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Survey paper

Wireless communication protocols in smart agriculture: A review on applications, challenges and future trends

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ABSTRACT

IoT based smart agriculture systems are important for efficient usage of lands, water, and energy resources. Wireless communication protocols constitute a critical part of smart agriculture systems because the fields, in general, cover a large area requiring system components to be placed at distant locations. There are various communication protocols with different features that can be utilized in smart agriculture applications. When designing a smart agriculture system, it is required to carefully consider the features of possible protocols to make a suitable and optimal selection. Therefore, this review paper aims to underline the specifications of the wireless communication protocols that are widely used in smart agriculture applications. Furthermore, application-specific requirements, which may be useful during the design stage of the smart agriculture systems, are highlighted. To accomplish these aims, this paper compares the technical properties and investigates the practical applications of five different wireless communication protocols that are commonly used in IoT applications: ZigBee, Wi-Fi, Sigfox, NB-IoT, and LoRaWAN. In particular, the inconsistencies in the technical properties of these protocols reported in different resources have been highlighted and the reason for this situation has been discussed. Considering the features offered by the protocols and the requirements of smart agriculture applications, the appropriateness of a particular protocol to a particular smart agriculture application is examined. In addition, issues about cost, communication quality, and hardware of the five protocols have been mentioned. The trending technologies with high potential for the future applications of smart agriculture have been introduced. In this context, the relation of the technologies like aerial systems, cellular communication, and big data analytics with wireless have been specified. Finally, the leading protocol and the smart agriculture application area have been highlighted through observing the year-based distribution of the recent publications. It has been shown that usage of LoRaWAN protocol has become more widespread in recent years.

1. Introduction

Internet of things (IoT) is a network of physical devices together with network components and data analytics tools. The building blocks of IoT such as sensors, network tools and software systems are all interconnected to enable them to collect, exchange and process data. Due to the recent technological developments, the widespread usage of IoT systems is on the rise. According to the predictions made by Cisco, there will be 75 billion devices connected to the internet by 2025 [1].

IoT has a great potential to revolutionize the businesses and society in terms of various aspects. For example, different applications of IoT are capable of efficiency increments, improvement in the quality of life, and achieving a better management. Countless physical devices and objects are mentioned as "Smart" devices (e.g., appliances, trash cans, water meters, vending machines). Such devices involve contemporary features that are accomplished by utilizing location-based technologies and exchanging data with each other ubiquitously. The utilization of IoT enables the governments to develop and deploy intelligent technical solutions, such as smart transportation systems [2], smart parking [3], smart homes and buildings [4], and smart bridges [5].

It is possible to implement IoT based systems in the agricultural sector as well. Some examples of these systems are real-time farm

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monitoring, weather prediction and water conservation. Like all of the IoT applications, these use cases require sensors, data collection and data processing, which allow them to be called examples of "Smart Agriculture (SA)".

Agriculture plays a critical role in the growth of the economies of countries and also for the human species because it allows production of the main sources of food. It also holds an important place in the development of human civilization. According to the United Nation Food and Agriculture Organization, 70% more food is needed to feed the additional 2.3 billion people across the globe by 2050 [6]. Due to the increased demand for food, additional effort is put into increasing the efficiency of food production. Employing the emerging technologies and techniques in the field of agriculture can be considered as one strategy to achieve this.

A generic farm monitoring IoT system involves deployment of different types of sensors such as environmental and soil sensors. Processing of the data collected by IoT sensors like CO_2, rain, temperature, humidity, soil moisture [7], and plant health information [8] may help in developing strategies to achieve improvement in productivity as well as economic profit. After being collected, these data are then sent to cloud servers through gateways by means of the communication protocol used in the system (Fig. 1).

One of the problems that the farming sector is facing today is climate change which results in inefficiencies in the weather forecast [9]. As a result, it becomes difficult for farmers to make strategic decisions for preventing damages due to uncertain weather changes. It is possible to make any emergent decision by using the IoT weather predictive models. In this way, farmers can make predictions on the rainfall and control pesticide waste. Hence, advanced irrigation and fertigation systems considering environmental parameters can be built.

It is possible to optimize irrigation water in farms through IoT systems. Using the sensors involved in such systems, various data are collected and they are stored in a cloud database for generating predictive models. Such models may be utilized to forecast weather conditions or water needs of the plants. As a result, the risk of throwing excess water to the plants is reduced. This brings about reductions in water costs as well as water-related issues.

When the wireless communication protocols suitable for SA systems are considered, they are expected to allow for convenient data transmission between the components of the system. As a result, it becomes possible to collect a large amount of data from a variety of sensors. These data can then be processed to improve efficiency in different aspects such as water saving by means of irrigation optimization or yield maximization through fertilizer optimization. The appropriateness of a protocol to an SA system may be evaluated considering different parameters such as range, power consumption, data transmission rate, and cost, which are provided as the most important parameters for wireless communications [10]. Each of these protocols have some advantages and disadvantages over others. Therefore, selecting the most suitable protocol for a particular SA system is an intensive task.

Considering the necessities in SA applications, usage of low power wide area network (LPWAN) communication protocols is becoming more widespread. The design of LPWAN protocols allows for a high number of low-power devices to be distributed over very large areas and establish a reliable connection between them. Long Range Wide Area Network (LoRaWAN), Sigfox, and Narrowband Internet of Things (NB-IoT) can be considered as the leading LPWAN technologies [11]. On the other hand, there are some widely used non-LPWAN protocols that are Wireless Fidelity (Wi-Fi) and ZigBee.

Obviously, the wireless link between the components is important and inherent feature of SA systems. Therefore, it is critical to evaluate the capabilities and the properties of the available wireless communication protocols at the design stage of the SA systems to fulfill their application-specific requirements. One example may be the sensors distributed uniformly over the entire farm. Providing power to these sensors and collecting data from them may be an issue especially when the farm spans over large areas. The power consumption associated with the communication protocol in such sensors is expected to be low while allowing for wireless data transmission to remote locations. As can be understood from this example, there may be various types of issues related with the SA application and the available protocols. Hence, it is essential to evaluate the features of the protocols together with the SA system requirements.

LoRaWAN, Sigfox, NB-IoT, Wi-Fi, and ZigBee may be considered as key protocols for SA systems because these are either recently developed or widely used protocols in SA applications. Also, they require different infrastructures and hardware for different level of budgets. Hence, these protocols may fulfill the needs of SA systems for various applications. Even though there are some other LPWAN protocols (such as MIoTy, NB-Fi, and Weightless) that are mentioned in the IoT literature, there no application examples of them in SA domain [12,13]. As a result, only these five protocols are involved within the scope of this study. As for the SA applications, it was found out that there are six major application types commonly mentioned in the relevant literature. These application types are water saving, weather forecasting, soil condition monitoring, fertilizer optimization, crop disease and pest management, and energy harvesting. Therefore, the suitability of the protocols for these application domains is discussed.

In the next section, existing review studies about SA mentioned, their limitations are highlighted, and contributions of this study are provided. That section is useful for understanding how this review differs from the existing ones and fills the gap in the literature. Since the paper focuses on smart agriculture applications, the general architecture of SA systems is introduced in Section 3. The commonly used layers in the literature are explained with a focus on the network layer. One of the aims of this study is to introduce the features of some wireless communication protocols within the context of SA applications. Therefore, in Section 4, such information is provided to accomplish this aim. This information

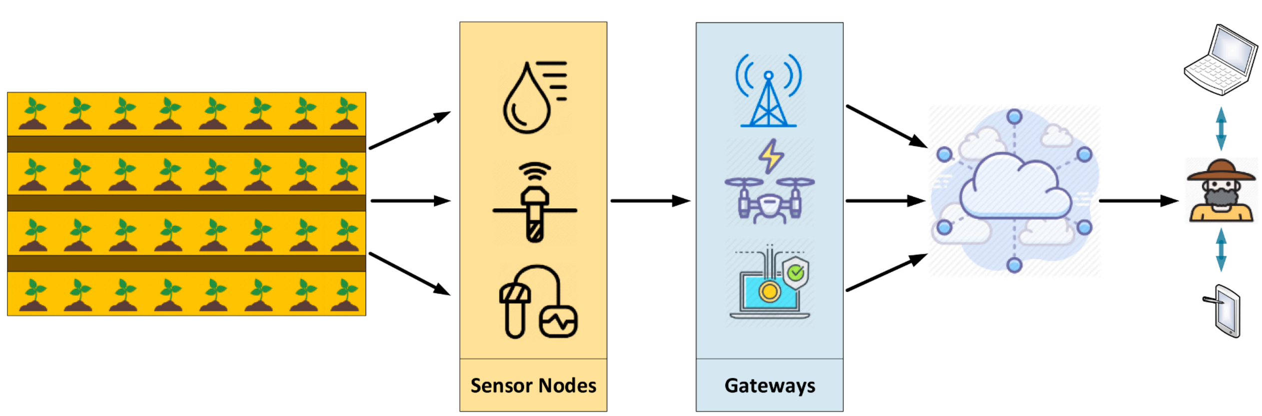

Fig. 1. End to end data flow in a smart farm.

involves comparing the significant properties of the protocols. Also, some inconsistencies in various sources are highlighted. Next in Section 5, requirements of the SA applications have been introduced together with some use cases. We believe that clear understanding of application-specific requirements and protocol-specific features, which are given in Sections 4 and 5, is critical at the design stage of the SA systems. So with this study, we also aim to provide an insight for the points to consider when designing an SA system. In Section 6, current challenges and limitations are provided within the scope of the paper. The future trends are highlighted in Section 7 to provide an idea on what protocols may be more common than others. We believe that understanding the leading protocol provides useful insight for future applications. Finally, the paper is concluded with Section 8.

2. Related works

2.1. Literature review and motivation

The wireless communication protocols are integral and important part of SA applications. This can be verified by the fact that they are discussed in some of the relevant review papers. For example, LoRaWAN and its potential for smart farming were discussed earlier by Citoni et al. [14]. It was stated that LoRaWAN is the most appropriate protocol for IoT as it satisfies three main metrics that are energy efficiency, coverage, and scalability. In that paper, the focus is given to the features and applications of LoRaWAN. Besides, limitations and research challenges of this protocol is provided and the associated low data transmission rate is underlined. In another work surveying IoT systems about arable farming, four of these key protocols (ZigBee, LoRaWAN, Wi-Fi and Sigfox) are said to be relatively common [15]. In that work, the related IoT systems are described using three layers: device layer, network layer and application layer. Challenges associated with each of these layers are given separately. Latency, data rate, wireless link quality and communication range are some of the given challenges about the network layer. However, comparison of these protocols and their applications are not provided explicitly in the paper. In addition, there are numerous review papers involve various applications of IoT in different fields of agriculture [16–18]. Yet, they do not explicitly mention the communication protocols in these applications. Furthermore, in some other previous surveys, properties of the IoT protocols are provided together with their example applications [14,15]. However, the inconsistent technical information given in different works are underlined in none of the previous review papers. Besides, the classification of SA studies based on both their application area and the utilized communication protocols are not discussed in detail yet.

In addition, many aspects of smart farming have been discussed by Farooq et al. [19]. For example, topics like cloud computing, big data storage, security issues, farm management as well as IoT protocols for SA are covered. The SA application domains were collected under three different topics as livestock monitoring, precision farming, and greenhouse monitoring. Each topic involves different applications such as weather monitoring, pest and crop disease monitoring, irrigation monitoring, and water management. Even though the scope of the paper is very wide, the information provided about the protocols is quite limited, and their limitations and advantages are not discussed for specific application domains.

Sinha and Dhanalakshmi made a thorough discussion about the important components of IoT in SA including new technologies, data analytics, and security issues [20]. The study involves sections about numerous application domains like management of water, nutrient, waste, soil, and irrigation. The importance of the wireless technologies has been mentioned in the paper, but there is no dedicated explanation for the wireless communication protocols for the application domains.

One survey paper where the reason for inconsistent information in the protocol specifications mentioned was written by Foubert and Mitton [10]. In that study, they propose a direct selection guide among the long-range wireless protocols after introducing their respective properties. The long-range protocols have been evaluated under two main categories as mobile band-based and ISM band-based. Even though an application example about of agriculture has been demonstrated in the paper, the main theme of the paper is not focused on various agricultural applications.

In addition to research papers, there are numerous whitepapers in which current state analysis and future forecasts about smart agriculture market are made. In particular, the estimated worth of the SA market for 2021 is reported to be USD 12.9 billion, and this amount is projected to increase up to USD 20.8 billion in 2026 [21]. It has been highlighted that the factors like world population growth and loss of arable lands increase the necessity of efficient usage of energy resources as well as the technology-supported agricultural production [22]. As a result, it is possible to conclude that utilization of energy efficient technologies is critical for sustainability of food production in a contemporary way. Besides, development of agricultural systems concerning the energy efficiency is important for fighting against the serious issues like climate change and global warming. In a very recent whitepaper, importance of digital technologies for agriculture has been exhaustively presented [23]. According to the whitepaper, the position of wireless sensors and networks in agricultural applications is very critical and their use is becoming more widespread together with IoT technology. The energy consumption issue of wireless sensors has been mentioned and the importance of research activities about it is underlined.

The increasing number of the SA systems and research papers in this field are obvious results of ever increasing human population in the world. Due to the large amount of studies published in the domain of SA for various applications, it is critical to categorize and analyze the most recent publications in this field. In addition, since the data transfer between the components of an SA system is commonly accomplished via wireless links, wireless communication protocols are important elements of SA systems. Hence, determination of most common protocols for specific applications is necessary for making predictions on the potential future directions of the related research in SA domain.

The protocols used in the wireless links are the major factors that affect the overall energy efficiency of the system because there is a continuous communication among the system components. Thus, evaluation of an SA system in terms of its energy consumption requires careful consideration of the wireless communication protocol used within the system. Therefore, an exhaustive comparison among the features of the widely used wireless communication protocols is necessary for fulfilling the requirements of a particular SA systems at the design stage. The motivation of this review study is to help the researchers recognize the prospective problems due to the limitations of the protocols and their application-specific advantages.

2.2. Research gaps and contributions

Despite the presence of various review papers about different aspects of SA systems, one can confidently claim that there is not a dedicated study discussing the features of different wireless communication protocols for specific SA applications. In particular, the existing studies either do not mention the possible applications of the protocols by comparing them or involve only limited number of protocols (See Section 2.1).

In this paper, we surveyed a comprehensive characterization of these key protocols and discussed their benefits for the future SA applications. To find the related papers, year-based search activities were performed in three platforms, namely, Web of Science, Scopus, and Google Scholar. Analysis of annual distribution of the available papers is a common method that can be seen in some other review studies [17,24]. The used search terms consisted of the name of the protocol together with "smart agriculture" keyword. The related search results were inspected manually. There were two main reasons for this manual inspection. *i)* Obviously, the search results contained papers from broad range of applications. However, the scope of this study is limited to six major application areas (see Section 1). Manual inspection of the search results was required to filter out those studies that were not about one of the six application areas. *ii)* In addition, it was observed that the results were not provided in detail in some of the conference proceedings. Therefore, such studies were not considered as complete work and hence excluded from the survey.

Furthermore, the review papers within the search results were used as alternative source for finding more studies of application scenarios. In other words, the appropriate references given in these review papers were explicitly reviewed before being added to the survey.

We also represent a set of attributes to objectively compare different kinds of protocols. Many papers involving an SA application have been carefully investigated and it has been found out that some protocols are more common. Therefore, we explored the applications in which these protocols are used and categorized them in terms of the following key points:

- Properties of the protocols used (operating frequency, data rate, range, power consumption, security, cost, limitations)
- Purpose of the application

Thus, the main contributions of the paper are the following:

1)When a communication protocol is considered, it is expected to find similar technical specifications in different resources. However, in the existing studies where one of the five communication protocols is used, it was observed that there is some inconsistent information about the protocols. This is an undesired situation since it may cause confusion at the design stage of SA systems. When the related review papers are investigated, no discussion about such inconsistencies have been encountered. Therefore, we consider this absence as a research gap, and in this study, highlight the inconsistent information found in the literature. This is accomplished by collecting most of the features and the corresponding technical specifications together and presented in an organized way. For this purpose, two tables (Tables 1 and 2) have been generated in Section 4. We believe that these tables facilitate the comparison of the technical specifications of these protocols and allows for reaching the protocol-specific features in a convenient way. In addition, the possible reasons for encountering such inconsistencies are discussed. Together with these discussions, the tables may guide the possible researchers for selecting the protocol appropriately and allow for reaching the particular study for the design details.

2)Considering the key points above, the appropriateness of a particular protocol to a particular SA application is discussed. For this purpose, features offered by the communication protocols have been explained (See Section 4) and the requirements for the SA applications are provided (See Section 5).

3)The open issues, challenges, and future technological trends have been evaluated within the scope of wireless communication protocols in SA. In particular, issues related with financial cost, security in SA systems, quality of the communication, and hardware optimization are mentioned. In addition, promising and popular technologies requiring effective usage of the communication protocols are listed as the trending topics such as aerial systems, cellular communication, big data analytics, and energy harvesting.

4)To highlight the leading protocol and the SA application area, year-based analysis of the existing studies has been performed. To achieve this, the papers in the literature are categorized considering their application area, the network protocols used and the year of publication. For each of the categories, rates of changes in the number of publications are calculated. Such an analysis allows for understanding the most common protocol as well as the SA application area together with generating future projections.

3. The architecture of smart agriculture

The IoT systems, in general, have architectures based on different layers. However, there is not a standard list of layers that is admitted by all the researchers [81]. The differences in the various sources are possibly because of the different necessities in the applications as well as the naming conventions preferred by the authors. For example, a smart city application may have several layers like physical, network, database, virtualization, data analytics, cognition, sensing, middleware, and application layers [82–84]. Similarly, in papers related to SA, different layers are mentioned. However, we decide to include those layers that are common in majority of the previous work [85–87]. These layers are the perception layer, network layer and application layer and they are detailed in the following subsections (Fig. 2).

3.1. Perception layer

This is the layer where the real-world integration is performed by collecting application-specific data through the sensors. It is constructed of physical objects (i.e. sensors and actuators) that can take physical quantities (temperature, humidity, wind speed and direction, solar radiation, air quality, etc.), process, store and transmit the data, and transform the data into digital control signals. The specifications of the hardware involved in this layer need to be determined according to the requirements of the application. For example, parameters like sensitivity, operating range and resolution of the sensors should be carefully inspected to decide if they are suitable for the intended measurement.

3.2. Network layer

This layer is considered as two different layers namely, the network (or gateway) layer and the transport (or transmission) layer by some authors [88–91]. On the other hand, it is considered as one single layer in some sources [15,19,25,56,92–94]. This layer makes the connection between the perception and application layers. This is the layer where the digital data collected from the physical environment is sent to the network gateway for storing them in a cloud or a local database. In SA applications, it beneficial to transmit the data wirelessly because the distance between the perception layer nodes and the network layer receiver is possibly very high. Besides, a wireless link will enable convenient and flexible location of the sensor in the field. For these purposes, the wireless data transfer between the sensors and the gateway is accomplished through various protocols such as LoRaWAN, Sigfox, NB-IoT, Wi-Fi, and ZigBee.

3.3. Application layer

It is the layer enabling the user interaction. The data collected at the perception layer is made available for the end-user at the application layer. This layer provides services by means of a set of IoT protocols (MQTT, XMPP, CoAP, RESTFUL, AMQP, etc.) for communicating with the database. This data is visualized for user information and possible user intervention. This layer is important for distant monitoring of the system related data (real-time or historical) and performing required actions remotely. Besides, these tasks requiring access to system data should involve authorization control which is accomplished in the application layer as well.

4. Wireless communication protocols in smart agriculture

Based on the range of coverage, the wireless communication protocols can be grouped under two main categories as long-range and short-range protocols. Usage of these protocols can be determined by considering the conditions and requirements of the system [63,95,96]. Long-range network protocols are capable of transmitting data from one device to another over vast distances and some examples are LoRaWAN

Table 1
Key Features of Wireless Communication Protocols in Smart Agriculture.

Part 1	Operating Frequency	Data Rate	Range (Coverage)	Power Consumption in Tx Times	Security	Battery Lifetime	Cost	Limitations
ZigBee	• 868/915 MHz [25,26,27] • 2.4 GHz [15,25,26,27,28–30] • 2.4/2.483 GHz [31]	• 20/40 kbps [26] • 250 kbps [15,25,32,26,27,31,33,28]	• 10 m [25,31] • 50–100 m [27] • 10-100 m [15,32] • 100 m [34,26] • 120 m [33]	• Low [27,33,28,35–42] • 1mW [15]	• High [42]	• 1+ years [43] • 2 years [44]	• Low [36] • Medium [28,41]	Line-of-Sight (LOS) between the sensor node and the coordinator node must be available [26]
Wi-Fi	• Sub – 1 GHz [30,45] • Sub GHz, 2.4/5 GHz [28] • 2.4/5 GHz [26,27,46,29] • 2.4/60 GHz [31] • 2.4/3.6/5/60 GHz [15,46]	• 150 kbps [30,47] ○ Mbps – 54 Mbps [28] • Mbps - 6.75 Gbps [15,46] • Mbps- 6.93 Gbps [31] • Mbps - 7Gbps [29] • 54 Mbps [33] • 11–54 and 150 Mbps [26,46] • 54 Mbps, 6.75 Gbps [27,46] • 1 Gbps Max [48]	• 50 m [33] • 6 – 50/70 m [32,29] • 100 m [34,31,49] • 20-100 m [15] • 140 m [27] • 100 – 1000 m [30,47]	• Moderate [33] • Medium [27,28,41] • High [32,36,37,39] • 1W [15]	• Low – High [45]	• Several Hours [50] • 3 Hours [51]	• Low [28] • High [36]	High power consumption and long access time (13.74 s) [26]
Part 2								
PSigfox	• Sub GHz [28] • < 1 GHz [41] • 433/915 MHz [46,52] • 868/915 MHz [26,46] • 868/902 MHz [31,46,53] • 908.42 MHz [15,25,46]	• 10-1000 bps [15,25,31] • 100 bps [54] • 100 bps 12/8 bytes Max [48] • 100-600 bps (Down-Up Link) [46,53] • 300bps [55] • < 1 kbps [28]	• 10 km [34] • 30-50 km [15,25,31] • 3-10-50 km (Urban-Rural) [56,52,54,45]	• Low [28][41]	• Low [55] • Low (AES-128) [57]	• 5 Years [58] • 7 ~ 8 Years [54] • 10+ years <2 uA [59]	• Medium [28,41] • <$ 10 [59]	**Low data rates** [26]
NB-IoT	• Cellular Bands [28] • Licensed LTE Frequency Band [53,52,58,60,61] • 180 kHz [15] • 455 -2140 MHz [46] • 900 MHz [62] • 450 MHz – 3.5 GHz [29]	• 170-250 kbps (Down-Up Link) [57] • 200 - 250Kbps [46,52,55,29] • 0.1 – 1 Mbps [28]	• 2-5 km [55] • 15 km [63] • 10/28 km [15] • 1 - 10 – 40 km (Urban-Rural) [52,54]	• Low [15] • Medium [28][41]	• High [55,60,61] • Very high (LTE Security) [59]	• 7 ~ 8 Years [54] • 10 Years] [64] [58] • 10+ years • <3 uA [59]	• $8–12 [64] • High [28][41] • $ 10/$ 3 (2019/2020) [59]	**Worldwide connectivity with long-range coverage and medium data rate with long battery life** [65–67]
LoRaWAN	• Various sub-GHz [28][25,46,29] • 869/915 MHz [26,46] • 868/900 MHz [15,46] • 868/915 MHz [31] • EU: 433, 863-870 / US: 433, 902-928 MHz / China: 470-510, 779-787 MHz / Asian: 920-923.5 MHz [46,53] • 433/868/780/915 MHz [27,52]	• 290 bps - 50 kbps [48] • 0.3-50 kbps [15,25] • 3-50 kbps [32,46,54,29] • LoRa: 0.3 - 37.5 kbps / FSK: 50 kbps [53] • 50 kbps [27,33,52,55,28] • 50 – 100 kbps [31]	• 2–5 km [27] • 5 km [34,26] • 15 km [31,33] • 2-5-15 km [15,25] • 5-15-20 km (Urban-Rural) [52,55,68] • 5-15-45 km (urban-suburban-rural) [54,64]	• Extremely low [33] • Low [28][32,27,46,36–41]	• High [64] • Medium [55] • Medium (AES-128) [59]	• 8 ~ 10 Years [53,54,66] • 8+ years <2 uA [59]	• Low Cost [36] • Medium [28] • $2–5 [64] • <$ 10 [59]	**Network size (scalability), data rate, and message capacity** [26]

Table 2
Other Features of Wireless Communication Protocols in Smart Agriculture.

	Standard	Modulation	Channel Bandwidth	Latency	Topology	Transmission Techniques
ZigBee	• **IEEE 802.15.4** [15,25,26] [31]	• **BPSK (+ASK), QPSK** [52] • **BPSK/OQPSK** [26]	• **2 MHz** [26]	• **16 ms** [27] • **20 ms- 30 ms** [69–72]	• **Multi hop** [30] • **P2P, tree, star, mesh** [26] • **Star, mesh** [73]	• **DSSS** [30]
Wi-Fi	• **IEEE 802.11a, b, g, n** [15,25,26,31]	• **BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM** [30] • **BPSK/OQPSK** [26] • **OFDM** [48]	• **1/2/4/8/16 MHz** [45] • **22 MHz**[26]	• **46 ms** [27] • **50 ms** [69–72]	• **Single-hop** [30] • **Point-to-hub** [26]	• **OFDM** [30]
Sigfox	• **IEEE 802.15.4 g** [26] • **Sigfox** [25,26,31,74]	• **Scarce (narrow band B-PSK)** [74] • **DBPSK(UL), GFSK(DL)** [26,48,58,73]	• **100 Hz** [11,26,71,74]	• **10s** [68] • **1s - 30s** [75]	• **Star** [26,73,76]	• **UL: DBPSK** [77]
NB-IoT	• **3GPP Rel.13** [15] • **3GPP** [11]	• **BPSK** [78] • **QPSK, OFDMA (UL), SC-FDMA (DL)** [58] • **π/2-BPSK or GFSK (downlink) π/4-QPSK (upl.), QPSK (downlink)** [73]	• **180kHz** [75,79] • **200 KHz** [52,60,61,79,80]	• **~1s** [75] • **1.4s - 10s** [11]	• **Star** [73] • **Cellular network** [76]	• **GFSK, BPSK** [77]
LoRaWAN	• **LoRaWAN** [15,25] • **LoRa Alliance™** [11] [31]	• **CSS** [52–54,48,73] • **GFSK** [26]	• **125/250/500 KHz** [11,26,58,59,64,71]	• **~3s** [75] • **10s** [68]	• **Star on Star** [26,54] • **Star** [73,76]	• **CSS** [77]

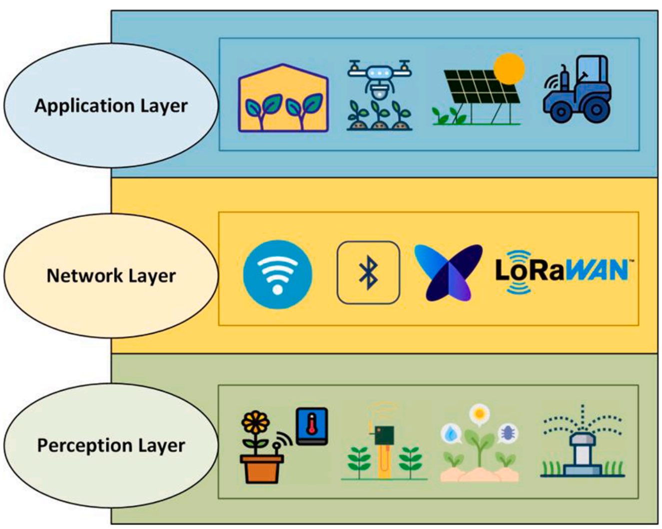

Fig. 2. Layers of a generic smart agriculture system.

[63], Sigfox [97], and NB-IoT [98]. These protocols are used within SA systems that require to connect devices in very large fields. On the other hand, short-range network protocols such as Wi-Fi [98] and ZigBee [99] allow data to be transferred over shorter distances, and are more appropriate for smaller scaled SA systems. Visual comparison of these protocols in terms of range, data rate and energy consumption are given in Fig. 3 and they are detailed by describing their technical specifications in the following sub-sections.

There exist numerous features of these protocols some of which are more significant than others in terms of IoT requirements. For instance, SA applications should be able to handle adequate data transfer rate, also have a large range of coverage because of the high number of sensors spread over the entire field. Besides, it is not practical to provide line power to all of the sensors individually. Therefore, the sensors may be powered by batteries and a high replacement interval for the batteries is desired. As a result, the total power consumption is another key parameter for sensors, which is affected by the power requirement level of the communication protocol used. The operating frequency of a protocol is a parameter that directly affects the other parameters like data rate, coverage, and energy consumption. For example, a high operating frequency is likely to cause more power consumption while allowing for a higher data rate. Like most of the systems connected to the internet, SA systems are vulnerable to possible cyber-attacks. Hence,

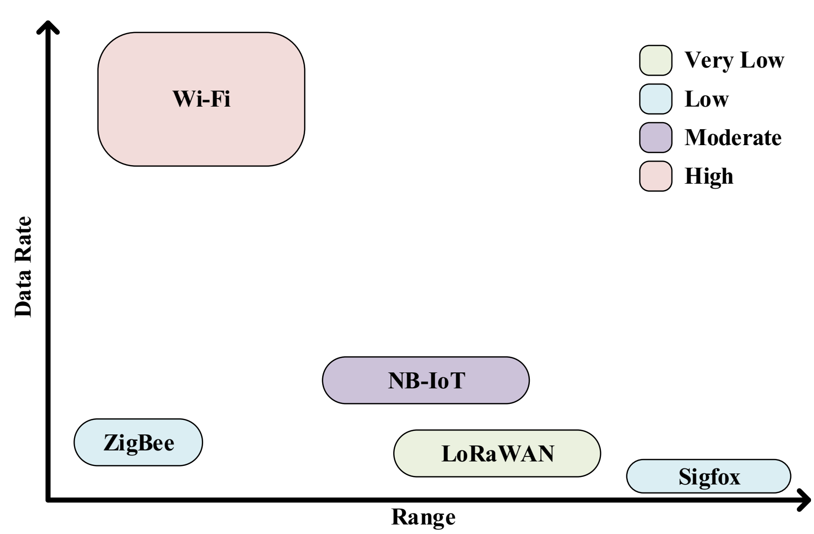

Fig. 3. Comparison of the wireless communication protocols. The power consumption levels are color-coded as shown by the legend on the top right side.

ensuring the security of the system at all layers is an important issue. The properties like power consumption, transmission rate, and coverage are mentioned as the important requirements of an IoT communication protocol in the literature [14,96,100]. Considering these key features, two different tables are created by collecting information from various sources to compare these protocols. The more significant properties involving the key features are collected in Table 1 and the other properties that are less commonly mentioned in the literature are given in Table 2.

As can be seen in Tables 1 and 2, different values for some properties of the protocols are specified in different sources. For example, the specified range for ZigBee changes from 10 m to 120 m according to information collected from different sources [14,15,26,27,31–34]. Similarly, in eight different sources, the minimum and maximum data rates for Sigfox are given in the range between 10 bps and 1000 bps [15,25,46,48,52–55]. The reason for such inconsistent information may originate from various causes. For instance, the specifications of the hardware used for taking the measurements affect the result. Also, the conditions of the medium (like humidity percentage) where the measurements are taken have some influence on the observations. Furthermore, licensed frequency bands for particular communication protocols in some countries may be different. Therefore, even though all other conditions are suitable for achieving a high data transmission range, it may be limited by constitutions of Information and Communication Technologies (ICT). However, the origin of such inconsistent information is mentioned in none of the references in Tables 1 and 2.

In a typical SA system, large number of sensors are involved and they are expected to communicate with the gateway from a distant location. Thus, a higher data rate is needed. In the short-range protocols, a solution to achieve larger coverage area is to add more network nodes to the system, however it increases the network complexity as well as the deployment cost [101]. Among the long-range protocols, Sigfox has the largest range but its data rate is about 1/250 times of NB-IoT and 1/50 times of LoRaWAN which makes it an improper solution for SA systems. By its second largest range, LoRaWAN has a data rate of about 1/5 times smaller than NB-IoT. However, in terms of power consumption and cost, LoRaWAN is superior to NB-IoT.

4.1. ZigBee

ZigBee is a Wireless Personal Area Network (WPAN) communication protocol based on the 802.15.4 standard. It was developed by ZigBee Alliance and its two major properties are being low cost and consuming low power, which make them suitable for home automation and networking [102]. ZigBee offers reliability, cost-effectiveness, security, low power consumption, 16-bit/64-bit addressing mode, and supports star, peer to peer, and cluster tree topologies. It has recently attracted the interest of the research community due to such important features and for the deployment of wireless sensor networks (WSN) [103].

The usefulness of ZigBee protocol for SA was shown in the numerous and diverse applications mentioned in the earlier works. In particular, low-power WSN topologies consisting of multiple sensors as end-nodes and a router for transmitting the data over larger distances may be equipped with ZigBee [19]. For instance, ZigBee-based WSN architectures exist for monitoring the temperature of soil and humidity as well as classifying the content of the soil moisture using deep learning methods [104]. Since the ZigBee hardware is widely available in the market, it is commonly utilized for quick prototyping by being attached to microcontroller boards [105] and single board computers [106].

Despite its common usage in SA, one major drawback of ZigBee is reported to be not having sleep-mode operation [107]. This situation may cause inefficient power consumption, which is a key factor for IoT applications. However, transition between active and sleep modes can be achieved by appropriate programming and hardware. One example can be monitoring of a greenhouse using ZigBee transceiver modules where power consumption analysis are performed for two different durations of sleep period [108]. Another example usage may be a ZigBee network with mesh topology developed for water saving [109]. In that work, the collected soil parameters are effectively transmitted to a distance of 75 m where an aggregation node exists for processing of the received data.

In the context of SA, the main challenge with using ZigBee may be the inefficient power consumption and the low range and data rate features. Therefore, utilization of this protocol is not appropriate when the agricultural land is very large and the distance between the sensor nodes is high. Instead, ZigBee is more suitable for small scaled experimental trial areas.

4.2. Wi-Fi

Wi-Fi is one of the earliest and most commonly used wireless technologies with the particularly IEEE 802.11 standard being released in 1997 [110,111]. It has been recognized as the most promising alternative to the Global Positioning System (GPS) for indoor context-aware and location-based services. It is mainly used in Wireless Local Area Networks (WLAN) through the use of the 2.4 GHz or 5 GHz frequency bands. Its transmission range may be up to 1 km and the minimum data rate is 150 kb/s.

As Wi-Fi is commonly available in many indoor and outdoor locations, it is considered as the first option for various IoT applications of SA like data collection and cloud connection [112] and condition prediction by means of data mining [113]. It may also be used together with other protocols in an SA system. For example, in a hybrid monitoring architecture for SA environment, ZigBee is used in the channels requiring low data transmission while Wi-Fi is utilized for the tasks like surveillance video streaming [114].

Nevertheless, the power consumption level of Wi-Fi is high for several IoT systems. Therefore, utilization of Wi-Fi may not be feasible in all SA systems because the power requirement for Wi-Fi is difficult to be satisfied in outdoor locations. To overcome this shortcoming, there are studies in which external power is provided through in-field photovoltaic solar panels [115]. The appropriateness of solar panel usage was shown by constructing a tree-structured WSN where the collected soil and environmental data at end nodes are transmitted to central fertigation unit. In addition, the power consumed by the nodes was reduced by adjusting the timing configuration of the data acquisition and transmission intervals.

One alternative scenario in which Wi-Fi is utilized can be a smart irrigation system based on soil moisture measurements and weather forecasting [116]. This application architecture involves establishment of a Wi-Fi link between the sensors in the field and a UAV that is used as a water-spraying agent in the system. The weather forecast information was fetched from an open weather API and this information was combined with the sensor data for spraying water to the field.

Even though Wi-Fi protocol is old and mature technology, the major limitation is its high-power consumption. Therefore, it becomes almost impossible to use this protocol when the hardware cannot be connected to main power line. Even though there are some efforts in using solar panels, this brings about the installation and maintenance costs.

4.3. Sigfox

Sigfox is a wireless communication technology that uses ultra-narrowband cellular networks therefore it is capable of performing transmission with low data rate. The cellular infrastructure allows Sigfox to be used in rural areas thereby making it appropriate for IoT and M2M systems [117]. One of the early usages of the Sigfox network was a system for localizing livestock in mountain grassland during the summer season [118,119].

With the help of Sigfox end-to-end communication, it can be possible to divide into various layers namely end layer, backbone layer and sensing layer and allow them to interact with each other to provide the application services for SA [120]. For example, monitor silo and tank levels, measure the temperature of grain stocks, protect remote farmhouses and outbuildings, secure gates and deter livestock thieves, optimize colony health with remotely monitored beehives, monitor food temperatures along the entire cold chain [121].

A water quality monitoring system can be provided as an example application of Sigfox in SA [122]. The architecture of this system takes advantage of two key properties of Sigfox that are operation with low duty cycle and using ultra narrow band. Since the first property results in low power consumption, the system is equipped with a solar panel for charging a Li-Po battery thus yielding an off-grid monitoring system. Furthermore, bidirectional control mechanism and improved security are mentioned as two important features of Sigfox for the monitoring system.

The main advantage of Sigfox for being deployed in various SA applications is reported to be possessing no requirement for additional facilities as well as having high coverage in majority of EU countries. In an irrigation management system developed recently, both Sigfox and LoRaWAN were used [123]. The system architecture was designed for vertical communication to the cloud, meaning that sensors only communicate with a local gateway (i.e. do not communicate with each other). The local communication was accomplished via LoRaWAN while the collected data at the local gateway is transmitted to a cloud server through Sigfox.

Despite its very low power consumption feature, Sigfox has low data transmission speed. In addition, it uses unlicensed ISM band frequencies which is prone to signal inferences and unreliable data transfer [10]. This situation may not be suitable for the agricultural applications where efficient data transfer is critical. For example, an irrigation control application based on continuous monitoring of soil moisture should be obtaining the relevant information on time, otherwise over-or under-irrigation situations may be encountered.

4.4. Narrow Band IoT (NB-IoT)

NB-IoT is considered as the latest radio access technology that emerges from Third Generation Partnership Project (3GPP) to enable support for IoT devices. NB-IoT provides a number of suitable deployment options with a massive coverage range. It coexists with Global System for Mobile Communications (GSM) and long-term evolution (LTE) under licensed frequency bands 900 MHz [62] and it holds a frequency bandwidth of 200 kHz [79]. It offers long battery life, excessive coverage area, low cost and high network security [124].

Two successful application examples of NB-IoT in SA can be given as livestock tracking and monitoring of environmental parameters in a greenhouse [125]. The architecture of the livestock tracker system enables instant reporting of the livestock location together with the system parameters such as the battery level. The location information, which can be determined via mobile networks or satellite systems, may also be useful geo-fencing applications. In the greenhouse monitoring system, the architecture contains many sensors to collect and monitor detailed data such as water pH level, light intensity and energy consumption. The system can run on batteries and features a two-way communication scheme for enabling firmware and software upgrade. The properties that make NB-IoT a suitable protocol for various SA systems may be extensible coverage, half-duplex communication, flexible power consumption based on the mode of operation, and improved security.

One other example SA architecture in which NB-IoT is utilized can be monitoring of a paddy storage [126]. The humidity information in the paddy bags was measured by pin sensors and this information is transmitted to a gateway using NB-IoT protocol. It was shown that a 10,000 mAh lithium polymer battery was able to run the system for 48 h.

Even though NB-IoT offers higher data rate than Sigfox and LoRaWAN, it uses licensed frequency bands which brings about subscription costs to the related system. Another source of cost for such a system may be the requirement of hardware upgrade when there is an existing LTE infrastructure [10]. In the context of smart agriculture, this may be a limitation when the reserved investment costs are not high enough to afford these costs.

4.5. Long-Range wireless area network (LoRaWAN)

LoRaWAN refers to a network layer protocol created by the LoRa Alliance and runs on LoRa chips. It uses the advantages of LoRa modulation to create networks, and it is focused on the IoT paradigm. LoRaWAN uses a star topology where the nodes, collect the sensor data and send it to the gateways. The gateways convert these data to a form that can be transferred via internet protocol (IP) and then forward it to a remote application server through the Internet. It has been specifically designed for IoT applications to connect a huge number of sensors, and appliances over a network spanning large areas.

The LoRaWAN architecture can be divided into two parts as front-end and back-end [95,127]. Gateway elements and end-node devices constitute the front-end part. On the other hand, the critical tasks like security assurance, data storage and query scheduling are performed by the network servers that are involved in the back-end part [128].

LoRaWAN is widely used in smart city applications because such applications require wide network coverage; however, its usage in other social aspects is getting more widespread. The investments for LoRaWAN infrastructure by governments and private operators started to be realized in the last four years in different countries [129]. LoRaWAN is commonly utilized in variety of SA application areas including weather forecasting [130], irrigation control and farm monitoring [14].

One notable feature of LoRaWAN is low power consumption, which makes it an ideal choice for SA systems. In the presence of solar-based energy harvesting capability, it was experimentally shown that the estimated battery lifetime of a LoRaWAN unit may be six times of a Wi-Fi unit and two times of a ZigBee unit [33].

An IoT architecture having dynamic number of layers for different application and computation scenarios was proposed earlier [131]. This dynamic structure was shown to be appropriate for various smart systems including SA. Experiments with different scales of SA were performed and it was reported that a message traffic of 1500 messages/minute can be handled by LoRaWAN protocol.

In another LoRaWAN-based SA architecture, a middleware layer exists at the center and this layer improves scalability of the system by allowing various modules be attached to it [132]. Ease of deployment and modularity features of LoRaWAN were provided as the leading reasons for using this protocol. Reliable data transmission was observed during the field experiments performed for three months.

Like Sigfox, LoRaWAN uses unlicensed bands and has the same security issues. In addition, it is known that LoRaWAN has a poor performance when direct line of sight is not available between the transmitting and receiving modules [10]. This situation may be a major drawback for those SA systems deployed in rural areas with uneven terrains.

5. Wireless communication protocols used in various smart agriculture applications

The developing nations have majority of their Gross Domestic Product (GDP) dependent on agriculture [133]. Agricultural activity extends from crop cultivation (farming), timber to livestock rearing for domestic consumption or economic purposes as raw materials to other activities. It is expected that there will be a vast food crisis in the near future because the estimated world population for 2050 is 9.7 billion [134]. To overcome this situation, investments in the development and deployment of IoT systems particularly in farm automation and SA have been increased. Even though there is a diverse range of applications of IoT in agriculture, the most common ones may be listed as follows:

1) Automated irrigation systems for saving water and time [135,136].

2) Collection of environmental data for weather condition forecasting [137].
3) Soil condition monitoring for yield maximization [138–140].
4) Crop monitoring to reduce costs [141].
5) Pest management for preventing diseases [142,143].
6) Utilization of renewable energy sources for cost minimization and sustainability [144,145].

There are numerous research activities in each of these fields and in the following subsections, the related works are collected according to their area of applications. The relevant references in which the utilized communication protocol is explicitly provided are summarized in Table 3. It should also be noted that only the studies published since 2015 are included in Table III.

5.1. Water saving

The efficiency of food production requires precise amount of irrigation in agriculture; however, the increment in the need for water eventually results in the relevant risk of its scarceness. It is also known that 70% of the freshwater in the world is required for irrigation of agricultural plants [384,385]. Therefore, efficient usage of the water resources is a critical task.

To avoid decrements in the yield amount due to water stress, the farmers generally tend to apply extra water. Obviously, this situation will have a negative impact on the productivity while consuming extra water and energy than needed. Besides, over-irrigation may cause some water-related diseases as well. Thus, in turn, SA makes it possible to use optimal amount of water, avoiding both under- and over-irrigation.

Simultaneous accomplishment of three key properties that are increasing crop yield, decreasing costs, and maintaining environmental sustainability has been the focus of the project “smart water management platform” (SWAMP). Development and performance assessment for hands-on applications of precision irrigation within this project were performed in four pilot areas in three different countries namely, Brazil, Italy and Spain [386]. FIWARE, an EU-funded IoT project in which solution libraries for smart applications [387] and precision irrigation [388], forms the basis of SWAMP project. It also has some common features with alternative smart agriculture initiatives such as “Flexible and Precise Irrigation Platform to Improve Farm Scale Water Productivity” (FIGARO) project [389] that aims at improving water efficiency while minimizing costs through a smart irrigation management platform. In order to outline the challenges and constraints of deployment of such IoT based large-scale pilots, Brewster et al. discuss several issues including technological and connectivity problems. They indicate that LPWAN technologies (such as LoRaWAN and SigFox) may be useful to overcome the issues related to coverage [390].

The majority of the studies collect and utilize environmental and weather related data such as temperature, humidity, soil moisture, and water level [234]. Among the studies concerning water savings, Andre et al. developed an irrigation system to optimize the irrigation timings [235]. This system is based on WSN for real-time collection of environmental data and LoRaWAN is suggested as the suitable protocol for the system. Another way to save irrigation water is to apply water locally to the required parts of the fields. A rule-based method is developed by Masaba et al. in which the dry parts of the field are determined via temperature, humidity and soil moisture readings [391]. This system utilizes BLE technology to establish connection between the sensor nodes at locations with no internet connection. Noha Kamal et al. design an IoT based water quality monitoring system for continuously measuring some parameters such as pH, turbidity, and temperature of River Nile [173]. The system is said to be suitable for deployment in irrigation canals of River Nile for optimal irrigation. Besides, the cloud connection of the system is established using Wi-Fi and extension for GSM protocols are suggested as future work.

As an example application of livestock management, Tanumihardja et al. designed a monitoring system for observing water level in troughs. The system employs a WSN that uses LoRaWAN as the wireless communication protocol [236]. It allows cattlemen to monitor their trough ubiquitously via mobile devices. A Raspberry Pi single board computer was used as a gateway to send the data to the server. Since the potential users of the system (i.e. the cattlemen) have possibly minimal familiarity with technological devices, it is designed to be self-configuring. To achieve low power consumption and remote access requirements, ATMega-based microcontrollers are in the sensor nodes that contain float switch sensors to measure the water level.

5.2. Weather forecasting and data analytics

Measuring and monitoring the weather-related parameters is an important task in agriculture since sunlight and rainwater are critical for photosynthesis and hydration of the plants. Hence, plant growth highly depends on the weather conditions. The unpredictable weather is one of the causes of the problems encountered by the farmers that eventually results in reduction of production and profit. Thanks to novel data analytics methods, it is possible to perform weather forecast by using historical weather data. As a result, it becomes possible for the farmers to get prepared for various unwanted cases such as pesticide poisoning or irrigation just before the rain. For example, if the measured soil moisture is at a level which an irrigation activity is required and a rainfall is expected in a short time period, then the farmer may choose not to initialize the irrigation.

One reason for performing weather forecasting or soil condition prediction is to achieve water savings. Various smart irrigation frameworks are developed by means of soil moisture [392] or soil water requirement [146] prediction to manage the irrigation scheduling.

Fraga et al. described a smart irrigation system that addresses limitations of urban areas such as not having direct access to the internet or electric grid [130]. They propose an architecture based on LoRaWAN to make communication with sensors and fog nodes. Eventually, optimal

Table 3
Wireless Communication Protocols and Corresponding Smart Agriculture Applications since 2015.

	ZigBee	Wi-Fi	Sigfox	NB-IoT	LoRaWAN
Water Saving	[106,146,147–172]	[9,46,106,173,169,170,174–224]	[122, 123,225]	[226–233]	[123,234,235,236,170,237–263]
Weather Forecasting and Data Analytics	[264–269]	[116,174,194,206,210,215,264, 270–275]		[229,276, 277]	[101,130,278,238,258,260,272, 279–288]
Soil Condition Monitoring	[88,89,106,114,139,289,153,165, 167,205,208,262,266,268, 290–301]	[9,104,106,114,289,174,176,187,190, 199,200,210,212,217,220,224,275, 302–322]	[217, 323]	[229,231, 324–326]	[93,132,234,238,250,251,254, 256,260,263,283,285,286, 327–339]
Fertilizer Optimization	[88,139,165,205,293,301,340, 341]	[106,115,195,212,310,312,315,321, 342,343]		[227]	[254,259,344,345]
Crop Disease and Pest Management	[106,294,346–348]	[106,349–354] [213]			[238,254,344,346,355–357]
Energy Harvesting	[33,145,156,158,253,358–364]	[33,190,200,204,217,303,365–370]	[122]	[371–373]	[33,132,253,356,364,367,368, 373–383]

irrigation schedule and weather forecasting tasks are accomplished.

Predicting a future value generally requires utilization of some machine learning methods [278]. Braga et al. make use of gradient boosting, random forest and deep learning to forecast evapotranspiration, a measure of water loss from the plant [393]. Another method based on support vector regression and k-means clustering is developed for prediction of soil moisture changes as a response to the weather conditions [289].

Even though the majority of the studies about forecasting uses LoRaWAN, there are other works based on the other communication protocols such as ZigBee [394], BLE [395], and Sigfox [396].

5.3. Monitoring of soil moisture, mineral and pH levels

The plants need water as a vital resource to live, grow, and reproduce. The water requirement of the different plant species may vary from one another. One common way to identify the water requirement of a particular plant is attachment of a sensor for measuring the soil moisture and the water content in the neighboring area [397–400]. Such a measurement enables the farmer be informed about the water content and hence be able to determine if an intervention is necessary. In addition, actuators (e.g. solenoid valves) can be automatically controlled by programming electronic hardware to which the sensors are connected [243]. If a low humidity level is detected by the moisture sensor, this data is processed and sent to the solenoid module as a control signal to provide the necessary water automatically.

Potential of hydrogen (pH) is a measure affected by the amount of different minerals present in the soil. Some examples of these minerals are nitrogen, potassium, calcium, iron, and sulfur where nitrogen and potassium being important minerals for the growth of the plant [401]. The pH level changes between 1 and 14 where increment in pH value indicates transition from high acidity to high alkalinity. The range of pH between 5.5 and 7.5 is said to be optimum for most plants for a proper growth [402].

ZigBee is one of the commonly utilized protocols particularly in the systems involving soil moisture sensing [403] and environmental data together with pH levels [297]. However, LoRaWAN is used in a WSN irrigation system in conjunction with aerial image processing where data transfer over longer distances is required. The system is intended for monitoring of agricultural parameters in cacao crops by providing information about weather, ground conditions, and water flow and pressure through a mobile application [330]. Monitoring of soil characteristics including pH level and data transfer over short distances via Bluetooth is another alternative solution for such applications [404].

5.4. Fertilizer optimization

Fertilizer can be defined as the substance containing key nutrients for plant growth. These nutrients may be important for particular parts of the plants. For example, nitrogen contributes to leaves; phosphorus is critical for root, flowers and fruit; and potassium is important for water movement through the stems [405]. Any lack or abundance of nutrients may lead to serious undesired effects on the plants. Therefore, applying correct type of fertilizers in optimal amounts is important since their uncontrolled usage may cause imbalance in soil nutrient levels. This situation may also contribute to climate change by triggering deforestation [120,406]. Nevertheless, an efficient fertilization practice requires determination of missing nutrients, fertilizer amount to be applied, and appropriate place for fertilization [407]. Satisfaction of these requirements needs to be done carefully and for this purpose, special fertilization methods using IoT have been proposed in the recent years.

The latest IoT applications for fertilization systems aim at automatic prediction of the areas with lack of nutrients in the fields [310]. Such a system allows for optimal usage of fertilizer resources by offering the possibility of consuming the fertilizer only on the required locations in the field. This optimization can be further improved by combining the fertilization process with the irrigation system [151,408–410].

Utilization of other technologies is possible in the fertilization systems. In particular, images collected through UAVs or remote sensing are useful for calculation of the normalized difference vegetation index (NDVI) that reflects important measures like crop health, vegetation amount and nutrients in the soil [29,411,412]. Hence, they allow for location-based determination of fertilizer requirements.

Recently, NB-IoT protocol for smart fertigation is utilized in a tomato greenhouse [227]. The related system design involves integration of irrigation and fertilization. The required amount of fertigation is automatically determined according to instantaneous greenhouse data. Eventually, yield increment, as well as water and fertilizer usage improvement, are achieved.

In a relatively older work, several issues such as irrigation, fertilization and management are addressed particularly in citrus cultivation. The related project is based on measurement of citrus soil moisture and nutrients using ZigBee to develop a system in which fertilization and irrigation are automated and integrated [88].

5.5. Crop disease and pest management

Like inappropriate amount of water or nutrients in the soil, pests are one of the other factors having impact on the crop yield quantity and quality. In particular, pests may cause diseases and hence, prevent the plant from a healthy and productive lifecycle. Therefore, timely detection of the threats caused by the pests is important for minimizing the crop loss. This detection process can be accomplished by IoT systems in which the data collected by the sensors is processed appropriately for pest detection.

One successful application can be provided as usage of satellite imagery [413] or UAV systems [414] for determining the location-based health status of the crops in the large fields. Additionally, smart traps successful applications of IoT-based pest management because they are capable of capturing, counting and identifying the insects automatically [415,416].

Optimal usage of insecticides is another important issue under this topic because their inappropriate usage may not provide complete prevention or may be harmful to the plant while killing the pests. In an earlier work, a disease and pest prediction system, which aims to warn the farmer when there is a risk of pest attack, was developed [417]. This system was tested by collecting numerous environmental data in an orchard and it can be helpful for applying appropriate amounts of insecticides on time.

An infection prediction method is developed as a part of an integrated smart farm management system [355]. The system involves a network framework in which a reliable communication between the IoT devices is ensured through LoRaWAN protocol. The prediction algorithm is tested on strawberry cultivation as a part of the system for estimating the occurrence frequency of pests infecting crops.

In another work developed for pest prevention in potato plants, climate data collected through low-cost sensors placed inside the farms is processed to generate a decision support system [347]. ZigBee protocol is used by the sensors for wireless communication within the system.

Furthermore, an early monitoring and control system against epidemic diseases in potato and tomato crops is proposed [418]. Such kind of system provides environmental monitoring data that maintain the growth of crops and predicts the conditions that lead to epidemic disease appearance. Since a typical agricultural area is very wide, the developers preferred to use cellular services due to its relatively long-range and robust wireless communication links. The system is proven to be efficient in optimizing the total amount of applied chemicals and improving the quality of crops.

On the other hand, image-based disease detection systems exist. In one of such works, the detection system utilizes image compression methods to decrease the total data sent to the cloud. The detection algorithm is based on segmentation methods together with support vector machines (SVM). The hardware part of the system involves Raspberry Pi as the single board computer, and the built-in Wi-Fi module is used to establish the cloud connection [351].

5.6. Energy harvesting

IoT devices and sensors are intended to work in distant areas where the line power is not readily available most of the time. This case is true for particularly SA systems. Besides, usage of batteries is not feasible because regular replacement or recharging of the batteries are required. Therefore, alternative methods for supplying power to such components need to be clearly defined. Some of the methods for providing power to IoT hardware include extracting energy from environment through specific circuitry. These methods utilize various aspects such as vibration [419], thermal energy [420], radio frequency [421], and solar energy [422].

Even though the majority of the previous studies on energy harvesting in SA systems are related with solar energy [190,423,424], some other works based on radio frequency are present [425]. Among the systems that utilize solar energy, LoRaWAN and ZigBee are the commonly used protocols.

A prototype device including a solar panel is designed and manufactured in order to collect and transmit data in a SA system [378]. The device uses LoRaWAN protocol for communicating with other components in the farming system. This work investigates the limitations of LoRaWAN and determines some network parameters like data rate and latency.

In another work, sensor nodes are powered with solar energy to take measurements from the environment and ZigBee protocol is used for communication between the nodes [145]. The performance of the solar-powered sensor node is compared with a non-solar one. It is shown that utilization of solar power increases the battery lifetime.

Solar energy is also used for battery charging purposes in SA systems to use that energy at a later time when the available energy is limited [361]. Lifetime of a WSN is maximized by addressing the related issues such as unstable energy harvesting and low panel conversion efficiency. Validation of the system is performed via a simulation environment in which 20 sensor nodes are placed and their communication is established with ZigBee protocol. The simulation results show that the lifetime of the sensor node as well as network throughput increases with the system.

6. Open issues and challenges

Deployment of SA systems with various scales are facing with various challenges that need to be overcome for efficient utilization of the technology in the future systems. Regardless of the raise that IoT has achieved over the last few years, various theoretical and practical challenges restrict its proper management and performance. These challenges are given in detail in the remaining part of this section.

6.1. Cost

Some of the cost issues can be specific for SA while others are related with general IoT systems. For example, sensors and gateways in an SA system may be expected to operate in harsh outdoor conditions in general. This situation will bring about extra concerns and costs about their manufacturing. In particular, some electronic equipment may require being water and dust resistant by fulfilling standards like IP68.

Other than the manufacturing costs, IoT components such as sensors, gateways and base station infrastructure may constitute majority of the hardware cost related with communication systems. This specific communication hardware is expected to meet the system requirements which directly affects the cost.

In order to preserve the reliable operation of the SA system over longer durations, maintenance must be performed on a regular basis. Therefore, the maintenance costs need to be considered during the feasibility studies before the deployment. Besides, one other source of operational costs may be the necessity of subscriptions. For example, NB-IoT protocol operates at licensed cellular frequency bands. This necessitates usage of service provider infrastructure and dedicated hardware both of which increase the deployment and operational costs. However, other protocols operating at unlicensed frequency bands do not have such drawbacks about the cost.

One final source of the cost may be due to the large amount of data generated. Obviously, collection, transmission, and storage of the system data in a reliable way is critical for efficient operation of SA systems. Furthermore, processing the data for making smart decisions to increase the yield requires usage of server computers with high computational power. Most of the times, this is accomplished by a paid subscription to a cloud server provider. The type of the subscription needs to be decided concerning the communication protocol used by the IoT system in the farm. The reason for such a concern is the maximum data rate offered by the protocols are different and at the same time, allowed download/upload limits depend on the type of the subscription. As a result, these limits should be consistent between the protocol and the subscription to ensure an effective and reliable data transfer.

6.2. System security

The gaps in the security system may cause several consequences like permanent loss of data and modification of data so that its reliability becomes debatable. On the other hand, unauthorized access to the secure data can result in privacy issues and eventually yield a reduced confidence in the customers. As a result, SA companies may be financially affected by the lack of security in their cyber systems.

In addition, one other serious threat may be the access of the third parties to the in-field physical devices. The device control being captured by the attackers may cause loss of the crops or plants if inappropriate treatment of necessary elements are applied in an uncontrolled way [426–428].

One major factor that increase the vulnerability of an SA system is having hardware components with limited computation and memory features. Therefore, it becomes infeasible to run complex attack-prevention algorithms as well as cryptographic algorithms on these devices [29].

There are different criteria that can be used for classification of vulnerabilities and risks in an IoT system, or more specifically in an SA system. One strategy for categorization of the treats may be considering the security issues in each of the layers of an SA system. Since the devices and protocols used in each layer is different, it is obvious that vulnerabilities associated with these layers require specific attention [429].

On the other hand, issues and limitations related with software and hardware of the IoT components may be source of the vulnerabilities [430]. In particular, the source of the vulnerability may be originating from the encryption standard used by the wireless communication protocol as well. For example, old version of Wi-Fi Protected Access (WPA) security standard is a well-known source of vulnerability. In a ZigBee network, the attacks may be targeting different layers of the communication. Adding malicious contents by eavesdropping on the radio channel or overwriting the memories of the nodes by adding a malicious node to the network can be given as two possible threats in a ZigBee network [431]. On the other hand, LPWAN technologies are reported to be vulnerable to threats like packet forging and replay attacks [432]. These issues are known to be originating from message integrity code (MIC) or sequence number (SN) protected by message authentication code (MAC) being short, which may eventually result in denial of service (DoS) or message injection.

In general, overall vulnerability of IoT systems is caused by the lack of compliance with the security standards or security recommendations made by the official authorities. It should also be underlined that the responsible behavior of all entities in production and supply chain is required for a complete security assurance in IoT systems. Unethical behavior of any entity (e.g. a non-standard manufacturing for cost saving) may hurt the security [433,434].

The risk of being cyber-attacked increases together with the level of vulnerability. Nowadays, the cyber-attack incidents are progressing in the agriculture sector due to excessive usage of digital devices that are continuously connected to the internet. The consequences of cyber-attacks in agricultural sector may cause human-related or financial problems. Some of the many examples can be given as disruption of delivery, snatching of private data such as confidential formulations and demographic information of the employees [435].

One strategy to enhance cybersecurity and mitigate the risks in SA is to utilize blockchain technology which allows shared control of a distributed ledger in a decentralized network [436]. The blockchain applications may be useful in an SA ecosystem by means of recording and tracking of the entire food production process [437]. By securing the details of the production steps such as breeding, fertilizing, processing, transporting, and warehousing, it becomes possible to provide confidence, ensure compliance with standards and resolve the possible problems.

6.3. Communication quality

Ensuring an uninterrupted communication in an SA system is important because sensor data should be collected consistently for a reliable smart decision system. Besides, status of the in-field actuators need to be checked and monitored continuously to prevent undesired situations. For example, monitoring of the status of a solenoid valve is important for preventing flood or over-irrigation situations.

There are various factors affecting the quality of wireless communication in SA applications as the components are expected to operate under outdoor conditions. Therefore, it is necessary to protect the hardware from being damaged by the weather events like rainfall and wind. Even though the protection unit increases the deployment cost of the system, this will not only reduce the maintenance costs but also contribute to the quality of the communication in longer times.

One other factor constituting a risk for communication quality is interference, which can be defined as distortion of a useful signal by some other signal. Therefore, an ambient containing numerous different signals simultaneously is prone to interference. In a smart farm equipped with many wireless sensor nodes as well as gateways, the possibility of interference is high and this situation is an obvious challenge for a reliable communication. The risk of interference is higher for the protocols using unlicensed frequency bands such as ZigBee, Wi-Fi, Sigfox, and LoRaWAN. On the other hand, the protocols like 5G and NB-IoT that use cellular networks with licensed frequency spectrum have lower possibility of interference. However, utilization of these systems require extra costs for hardware infrastructure and subscription [52].

6.4. System design and hardware optimization

Any redundant hardware will increase the investment as well as the maintenance costs in a system, eventually yielding profit decrement in the agricultural sector. Therefore, it takes a careful design process to determine the number and type of the sensors together with the gateways in an SA system. The system design and the protocol to be used are mutually affected by the parameters like the distance between sensors, total data transmission rate over the wireless links, and the power consumption at the sensor nodes. Obviously, this is a complicated optimization problem where many constraints should be taken into consideration.

7. Future Trends

In the SA systems, collective utilization of various technologies is emerging. This situation is observable in the recent publications about SA and IoT. In the following subsections, the expected future trends in SA applications are elaborated by mentioning the technologies for data collection, data processing, and data transmission.

7.1. Aerial systems and satellite communications

The sky-level observation of the agricultural fields has been made possible by the developments in the aerial technology. Since such observations allow for larger areas of the field to be inspectable simultaneously, various contemporary applications utilizing aerial systems have emerged in the last decade. While the earlier efforts in this domain focused on simple tasks like remote monitoring and observation [438,439], later applications involve more sensitive measurements such as crop yield mapping [440], pest management [441], vegetation index calculation [442].

The agricultural data collected at high altitudes primarily contain the images or videos of the field as well as the GPS-based coordinate information. These images may be regular RGB, thermal, infrared, multispectral, or hyperspectral images depending on the type of the application. Therefore, processing of these data in a collaborative manner to perform a specific task can be considered as a promising research area.

The aerial data collection from the fields may be performed through different means among which UAVs [24,443] and airships [444] are common. These vehicles may be operated either manually by a remote control or automatically by loading specific missions to the vehicle. In both cases, wireless data transmission between the vehicle and the ground station or the satellite systems may be required. In the manual operation, the control signals are received from the remote control used by an operator. This means that the vehicle needs to be inside the coverage region of the remote control during the entire operation. Whereas in the autonomous operation mode, the location of the vehicle is typically controlled by the GPS signals which require an active communication with the related satellites. Therefore, it can be understood that a wireless link to a reference device is crucial for a reliable operation of the aerial vehicles. The features like controlling the vehicle over vast distances or maintaining a safe flight in case of an interruption in the GPS signal can be considered as important future applications under this topic.

Besides, it was recently reported that a multi-UAV system may be more efficient than a single UAV in accomplishing multiple tasks [445]. Therefore, a real-time wireless communication between the UAVs should be established and maintained to ensure a high degree of coordination in the system. Since the UAVs are expected to move in a collaborative manner, an ad-hoc networking architecture is expected to be developed for such systems. Despite some recently proposed ad-hoc architectures for routing data packets among the UAVs, design of multi-UAV communication systems is very critical for future applications.

Satellite imagery can be considered as another solution for agricultural monitoring and data collection. The availability of very high resolution (VHR) and near-infrared (NIR) images make it possible to improve agricultural practice through weed and pest detection, yield calculation and irrigation planning [446–448]. Even though this technology does not require a vehicle to fly over the field, the access to a satellite may require a higher overall budget.

Advantages of aerial systems are unquestionable in the challenging environmental conditions of SA practices. With their properties like easy operation and high mobility, aerial systems can contribute to high-quality data collection, system scalability, and eventually increments in profit.

7.2. Fifth generation cellular communications

With the emergence of fifth generation (5 G) cellular communication technology, it has now become possible to provide fast and reliable internet connection to components of SA systems. As a result, smart farm requirements like large amount of data exchange, low energy consumption and, wide coverage can be satisfied by utilization of 5G. It is also worth mentioning that the existing cellular network availability in rural regions is very limited. This problem is addressed by deploying 5 G infrastructure in the rural areas and hence, performing labor-intensive tasks like planting, harvesting, fertilization and irrigation with minimal manual intervention [449]. Accomplishment of such tasks requires usage of 5 G remote sensors allowing seamless data transfer which enables continuous monitoring, data collection and control [450].

As the future applications of 5 G in SA increase, the volume and variety of agricultural data will increase which eventually push research activities on big data analytics methods. Besides, the possibility of connecting the individual farms will allow for efficient usage of resources by managing the smart farms in a collaborative manner. Another impact can be the reduction in the need for human labor force because accurate crop inspections can be performed through 5 G supported systems.

One area of wireless communication commonly mentioned together with 5 G technology is machine-type communications (MTC) in which the data transmission between the sensors and IoT appliances is performed with no human intervention. Provided that the system is initially designed for MTC requirements then 5 G may be a suitable solution as it allows for reliable communication in remote areas which is usually the case in SA [451,452]. Besides, MTC can be used suitably with Sigfox [453] and NB-IoT [454], which are known to be suitable LPWAN protocols in SA.

7.3. Big data analytics, cloud and edge computing

Enhancement of crop quality and quantity requires continuous collection of in-field data and monitoring of the plant status. Therefore, from the initial sowing and cultivation phase until reaching to the final consumer, various types of data are collected in the domain of SA. As a result, the total amount of data with various types becomes very large. Descriptive data such as chemical attributes of the soil, satellite imagery reflecting the physical characteristics of the farming area, aerial images collected using UAVs, and structured data from IoT sensors are some examples of these data [455].

This type of data is typically named as big data, which requires specific hardware and methodologies for being processed. The clustering and classification methods as well as rule based learning methods are some of the strategies useful in processing of big data [456]. Particularly, artificial neural networks (ANN), support vector machines (SVM), discriminant analysis and decision trees are reported to be useful methods for this purpose [457,458]. However, these algorithms cannot be executed on regular computers. Due to the large amount of data, this processing should be performed on distant cloud computers having suitable hardware to handle the big agricultural data [459]. This situation can be considered as another pushing factor for the emergence of fast and reliable communications protocols being used in SA because transmission of the big data to the cloud computers is infeasible with slow internet technologies with small coverage. The concept of edge computing is worth discussion at this point because it mainly aims at reduction in the total amount of transmitted data to the cloud. In other words, it becomes possible to save bandwidth by reducing the network traffic. This is accomplished by pre-processing the collected agricultural data at local edge devices before being transmitted to the distant cloud computers. The pre-processing computation performed at edge devices, namely edge computing, outputs the required data for the cloud computing. Therefore, only the data necessary for cloud computing is transmitted through the network. The steps of edge computing may involve different data compression or dimensionality reduction methods to decrease the amount of data. Since the computational load of edge computing is not as high as cloud computing, the edge devices may be hardware with limited computational capabilities such as single board computers or microcontroller boards.

Edge computing has high potential for contributing SA in various domains such as increased crop production, farm security, and food supply chain. However, services based on edge and cloud computing are not mature enough for being adopted in SA [460].

7.4. Infrastructure for LPWAN technologies

The LPWAN protocols operating at licensed frequencies require installation of relevant infrastructure for being used actively. In addition to their main features like low power consumption and having wide range, they offer more reliable data transfer, which is a critical feature for SA systems. Among them, NB-IoT can be noted as an emerging technology as the investments made by industry as well as interest from the academia to NB-IoT are on the rise [120]. As a result, increments in the studies for widening the coverage of LPWAN protocols are expected in the near future.

On the other hand, the major limitations of short-range protocols such as power consumption and coverage are the issues addressed by LPWAN technologies. LoRaWAN protocol contributes to LPWAN technologies by providing additional advantages such as scalability and security for SA systems [461]. Since the required infrastructure for LoRaWAN is relatively simpler than NB-IoT, the related hardware is easier to install and use.

7.5. Efficiency in energy harvesting and consumption

Since the majority of SA components are required to operate in remote areas, most of the time, it is neither possible nor feasible to provide on-grid power to all elements of an SA system. The efforts for finding a solution to this situation have concentrated on two main topics that are (*i*) minimization of power consumption in IoT devices, and (*ii*) energy harvesting from environmental conditions.

Low power consumption can be achieved by optimizing the circuit design of the sensors for application-specific purposes. In addition, frequency and duration of sleep mode operation may be adjusted for efficient energy consumption. Furthermore, development of dedicated communication protocols consuming reduced power during data transmission is another topic that may be important for future applications. However, in general, such protocols achieve reduction in power consumption at a burden of smaller overhead thereby resulting in a decreased security and reliability.

On the other hand, utilization of renewable energy sources, particularly solar energy, is expected to be more widespread because they provide off-gird energy to the system. One limitation of photovoltaic systems may be the lack of energy generation during nighttime and cloudy weather. Therefore, advancements in the energy storage technology, as well as the smart gird systems for efficient utilization of energy in a collaborative manner, may be expected in the future.

7.6. Protocols and application areas

In the current state of SA applications, most of the studies are small scaled examples that contain testing of different communication protocols and IoT hardware. Thus, it is necessary to deploy large-scaled systems to be able to evaluate the usefulness and generate feedback information for future development of practical SA systems [390].

The fast-evolving technological aspects have an impact on changing our daily habits by making various possibilities to emerge during the years while causing some others to lose their importance and popularity. A similar situation is true for the application areas and the utilized communication protocols in SA systems. To support this statement, various distributions of the papers in Table 3 are investigated. These distributions are generated by categorizing the papers according to their publication year in addition to the area of application and the utilized communication protocol. As a result, it became possible to understand which communication protocol and which application area are emerging in the recent years. In other words, these distributions allow for highlighting not only the most common application areas and protocols but also how their domination change over the years. Thus, it becomes possible to generate a future perspective using the current trends in SA. For this purpose, two pie charts and two 3D bar graphs are generated. Specifically, the charts in Figs. 4 and 5 show the percentage of papers utilizing the specified protocols and their application areas, respectively. More detailed year-based distributions, which are useful for understanding the trends, are provided by the bar graphs in Figs. 6 and 7.

It is clear from Fig. 4 that Wi-Fi is the mostly used protocol and it is followed by LoRaWAN and ZigBee. Majority of the studies use these protocols whereas the percentages of the other two protocols (Sigfox and NB-IoT) are about 1/10 times of these dominating ones. Besides, more than 60% of the studies in the literature are about either water saving or soil condition monitoring. The next popular application area is energy harvesting, yet its percentage is around half of soil condition monitoring as can be seen in Fig. 5.

The annual distribution of total number of studies has an increasing trend (Figs. 6 and 7). When the protocol-specific distribution in Fig. 6 is inspected, it may be seen that ZigBee is present in all years, and Wi-Fi and LoRaWAN are absent in only one of the years. However, total number of usages for ZigBee and Wi-Fi decrease in 2018 and 2019. On the other hand, LoRaWAN can be seen as an emerging protocol as its usage increased in the last five years. Other LPWAN protocols, Sigfox and NB-IoT, appear only in recent years with a very limited number of usages. The application-specific distribution in Fig. 7 shows that number of soil condition monitoring applications increases until 2018 but it starts to decrease in 2019. Nevertheless, the other widely used application, water saving has an increasing trend since 2015. Besides, energy harvesting applications are present since 2016 and its rate has increased in the last three years.

In addition to analyzing number of papers, it is also useful to compare the percentages of papers according to recent years. In Fig. 8, annual rates of the protocols are provided while the rates are given for the application areas in Fig. 9. It is obvious that domination of ZigBee and Wi-Fi is affected by the emergence of LPWAN technologies in 2018 and 2019. In particular, usage of LoRaWAN is on the rise as it has about 30% of share in the last four years. On the other hand, the rate of studies about water saving and soil condition monitoring has the highest values in the recent years. However, share of water saving slightly decreased after 2017 as a result of increments in investments for efficient usage of energy resources.

According to these distributions, it may be concluded that LoRaWAN is the promising protocol for SA and the applications for economic usage of resources (i.e. water saving and energy harvesting) are on the rise. These inferences are consistent with the ultimate goal of efficient usage of world resources. In addition, Wi-Fi still stands as a popular short-range protocol due to its common availability.

8. Conclusion

In this paper, utilization of five different wireless communication protocols in various smart agriculture applications has been surveyed. The benefits offered by these protocols for six different application areas are highlighted and example case studies in these areas are provided. The focus of the study has been given to those protocols that are commonly used in IoT systems for wireless communication. The application-specific suitability of the protocols is discussed considering

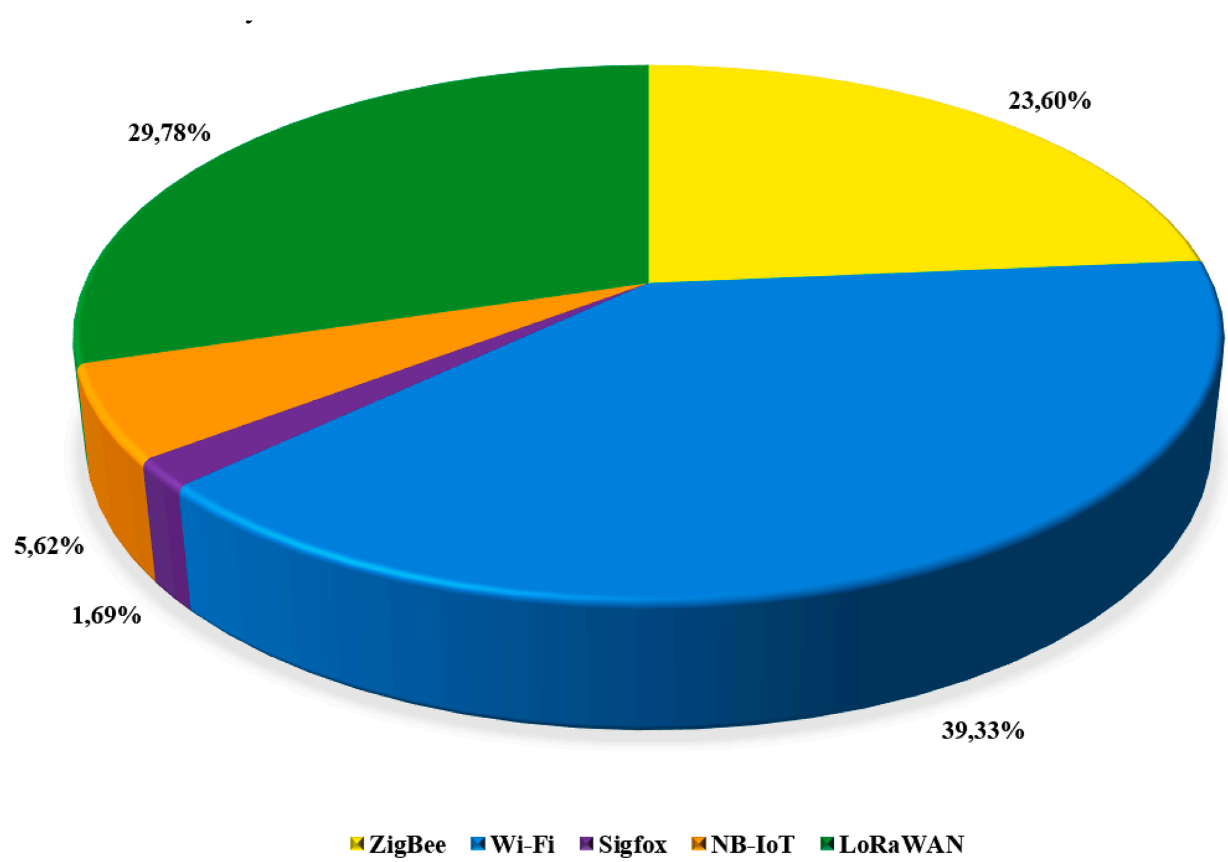

Fig. 4. Distribution of the papers according to communication protocols.

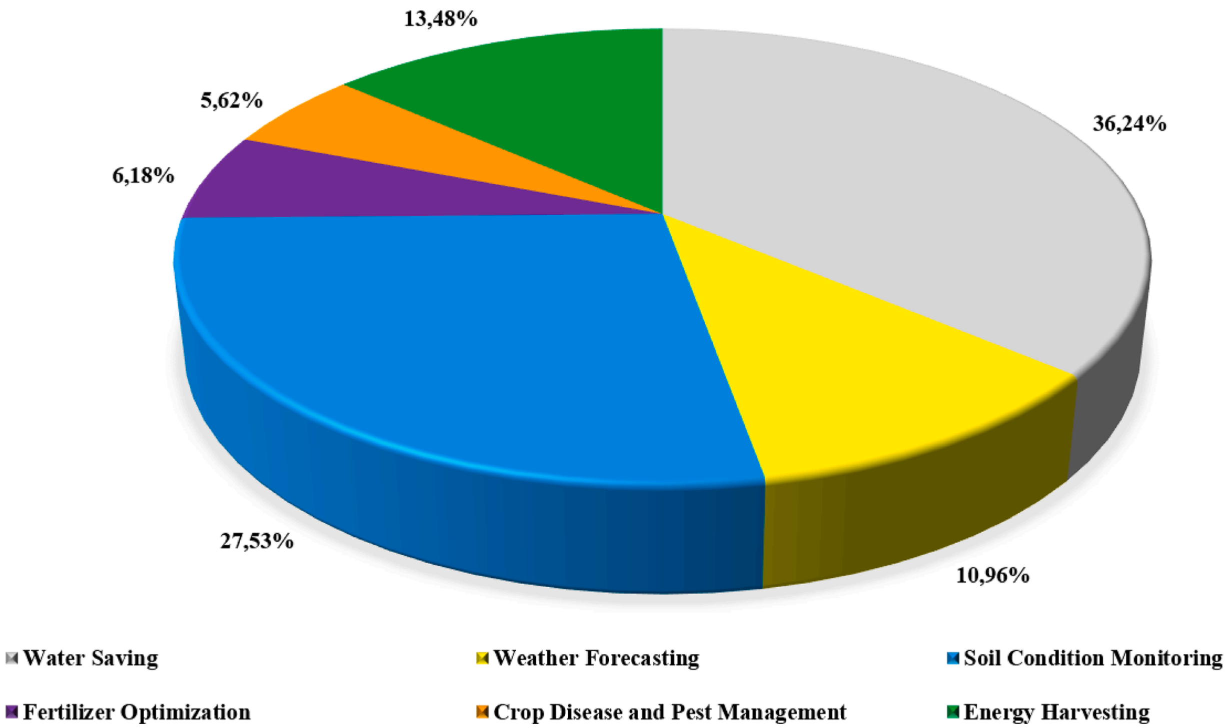

Fig. 5. Distribution of the papers according to application areas.

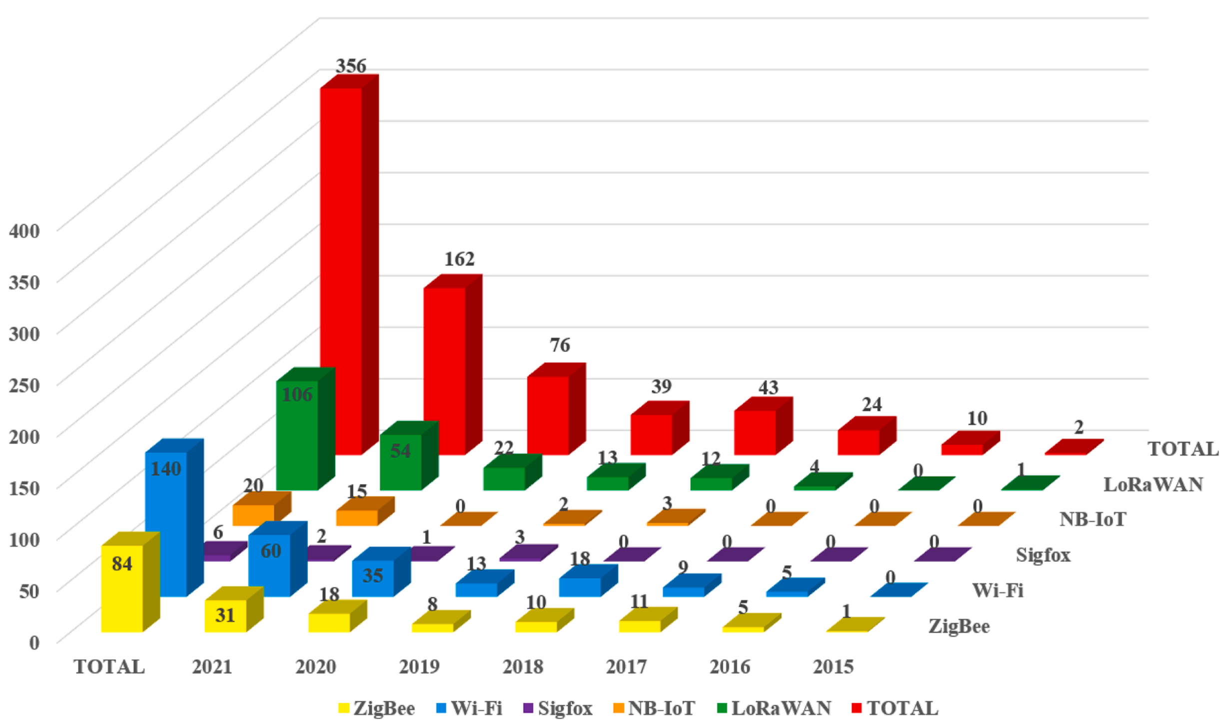

Fig. 6. Year-based distribution of the papers according to communication protocols.

the requirements of the applications together with the features of the protocols. Besides, the future trends related to these protocols are underlined by accounting the possible requirements in the future and investigating the number of annual publications about various smart agriculture applications utilizing a protocol within the scope of this paper.

The open issues and challenges are discussed to understand the limitations that prevent the SA systems from being deployed and used commonly. The system security and costs are the two leading factors of this situation. In addition, educated farmers having more familiarity with IoT and are more comfortable with digital technology are necessary for expedited adoption.

The future of the wireless communication protocols in SA has been evaluated by considering the leading recent technologies used in different applications. Aerial systems, satellite communications, 5G networks, and cloud computing are some examples of the technologies

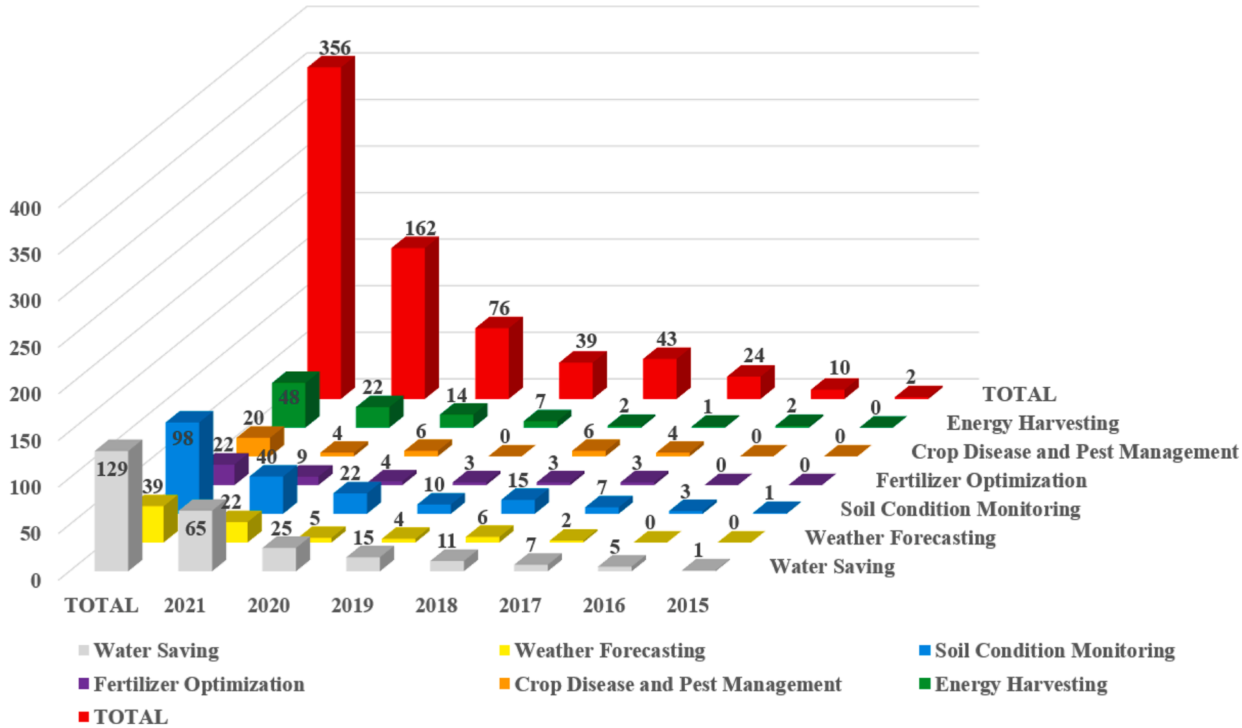

Fig. 7. Year-based distribution of the papers according to application areas.

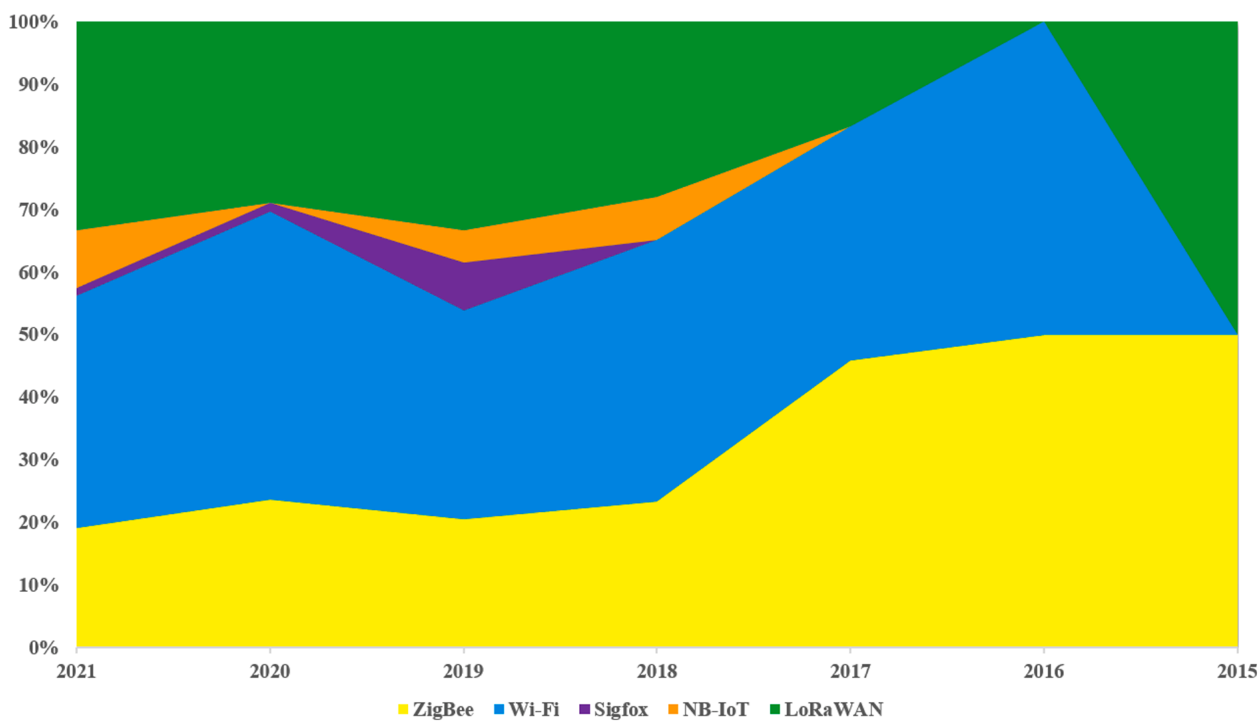

Fig. 8. Annual rates of communication protocols mentioned in the papers.

shaping the future opportunities and necessities in SA applications. Furthermore, it is underlined that infrastructure installation for LPWAN protocols is expected to be more common to ensure more secure data transfer over longer distances.

There is a large number of publications in the literature mentioning the technical specifications of the protocols involved in this paper. The technical data in different sources are expected to be similar; however, some of the information provided in these publications are inconsistent. The circumstances in which the technical data is measured and the hardware used for deployment may be the source of the differences in these data. Nevertheless, such details are not given in the previously published papers.

Considering the major advantage (the long-range communication capability) of NB-IoT, Sigfox, and LoRaWAN, they are appropriate for large-scale commercial smart farms. Since it is neither practical nor feasible to provide line power to all devices in such farms, the next

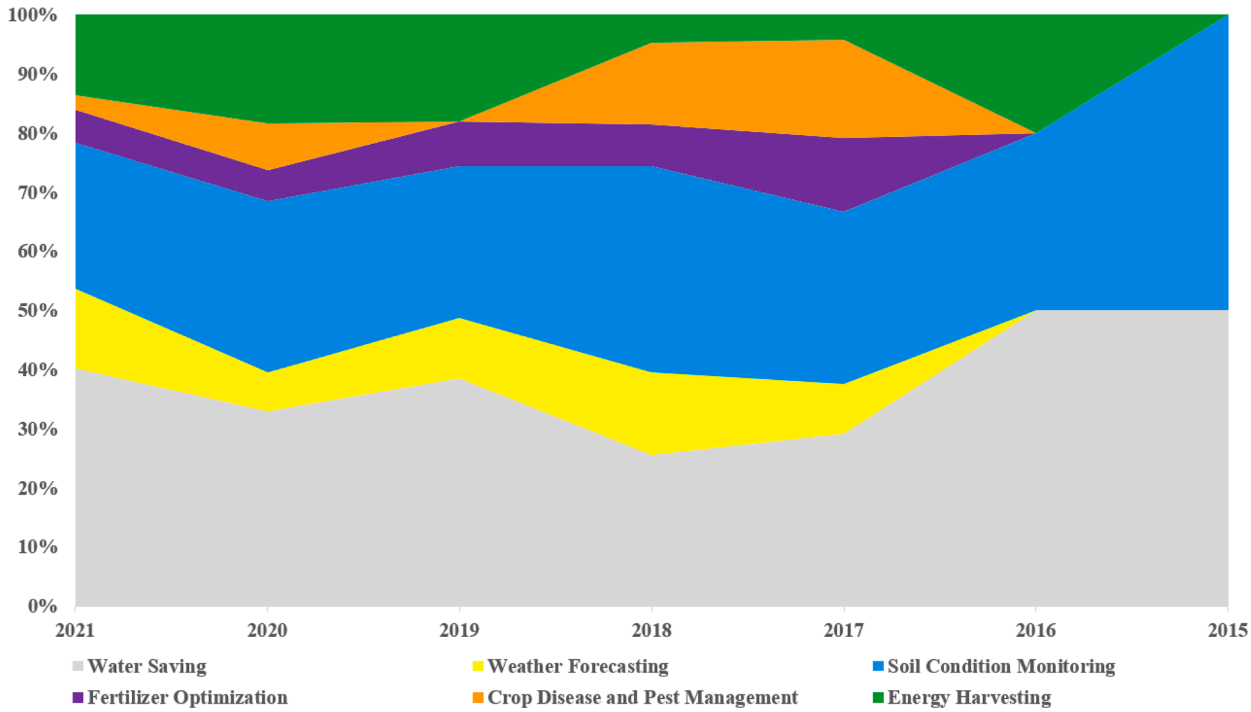

Fig. 9. Annual rates of application areas mentioned in the papers.

concern should be the power consumption. Due to the relatively high-power requirement of NB-IoT, the other two protocols may be considered as more appropriate for smart agriculture applications. In addition, the low latency benefit of NB-IoT is not a high-priority requirement for smart agriculture. On the other hand, the low data transfer rate of Sigfox makes it unsuitable for large fields involving a high number of sensors. At this point it may be underlined that, in general, there is a correlation between the energy consumption and data transmission speed of a protocol. In other words, when the data should be transferred at a higher rate, the appropriate protocol is expected to consume more energy. Development of new protocols for improving this situation may be a topic that can be a valuable future technology.

In order to reveal and underline the trending protocol in SA, year-based distribution of the published papers within the scope of this study has been observed. The papers obtained through the search strategy explained in Section 2.2 were categorized according to the application areas and the communication protocols. As a result of this categorization step, Table 3 has been generated to see the annual distributions of the studies. These year-based distributions are presented and discussed in Section 7.6, and visualized in Figs. 4 - 9. According to the analysis results, LoRaWAN has the highest number of uses in all of the smart agriculture application areas among LPWAN protocols. When the advantage of being an open standard is combined with other benefits like low power consumption, long-range and sufficient data transfer rate, LoRaWAN may be the optimal solution for most cases.

Even though the widespread usage of LPWAN technologies is increasing in recent years, short-range communication protocols are still commonly used in research projects, prototyping and small fields. These protocols provide higher data rates in general while requiring relatively high power. Despite the drawback of their high-power consumption, the required hardware for these protocols can easily be accessed on the market. This ease of accessibility makes them the first choice for rapid prototyping and development.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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