriculture is a well-suited field for the integration of Zigbee. For example, [85] developed an intelligent irrigation system based on the Zigbee network protocol. In this system, the sensor node involves soil moisture sensors that aim to control the water level in the soil, while the actuator node is meant to take actions considering the soil’s water level. Zigbee also shows advantages in protected agriculture due to its capability to overcome the limitations of wire connection and facilitate greenhouse management development [86]. Incorporating Zigbee-based WSN systems is a step forward in the automation and efficiency of greenhouse environment monitoring and control since they can be easily maintained [87]. The climate conditions of greenhouses (e.g., humidity, temperature, light, and air pressure) can be monitored and controlled in real-time owing to WSN, thereby optimizing plant growth, increasing yield production, and mitigating harmful disasters in farms [51]. Greenhouses could greatly benefit from the low power consumption and long communication range of WSN to monitor and predict the health of plants, ensure adequate supply of nutrients, and provide a cost-effective approach for precision agriculture in greenhouses [88].

With high similarity with WSN, RFID is another wireless sensor technology that has gained scholars’ attention [32]. It is developed for identifying, categorizing, and tracking the flow of goods [5]. As such, RFID simplifies the tracking of agricultural products [5], irrigation facilities management [89], and wireless real-time communication

with agriculture sensors (e.g., soil temperature sensors) [55]. Furthermore, RFID tags provide energy harvesting capabilities because the power of the radio-frequency field can exceed what the tag requires for its operation [23]. In agriculture, energy harvesting is crucial to extend the lifetime of sensor nodes [51] and improve the performance of WSN-based systems [27]. When powered by energy harvesting, WSN can contribute to developing more sustainable agricultural systems that increase farming productivity and efficiency.

While the importance of WSN in supporting precision agriculture has been widely recognized in the academic literature, several knowledge gaps can be usefully addressed in future studies. For instance, more focus should be placed on designing more energy-efficient sensors to reduce the cost of wireless systems and improve the accuracy and efficiency of farming operations [90]. One research direction worth examining is the improvement of quality of service (QoS) of WSNs in terms of maintenance and implementation costs, coverage, reliability, and energy consumption. This is crucial as the shift from traditional agriculture to precision agriculture requires accuracy, easily configurable topology designs, and appropriate hardware and software for coping with field environments [91,92]. In addition, the integration of WSN in agriculture may necessitate the effective management and control of a large number of sensors through reliable connectivity and with a simple configuration [93]. Moving forward within this direction means that future studies will have to identify the topologies, configurations, and communication protocols of WSNs that should be considered in different agriculture scenarios. Future research also needs to investigate WSN system viability and how they achieve agriculture sustainability considering their long-term impacts on economic, environmental, and social dimensions.

4.2. Potentials of IoT, Cloud Computing, and AI for Agriculture

The second cluster (shown in green) indicates the critical role of IoT and other complementary technologies in enhancing WSN implementation in agriculture. IoT has altered the operation modes of agriculture and increased agricultural automation [4,5,94]. According to [95], IoT facilitates crop monitoring, optimizes agricultural productivity, and increases farmers' profitability. IoT provides a platform to maintain real-time data and alert farmers to take necessary actions. Furthermore, with the support of IoT sensors across farms, farmers can obtain an abundance of useful data, including soil, water, and temperature.

IoT's ability to act as a framework to integrate several technologies, including wireless sensor and actuator networks (WSANs), AI techniques and methods (e.g., ANN and ML), computing technologies (e.g., cloud computing), UAVs, geospatial technologies, end-user applications, among many others have recently gained scholars' attention [4,5,49,96]. Keywords such as "cloud computing", "LoRa", "ML", "ANN" are therefore included in this cluster. Coupled with WSN, cloud computing offers high-quality services, hardware-agnostic application tools, and sufficient storage capacity and computational resources to maintain and process the data generated at the network [5]. Furthermore, cloud computing helps to overcome the weaknesses of WSNs owing to its ability to offer open, more flexible, and reconfigurable applications for monitoring and controlling agricultural processes [97]. Similarly, cloud-based agriculture systems could be utilized to develop a reliable architecture for farmers to gain timely and on-the-spot data via WSN [98].

The contribution of LoRa to agriculture is also highlighted in the literature. As such, LoRa represents one of the popular modulation techniques that could be implemented in agriculture [99,100]. Owing to its long range, LoRa supports irrigation and several precision agriculture applications and enables wireless communication to remote fields [101]. LoRa can be adequately utilized in vast agricultural fields. Combined with LoRa transceivers, WSN can augment sustainability in agriculture by equipping farmers with insightful and usable data [102]. While the deployment of WSN generates massive and various data, there is a need to process and make use of these data in agriculture. In this regard, machine learning is a useful technique that could be applied to the data generated by WSN, thereby performing predictions in agriculture. These include estimations of available water for

irrigation [101], nutrients [4], and plant growth [103]. As another AI technique, ANN is also demonstrated useful to reinforce the predictive capabilities of farmers. ANN can use agriculture data collected by IoT sensors to select crop varieties and predict their production rate [104], estimate the levels of phosphorus in the soil [105], and support decision-making processes [106].

Summarizing, the literature on the possibilities of these technologies is rich, and several opportunities for future research exist. For example, scholars need to investigate how IoT and WSN can be applied in protected agriculture to reduce human intervention, save energy, and maximize efficiency in field monitoring. Examination of the methods and solutions to secure agriculture data is necessary to ensure that WSN becomes a resilient, safe, and trustable network. In the context of cloud computing, further studies are required to understand the role of this technology to bring financially economical agricultural systems [107] and enhance their technical properties, including scalability, efficiency, storage capacity, and overall performance [108]. To further accelerate the transition toward data-driven agriculture, the development of more precise, accurate, and efficient machine learning algorithms constitutes an intriguing opportunity for future research. This is crucial as farmers can rely on machine learning to extract insights from the data-intensive processes and support decision-making in farming operational environments. As a popular AI tool, scholars also need to examine the contributions of ANN at each stage of agricultural production and how this technology can solve relevant tasks and pending issues in the agriculture sector.

4.3. Potentials of Clustering and UAVs for Agriculture

Energy efficiency and consumption are the main research foci of the third (blue) cluster. Currently, there are extensive debates about energy consumption, resource limitation, and global warming at the global level [109–111]. WSN and other enabling technologies could contribute massively to energy efficiency in agriculture. As shown in Table 7, the high occurrence of “Sensor Network”, “Clustering”, and “Energy Efficiency” reveals that the effective utilization of resources is of paramount importance in agriculture. To maintain the stability of WSNs, clustering could be used to collect data from sensor nodes, achieve energy efficiency, and prevent channel contention and packet collision [112]. Clustering is vital to prolong the lifetime of sensor networks and respond to the needs of precision agriculture, which requires advanced methods and technologies to minimize costs and maximize productivity [113]. To solve the energy consumption of sensors and WSN in general, several researchers developed various initiatives, including DEC routing protocol [114], mobile data collector routing protocol [115], MAC protocol [116], clustering technique [117], cluster-based routing protocol [118], LEACH protocol [119], localization and clustering techniques [120], among many others.

Furthermore, agriculture implies large-scale monitoring, which can benefit from the merge of WSN and UAVs. For instance, [121] argue that UAVs can be a good alternative for demanding activities that need long observation periods, multiple sensors, data management, long-term stability, energy and computational resources, and high temporal and spatial resolution. With the evolution of UAVs and vehicular networks, WSNs can gain additional functionalities because UAVs make some nodes dynamic and collect data and maintain wireless communication in areas lacking fixed communication infrastructure [122]. Through navigation data and the waypoints produced by the ground station, UAVs could autonomously navigate the targeted waypoints and collect field image data [123]. UAVs are also equipped with the necessary features to capture the required images, map the fields, and detect pests, diseases, or water stress on the crops [124]. By leveraging their software and hardware, UAV activities (e.g., pesticide spraying) can be monitored by means of the feedback from WSN placed at the ground level in specified locations on the agriculture field [125]. Nevertheless, the performance of UAVs rests on the routing protocol applied. For example, geographic routing protocols, which offer high mobility networks and high performance with large UAVs, could boost UAV navigation capability. Meanwhile, energy-

ware routing protocols and those requiring ample space are more suitable for improving UAV power capability and storage capacity [126].

With the design of more energy-efficient algorithms for WSNs, there is an urgent need to propose clustering methods that can use available resources in agriculture WSNs more efficiently, thereby extending network lifetime and increasing energy efficiency. The investigation of how to optimize the performance of UAVs when WSNs are used as a source of information is encouraged for future studies. This is important as after applying the chemicals by the UAV, [127] discovered that some areas of the crop did not have enough chemicals due to speed and wind direction. As a result, the effective development of WSN-based agriculture systems with mobile nodes (i.e., sensors mounted on UAVs) and UAVs require the deployment of lightweight software, the implementation of energy-efficient routing protocols, and the minimization of data transferred from WSN to UAVs.

4.4. Development of Smart Irrigation

The yellow cluster presents the WSNs' role in developing smart irrigation systems. On the one hand, water is a scarce resource necessary for the sustainability of the earth and human beings that need to be preserved [128]. On the other hand, water is a necessary input for agriculture productivity that should be managed to ensure optimal crop yields [129]. WSNs are one of the most promising solutions that can be applied to develop smart irrigation systems [26]. Sensors distributed across the field and connected through a wireless network could provide more detailed and accurate information about soil moisture, humidity, temperature, and other critical indicators compared to old wired methods. This information could be utilized to automate irrigation and improve precision agriculture practices [32]. In other words, each part of the land will receive the necessary optimum amount of water based on the real-time data that WSN provides. WSN facilitates irrigation management and rescheduling by automating access to infield soil moisture status and controlling irrigation, maximizing the efficient utilization of water, and improving crop production [33].

Microcontroller-based gateways could be used to control the quantity of water [130]. Microcontrollers are essential in agriculture because they can convert analog data to digital data and provide automation and digital remote access capability [131]. Equally, GSM technology could be used to share the data and information with farmers [132]. Hence, farmers could optimize their crop yields and water usage simultaneously. The researchers in this cluster are interested in WSN's role in developing smart irrigation systems. They explored how better monitoring systems utilizing wireless sensors should be developed to provide helpful information (e.g., soil moisture and temperature) based on different communication (e.g., GSM) and computing (e.g., Atmega328P microcontroller) technologies for irrigation automation and efficiency [26,29,133]. For example, Giri and Pippal, [130] develop an automated irrigation system based on WSN and GPRS, [134] design a system based on WSN and GPRS/GSM network to monitor soil and irrigation water and optimize water consumption, and [135] utilize WSN for promoting a site-specific precision irrigation system.

The cost of implementing WSN-based irrigation systems may not be affordable to small and budget-constrained farmers; thus, future research should investigate the technical and economic factors that explain the acceptance of these systems in the agriculture sector [124]. Additionally, scholars not only could contribute to research surrounding water management by optimizing water use via the implementation of novel technologies such as WSN, IoT, AI, and computing technologies [136–138], but they could also concentrate on alternative water resources such as graywater, drainage water, and recycled wastewater [139], or developing various irrigation methods such as flood irrigation, spray irrigation, drip irrigation, and nebulizer irrigation [124].

4.5. Soil Management

The last (purple) cluster deals with the critical role of WSN in enhancing soil management. The vital importance of soil property and conditions in agriculture is undeniable. Any advancement in soil monitoring and management is a key factor in improving resource efficiency, optimizing irrigation, maximizing crop yields, and minimizing environmental effects [140,141]. WSN has the potential to play a vital role in soil management because of its capability to handle huge amounts of data regarding different soil attributes [34]. With WSN, soil data are sensed and gathered continuously. Sensor nodes could perform minor processing, and the data and information are sent to the base station for further analysis. The resulting insightful information could be utilized to measure the needs of crops, determine the schedules (e.g., irrigation), and overall improve decision-making and productivity [29]. To be more specific, sensor nodes could be implemented to assess the suitability of the farmland for cultivation [82], analyze the spatiotemporal variation of soil temperature [142], and monitor temperature, humidity, and soil moisture in real-time in greenhouses [143]. Furthermore, sensor nodes could monitor soil physical and biochemical attributes to increase productivity and decrease environmental footprint [144]. Sensor nodes also could measure, monitor, and integrate various soil quality parameters [145]; automate irrigation through humidity, temperature, and pH sensors [133]; and measure soil resistivity [146].

While academicians and practitioners are increasingly studying WSN's potential for soil management practices, future research needs to address some challenges and research gaps. For example, improving sensing performance and reliability, enhancing energy efficiency, data processing capability of sensor nodes and wireless communication, developing energy-independent sensors [141], and improving power sources [34] are important research areas. In addition, future work should scrutinize the minimum number of sensor nodes required to minimize the overall cost of WSN deployment in agriculture and achieve acceptable sensing accuracy of soil.

5. Conclusions

5.1. Discussion of Findings

The main goal of this study was to synthesize WSN applications in the agriculture sector and advance the existing literature by highlighting several knowledge gaps for future research. Using a bibliometric analysis and qualitative review of selected publications, we determine the most important topics in existing research and unravel emerging and prospective avenues for future research. To perform the analysis, a set of 2444 papers was chosen and considered for the final review. The review findings can be useful to scholars actively examining WSN within the context of agriculture. Despite the growing literature on WSN, there is still a scarcity of publications providing a holistic view of the future developments of WSN in agriculture, broadening the understanding of the subject and bridging this knowledge gap. Therefore, our investigation attempted to achieve this by identifying various topics and research foci at the nexus of WSN and agriculture. Several relevant insights can be obtained from this review. First, the number of publications dealing with WSN applications in agriculture has remarkably increased during 2002–2021. The journal-wise distribution of WSN-related publications indicated that *Sensors*, *Wireless Personal Communications*, and *IEEE Sensors Journal* are the major outlets contributing to the WSN and agriculture literature. Our study highlights the relevance of these journals and their role in advancing WSN applications in agriculture over time. Regarding the worldwide impact, Asian countries were the most cited. The current review draws several exciting insights concerning the role of WSN to support agriculture operations and increase the efficiency of farming processes. From this perspective, we identified the most globally cited papers (see Table 4). As per these publications, WSN applications are striving to establish an efficient and sustainable agriculture sector and respond to precision agriculture needs. WSN technologies garnered significant attention and gained momentum due to their ability to increase farmers' understanding of crop conditions, resource use, and

environmental circumstances, which would otherwise be challenging to capture. Another benefit of WSN consists in automating field operations, maximizing crop yields, enhancing food quality and safety, and increasing sustainability. As a result, farmers can rely on the technology to support their decision-making procedures, reduce human intervention, improve prediction accuracy, and decrease pesticide use.

By analyzing the keyword dynamics, our research found that WSN, IoT, Zigbee, RFID, UAV, and cloud computing are some of the common technologies explored in the context of agriculture. WSN represents a significant enabler for precision agriculture since it helps collect, monitor, and analyze data from agriculture [28]. Similarly, WSN combines IoT sensors to interconnect, thereby sensing real-time soil and climate conditions [147] and automating irrigation. IoT, clustering, RFID, and UAV are crucial enablers for establishing smarter and more sustainable agriculture, benefiting farmers and consumers. Aside from mirroring the progress of digitization, the identified themes illustrate that WSN applications in agriculture are growing dramatically. However, despite the extensive research on WSN, it is crucial to highlight the dearth of studies investigating the convergence of WSN and other embryonic technologies such as blockchain, 5G, augmented reality, and vertical farms. Integrating these technological developments enables farmers to perform more efficiently and innovatively; nonetheless, the pending question remains how these solutions influence negatively. Therefore, our review results uncover and emphasize the urgent need for more research investigating how WSN can reshape farming policies and achieve holistic and inclusive sustainability in agriculture supply chains.

5.2. Research Implications

This study offers insights for researchers, practitioners, and decision-makers to better grasp the applications of WSN in agriculture and draw their attention to scholarly output, research foci, and prospects for flourishing WSN systems in farming operations. Our study is useful for scholars attempting to increase their understanding of what has been researched to date in WSN and agriculture and what needs further examination. In this respect, the relevant findings from employing the keyword co-occurrence clustering are the predominant themes from the past literature on WSN applications in precision agriculture, IoT, cloud computing, artificial intelligence, UAVs, smart irrigation, and soil management. By taking advantage of these technologies, farmers can shift toward smarter agriculture and make existing farming systems more robust, sophisticated, and efficient. To illuminate researchers' views on WSN-related topics, seminal works in the literature can be built upon to comprehend the entire field and uncover the hot and neglected areas of WSN research in agriculture. Furthermore, the identification of research foci and topics was made through analyzing the keyword co-occurrence network. Based on the generated clusters, the core content of WSN research and knowledge gaps were discovered. The three thematic hotspots in the WSN literature essentially focus on various technologies, including IoT, AI, UAV, RFID, and cloud computing. The review findings indicate that WSN is not a standalone technology; instead, it combines diverse hardware and software technologies to improve agriculture. The relationships among the key topics also ascertain the essentiality of WSN deployment in agriculture and the potential of the technology to offer more efficient agri-food processes. As a result, researchers, farmers, and practitioners must work hard to improve the interoperability of WSN-based agriculture systems and devise appropriate and responsive practices and measures.

Overall, the present study leverages a new approach to systematize WSN research in the context of agriculture, using techniques derived from bibliometrics to reach an objective and quantitative evaluation of the current state of WSN literature. To the authors' knowledge, no exclusive and comprehensive review of WSN research exists so far, albeit the mounting interest in the technology and its critical role in promoting more efficient and sustainable agricultural practices. Our analysis of the present status of this research domain and knowledge gaps may favor the development of new studies and contribute to the global scholarly production on WSN and agriculture.

5.3. Limitations and Future Research Directions

Despite its significant contributions, this review has some shortcomings that need to be considered when interpreting the findings. One of the main shortcomings is that we only chose publications from a single scientific database, Scopus. Although Scopus is regarded as a source of publications, further research may consider other alternative scientific databases such as the Web of Science to extend our review findings by providing additional insights, research trends, and other theoretical perspectives. Moreover, the literature clustering via keyword co-occurrence network can be supplemented by other bibliometric techniques such as co-citation network analysis or bibliographic coupling to generate additional insights. Finally, as discussed in each cluster, we identified various research gaps to address WSN applications in agricultural practices. Energy efficiency in all parts of the system from design to sensors to communication and clustering protocols, implementation and maintenance costs, various technologies' integration and their complementarities, social impacts and environmental footprints, and WSN systems' viability and reliability are among the exciting topics for further research.

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