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SURVEY

Internet of Things and Wireless Sensor Networks for Smart Agriculture Applications: A Survey

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ABSTRACT The increasing food scarcity necessitates sustainable agriculture achieved through automation to meet the growing demand. Integrating the Internet of Things (IoT) and Wireless Sensor Networks (WSNs) is crucial in enhancing food production across various agricultural domains, encompassing irrigation, soil moisture monitoring, fertilizer optimization and control, early-stage pest and crop disease management, and energy conservation. Wireless application protocols such as ZigBee, WiFi, SigFox, and LoRaWAN are commonly employed to collect real-time data for monitoring purposes. Embracing advanced technology is imperative to ensure efficient annual production. Therefore, this study emphasizes a comprehensive, future-oriented approach, delving into IoT-WSNs, wireless network protocols, and their applications in agriculture since 2019. It thoroughly discusses the overview of IoT and WSNs, encompassing their architectures and summarization of network protocols. Furthermore, the study addresses recent issues and challenges related to IoT-WSNs and proposes mitigation strategies. It provides clear recommendations for the future, emphasizing the integration of advanced technology aiming to contribute to the future development of smart agriculture systems.

INDEX TERMS
Internet of Things, wireless sensor networks, wireless network protocols, smart agriculture applications.

I. INTRODUCTION

In the agricultural sector, there has been substantial technological progress, integrating advanced innovations such as the Internet of Things (IoT), Wireless Sensor Networks (WSNs), Wireless Network Protocols, Unmanned Aerial Vehicles (UAVs), Artificial Intelligence (AI), Agricultural Robotics, Big Data Analytics, and Blockchain systems. The increasing global adoption of IoT systems signifies an evolution towards innovative approaches, utilizing device-generated data to enhance productivity. IoT enables connections between machines and humans on a broader scale, primarily facilitating real-time information sharing across independent networks. Within this framework, real-time data captured by intelligent computational sensors can be effortlessly transmitted to people worldwide via the internet, regardless of time or location.

Agriculture, a cornerstone of economic development, forms a significant portion of a developing country's gross domestic product (GDP) [1]. The imminent food crisis, exacerbated by rapid population growth, necessitates urgent measures to enhance production and meet the rising demands [2]. These challenges-food crisis and population growth-pose threats to preserving the agricultural chain. The global population is projected to reach 8.5 billion by 2030 and nearly 10 billion by 2050 [3], [4]. Researchers

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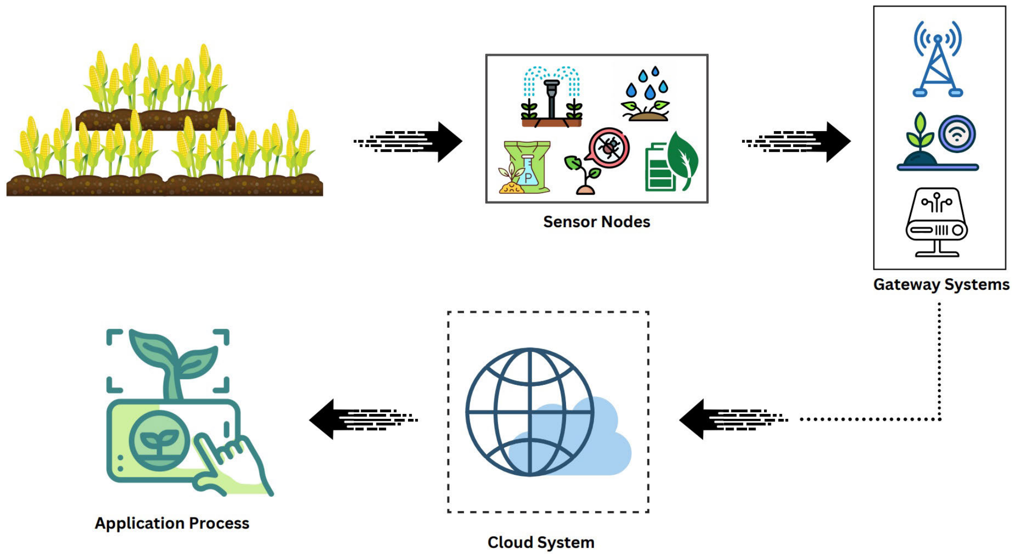

FIGURE 1. A process of IoT-based SA system.

actively explore and leverage advanced technologies such as WSNs and the IoT to boost agricultural productivity [5]. The integration of IoT with WSNs has revolutionized the agricultural sector, improving production efficiency and resource distribution, especially in SA [6]. The global IoT market is poised for significant expansion, offering new opportunities for integrating agricultural applications, including irrigation, soil monitoring, pest control, and greenhouse environmental monitoring [7], [8]. Beginning with an initial valuation of 18.12 billion in 2021, the market witnessed a remarkable surge to 91.91 billion in 2022, followed by a precipitous decline to 21.89 billion in 2023. Projections suggest a sustained upward trend, reaching a valuation of 43.37 billion by 2030. This trajectory is supported by the anticipated compound annual growth rate of 10.2% forecasted between 2022 and 2030. [9]. Sensor-based devices facilitate data collection and analysis, empowering informed decision-making for farmers, a crucial aspect in rural areas with limited power supply.

Recent WSNs have evolved, enriching human lives through numerous applications, promising essential convenience [10]. They have become a widespread and expanding network, finding broad utility in agriculture, environmental monitoring, industrial automation, and transportation systems [11]. Within the evolving landscape of WSNs, a key aspect is the global connectivity of access points, linking to many wireless sensor nodes scattered across diverse locales, diligently gathering data on a spectrum of physical parameters [5], [12]. Acquiring such data from remote locations will be as effortless as managing cellular data online [13]. At the heart of this intricate IoT framework lies its central monitoring infrastructure, WSNs [14]. Current research increasingly focuses on ensuring the sustainability of IoT-WSNs, given their inherent resource limitations [8].

In the context of SA, integration, and interaction among intelligent entities are propelled by IoT, marking a transformation in a technologically advanced era [7], [25], [26], [27]. This integration includes IoT combined with WSNs, encompassing soil-embedded sensors for environmental monitoring. It features diverse transceivers, microcontrollers, and communication protocols for efficient data transmission, fundamental for control and monitoring. A vital component of this integration is WSN, embracing many sensors and showcasing substantial advancements within SA [28]. However, the rapid proliferation of sensor devices raises concerns about energy consumption, prompting focused research [11]. Given the vast agricultural landscape, efficient and extended operation of sensor nodes is imperative to meet specific application requirements. IoT-WSNs have become crucial, facilitating data provision to other layers and technological advancements. They are designed with multiple innovative battery-powered nodes, employing wireless connectivity for seamless communication.

These nodes, enriched with advancements in Microelectromechanical systems (MEMS), now have a smaller profile, reduced cost, and enhanced energy efficiency. They are strategically positioned across the landscape, diligently collecting data from the farm and its surroundings, encompassing vital metrics such as soil moisture, temperature, humidity, and crop well-being. In addition, embedded microcontrollers within these nodes allow for essential data processing. The harvested data and insights reach a central hub or base station through direct and indirect transmission. This dynamic flow of information brings about a marked enhancement in the decision-making apparatus shown in Figure 1. WSNs offer substantial advantages and competencies, especially in elevating monitoring precision, automation prowess, and optimization finesse. This surge in potential has prompted

TABLE 1. A comparative analysis of IoT-WSNs in the present and existing survey papers in the field of SA applications.

Year	References	Architectures	WNP	Survey	AI	AGI	Robotics	UAVs	BDA	5G-6G	Blockchain	Renewable Energy	Privacy & Challenges
2019	[15]	×	✓	×	✓	×	×	✓	×	×	×	✓	✓
2019	[16]	×	×	×	×	×	×	×	×	✓	×	×	✓
2020	[17]	✓	×	×	×	×	×	×	×	×	×	×	✓
2020	[18]	✓	✓	×	✓	×	×	×	✓	✓	×	×	✓
2021	[19]	✓	✓	×	✓	×	×	✓	✓	×	×	×	✓
2021	[20]	✓	✓	×	✓	×	✓	✓	✓	×	✓	×	✓
2022	[21]	✓	×	×	✓	×	✓	✓	✓	×	✓	×	✓
2022	[22]	×	✓	×	✓	×	×	✓	✓	✓	✓	×	✓
2023	[23]	✓	✓	×	✓	×	✓	✓	✓	×	×	×	✓
2023	[24]	✓	×	×	✓	×	×	✓	✓	×	×	×	✓
2023	This study	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

numerous scholars to delve into its promising applications within agriculture.

Integrating applications with WSNs in agriculture offers significant advantages, covering various aspects such as irrigation control, plant disease and pest monitoring, fertilizer optimization, autonomous agricultural machinery, and UAVs for crop monitoring. These technological advancements synergize to drive agricultural automation, with the overarching objective of enhancing the long-term sustainability of food production in the agricultural sector. Key components such as land evaluation, crop protection, and yield forecasting are crucial in ensuring global food production. Real-time monitoring of field conditions and effective agricultural field management are made possible through wireless sensors and mobile networks. Additionally, technology empowers farmers to gather critical data and create accurate yield maps, facilitating precision agriculture and the production of high-quality crops at an economical cost using WSNs.

WSNs with IoT play a fundamental role in SA by providing essential information for specific systems and applications. A condensed overview of the main aspects includes:

- Irrigation Systems: WSNs actively monitor water usage, enabling farmers to manage water resources effectively and prevent excessive irrigation. Furthermore, they facilitate real-time monitoring of soil moisture content, allowing farmers to identify areas with drainage issues or sub-optimal irrigation distribution.
- Soil Moisture Monitoring Systems: WSNs continuously measure and transmit soil moisture data at various depths, empowering farmers to optimize irrigation practices and mitigate under and over-watering challenges.
- Fertilizer Optimization and Control: WSNs are valuable tools for monitoring soil nutrient levels and providing real-time information regarding the soil's nutritional status. Through thorough soil data analysis, WSNs assist in fine-tuning fertilizer applications by offering precise recommendations on quantities and optimal timings.
- Early Stage Control of Pest and Crop Diseases: WSNs gather essential data on temperature, humidity, and other factors affecting pest and disease development. By enabling early detection and timely intervention, this data equips farmers with the necessary insights to prevent or minimize crop damage.
- Energy Saving and Power Consumption: WSNs facilitate monitoring energy consumption within agricultural operations, including irrigation systems. This monitoring capability empowers farmers to identify potential areas for energy conservation and optimize power usage, leading to adopting more sustainable and efficient farming practices.

In the agricultural domain, IoT-WSNs collect precise and extensive real-time field data. Various communication protocols, including ZigBee, WiFi, SigFox, and LoRaWAN, find typical applications in SA. These technologies significantly contribute to sustainable and precise agricultural production by ensuring long-distance coverage, low data packet loss, low power consumption, and effective connectivity. In SA, leveraging IoT-WSNs and wireless communication protocols is essential. Sensors strategically positioned across the agricultural landscape collect critical soil moisture, temperature, and humidity data. These sensors connect to nodes equipped with the wireless communication protocol, forming an IoT-WSN. The collected data undergoes analysis to enable well-informed decision-making, facilitating precise resource allocation, automated irrigation, and timely actions to optimize crop growth. This integrated IoT-WSN strategy significantly enhances agricultural practices, ultimately promoting sustainable and efficient farming operations in the long run.

The IoT-WSN system represents a fusion of state-of-the-art technologies, integrating AI and its subsets to enhance operational efficiency within SA systems. Machine Learning (ML) and Deep Learning (DL) are particularly prevalent in IoT applications, especially in the SA domain. Ongoing research efforts are focused on refining and streamlining this architecture for optimal integration into SA applications. Since IoT systems operate entirely online, privacy concerns emerge as a critical consideration. A robust big data system in SA is critical, enabling data-driven decision-making for farmers and stakeholders. While blockchain systems effectively address data privacy concerns, further advancements are essential. Current research findings are significant, offering valuable insights, illuminating existing gaps, and inspiring the conception of innovative technologies for future SA research.

Additionally, farmers are interested in adopting novel, advanced, and cost-effective systems into their agricultural operations, highlighting the importance of cost-effectiveness in IoT technology amalgamating modern systems. In this context, comprehensive reviews and survey papers are key in observing research gaps, presenting a proactive technological roadmap, and guiding researchers toward effectively advancing the SA system.

In recent years, there has been a significant increase in reviews and survey papers focusing on WSNs-based SA systems. Table 1 presents a detailed comparative analysis, comparing the present review study and existing survey-review publications. This analysis thoroughly investigates past research contributions across four key sections: IoT-WSNs and their communication protocols for SA systems, integration of AI with WSNs in SA applications, leveraging Artificial General Intelligence with IoT-WSNs in SA applications, and critical factors in WSNs-based SA applications. The review extensively delves into IoT-WSN architectures and their associated wireless network protocols, comprehensively assessing their applications across five prevalent SA domains since 2019. This exploration emphasizes privacy considerations and challenges in integrating IoT-WSNs into SA practices. Furthermore, the study evaluates future trends and potential applications of WSNs in conjunction with emerging technologies, aiming to enhance the efficiency and productivity of SA practices by leveraging IoT-WSNs alongside state-of-the-art technologies. The contribution of this research is summarized as follows:

I. This research extensively examines existing literature related to SA, focusing on the IoT, WSNs, and wireless communication technologies. The study involves a thorough analysis, categorizing articles by publication year since 2019, IoT-WSNs application area, and network protocols. The analysis sheds light on reviews of IoT-WSN architectures and their associated network protocols for SA systems.
II. Examination of wireless communication protocols for SA, including Zigbee, Wi-Fi, SigFox, and LoRaWAN, emphasizes their characteristics and practical applications.
III. A comprehensive survey discusses five key applications within SA: irrigation systems, soil moisture monitoring, fertilizer optimization, pest and crop disease control, and energy optimization. Additionally, the survey explores integration with wireless communication protocols since 2019.
IV. This study thoroughly explores the discussion regarding current challenges and open issues in SA technology. This involves addressing concerns about IoT-WSNs scalability and reliability, data privacy and confidentiality, network security and intrusion detection, data integrity and authenticity, user privacy and consent, resilience to attacks and failures, location privacy, power consumption, and cost and standardization. Potential solutions to these challenges are also thoroughly examined.
V. Furthermore, an extensive future recommendation encompassing advanced architectures involving AI and AGI systems, agri-robotics, Big Data, blockchain analytics, 5G and 6G, and renewable energy that can be utilized for SA applications are addressed. These advancements hold the potential to create new opportunities for sustainable, cost-effective, and user-friendly agricultural systems for future farmers.

The subsequent sections of this paper are organized as follows: Section II provides an extensive review of the existing literature. Section III discusses the architecture of IoT and WSN for SA, encompassing its layers. In addition, Section IV elucidates wireless communication protocols for the WSN SA application and their respective properties. Furthermore, Section V delves into IoT-WSNs with network protocols for SA applications. Afterword, Section VI comprehensively addresses the current challenges and limitations of IoT-WSNs. Following this, Section VII explores future trends and research opportunities entailing advanced technology integration with IoT-WSNs. Finally, Section VIII encapsulates the conclusion, summarizing the study's findings and insights.

II. RELATED WORK

The advent of the WSN produced a new direction of research. However, with a rapidly increasing number of studies based on essential data information, relevant studies must be significantly studied and reviewed. Khanna et al. conducted an in-depth review of existing challenges within agricultural operations while simultaneously projecting potential research advancements for emerging scholars. This approach aims to enhance their comprehension of the constantly evolving landscape. The article meticulously delineates its origins and evolution, explaining its growth and advancements. The study follows a systematic structure, commencing with foundational principles and progressively delving into functional intricacies while acknowledging the constraints and impediments in the agricultural domain. The findings present thorough and precise observations, examining precision agriculture using IoT and WSNs, aligning diligently with contemporary market imperatives. Furthermore, prospective research directions in IoT for precision agriculture are outlined, demonstrating thoughtful consideration of impending challenges [16]. Shi et al. presented an organized literature review on IoT research and implementations within protected agriculture spanning the last decade. Their analysis enclosed an assessment of the different inputs from various scholars and entities. The study thoroughly reviewed diverse SA applications involving WSNs and sophisticated agricultural systems. Additionally, they explored the hurdles and potential directions for future research in this domain [29].

Kumar et al. thoroughly examined and presented a study on integrating IoT and WSNs for SA applications. The study emphasized the design of intelligent techniques to enhance agricultural processes, alleviating the instrumental role of WSNs in advancing the SA. Additionally, they meticulously explored a wide range of applications of WSN and IoT within the agricultural domain, with a particular emphasis on sensors utilized for crop management in the context of precision agriculture [30]. Kour et al. proposed and reviewed the role of advancing IoT technologies in SA systems. Their research focuses on enhancing both hardware and software systems. The scholarly article thoroughly investigates various projects in the public and private sectors, aspiring to offer sustainable and intelligent solutions for agriculture. The study provided a detailed summary of the current scenario, applications, potential research areas, limitations, and prospects in this SA field [17].

Tao et al. summarised scientifically validated publications on IoT communication technologies in SA to address this matter. This study applied a detailed investigation from ScienceDirect, IEEE Xplore, and Scopus platforms. 94 research articles were inspected after the 886 titles were reviewed for relevancy [31]. Abdollahi et al. introduced a review paper and demonstrated the contribution of WSN in agriculture applications based on current academic literature. In this study, they applied bibliometric techniques; 2444 publications were extracted from the Scopus database and examined to specify the temporal distribution of WSN research, the most productive journals, the most cited authors, the most influential studies, the most relevant keywords [32].

Avşar et al. introduced a research initiative that delves into the remarkable features of wireless communication protocols such as ZigBee, Wi-Fi, Sigfox, NB-, and LoRaWAN. The study outlines the technical attributes and real-world applications of these protocols commonly employed in IoT applications and examines variations in technical specifications reported across different sources. Furthermore, the study addresses IoT wireless communication protocol's privacy implications and future trends in SA applications [33]. Pandey et al. have comprehensively reviewed available IoT solutions, including soil health monitoring, crop health monitoring, smart irrigation, and real-time weather forecasting in the SA domain [34]. Gulati et al. reviewed the literature with a precise awareness of WSN for energy preservation and collection of data [35]. IoT and WSN constantly demand internet connection; therefore, this architecture has a security issue. Sinha et al. presented and reviewed the recent issues and challenges of IoT-based SA applications [21]. Similarly, Xu et al. reviewed and summarised the present crisis of IoT in the SA domain xu2022review. ML and DL, a subset of AI, are also commonly applied in SA. It helps to prevent the loss of agricultural yield. Rahaman et al. proposed a review paper based on WSNs and ML and their applications, issues, and challenges in SA platforms [36].

Sethi et al. discussed and reviewed the architecture of IoT and WSNs in the context of SA applications. The application of agricultural IoT in various sectors is also addressed in this study. They explored the existing challenges within agricultural IoT and provided a forecast for its future growth. The key aspects covered in their work encompassed the progress and design of IoT with WSNs, novel sensors, SA applications, and the utilization of data for screening plant and animal life [37]. Pathmudi et al. conducted an extensive literature review, focusing on essential technologies for enabling SA architectures. They precisely compared and provided insights into various components such as sensors, controllers, communication standards, and advanced machinery. These sensors continuously collected substantial data from agricultural fields, then transmitted to a centralized control unit for comprehensive analysis, addressing the specific needs for water, fertilizer, pesticides, and more. The study emphasized elucidating the architecture and significance of data analytics in agricultural IoT with WSNs. Furthermore, the research deeply analyzed critical challenges and unresolved issues about agricultural IoT technology [1]. Adli et al. undertook a comprehensive literature review on integrating AI and the IoT in the SA domain. The objective was to explain the current strides, applications, and advantages in the context of SA. The exploration involved a deep dive into AI and IoT, encompassing the utilization of smart devices within IoT frameworks and the application of AI methodologies. Eventually, the research integrated into the challenges that hinder the effective implementation of AI in IoT technology for SA, offering valuable insights into potential improvements and solutions [38].

This study's primary objective was to explore academic articles between 2019 and 2023 focusing on IoT-WSN applications in SA. The inclusion criteria encompassed openly accessible research papers, well-cited scientific publications, and the latest research-based papers. The survey covered a wide spectrum, including journal articles and conference papers. The approach involved a comprehensive literature review to provide a landscape overview. The process comprised searching, selecting relevant studies, and conducting a detailed analysis. The central research questions guiding this review were:

I. The role of IoT-WSN architectures in SA applications.
II. Integration of IoT-WSNs with wireless communication in SA applications.
III. Leveraging advanced technology using IoT-WSNs for SA.
IV. Challenges faced by IoT-WSN architecture in fulfilling this purpose.

To compile related work addressing these research questions, keyword-based searches were executed across reputable databases such as Google Scholar, Web of Science, IEEE Xplore, Scopus, ScienceDirect, Multidisciplinary Digital Publishing Institute (MDPI), and Springer. The emphasis was on journal articles and conference papers. A carefully devised search term with relevant keywords was employed.

To streamline the literature review, clear inclusion and exclusion criteria were established. Articles must be published in English, directly addressing the study objectives, and indexed in selected databases. The search engine was optimized using key phrases such as "IoT for SA," "WSNs for SA," "IoT-WSNs in agriculture," and related variations, which had to appear in the title, abstract, or anywhere within the document.

III. ARCHITECTURE OF IoT AND WSNS FOR SA APPLICATIONS

WSNs integrated with IoT technologies have rapidly advanced across various agricultural domains. The IoT system serves as a network wherein physical devices, machinery, sensors, and objects communicate seamlessly without requiring human intervention. Within this framework, WSNs are crucial, extending their influence across many real-time agricultural applications. These IoT and WSNs are structured with multiple layers in the SA application, illuminated comprehensively in the subsequent subsections. The overview of IoT and WSN architectures is shown in Figure 2 and 3.

A. IoT ARCHITECTURES

The emergence of IoT is an essential feature in contemporary agriculture systems, driven by the rapid progression of agricultural technology [39], [40]. IoT encompasses several critical segments, including sensors and devices, connectivity, action and automation, and user interface and interaction [1], [41]. These elements gather data from agricultural yields, allowing farmers to make informed decisions. Additionally, these elements are connected within various layers of IoT architectures for SA applications. However, determining an architecture for -based SA poses challenges due to the extensive potential scale and specific requirements, such as soil conditions, weather dynamics, and geographical variations [13], [42], [43].

Moreover, integrating IoT devices and systems into agricultural practices necessitates diligent efforts [44]. These efforts encompass acquiring IoT devices and utilizing various protocols and standards to ensure seamless compatibility and integration. In agricultural IoT configurations, sensors and devices generate substantial data, heightening the complexity of real-time data management, processing, and analysis. The designated framework for this purpose should efficiently facilitate structured data storage, efficient processing, and robust analytical capabilities [45]. The agricultural sector emphasizes precise and timely data, highlighting the necessity of ensuring the selected architectural structure is trustworthy and robust. It must have the capacity to maintain continuous collection and processing of data, even under adverse environmental circumstances or in the presence of challenges with network connectivity [46], [47].

On the other hand, ensuring a balanced integration of envisioned architectural features, functionalities, and the designated budget is essential. This is especially critical for small-scale farmers or financially constrained organizations. At the beginning of rapid advancements in IoT technologies, it is significant to underscore the importance of selecting an adaptable architectural framework [48], [49]. This architecture should incorporate emerging technologies and standards, ensuring the enduring relevance and effectiveness of the IoT-based SA system without interruption. Emphasizing the need for this strategic preference ensures the system's sustained applicability and efficiency.

The architecture of IoT technologies is employed based on various methodologies, varying from application to application [50], [51], [52]. This results in diverse design and deployment patterns. Instead, it must be customized based on specific needs. Typically, architecture is structured in a framework comprising three, four, and five layers for SA applications [26], [49], [50], [52], [53], [54], [55], [56]. Originating from a hierarchical framework of three to five layers, the IoT architecture is conventionally described, featuring primary and most common layers, including the perception layer, connectivity layer, and application layer for the SA application [20], [33], [50], [57]. These layers are also mentioned as the lower layer in the IoT architecture [21]. Furthermore, the other layers are the middleware and processing layer [44], [58], [59]. In the below subsection, we described the primary and main layer of IoT architecture for the SA system.

1) PERCEPTION LAYER

The perception layer, also known as the physical layer, is a crucial component in the IoT framework [13], [60]. It operates as a robust interface, enabling appropriate interaction between the physical and digital domains [33]. This layer is essential for immediately collecting diverse data from sensors and devices [44]. It encompasses critical environmental parameters such as weather conditions, wind flow, humidity, etc. For example, Zeng et al deployed an ultrasonic water level gauge for measuring the water level of a smart irrigation system [57]. The perception layer within the SA application presents typical challenges due to complex requirements during crop and environmental monitoring, especially in unfavorable conditions [60]. Enhancing the energy and communication infrastructure in agricultural fields is crucial, and using wired power and communication channels to connect IoT nodes is not practical or cost-effective. Data collection processes have progressed, integrating various tools. For example, sensors and cameras use Bluetooth, wireless networks, and short-distance wireless and wired transmission methods to transmit data to the central gateway [1], [61]. The sensing layer employs relevant devices to convert biological data into web-accessible information, constituting a foundational step in network control.

2) CONNECTIVITY LAYER

The communication layer, recognized as the network and transport layer, facilitates uninterrupted communication and data transfer across diverse devices, constituting the

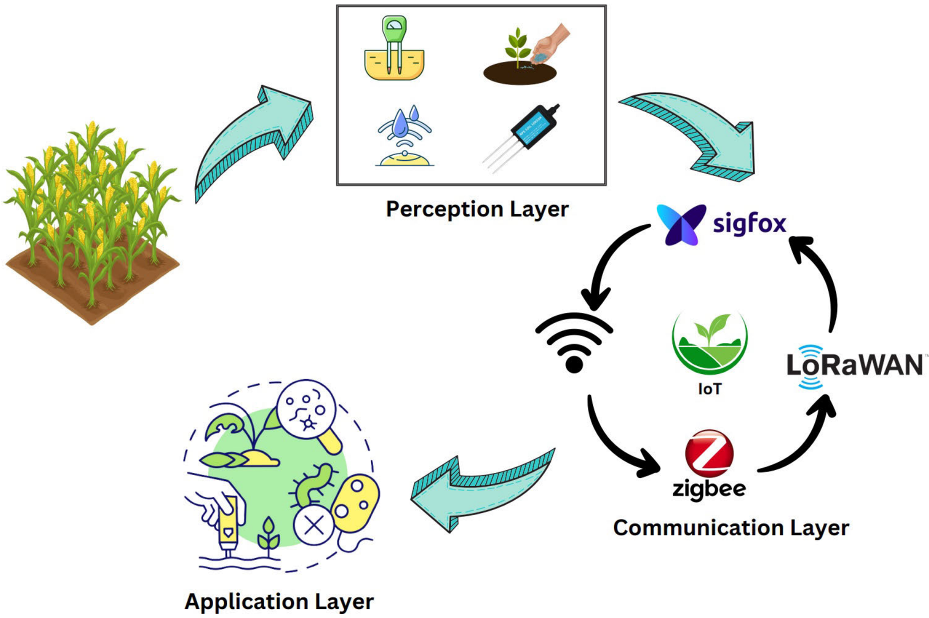

FIGURE 2. Architecture of IoT for SA application systems.

fundamental framework of IoT architectures [62], [63], [64], [65]. A profound understanding of the sophistication of the communication layer is critical to optimizing IoT networks, fostering scalability, resilience, and secure data exchange, thus propelling the potential and applications of IoT technologies across various domains. As the key element of the entire system, this layer delivers data transmission from the perception layer to the application layers [66]. The data transmission channels, encompassing wired or wireless, short or long-distance mechanisms, serve as foundational components. These channels effectively utilize both network infrastructure and wireless sensors. Attaining consistent and reliable performance in data transmission is paramount, especially in light of the substantial interference prevalent in the complex agricultural production environment and frequent climate changes that continually challenge this technology [67], [68].

3) APPLICATION LAYER

IoT has revolutionized the SA system, fundamentally transforming agriculture and agribusiness approaches. The IoT application layer, central to this transformation, drives the functionality and intelligence of IoT applications, particularly in intelligent agriculture [69], [70]. This layer integrates data from diverse sensors and devices in agricultural settings, enabling insightful analysis and informed actions [48], [66]. Advanced technologies within this layer, such as ML algorithms and predictive analytics, drive precision farming, optimizing resource allocation crop management, and fostering sustainable agricultural practices [71]. The application layer processes information and makes critical decisions [72]. It closely integrates IoT technology with agricultural production, utilizing data analysis from the connectivity layer [73]. It also possesses related equipment to achieve SA management [9]. Given the complexity of crop data and climate change, technology proves pivotal in identifying agricultural production process issues aligning with user needs.

B. WSN ARCHITECTURES

WSNs are essential in IoT technology because they collect and transmit data from various physical phenomena and environments. They operate as the information-gathering infrastructure of IoT by capturing real-time data through diverse sensors placed across different locations [74]. This collected data is relayed to centralized systems for analysis, interpretation, and informed decision-making. Especially within the SA system, WSNs manifest as a connected network of sensor nodes utilizing wireless connections. These nodes possess diverse functionalities, encompassing processing, transmission, and sensing capabilities, empowering them for self-organization, self-configuration, and self-diagnosis [75]. The categorization of WSNs is contingent upon their deployment contexts, with notable classifications being terrestrial WSNs (TWSNs), wireless underground sensor networks (WUSNs), underwater WSNs (UWSNs), wireless multimedia sensor networks (WMSNs), and mobile wireless sensor networks (MWSNs) [76], [77], [78]. TWSNs and UWSNs are commonly utilized in SA applications [23], [79]. In contrast, WUSNs are positioned underground, requiring a higher node density due to the restricted communication range caused by soil attenuation of higher frequencies [77], [80]. Scholarly literature extensively explores the various applications of WSNs in agriculture, encompassing activities

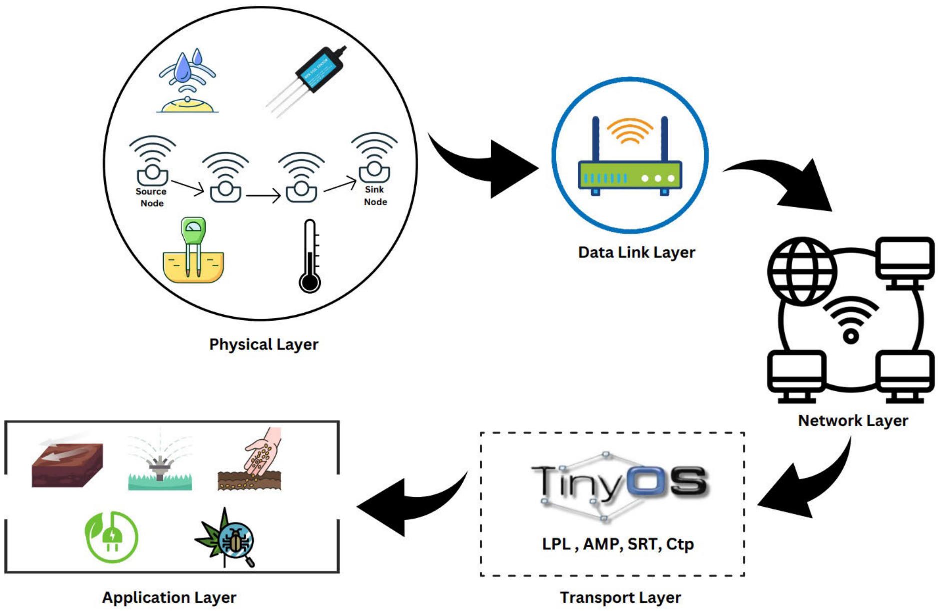

FIGURE 3. WSNs architecture for SA application.

such as managing irrigation, assessing water quality, and monitoring the environment. Exploring these applications underscores the pivotal role of WSNs in propelling advancements in agricultural practices.

A WSN typically comprises five foundational layers within its architecture: the physical, data link, network, transport, and application layers [81], [82]. The details of these layers are given below.

1) PHYSICAL LAYER

The physical layer is the foundation of a WSN, encompassing crucial hardware components and communication interfaces. In the SA domain, this layer holds various sensors meticulously designed to measure essential environmental parameters such as temperature, soil moisture, and sunlight exposure [64], [83]. These sensors play a pivotal role by converting these physical parameters into electrical signals, forming the bedrock for comprehensive data collection within the agricultural environment. For WSNs, the most relevant and widely recognized set of standards is the IEEE 802.15 family [84]. Specifically, the IEEE 802.15.4 standard defines the physical and Medium access control layer (MAC) specifications for low-rate wireless personal area networks (LR-WPANs) extensively utilized in WSNs [85], [86]. This standard is crafted to deliver low-cost, low-power, and low-data rate communication, catering to diverse applications, including WSNs.

On the other hand, in the data flow, sensor nodes actively collect data and transmit it to a centralized node, ensuring processing aligns with user requirements. The physical layer is entrusted with transmitting bitstreams, carefully selecting frequencies, generating carrier frequencies, modulating data, encrypting data, and detecting signals [87]. This layer encompasses the definition of transmission medium specifications and intricately involves establishing the network topology, incorporating the crucial functions of encoding and decoding signals.

2) DATA LINK LAYER

The layer above the physical layer is the data link layer, which establishes reliable and secure connections between adjacent nodes in the network [81]. In the context of SA, this layer ensures error-free communication among sensors, the central base station, and sensor nodes, allowing for precise monitoring of field conditions and crop health [88], [89]. It handles multiple functions, including multiplexing data streams, frame detection, MAC, and error control implementation [90]. Additionally, the data link layer ensures the dependability of both point-to-point and multi-point channel access strategies through efficient scheduling and proficient buffer management [91].

3) NETWORK LAYER

The network layer is positioned higher within the WSN architecture and is crucial in overseeing routing and data packet progression among diverse sensor nodes [92]. It optimizes data flow significantly from sensors scattered across extensive farmlands to the central server or gateway, making efficient routing a vital aspect for well-informed decisions in SA, particularly in irrigation, pest control, and resource management. The network layer's primary function lies in routing, establishing a pathway through intermediary nodes from the source to the destination node [93]. Research in this layer primarily focuses on developing highly efficient routing protocols that meet various constraints, encompassing energy efficiency, quality of service (QoS), and robustness. Moreover, the network layer integrates the communication network protocol selected from the existing network protocols for WSN, encompassing features relevant to precision agriculture applications.

4) TRANSPORT LAYER

The transport layer assumes a critical role, ensuring reliability and effectively managing congestion to prevent or mitigate it. Specific protocols are in place within this layer to serve these essential functions, employing either upstream or downstream techniques [94]. These protocols can be categorized as packet-driven and event-driven [95]. The collaborative capabilities demonstrated by sensor nodes are the fundamental basis for the operations of this vital layer. In addition, the transport layer is crucial in maintaining end-to-end communication and data integrity [96]. In the context of advanced agricultural applications, this layer can ensure the consistent and reliable transmission of data packets from sensors to the application layer. It efficiently manages data flow, meticulously maintains packet sequencing, and applies necessary error correction measures to ensure that crucial agricultural data reaches the applications with the highest accuracy and precision.

5) APPLICATION LAYER

In the domain of SA, the application layer holds great significance. It supports various applications crucial for optimizing agricultural practices, enhancing yields, and promoting sustainable farming methods [97]. Farmers and analysts can easily visualize field data on their mobile devices and computers through this layer, aiding in informed decision-making. This layer also plays a pivotal role in analyzing field data, providing valuable insights [83]. Moreover, the application layer controls essential management functionalities within the WSN. It efficiently manages traffic, offers software for diverse applications, and converts data into understandable formats. These functions encompass network management, query processing, communication, time synchronization, and localization [98].

IV. WIRELESS COMMUNICATION PROTOCOLS FOR IoT-WSNS IN SA

WSN developed various wireless sensing devices placed over a broad location. These appliances include distributed communication network protocols that gather data from the agricultural yield and centralize adequately to commission the collected data. The state-of-the-art WSN comprises several affordable sensing devices utilizing low-power communications network protocols, such as ZigBee, SigFox, WiFi, and LoRaWAN. WSNs are distinguished functionally from the usual sensing device collection by their network capabilities, which allow performance between sensing assets.

The network protocol is also classified into long-range and short-range protocols depending on their area coverage and properties. For this purpose, long-range network protocols can convey data over a long distance; in contrast, short ranges can transmit within a short distance [33], [99]. The essential features and attributes of these four protocols are shown in Table 1. The short-range and long-range protocols are given below.

A. SHORT-RANGE PROTOCOLS

1) ZIGBEE

The Alliance has introduced ZigBee technology based on the IEEE 802.15.4 standard, employing a wireless communication approach that conserves power and integrates a high-speed, energy-efficient standard protocol [84], [100]. ZigBee operates within multiple radio frequency bands, including 2.4 GHz, 915 MHz, and 868 MHz, achieving an impressive transmission speed of 250 kbps. Notably, ZigBee can function in a low-power sleep mode using batteries for extended periods [23]. It supports various network techniques, encompassing star, tree, and mesh topology, resulting in three primary Zigbee network types: star, tree, and wireless mesh network topology [101].

Zigbee wireless networks facilitate autonomous wireless data transmission in the agricultural IoT-WSNs domain. It ensures convenient and stable remote data transmission through successive integration with wired data transmission. Continuous advancements in IoT-WSNs microprocessor research and development are evident, especially in integrating wireless sensing, control, communication, and data processing functions within the microprocessor [27]. Concerning real-time monitoring in agricultural production, utilize intelligence systems for precise functional and monitoring tasks in field cultivation, irrigation and fertilizer, and well-established production processes. Agricultural IoT supports enriched planting experiences and precise crop management.

Remarkable strides have been taken in the development of high-precision information monitoring and diagnostic equipment, significantly advancing the application of IoT in agriculture. Currently, equipment for acquiring crop and plant information, monitoring environmental information, and tracking animal behavior plays a pivotal role in the SA system. The vital data required for crop monitoring is gathered using various Zigbee sensors in battery self-powered mode, forming a wireless sensor network [102], [103], [104]. Given the substantial number of Zigbee nodes required in production, establishing a robust network topology is essential to facilitate fast communication between network nodes [105].

2) WIFI

Wireless Fidelity (WiFi), officially introduced by the Wireless Ethernet Compatibility Alliance (WECA) in the late 1990s [106], [107], represented a significant advancement

TABLE 2. Overview and characteristics of ZigBee, WiFi, SigFox, and LoRaWAN.

Attributes	ZigBee	WiFi	SigFox	LoRaWAN
Topology	Star and mesh cluster	Star	Star	Star-of-stars
Data rate	250 kbps	150 kbps	100 bps and 600 bps	0.3–27 kbps
Network	WPAN	WLAN	LPWAN	LPWAN
Frequency	2.4 GHz	2.4/60 GHz	868/902 GHz	-
Standard	IEEE 802.15.4	802.11g	SigFox	LoRaWAN
Coverage range	10–100m	10-50m	30–50 km/3–10 km	5-15-45 km
Features	Built on PHY and MAC layers of IEEE 802.15.4	Access and availability, flexibility and cost savings	Highly efficient energy and long-range	Low power, long range

in wireless technology. Functioning as a wireless local area network (WLAN) technology, it effectively replaced Ethernet, granting devices the ability to connect to the internet without being tethered by wires or cables. Operating in compliance with the IEEE 802 communication standard, devices equipped with WiFi communicate via radio signals across the airwaves with an access point (AP), an essential piece of networking hardware connected to a wired or cellular network [108]. This technology covers a range of radio frequencies, spanning from 2.4 to 60 GHz, and precisely defines the structure of data packets [23], [33]. WiFi is widely adopted across a spectrum of devices, primarily due to its coverage range, typically 3-7 km, with a large transmitting antenna and its potential to achieve information transfer speeds of up to 700 Mbps [109], [110].

In the IoT applied in SA, integrating computing and WiFi-based long-distance networks facilitates connectivity within agricultural and farming processes, particularly in rural areas. It is used to transmit information within the system due to its high throughput and ease of integration with web-based services. WiFi integration is essential while measuring critical field parameters such as water quantity, soil humidity, and temperature [111]. It is ideal for establishing communication between the sink nodes and gateways or connecting to the cloud via the internet. WiFi finds specific applications in agricultural IoT, encompassing crop disease detection, precision greenhouse farming, and remote diagnosis [112], [113].

B. LONG-RANGE PROTOCOLS

1) SIGFOX

SigFox is a Low-Power Wide Area Network (LPWAN) technology designed to transmit minimal data volumes, typically ranging from a few bytes to hundreds of kilobytes [114]. The core modulation technique employed is Differential Binary Phase-Shift Keying (D-BPSK), operating within a fixed bandwidth of 100Hz and achieving efficient spectrum utilization [25], [33]. The transmission speed varies, offering rates of 100bps in Europe and a higher 600bps in the U.S.A. region. Operating within the unlicensed frequency spectrum below 1GHz, SigFox utilizes 868MHz in Europe and 915MHz in the U.S. [115]. This Ultra-Narrow Band modulation, known for its minimal power consumption, is ideal for establishing robust connections between nodes and the base station, especially when combined with the Chirp Spreading Spectrum. The D-BPSK modulation is relatively straightforward to implement [116], [117]. Moreover, SigFox handles small data packets, typically composed of 12 bytes, and operates within a bandwidth of 100 Hz [118]. A key strength of SigFox lies in its outstanding power efficiency, capable of sustaining operations for up to an impressive 15 years on a single battery charge [119]. This network technology operates in a frequency band between 860 and 920 MHz [120]. The coverage range spans 10 to 40 km, and the information transfer speed can reach 600 bits per second [121].

Owing to Sigfox's advanced network protocol features, it finds extensive applications within -WSN-based SA systems [7]. It is notably used to implement cloud-based WSNs for irrigation systems, real-time agricultural data collection, and energy harvesting [118]. Moreover, SigFox has been utilized to develop solar-powered autonomous sensor nodes, effectively collecting meteorological parameters and demonstrating successful assessment, particularly in vineyard environments [118].

2) LORAWAN

LoRaWAN is a low-power, wide-area networking protocol developed to enable communication among low-energy devices in various IoT applications [101]. It operates over unlicensed radio frequencies, allowing for long-distance communication with minimal power consumption [122]. The technology uses chirp spread spectrum modulation, making it ideal for connecting devices over several kilometers in urban or rural environments [123]. This wireless communication technology consumes energy infrequently and operates in an unlicensed band [124]. Its coverage range is about 20 km, and the information transfer speed can reach 100 kbps [125], [126].

Additionally, LoRaWAN utilizes various spreading factors (SF) from SF7 to SF12, strategically managing the trade-off between transmission range and data rate [127]. Among them, SF12 achieves an extensive communication range at the cost of a lower data rate [128]. LoRa is the fundamental physical technique integrated with the LoRaWAN MAC layer, serving as a foundation for various applications [129]. The architectural design of LoRaWAN nodes is structured into three distinct classes: A, B, and C [130]. Class A nodes exhibit minimal power consumption, efficiently transmitting a limited number of data packets to the gateway and spending most of their time idle [131]. In contrast, Class B nodes, in addition to the reception windows resembling Class A, open specific reception windows during scheduled time slots [130]. Meanwhile, Class C nodes maintain a perpetually open window for reception, except during data transmission, resulting in higher energy consumption than their counterparts in the other two classes [132].

V. IoT-WSNS IN SA APPLICATION

Agriculture is essential for any nation and a pillar of the economy. SA is a significant aspect and rising contemporary topic for all nations. The world's inhabitants are rapidly increasing, and the demand for food boosts as the population extends. The production of food and recovering the individual's fundamental needs can only be possible by concentrating on the agriculture sectors. Thus, automation should be incorporated into agriculture and reformed from traditional to SA. For this purpose, IoT-WSN is frequently utilized in SA applications. Several agricultural applications are discussed In the following subsections. WSN-integrated IoT-based SA applications utilizing wireless network protocols are summarised in Table 3.

A. IRRIGATION SYSTEM

The smart irrigation system (SIS) is a scientific domain that uses data-intensive approaches to improve agricultural productivity while decreasing environmental impact. Advanced agricultural processes generate data from different sensors, leading to a better understanding of the operational circumstances and process activities. It allows extra accurate and efficient decision-making. The SIS improves performance and is an emerging approach that automates irrigation systems and conserves water usage. This process modifies irrigation based on actual soil and weather conditions, allowing farmers to fulfill their needs with a recently adopted method that preserves the water for the irrigation process. Hence, WSN and wireless network protocols are utilized in the irrigation system to achieve this facility [133].

Routis et al. have presented an innovative IoT-based prototype system for precise crop irrigation. This system utilizes microprocessors and a Single-Board Computer (SBC) to collect sensor data, monitoring essential soil parameters, including soil moisture, humidity, temperature, and ultraviolet (UV) light. A significant feature is Raspberry devices, which incorporate powerful 4-core CPUs operating at 1.5GHz, underscoring their computational efficiency compared to the Arduino UNO's operation at 16MHz. The system integrates various sensors, including Capacitive Soil Moisture sensors, the DHT22 sensor for measuring air humidity and temperature, and the VEML6070 UV sensor, which is essential for monitoring UV radiation and its influence on crop growth. This study substantially contributes to agricultural technology and IoT applications for crop management [201].

Vandome et al. proposed low energy consumption and cost-effectiveness wireless soil moisture sensors, making them accessible both from a technical and economic perspective. This innovative sensor employs a precise calibration method based on a single parameter, enabling real-time monitoring of irrigation water requirements. Importantly, it was intentionally designed to meet the specific needs of water users and was successfully implemented within a Tunisian irrigation scheme, effectively addressing significant water use efficiency challenges. They evaluated the sensor by testing the WSN on pilot plots throughout a growing season and comparing its performance to commercial sensors. Notably, Wi-Fi technology was skillfully employed for communication within the network. Furthermore, the authors provided valuable insights by advocating for using these cost-effective sensors for real-time irrigation monitoring and as a pivotal tool for improving water resource management [283].

Fernández et al. proposed an economical cloud-based irrigation system that relies on WSN-based micro-controller ESP32-Lora and internet connectivity via the SigFox network. The results obtained validate the system's stability and robustness. This system had various sensors to measure different irrigation parameters, encompassing hydraulic network and environmental variables, including air temperature, humidity, irradiance, wind speed, precipitation, and soil variables such as humidity, temperature, pH, and matric potential. The study demonstrated the effectiveness of an IoT-based solution for irrigation control and management, offering scalability suitable for diverse agricultural contexts. The deployment of cost-effective SigFox technology addresses the connectivity and energy availability challenges of SA systems in rural areas [291].

Mathew et al. developed an IoT-based system to enable farmers to estimate irrigation water requirements. This innovative system employs sensors to detect soil moisture and temperature, with the collected data transmitted to the LoRaWAAN system for comprehensive analysis, including evapotranspiration calculation. The determination of global evapotranspiration is facilitated through Cropwat software, while the sensor data undergoes examination, enabling precise estimations tailored to microclimate conditions. The chosen Rx-MCU is the ESP32 MCU, equipped with integrated Wi-Fi connectivity to ensure uninterrupted internet gateway connection, facilitating seamless data streaming into application layer services. This approach is firmly grounded in WSNs, significantly enhancing the efficiency of both data collection and transmission [284].

B. SOIL MOISTURE MONITORING SYSTEM

Soil moisture plays an important role in an agricultural field that massively contributes to crop growth [493], [494]. It is recognized as one of the major drivers for plant ecosystems and a significant state variable for the irrigation system of the agriculture field [495]. Soil moisture is strongly variable and depends on various soil properties and terrain attributes [496].

TABLE 3. IoT-WSNs-based applications with wireless network protocols.

Applications	ZigBee	WiFi	SigFox	LoRaWAN
Irrigation system	[105], [134]–[206]	[83], [93], [105], [112], [148], [179], [180], [204], [207]–[289]	[290]–[292]	[111], [128], [129], [131], [161], [188], [230], [233], [248], [259], [267], [272], [283], [284], [289], [291], [293]–[347]
Soil moisture monitoring system	[105], [156], [182], [188], [195]–[204], [243], [348]–[359]	[83], [105], [112], [156], [204], [242], [244], [245], [247], [255], [258]–[276], [280], [282]–[289], [357], [358], [360]–[383]	[384]	[111], [122], [129], [257], [259], [267], [272], [283], [284], [289], [295], [298], [299], [306], [317], [321], [324], [332]–[339], [341], [345]–[347], [385]–[410]
Fertilizer optimization and control	[105], [137], [140], [143], [144], [157], [170], [182], [183], [190], [195], [198], [200], [353], [411]–[416]	[105], [112], [210], [234], [244], [261], [267], [273]–[275], [285], [287], [288], [365], [368], [375], [380], [417]–[422]		[122], [267], [297], [298], [340], [347], [385], [391], [405], [423]–[434]
Early-stage control of pest and crop diseases	[105], [149], [157], [176], [190], [198], [200], [348], [359], [435]–[440]	[83], [105], [261], [267], [273], [288], [375], [403], [422], [441]–[446]		[161], [267], [305], [324], [391], [403], [430], [446]–[461]
Energy saving and power consumption	[102], [105], [190], [195], [196], [198], [200], [201], [203]–[206], [357]–[359], [438], [440], [462]–[473]	[128], [241], [242], [247], [249], [258], [271], [275], [276], [283], [288], [357], [362], [379], [382], [464], [474]–[477]	[290]	[111], [128], [129], [259], [267], [283], [306], [324], [334]–[336], [338], [341], [399], [402]–[404], [410], [438], [464], [468], [473], [476], [478]–[492]

Therefore, a modern, sustainable, automatic, low-cost, and power-efficient soil moisture monitoring process is required. Soil moisture monitoring systems can be performed with various procedures. In these terms, WSN is one of the most utilized approaches to monitoring soil condition and moisture [84], [497]. Based on this, several works have been done to monitor the soil nutrient, PH, and moisture monitoring by using WSN.

Mohammed et al. introduced a real-time, fully automated WSN prototype for irrigation systems. This innovative system relies on automated WSN technology to respond to soil conditions, particularly soil moisture, for informed irrigation decisions. It utilizes the ZigBee protocol integrated into the XBee module and incorporates a cost-effective capacitive soil moisture sensor to measure soil moisture levels at each ZigBee node. Integrated with the low-cost soil moisture sensor, this system demonstrated promise in enhancing agricultural practices and conserving water resources [203].

Patrizi et al. submitted WSN architecture that leverages Long Short-Term Memory (LSTM) technology to develop a virtual soil moisture sensor. This virtual sensor utilizes data collected by other transducers on the same node. They utilized the ESP32 system-on-a-chip microcontroller to efficiently process and transmit data to a centralized gateway through the WiFi protocol. The WSN consists of ten independent sensor nodes, each equipped with an array of environmental sensors for air temperature, humidity, soil temperature, soil moisture, and radiation. An essential challenge addressed in this work was measuring soil humidity. In response, the study introduced a sophisticated soft sensing algorithm based on the DL algorithm, resulting in a virtual soil moisture sensor capable of overcoming the limitations of physical sensors and enhancing precision in soil moisture measurements [379].

Wu et al. presented a soil quality monitoring system to enhance agricultural practices. This system designated users to conduct real-time monitoring of their farmland via a mobile application, providing a convenient means to establish and customize soil parameter thresholds. Their research offered a novel approach to integrating IoT technology into agricultural soil measurements, incorporating multiple sensors for temperature and moisture, a microprocessor, a microcomputer, a cloud platform, and a dedicated mobile application. The wireless sensors efficiently collect and transmit real-time soil information, with the mobile app serving as a central monitoring hub through the cloud platform. Data transmission facilitated by the LoRa module ensures precise measurements that closely align with those obtained through calibration equipment. Field experiments have showcased the system's ability to predict soil moisture and temperature with enhanced accuracy, drawing upon data from various soil layers. This system equipped users with the necessary tools to promptly assess soil conditions, enabling routine checks for changes in soil quality [406].

C. FERTILISER OPTIMIZATION AND CONTROL

The world faces a food supply crisis, with less food production than population growth [498]. Besides, there needs to be more integration and utilization of state-of-the-art technology in agricultural applications [499]. The annual food production is also damaged due to a lack of soil fertility, moisture, and fundamental nutrients of NPK [500]. On the other hand, conventional methods are even applied to measure the soil nutrients and apply a fertilizer that is also harmful to crops and soil. The excessive volume of fertilizer can damage the standard scale of PH and the soil nutrition of agricultural land [501]. To address this challenge, it becomes essential to form a precision agriculture exercise through IoT with the involvement of IoT and WSN. Soil nutrient and fertilizer investigation using WSN allows different applications, including remote soil fertility monitoring.

Contreras et al. introduced SAgric-IoT, an SA system integrating IoT and DL technologies. This sophisticated system aims to monitor environmental conditions, swiftly detect diseases, and automate irrigation and fertilization processes within greenhouses. It comprises four key components: WSN for environmental monitoring, cameras for visual data, a gateway for centralized control, and a processing and storage unit. The gateway operates using three distinct communication protocols–ZigBee for sensor connectivity, Wi-Fi for cameras, and a cellular interface for transmitting data to the central unit. Notably, SAgric-IoT demonstrates remarkable efficiency in minimizing packet loss, thereby significantly conserving energy [105].

Senapaty et al. introduced the IoTSNA-CR model, utilizing IoT technology to analyze soil nutrients and suggest optimal crops, aiming to enhance productivity while reducing fertilizer usage. The model begins with IoT sensors collecting data in cultivation areas, followed by real-time storage in cloud services, accessible via an Android app, and undergoing subsequent data processing and analysis. A cost-effective WSN sensory system integrated various sensors to monitor soil attributes—temperature, moisture, pH, GPS, and color—efficiently gathering diverse data, including NPK values, timestamps, and geolocation specifics. Research advised using Agrinex NPK soil testing tablets and an LDR color sensor for soil sample analysis, with results stored in Firebase cloud storage. Interconnected through the ESP8266 Wi-Fi module and Arduino microcontroller, sensor nodes formed a low-power, efficient wireless network. The pivotal FC28 soil moisture sensor significantly enhanced the IoTSNA-CR model's effectiveness by evaluating soil water content [112].

Doan et al. proposed a WSN framework employing LoRa technology for remote monitoring within agricultural settings. This network consisted of three strategically placed LoRa sensor nodes within separate rice fields, tailored to different crops and utilizing various tillage and fertilization methods. These nodes gathered essential environmental indicators for effective monitoring, encompassing temperature, air humidity, soil moisture, water pH, CH_4, and NH_3 levels. Research findings underscored the system's effectiveness in monitoring the rice cultivation environment, ensuring robust and comprehensive data transmission, network security, and impressive long-range signal transmission of up to 3.5 km at a reasonable cost. The framework demonstrated proficiency in long-distance data transmission, maintaining secure data transfer from source nodes to the central gateway, ensuring high reliability, and facilitating seamless deployment for extensive agricultural monitoring [347].

D. EARLY STAGE CONTROL OF PEST AND CROP DISEASES

Damaging crop production due to various factors, pests, and crop diseases is one significant issue, as a large quantity of crop is wasted every production cycle by affecting pests and diseases [84], [502]. Thus, an early-stage sustainable decision support system is mandatory to enable the farmer to carry out proper actions in profitable harvesting [503]. A smart monitoring system should employ state-of-the-art sensor technology to solve plant diseases and pest-related concerns. WSN systems can collect data and store them in a cloud platform with the help of network protocols and process them, which helps to make early decisions to prevent pest and crop diseases [36], [47].

Additionally, Crop disease detection is a massive challenge in precision agriculture applications since crop diseases cannot be accurately predicted by analyzing individual disease causes. Azfar et al. introduced an IoT sensor system explicitly designed for pest detection and control, real-time detection of Cotton Flying Moths. This system experienced rigorous testing in controlled and uncontrolled environments to evaluate its accuracy and efficiency. The innovative prototype integrated a series of precise infrared sensors, a communication module based on Zigbee technology, an Arduino 2560 Mega board, a lithium polymer battery to power the sensor, a gateway device, and a UAV configured to act as a pesticide sprayer upon detecting pests. The pest detection algorithm, embedded within the system, monitors changes in reflected light to identify the presence of flying insects. Upon detection, the system sends an alert to the gateway device, which transmits the detection coordinates to the drone/UAV. Subsequently, the drone responds by spraying pesticide in the identified pest-infested area [440].

Strawberry cultivation is a significant agricultural venture, offering considerable advantages over various vegetable crops [504], [505]. Despite its prominence, the sensitivity of strawberries renders them highly susceptible to diverse pests and diseases. Resorting to chemicals and pesticides for protection significantly hampers production efficiency due to this sensitivity. To address this challenge, integrating deep computer vision architectures has been pivotal. Cruz and colleagues introduced a novel approach, employing the Yolo V5 computer vision architecture within an IoT system designed for strawberry disease detection. This innovative system utilizes LoRaWAN and WiFi protocols for internal data transmission and employs the Message Queuing Telemetry Transport protocol for data uploading to the internet [403].

Hnatiuc et al. developed an innovative IoT sensor network paired with a LoRaWAN-based system designed precisely for intelligently detecting grapevine diseases and collecting essential environmental and plant-related data. This technology was deployed within the experimental plots of the Research Station for Viticulture and Enology (SDV) to offer early insights into grapevine health. Data transmission across the Wi-Fi network was facilitated through the LoRaWAN-EU868 protocol. The study is balanced to extend its investigation to analyze results from IoT sensors trialed across vineyards in diverse regions [446].

E. ENERGY SAVING AND POWER CONSUMPTION

Advanced agriculture uses new processes, such as precision agriculture, to optimize the workflow under environmental aspects. For this purpose, WSN is incorporated with IoT, and network protocols combined with systems are used. Various required WSN nodes and actuators are also equipped. Such equipment requires a continuous power supply to achieve non-stop services [506]. In the PA-based WSN, energy consumption may differ due to additional parameters, i.e., active computational overload or sensor density deviations [507]. The existing conventional energy harvesting strategy cannot serve under such a requirement while harvesting and thus may reduce the overall lifespan of the network and entire system. To meet the energy requirements, a significant energy harvesting design is required [508].

Recent advancements and development of technology with low-power consumption, IoT, and WSN have been tremendously utilized and deployed for various SA applications. WSN has improved agricultural productivity and efficiency in agriculture yield. However, the energy and power shortage of WSNs is a major issue as instantly charging batteries is usually demanded [509], [510], [511], [512]. Sadowski et al. proposed an agricultural monitoring system with energy harvesting regarding these factors. The study presented a comparison arrangement between ZigBee, WiFi, and LoRaWAN wireless network protocols. It has been demonstrated that LoRaWAN demanded less power than other protocols within agricultural monitoring systems where power consumption and legibility of the network are considered. The experimental results recommended selecting wireless technology for future agricultural monitoring applications [464].

Similarly, Arshad et al. introduced a study based on a smart sensor module with an advanced irrigation system and supervised fertilizer architectures. The system has incorporated WSN, cloud-utilizing decision support layers, and networking-based DSS to recommend cautiousness for optimum sustainable agricultural field and production. For this purpose, A WSN node is equipped with an MCU LoRaWAN wireless module. The sensor node with LoRaWAN is connected to solar panels for stored energy since LoRaWAN can achieve enormous distances with low energy [267], [403].

VI. ISSUES AND CHALLENGES OF IoT-WSNS-BASED SA SYSTEMS

Despite the remarkable progress in integrating -WSN-based methods within SA, significant limitations must be carefully considered and addressed through proactive mitigation strategies. These obstacles manifest in various aspects, encompassing the system's infrastructure, the devices utilized, the network structure, and the crucial element of securing the data [64]. Constructing an adequate architecture for IoT-WSNs-based SA systems is challenging, requiring the continuous integration of diverse devices, sensors, actuators, and communication interfaces into a unified and efficient framework [513]. Striking the right balance between integration, system reliability, and scalability presents a considerable challenge [514].

Moreover, the diverse range of devices employed in IoT-WSNs-based SA systems, such as sensors for measuring soil moisture, drones for aerial surveillance, and automated irrigation systems, continuously pose challenges related to careful selection, setup, and maintenance. Factors such as device compatibility, power efficiency, durability, and cost-effectiveness are critical considerations in their deployment, representing ongoing challenges within this technological framework. Addressing the complexities of the network architecture in IoT-WSNs-based SA setups is equally essential, requiring the establishment of a strong, low-latency, and high-bandwidth network capable of managing the constant flow of data generated by numerous devices. Deliberate planning for scalability and reliability is vital to meet the heightening demand for real-time data processing and decision-making in profound SA applications.

A. SCALABILITY AND RELIABILITY

Substantial dual challenges exist within the domain of SA propelled by -WSN technology. These challenges encompass ensuring scalability and defending reliability, significantly influencing the system's efficacy and enduring sustainability. Scalability emerges as a central concern due to the increasing

TABLE 4. A summary of issues and challenges of IoT-WSNs based SA domain.

References	Critical Issues and Challenges	Recommended Steps and Resolving Actions
[9], [9], [21]–[23], [47], [515]–[519]	Scalability and Reliability: data traffic, potentially causing network congestion, delays in data transmission	Well-optimized network blueprints, resilient communication protocols, effective power management techniques, and dependable fail-over mechanisms.
[13], [21], [21], [515], [517]–[521]	Data Privacy and Confidentiality: unauthorized access, breaches, data misusage, identifying individuals farmers or agriculture stakeholder through data analysis, and robust encryption, effective authentication, and appropriate access control measures	Encryption protocols, secure data transmission methods, routine security assessments, and educational initiatives on privacy best practices.
[1], [64], [72], [521]–[527]	Location Privacy: track the location of farming equipment, livestock, Unauthorized access to precise location data	Robust privacy-preserving mechanisms and compliance with privacy regulations, ethical use of location data.
[13], [33], [61], [69], [131], [498], [525], [528]–[541]	Network Security and Intrusion Detection: security risks including node compromise, tampering, malicious attack, unauthorized access, data breaches, cyber-attacks, and adapting suitable IDS	Robust encryption techniques, secure communication protocols, efficient access, formidable security measures and energy-efficient operations.
[13], [93], [542]–[553]	Data Integrity and Authenticity: manipulation and tampering with sensor data, unauthorized alterations, introducing fabricated data	Considering massive amounts of data generated and transmitted across these networks, maintaining data integrity ensuring, review of data authenticity, secure authentication processes, and cryptographic techniques, digital signatures, message authentication codes, and integrity checks.
[13], [28], [526], [550], [554]–[559]	User Privacy and Consent: securing from hacking and data stolen, encompassing personal and operational data	Implementing transparent data usage policies, employing robust anonymization techniques, empowering users, effective communication of the purpose of data collection.
[49], [97], [560]–[564]	Resilience to Attacks and Failures: failure and disrupt agricultural operations	Implementing redundancy, fault tolerance mechanisms and backup systems.
[33], [68], [205], [334], [565]–[572]	Mitigation of Power Consumption: fixed battery life, high hardware costs, energy shortages, necessitating regular battery recharging	Energy-efficient routing protocol, implementation of renewable energy in SA systems
[21], [23], [27], [523], [573]–[579]	Optimizing hardware and software costs, expenses associated with imported agricultural devices, costs remain a notable gap in current research, lack of standardized data representation and operational procedures	Collaborative efforts among researchers and stockholders, establishment of necessary standards for effective IoT implementation

implementation of -WSN devices, resulting in a burgeoning network interconnecting various intelligent devices, sensors, and actuators [9], [23]. This growth presents challenges in effectively managing the expanding array of devices and the resulting surge in data traffic, potentially causing network congestion, delays in data transmission, and diminished overall system performance [22], [47]. Simultaneously, guaranteeing reliability is pivotal, ensuring a consistent and precise data flow, an indispensable component for well-informed agricultural decision-making. Aspects such as irregular network connections, device malfunctions, and power disruptions can undermine the system's trustworthiness. Effectively addressing these hurdles necessitates a comprehensive and integrated strategy encompassing well-optimized network blueprints, resilient communication protocols, effective power management techniques, and dependable failover mechanisms [21], [515], [517], [518], [519]. Achieving a meticulous balance between scalability and reliability becomes critical, fostering a sustainable and resilient -WSN-based SA system capable of adeptly meeting the evolving requisites of contemporary agriculture [9], [516].

B. DATA PRIVACY AND CONFIDENTIALITY

Incorporating -WSN technology into the sphere of SA introduces significant barriers concerning the security and privacy of data [98]. As SA systems become more interconnected, significant volumes of sensitive data are gathered, encompassing information on crop yields, weather patterns, and details about farmers and consumers [520]. Ensuring this data is covered from unauthorized access, breaches, or misusage is essential [13]. Privacy concerns emerge due to the potential risk of identifying individuals or businesses through data analysis [21]. Furthermore, the distributed deployment of -WSN devices, often across remote agricultural sites, challenges establishing robust encryption, effective authentication, and appropriate access control measures [521]. Insufficient security measures may lead to unauthorized data access, tampering, or intentional harm. Striking a balance between leveraging data analytics to improve agricultural productivity and upholding individual privacy and data security is a multifaceted yet vital objective. Addressing these challenges necessitates a comprehensive approach encompassing encryption protocols, secure data transmission methods, routine security assessments, and educational initiatives on privacy best practices for all IoT-WSNs-based SA ecosystem stakeholders [46], [68], [513], [522], [557], [580], [581], [582].

C. LOCATION PRIVACY

The advent of -WSN technology in SA has significantly enhanced data collection and decision-making processes.

However, this integration has introduced a crucial concern about location privacy. IoT-WSNs often necessitate the deployment of sensor nodes in agricultural fields to monitor various parameters and activities. These nodes can precisely track the location of farming equipment, livestock, and even the farmers themselves [1], [64], [522], [523]. While this location data is indispensable for optimizing farming practices, it raises substantial privacy challenges. Unauthorized access to precise location data can violate the privacy of farmers and stakeholders, potentially leading to misuse or security breaches [521], [524], [525]. Robust privacy-preserving mechanisms and compliance with privacy regulations are essential to address these concerns and ensure the responsible and ethical use of location data in IoT-WSNs-based SA [72], [526], [527].

D. NETWORK SECURITY AND INTRUSION DETECTION

The inherent interconnectivity of IoT-WSNs renders them susceptible to a range of security risks, including node compromise, tampering, and malicious attacks [525], [528], [529]. Threats such as unauthorized access, data breaches, and cyber-attacks pose significant data integrity and confidentiality risks as data transits these networks [13], [530], [531]. Addressing these challenges involves developing robust encryption techniques, secure communication protocols, and efficient access controls for safeguarding sensitive data from unauthorized access [33], [61], [532], [533], [534], [535], [536], [537]. Additionally, the limited resources of sensor nodes in WSNs add complexity to implementing robust security measures while maintaining energy efficiency. Intrusion detection systems (IDS) are crucial in identifying and mitigating potential security breaches [69], [538], [539], [540]. However, adapting IDS to suit the specific characteristics and limitations of IoT-WSNs remains a significant challenge. The right balance between formidable security measures and energy-efficient operations is paramount for establishing a secure and reliable IoT-WSNs-based SA architecture [131], [498], [541].

E. DATA INTEGRITY AND AUTHENTICITY

Maintaining data integrity and authenticity is critical for reliable decision-making in SA. Manipulation or tampering with sensor data can lead to erroneous conclusions and potentially harmful actions. Considering the massive amounts of data generated and transmitted across these networks, ensuring the accuracy and reliability of the data becomes imperative [542], [543], [544]. Potential challenges stem from attempts at data tampering, unauthorized alterations, or introducing fabricated data into the system [545], [546], [547]. Maintaining data integrity, ensuring it remains accurate and unaltered throughout its lifecycle, presents a formidable challenge [548], [549]. Equally critical is validating data authenticity, confirming that the data originates from a credible and genuine source [548], [550]. Effective solutions necessitate the development of robust data validation methods, secure authentication processes, and cryptographic techniques to ensure the integrity and authenticity of the data [13], [93], [550]. Techniques such as digital signatures, message authentication codes, and integrity checks can be implemented to verify the authenticity and integrity of the data collected from sensor nodes [548], [551], [552], [553].

F. USER PRIVACY AND CONSENT

In IoT-WSNs-based SA, preserving user privacy and obtaining informed consent is essential. These systems gather a wide range of user data, encompassing personal and operational data, raising valid concerns regarding data privacy [554], [555]. Users have a rightful expectation that their data will be handled ethically, securely, and in compliance with privacy regulations [556]. Obtaining informed consent poses a significant challenge due to the diverse and often distributed nature of data collection in SA. Users must be fully informed about the data being collected, its intended use, and who will have access to it. Striking a balance between optimizing agricultural practices through data utility and safeguarding user privacy is crucial [28]. Implementing transparent data usage policies, employing robust anonymization techniques, and empowering users with control over their data are vital steps in addressing these privacy and consent challenges [526], [550], [557], [558]. Effective communication of the purpose of data collection, the intended use, and potential risks to stakeholders is essential to obtain informed consent from users [13], [550], [559].

G. RESILIENCE TO ATTACKS AND FAILURES

SA depends significantly on the uninterrupted operation of IoT-WSNs [97], [560]. The reliability of this domain is crucial, as any compromise or failure can severely disrupt agricultural operations and impact productivity. Implementing redundancy, fault tolerance mechanisms and backup systems are vital to mitigate these risks [561], [562]. Redundancy ensures the maintenance of critical functions by providing backup paths or components in case of failures, ensuring continuous system operation. Fault tolerance mechanisms detect and manage failures, enabling quick recovery and continued functioning without significant performance drops [97], [563]. Backup systems act as safety nets, preserving critical data and functionalities accessible in case of failure [49], [564]. These actions collectively enhance the resilience of IoT-WSNs against potential attacks and failures, ensuring continuous monitoring and data availability for optimal agricultural outcomes.

H. MITIGATION OF POWER CONSUMPTION

Efficient power management is essential in IoT-WSNs-based SA. These systems are crucial for applications such as in-field monitoring and real-time tracking of field conditions, significantly reducing yield losses caused by unforeseen circumstances. However, despite their importance in agricultural contexts, persistent challenges stem from fixed battery life, high hardware costs, and limited bandwidth [33], [68],

[205], [565]. A significant aspect of these challenges is energy shortages, necessitating regular battery recharging to maintain an uninterrupted power supply [334], [566], [567]. Insufficient power provision can disrupt the entire system, causing interruptions in seamless farmland monitoring. IoT-WSNs comprise numerous sensors with limited energy resources deployed based on specific requirements. Therefore, in developing an energy-efficient routing protocol, renewable energy implementation in SA can be an essential requirement [568], [569], [570], [571], [572]. Current routing systems often feature complex architectures, underscoring the need for proactive approaches to address this concern and enhance power efficiency.

I. COST EFFECTIVENESS AND STANDARDIZATION

In IoT and WSNs applied in SA, a primary global research focus is optimizing hardware and software costs to improve system efficiency [23]. This focus is particularly vital in developing nations seeking to reduce expenses associated with imported agricultural devices [573]. While international farming entities have made technological advancements, the challenge of further reducing costs remains a notable gap in current research [523], [574]. Standardization is important in IoT as numerous studies need more standardized data representation and operational procedures, hindering seamless integration [575]. Emphasizing standardization becomes pivotal for driving IoT advancements alongside cost-effectiveness. Its potential lies in reducing initial barriers, addressing interoperability issues, and fostering healthy competition among various products and services. The evolution of security, communication, and identification standards within IoT demands a suitable approach to developing new technologies [21], [27]. Collaborative efforts among researchers are essential to define industry-specific guidelines and establish necessary standards for effective IoT implementation [576], [577]. This collective endeavor will pave the way for a more robust and efficient IoT framework formed specifically for SA applications [576], [578], [579].

VII. FUTURE PROSPECTS AND OPPORTUNITIES

State-of-the-art digital technologies have significantly progressed, integrating seamlessly with IoT-WSNs to augment the sustainability of SA applications. This integration substantially optimizes the entire scope of agricultural processes, from cultivation to harvest, encompassing the entire agricultural sector. These visionary initiatives stand on the point of a substantial transformation in the agricultural landscape.

The customization of digitization necessitates a substantial financial expenditure to align with the specific needs of individual farmers. To enhance the reliability of this digitization, embracing government-backed initiatives, grants, strategic public-private partnerships, and open data policies becomes essential. These initiatives should be accompanied by regionally focused research efforts to reinforce their effectiveness. Precision in composing digitization to unique needs mandates a significant financial commitment to organize to the specific demands of individual farmers. Transparent data policies are equally vital and assurance reinforcement through regional research endeavors. A systematic approach involves the meticulous implementation of a well-structured roadmap for the development of SA systems. This journey initiates with establishing a foundational architecture comprising essential components and more streamlined functionalities.

A. AI IN SA APPLICATION

The agriculture landscape is rapidly expanding, presenting various future trends and prospects. At the forefront of this expansion is the digital strategy, which encompasses a range of advanced technologies. AI is a computer system advancement standard aiming to replicate human intelligence and facilitate intricate decision-making processes. It assumes a critical position within SA, where the IoT-WSNs play a prominent role. Its capabilities extend into meticulous sensor data analysis, empowering stakeholders to make well-informed decisions regarding crop management, resource optimization, and predictions concerning future agricultural trends.

1) ML

As a subset of AI, ML is intricately focused on nurturing computer systems capable of learning and evolving through experiences. When applied to IoT-WSNs in agriculture, ML algorithms meticulously analyze historical and real-time data [583]. The objective is to optimize irrigation patterns, predict and proactively address crop diseases, and automate various agricultural processes [36], [584]. This integration significantly enhances efficiency and overall productivity within the agricultural landscape [36], [522].

2) DL

DL, an advanced ML technique, employs neural networks with multiple layers to replicate the intricate structure of the human brain. DL algorithms emerge as indispensable tools in IoT-WSNs tailored for SA [27], [585]. They engage in sophisticated data analysis, excel in image recognition, and unravel complexities in NLP. The application of DL leads to a comprehensive understanding of agricultural processes. Computer Vision is pivotal in empowering machines to interpret and comprehend visual information extracted from images or videos. Its integration within IoT-WSNs for agricultural purposes amplifies the potential for monitoring crop health, swiftly detecting diseases, and accurately assessing growth stages through meticulous analysis of imagery data [586], [587]. This, in turn, enables timely and well-informed interventions in agricultural practices, promoting efficiency and yield.

In recent years, integrating state-of-the-art AI technologies with the -WSN has emerged as a beacon of transformative potential within the agricultural sector. This integration presents an unparalleled opportunity to optimize farming practices, enhance resource utilization, and significantly boost agricultural output. The subsequent sections comprehensively delve into several AI-based technologies that can be effectively utilized to further the cause of sustainable agriculture, discussing their potential impact and contributions to the agricultural landscape.

3) FEDERATED LEARNING (FL)

A federated learning approach is promising for AI based on -WSN. It allows models to be trained across multiple edge devices or servers while keeping data localized [588]. In agriculture, where data privacy is crucial, this technique enables collaborative model training without centralized data storage [589]. Farmers can contribute to a global model without sharing sensitive data, improving model accuracy for various agricultural tasks. The federated deep learning approach enhances resource usage and data privacy, leading to classification results comparable to the fundamental ML setup. Applying this sophisticated learning method involves incorporating IoT technology to identify crop diseases precisely [590], [591]. Furthermore, encryption techniques can be employed when sharing trained models to address privacy issues in the federated setting [592].

4) EXPLAINABLE AI (XAI)

Transparency in AI is fundamental for establishing trust and comprehensibility of AI systems, especially within the domain of SA [593]. XAI integration is key in ensuring that AI models provide clear and understandable explanations for their decisions. Within SA, XAI demonstrates diverse applications, encompassing critical tasks such as monitoring crop growth, assessing crop health, and efficiently managing pests and diseases through integration with IoT-WSNs [594], [595]. Consequently, this framework becomes imperative for farmers and stakeholders, enabling them to learn AI-driven insights and recommendations concerning crucial aspects such as crop management and resource allocation within agricultural processes. Moreover, the fusion of XAI-based models with state-of-the-art feature optimization techniques can significantly enhance real-time malware detection in SA applications [596]. By explaining the insights derived from AI model data and demystifying the indistinct nature of black box predictions, XAI effectively bridges the understanding gap by shedding light on the rationale behind these predictions-an aspect often elusive in conventional AI models [597].

5) REINFORCEMENT LEARNING (RL)

RL involves training AI agents to make sequential decisions to maximize rewards, making it a viable solution for data-deprived scenarios. In SA, RL opens up extensive opportunities. Particularly, when integrated with IoT-WSN, RL can optimize crucial crop management decisions, including irrigation schedules, pesticide application, and harvest timing [14]. Applying Deep Reinforcement Learning within crop classification systems for precision agriculture is a promising approach to tackling farmers' challenges. DRL-based advanced agricultural techniques effectively filter out suboptimal choices, significantly enhancing crop production within the crop recommendation system [598]. Furthermore, RL is essential in addressing the area coverage problem related to monitoring crop health in semi-structured farm settings [639]. RL agents adeptly learn from environmental feedback provided by sensors, ultimately enhancing precision and efficiency in crop management [499].

6) GRAPH NEURAL NETWORKS (GNNS)

GNNs demonstrate high effectiveness in unraveling complex relationships within agricultural data. Particularly in the IoT-WSNs in SA, GNNs excel in capturing and modeling the interconnectivity among various factors that significantly impact crop health and yield. Leveraging data from multiple sources, such as sensors, weather patterns, and soil conditions, GNNs deliver valuable insights for optimized crop analysis and management. Additionally, GNNs find practical application in field-road classification methods based on GNSS recordings from agricultural machinery [599]. These methods enhance revolution classification accuracy, designed explicitly for farming machines [600]. Another significant application involves employing GNN models to predict the concentration of heavy metals in both soil and crops, including staple crops such as rice [601].

7) GENERATIVE ADVERSARIAL NETWORKS (GANS)

GANs demonstrate the capability to simulate the growth and development of crops under a diverse range of environmental conditions. This simulation proves invaluable for farmers as it equips them with the foresight to anticipate crop responses in various circumstances, aiding in making informed decisions concerning planting strategies, resource allocation, and risk management [602], [603]. Furthermore, AI leveraging DL is fundamentally transforming the analysis and modeling of agricultural images. Image augmentation is essential in enhancing the precision of DL models while reducing the need for manual efforts in image collection and annotation [604]. This augmentation is accomplished through the algorithmic generation and expansion of datasets. Moving beyond traditional data augmentation methods, Generative Adversarial Networks (GANs) in Computer Vision introduce innovative approaches to acquire effective data representations and generate highly realistic samples [605]. The potential of GANs to synthesize authentic and diverse images presents novel opportunities to enhance the performance of DL models tailored for agricultural applications. These advancements are particularly advantageous in scenarios where extensive labeled image datasets are inaccessible. Additionally, utilizing GAN-based data augmentation techniques enhances imaging classification tasks by generating artificial images, effectively doubling the training data for existing classes, thereby improving classification performance [606].

TABLE 5. A summary of future perspective and recommendation for IoT-WSNs-based SA system.

References	System/Architecture	Future Prospects and Recommendation
[14], [27], [36], [499], [522], [582]–[609]	AI	Integrate cost-effective sensors, ML, DL, XAI, GNNs, GANs, and self-supervised learning for advanced SA with improved resource management and transparency. Prospects involve sustainability via XAI, GNN complex modeling, GAN data generation, and self-supervised learning insights. Recommendations include XAI and self-supervised learning research, exploring GNNs and GANs integration, prioritizing reinforcement learning for autonomy, addressing data security, promoting farmer education, and ensuring cost-effective scalability.
[610]–[616]	Artificial General Intelligence (AGI)	AGI enhances real-time communication, streamlines farm management, fosters knowledge exchange, and improves crop monitoring and market predictions. Recommendations comprise ongoing R&D, user-friendly interfaces, data security, farmer training, IoT-WSN integration, emotional intelligence exploration, sustainability, and scalability for wider farming community adoption.
[7], [515], [617]–[619]	Agri-robotics	Autonomous, sustainable farming with real-time decision-making. Continuous robust data analysis, farmer training, data security, scalability, environmental impact reduction, predictive maintenance, fostering collaboration, and cost-efficiency to drive agriculture sector adoption and sustainability.
[431], [620]–[623]	UAVs	Real-time data collection for precision farming encompasses technology advancements, robust data platforms, training, data security, scalability, environmental sustainability, regulatory compliance, and cost-efficiency to promote adoption.
[14], [23], [74], [624]–[626]	Big Data Analytics (BDA)	Unlocks potential for data-driven insights, predictive modelling, and sustainability. The roadmap includes advanced data processing, machine learning, data security, farmer training, scalability, collaboration, and cost-efficiency to facilitate extensive utilization.
[538], [627]–[633]	5G and 6G for SA	It holds immense potential for real-time data transmission, enabling precision farming and remote monitoring. Key focus areas encompass infrastructure development, regulatory support, farmer training, data security, and integration to unlock the full capabilities of these technologies for sustainable and efficient agriculture.
[65], [627], [634]–[636]	Block Chain Systems	It offers transparent, decentralized data management. The path forward involves investing in infrastructure, standardizing data, empowering farmers, ensuring data security, and fostering collaborations to maximize the technology's potential, reinforcing data integrity and trust in agriculture.
[63], [567], [623], [637], [638]	Renewable Energy Integration	It promises sustainability and efficiency, encompassing advanced energy storage, AI-driven optimization, distributed grids, seamless integration, and collaborative sharing for greener, more productive farming.

8) SELF-SUPERVISED LEARNING

Self-supervised learning is gaining prominence in SA, especially when access to labeled data is scarce. This methodology empowers AI models to determine and extract meaningful features from extensive collections of unlabeled data, presenting a notable advantage in situations where annotating data demands substantial resources [607]. Integrating self-supervised learning techniques proves especially advantageous in -WSN-based systems, emphasizing efficiency and optimal resource utilization [608]. This avenue allows for robust data processing, extracting valuable insights without heavy reliance on extensive labeled datasets [609]. Consequently, it amplifies the capacity for well-informed decision-making in precision agriculture.

B. ARTIFICIAL GENERAL INTELLIGENCE IN SA APPLICATION

Artificial General Intelligence (AGI) is positioned at the cutting edge, demonstrating the substantial potential to wield a profound influence across various sectors, and agriculture is a prominent domain in this regard [610], [611]. AGI, especially in Natural Language Processing (NLP) and Agri-Robotics, can enhance crop yields, reduce waste, and promote sustainable farming practices [613], [640], [641]. This prowess uniquely positions AGI as a promising solution to the intricate challenges faced by the agricultural sector.

1) HUMAN-IN-THE-LOOP AI

Human-in-the-loop AI is a symbolic integration of human expertise with AI systems, facilitating collaborative decision-making [612]. Human experts contribute by providing input, validating AI-generated insights, and guiding AI models to ensure precise and dependable outcomes. This collaboration significantly enhances the accuracy and relevance of AI-driven insights within SA [613], [614].

2) CONVERSATIONAL AI AND AGRI-CHAT APPLICATIONS

Conversational AI, representing a pinnacle of technological advancement, entails the development of AI systems highly proficient in engaging with humans using natural language. Its specific application in SA is exemplified through Agri-Chat Applications, effectively interacting with farmers [642].

These applications provide real-time assistance, share invaluable insights, and offer essential crop management and pest control guidance. Particularly, technologies such as ChatGPT have the capability to analyze agricultural data, presenting immense potential for various agricultural applications such as crop forecasting, soil analysis, crop disease and pest identification, precision farming, and efficient irrigation scheduling [615]. The profound importance of these applications lies in their significant contribution to knowledge dissemination and the facilitation of seamless communication within the agricultural community.

3) VOICE ASSISTANTS FOR FARM MANAGEMENT

Voice-activated assistants, designed explicitly for farm management, herald a transformative stride in operational efficiency. They empower farmers to seamlessly structure their schedules, oversee equipment, and stay instantly informed through simple voice commands. These tools not only enhance accessibility to information but can also play a crucial role in promptly notifying farmers about any issues with the crops. Such immediate notifications enable farmers to take timely actions, potentially leading to a successful harvest [643], [644]. Consequently, this hands-free approach substantially amplifies productivity and streamlines the day-to-day management of farms. Farmers can now redirect their precious time and resources towards other critical agricultural tasks, advancing efficiency in the agricultural landscape.

4) COLLABORATIVE AI PLATFORMS FOR KNOWLEDGE SHARING

Innovative, collaborative AI platforms serve as sophisticated mediums to cultivate a culture of knowledge sharing and collaboration among farmers, researchers, and experts within the agricultural domain. These platforms facilitate collective problem-solving, exchanging worthwhile insights, and disseminating best practices. By leveraging the collective expertise of the agricultural community, these platforms empower individuals to optimize processes and elevate overall productivity. This concerted effort leads to implementing sustainable agricultural practices, aligning with ecological and agricultural sustainability principles.

5) EMOTION ANALYSIS FOR CROP MONITORING

Emotion Analysis technology marks a significant advancement in monitoring the health of crops. It thoroughly assesses plant well-being and stress levels through a detailed analysis of physiological and growth patterns. This analytical method provides crucial insights into how crops respond to their environment, such as understanding human emotions. It allows a more profound comprehension of their health and reactions to environmental factors. With such insights, agricultural practitioners can implement timely interventions to optimize growth conditions, promptly diagnose diseases, and tailor the agricultural environment to meet the specific needs of the crops. Ultimately, this innovative technology substantially improves crop yield and the overall quality of agricultural produce, presenting a promising path for sustainable and efficient farming practices.

6) AI-DRIVEN MARKET ANALYSIS AND PRICE PREDICTION

The application of AI-driven Market Analysis represents a significant advancement, employing complex algorithms to analyze market dynamics such as trends, consumer behavior, and economic indicators [645], [646]. Predictive models are central in foreseeing market prices, estimating demand-supply dynamics, and predicting trade fluctuations [616]. These data-driven insights empower farmers and stakeholders, enabling them to make strategic decisions and adapt to the dynamic nature of the market effectively. This approach enhances their resilience and ability to thrive in a constantly evolving market landscape.

C. AGRI-ROBOTICS

Agri-robotics involves the integration of robotic systems and automation technologies into agricultural practices. Combined with IoT-WSNs, these robotic systems are further enhanced by integrating sensor data optimizing tasks such as precise planting, monitoring, and harvesting [7]. This ultimately enhances efficiency and productivity in agriculture. These robots possess precise supratemporal resolutions due to their specialized sensing and actuation capabilities, potentially reducing labor while improving agricultural processes [515]. Additionally, drones are crucial in pesticide spraying, irrigation, crop harvesting, seed sowing, and soil cultivation, essential in transforming traditional farming practices [617].

D. UAVS

UAVs, commonly referred to as drones, are equipped with a suite of cameras and sensors, establishing them as essential tools for data collection and monitoring within the agricultural sector. When integrated with IoT-WSNs, UAVs facilitate aerial data collection, providing a real-time and in-depth understanding of the agricultural landscape [431], [620]. This integration significantly contributes to the precise assessment of crops and efficient agricultural management. Considerable research studies have investigated the potential of UAVs in data collection for agriculture, underscoring the efficacy of UAV-WSN systems in SA. For instance, researchers have explored a UAV-enabled agricultural system, wherein the UAV acts as a decode-and-forward relay, enhancing communication between controllers and multiple robots. Additionally, UAVs have been utilized to design optimal flight paths, generating UAV trajectories for efficient data collection from sensor nodes with non-uniform distributions, thus enhancing the overall effectiveness of data gathering [621], [622], [623].

E. BIG DATA ANALYTICS (BDA)

Big data analytics in IoT-based agriculture leverages advanced data analysis methodologies to extract valuable insights from the extensive data generated by IoT devices within agricultural settings [14], [74], [624]. These IoT devices, furnished with various sensors, actively gather diverse data concerning soil health, prevailing weather conditions, crop growth patterns, equipment performance, and more. The process of big data analytics involves discerning patterns, trends, and correlations within this data, all of which are critical for informed, data-driven decision-making aimed at enhancing agricultural practices. This analytical approach anticipates future trends and conditions by analyzing historical and real-time data, empowering proactive decision-making. It optimizes the usage of vital resources, such as water, fertilizers, and pesticides, by precisely tailoring their application to the specific requirements of the crops. The role of big data analytics in assisting farmers in making informed choices regarding the cultivation of diverse crops, considering seasonal variations such as winter and summer, cannot be overstated [23], [625], [626]. This analytical approach has demonstrated high cost-effectiveness, especially for small-scale farmers, and exhibits potential for indoor application within households.

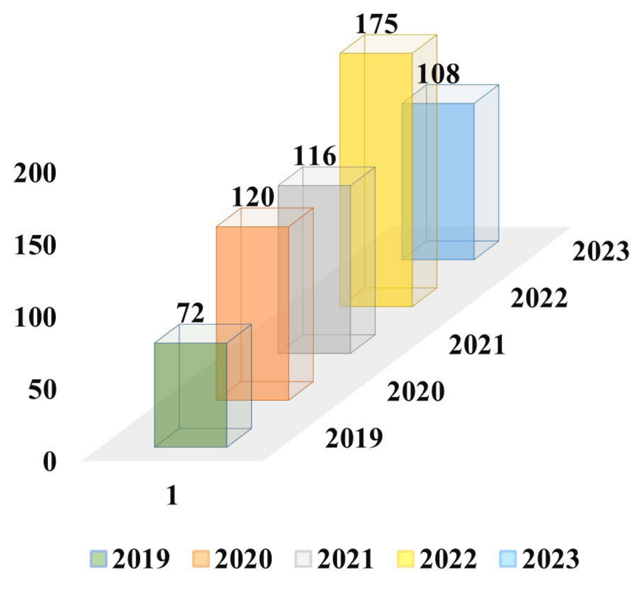

FIGURE 4. Progression of IoT-WSNs and network protocols in SA systems.

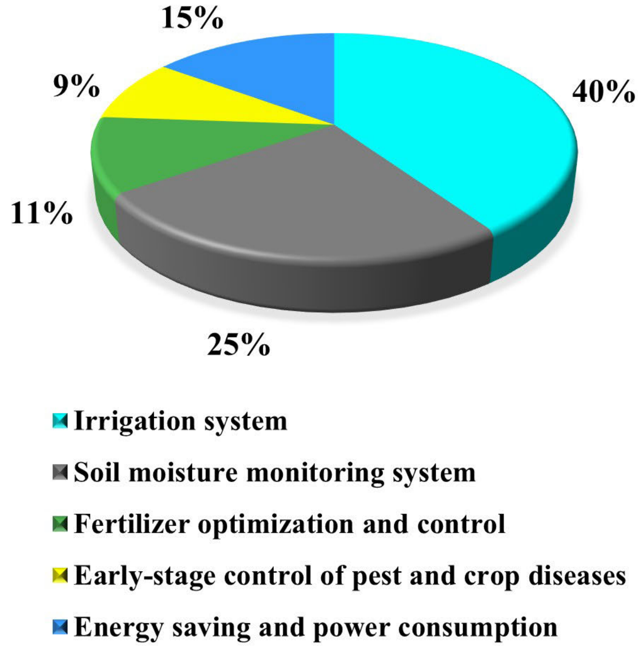

FIGURE 5. Yearly evolution of research contributions in IoT-WSN within SA applications.

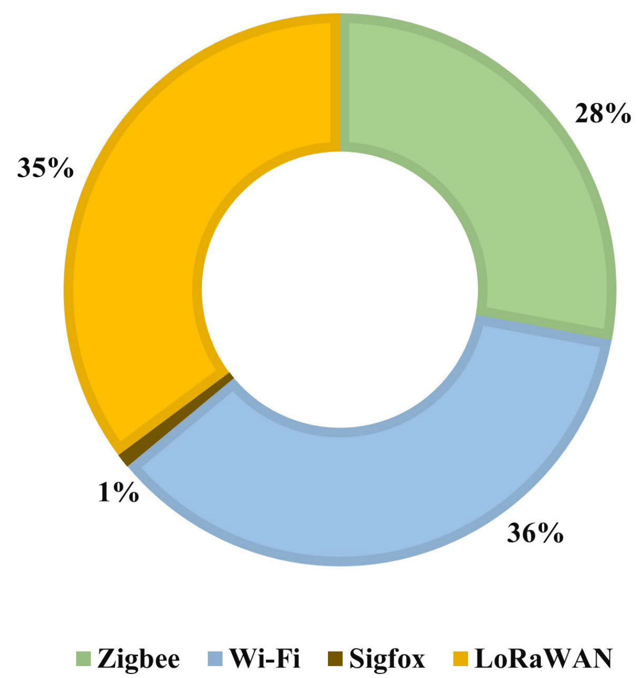

FIGURE 6. Research contribution distribution in IoT-WSN with their network protocols in SA applications.

F. 5G AND 6G FOR SA

The advancement of 5G and the promising revolution of 6G within IoT-WSNs bear substantial implications for the agricultural sector. 5G, constituting the fifth generation of wireless technology, represents a remarkable leap forward, offering significant enhancements such as accelerated data speeds, diminished latency, and improved connectivity. These enhancements translate to heightened real-time monitoring and faster transmission of sensor data, ultimately refining coordination among devices in agricultural applications [538], [627]. Looking ahead, 6G technology, still in its developmental phase, holds the potential to revolutionize data collection and analysis, potentially achieving speeds in the range of terabits per second, thereby ensuring exceptionally timely and precise insights for farmers [628], [631]. Incorporating 5G and the envisioned capabilities

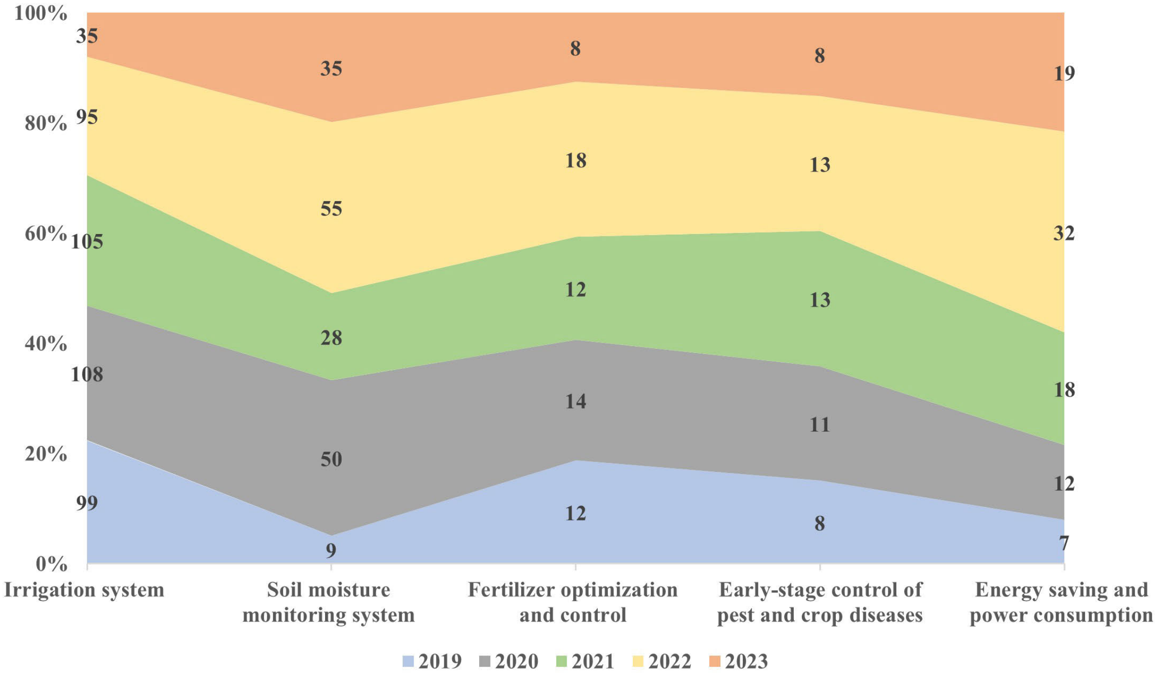

FIGURE 7. Annual research contribution rates in SA application areas.

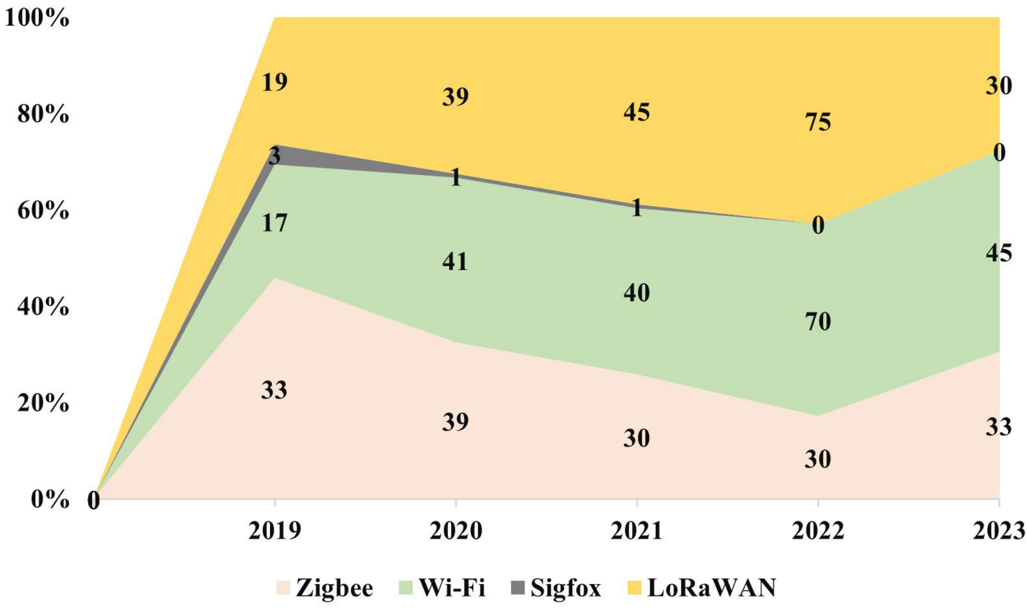

FIGURE 8. Annual wireless network protocol rates in IoT-WSN research within SA Applications.

of 6G within IoT-WSNs for agriculture holds immense promise. This combination facilitates real-time monitoring of critical factors such as soil conditions, crop health, weather patterns, and equipment performance, empowering optimized decision-making. The present generation of intelligent agricultural applications, relying on a relatively restrained number of wireless sensors, necessitates improved accuracy and effectiveness. However, the ongoing development of 6G- communication technologies sets the groundwork for the future of intelligent and sustainable agriculture [629]. 6G-technology pledges to enable the interconnection of various extensive sensors, granting farmers the capacity to gather intricate, plant-specific information. This transformative potential fueled by 6G- technology is poised to revolutionize SA, ensuring precise data collection, advanced robotics, and precision agriculture in remote locations, rendering agriculture significantly more efficient, sustainable, and cost-effective.

G. BLOCK CHAIN SYSTEMS

Blockchain technology, a decentralized and highly secure digital ledger, plays a crucial role in documenting transactions across a network. When integrated with IoT-WSNs, it ensures secure and transparent record-keeping within the domain of SA, particularly benefiting supply chains, traceability, and transactions. This integration significantly strengthens trust and operational efficiency throughout the agricultural ecosystem by assuring data integrity and fortifying defense against potential threats. One notable application involves countering data manipulation attacks, where crucial information about crops with minimal pesticide usage is securely stored within the blockchain's immutable ledger [627], [634], [635]. This advancement ensures the integrity and reliability of essential agricultural data, ultimately contributing to enhanced decision-making processes.

H. RENEWABLE ENERGY INTEGRATION

Incorporating renewable energy sources such as solar and wind power into IoT-WSNs for agriculture is crucial, aiming to establish sustainable and environmentally friendly energy solutions for powering devices and systems in remote agricultural regions [63]. Integrating renewable energy contributes to energy efficiency and environmental sustainability within the agricultural landscape. By incorporating energy from renewable sources into the IoT-based SA observation systems, sustainability and cost-effectiveness are markedly enhanced [637]. Using solar or wind power to energize the system diminishes reliance on conventional power sources, consequently reducing energy expenses and decreasing carbon emissions. Additionally, the scalability of this integrated system makes it viable for adoption by small-scale farmers who may lack access to conventional power sources.

I. IoT-WSNS AND THEIR PROTOCOLS IN FUTURE SA APPLICATIONS AREAS

In recent years, the integration of the IoT has led to significant advancements in agriculture, as shown in Table 3. Notably, there has been a 2.4% increase in IoT's growth, currently rising by 1.5%, as shown in Figure 4, which has captured substantial attention within the agricultural community. Farmers have extensively adopted IoT frameworks throughout the agricultural process, particularly in irrigation systems. They are renowned for their precision, efficiency, remote monitoring, and data-driven decision-making, as shown in Figure 5.

IoT has notably enhanced agricultural efficiency by linking devices, instruments, and stakeholders, reducing labor costs and increasing overall productivity. Farmers seek reliable, cost-effective, and power-efficient IoT devices seamlessly integrating with WSNs. The landscape of wireless network protocols is evolving, witnessing a significant shift towards low-power alternatives such as LoRaWAN, outperforming Wi-Fi due to its efficiency, network coverage, and minimal power requirements in SA, as shown in Figure 6.

Moreover, SigFox, operating on narrowband technology and offering extensive coverage with fewer base stations, remains an area of interest for IoT research in agricultural systems. Although its usage has maintained a 1% rate since 2019, as shown in Figure 6, SigFox and LoRaWAN, both with low power consumption, differ in flexibility. LoRaWAN, due to its greater flexibility, is better suited for specific agricultural setups requiring increased control or distinct coverage patterns.

A detailed analysis of research contributions emphasizes a significant focus on irrigation systems, soil monitoring, and energy optimization. Soil monitoring saw a slight decrease post-2021, while by the end of 2022, as shown in Figure 7, there was an increase in fertilizer optimization through IoT, along with applications for energy savings and plant pest and disease control in SA. Regarding network protocols, the rise of LoRaWAN significantly impacted the dominance of ZigBee and Wi-Fi from 2020 to 2022, securing a 35% share over the past five years, as shown in Figure 8. This positions LoRaWAN as a promising protocol for efficient resource utilization in SA. Simultaneously, Wi-Fi retains its popularity due to widespread availability and short-range capabilities.

VIII. CONCLUSION

Integrating IoT with WSNs in SA aims to maximize yield and optimize agricultural processes. This comprehensive IoT with WSNs architecture facilitates effective monitoring and control of agricultural fields, enabling valuable data collection to address current challenges. Wireless communication protocols are essential in efficiently transmitting the collected data to the system.

Integrating WSNs with IoT and wireless network protocols has proven cost-effective and efficient in SA applications, minimizing agricultural expenses. Notably, these integrated systems exhibit low cost, low power consumption, and enhanced efficiency. This survey presents a detailed review of the state-of-the-art IoT technology and the deployment of WSNs with wireless network protocols for SA applications since 2019.

The study extensively explores the architecture of IoT-WSN integration with network protocols in the SA domain, shedding light on prominent network protocols such as ZigBee, WiFi, SigFox, and LoRaWAN. These protocols have found significant utility in IoT-WSNs SA applications, including irrigation systems, soil moisture monitoring, fertilizer optimization and control, early-stage pest and crop disease management, and energy-saving measures. The study deliberates on current challenges and issues in this domain, aiming to provide insights and potential solutions for further advancements in integrating IoT-WSNs for the future of SA systems.

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