Review of IoT and electronics enabled smart agriculture

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Abstract: The population increases at an exponential rate as human society advances, and pollution is increasingly depleting the availability of resources such as water and land. All these problems are thought to require the use of smart agriculture. By reducing use of chemical fertilizers and pesticides, smart agriculture could mitigate land pollution and increase the sustainability of agricultural practices while also greatly enhancing the agro-ecological environment, yield, and quality of crops. The steps to make agriculture smart are made possible through data and communication technology, which helps with automatic operation and cultivation. Moreover, advances in wireless communication protocols will bring agriculture to a more intelligent stage. This study provides an overview of IoT technology and its application in the smart agriculture industry to make crop production automatic and intelligent by assessing their architecture (IoT devices, communication technologies, and processing), their applications, and research timelines. The communication protocols that have established uses in agriculture are reviewed first in this article. Various wireless communication protocols such as WiFi, ZigBee, SigFox, LoRa, RFID, NFMI, Terahertz, and NB-IoT were summarized, and their applications in various fields were also studied. These protocols in smart agriculture can effectively and efficiently address environmental data, water saving, monitoring of animal behavior, accuracy, power efficiency, cost reduction due to low power consumption, accuracy, wide transmission, simple in operation and cost effective. The most commonly used microcontrollers are Arduino (to develop autonomous machines), Raspberry Pi (to store data), and 8-bit microcontroller (to process data). In addition, it is important to take advantage of modern communication technology to enhance crop production. This study also examines the future opportunities and trends for IoT applications in smart agriculture, along with the ongoing challenges and issues that need addressing. Furthermore, it provides crucial insights and guidance for future research and the development of IoT solutions. These advancements aim to improve agricultural productivity and quality while facilitating the transition to a more sustainable agroecological future.

Keywords: IoT, smart agriculture, microcontroller, sensor, SigFox, LoRa, ZigBee
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1 Introduction

Demand for food production increases along with population growth. According to the report of FAO[1] there will be 9.73 billion people in the world by 2050, and that number will continue to increase until it reaches 11.2 billion by 2100. The total food grain of India increased from 176.39 to 297.50 million tonnes (Mt)[2] from 1990-1991 to 2019-2020, while the population increased from 873.3 million to 1.38 billion[3] during the same period. To meet the food demands of an increased population day by day, there is a need to increase food production. Currently, India's food grain production in 2021-2022 is 314.51 Mt, up from 50.82 Mt in 1950 due to the introduction of the Green Revolution[4]. The per capita availability of food was 507.8 g per person per day[5]. In 2050, the world's population is expected to be nearly 10 billion, requiring a 70% increase in food production[6]. To address the growing demand for food, the agriculture industry requires a combination of information services, automation, and robotics. This integration involves leveraging information and communication technologies, drones, robotics, artificial intelligence (AI), the Internet of Things (IoT), and big data.

The agricultural sector is one of the most significant sources of national income for most of the developing countries. Currently, there are several issues faced by developed countries such as soil salinity, temperature, and climate which lowers crop productivity[7].

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Additionally, the adverse climate affects product yield and quality, and makes soil vulnerable to desertification[8]. Therefore, implementing innovative technology to increase agricultural production is essential for these countries[9]. A key element of the technology behind smart agriculture is the use of IoT[10]. Smart agriculture covers a wide range of aspects relevant to crop production, including monitoring of changes in climate conditions, soil properties, soil moisture, etc. Robots, unmanned ground vehicles, drones, and ground sensors are just a few examples of remote sensors that can be linked by the IoT technology since it enables the automatic operation of equipment that is connected to the internet[11,12]. The key goal of precision agriculture is to strengthen spatial management techniques for crop production while minimizing the waste of pesticides and fertilizers[13].

With the increasing population in the future, there will be an urgent need to use innovative methods and technologies in agriculture to meet the needs of people. This has resulted in the application of the IoT in agriculture[14]. After the computer, internet, and mobile communication networks, which change conventional paradigms and welcome a new era of technology, IoT will bring in a new revolution in the worldwide digital economy. Additionally, it consists of three dimensions: autonomous networks, intelligent applications, and accomplishing information items. IoT is a network of all things that are integrated into devices, sensors, machines, software, and people through the online platform to communicate, share information, and interact in order to provide a comprehensive solution between the real world and the virtual world[15,16]. There are various areas in which IoT is used, including precision farming, supply chain management, data analysis, monitoring farms and forestry, aquaponics farms, tracking and tracing, environment monitoring, transportation and logistics, smart traffic, smart buildings, healthcare, and public safety. These uses are made possible with smart and network technology, which have provided elements alongside communication, sensor, and action capabilities, as shown in Figure 1. IoT technology has emerged as a viable solution for several agricultural applications, providing an adjustable control mechanism to collect on-field data in real time[17,18]. Today, IoT has connected all agricultural equipment and devices, making it possible to manage agriculture more effectively by making the right choices for sowing, spraying, weeding, irrigating, supplying fertilizer, harvesting, and threshing operations[18]. IoT technology evolves in conjunction with the development of the Internet. The monitoring of agricultural goods is transforming primarily because of ongoing advancements in IoT technologies. The use of IoT-related technologies has undoubtedly increased the quality and safety of agricultural goods. The efficiency and accuracy of devices that track plant growth and even livestock production are improved by smart farming. To collect information from various sensing devices, wireless sensor networks (WSNs) are used. Cloud services must be combined with IoT to aid decision-making for analyzing and processing data[19]. ICT, ground sensors, and control systems deployed on robots, autonomous vehicles, and other automated devices are all important in smart farm management. High-speed internet, novel mobile technology, and satellites are all necessary for the success of smart systems. James et al.[20] reported that with the use of multiple satellite images and sensors installed in farms (growing paddy and bananas), they deployed IoT in real-time to detect and identify leaf diseases that hinder crop growth. This system helped in data analysis and decision-making before communicating the results to the farmers by virtue of the server.

According to the Food and Agriculture Organization[1], pests, diseases, and a lack of effective crop monitoring cause 20% to 40% of crop losses each year. As a result, the employment of sensors and smart systems allows for the monitoring of meteorological variables, fertility status, and the determination of the precise amount of fertilizer required for crop growth. The fertility of the soil is negatively affected by inadequate fertilizer use. IoT used in various agricultural applications are shown in Figure 2. The objective of this paper was to review the current application of IoT in monitoring agricultural product quality and safety in production, processing by using sensors, protocols, microcontrollers used in IoT, and common IoT technologies. Challenges, future directions, and technical problems were also discussed in this study.

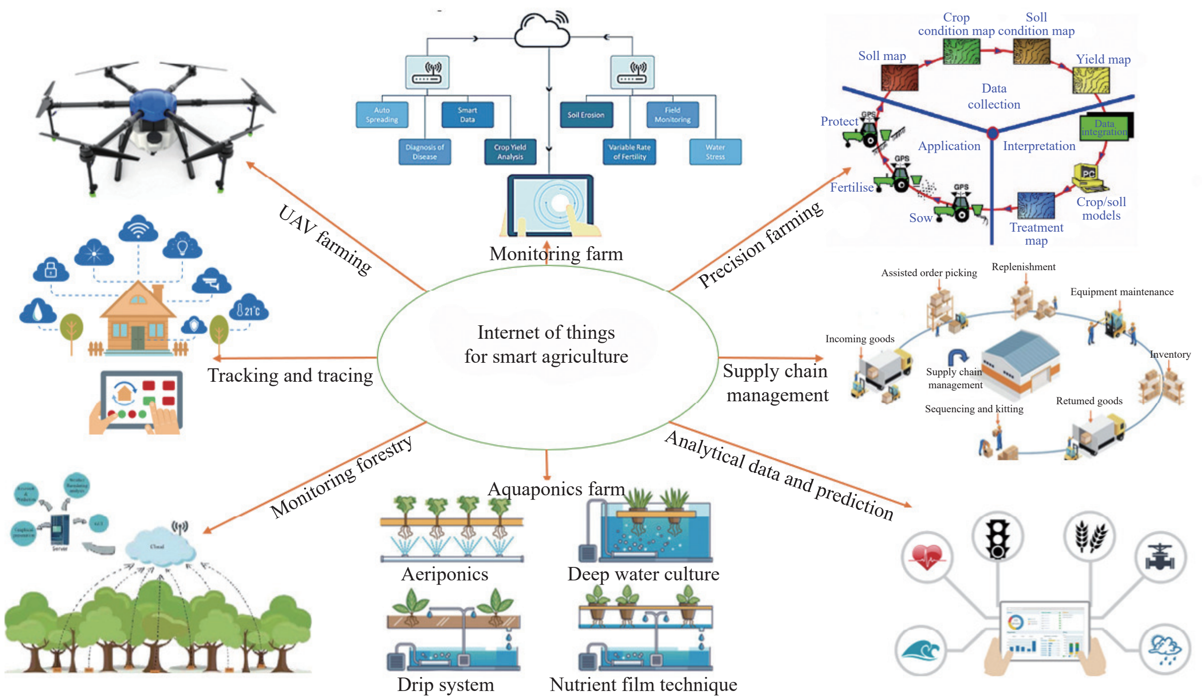

Figure 1 Schematic diagram illustrating application of Internet of Things in different areas for smart agriculture

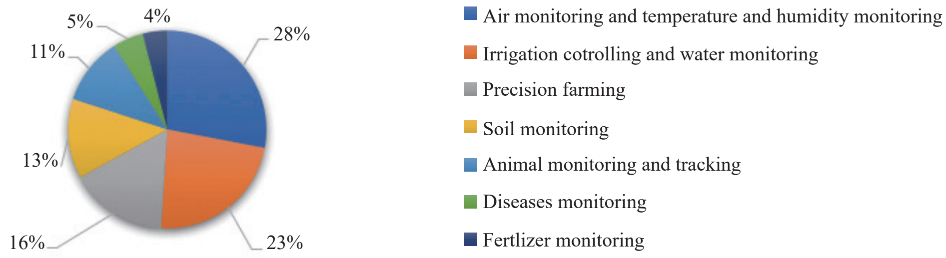

Figure 2 Sector-wise application of Internet of Things for smart agriculture[19]

2 Smart farming

Historically, the traditional Agricultural Era 1.0 was defined by methods focused on food production in cultivated fields to sustain both humans and livestock[21]. This period relied heavily on animal and human labor, with farming tasks primarily accomplished using hand tools such as sickles and shovels. Consequently, productivity was relatively low due to the manual nature of most agricultural work. In the Agricultural Era 2.0, the introduction of steam engines marked the advent of new and innovative machinery in farming. This era was characterized by the extensive adoption of agricultural technology and a significant increase in the use of chemicals by farmers, which enhanced farm productivity and efficiency. However, it also brought about severe negative impacts, such as chemical pollution, environmental degradation, resource depletion, and excessive energy consumption.

The rapid advancement of computers and electronics in the 20th century led to the emergence of Agriculture 3.0. This era saw significant improvements in agricultural operations through programmable machinery, robotics, and other innovations. These advancements addressed the challenges of Agriculture Era 2.0 by improving labor distribution, enabling precise irrigation, reducing chemical use, delivering site-specific fertilizers, and enhancing pest control technologies, thereby adapting policies to the new era. Agriculture 4.0 represents the next phase, driven by modern technologies such as IoT, big data analysis, AI, cloud computing, and remote sensing. This phase focuses on developing cost-effective sensor and network platforms aimed at optimizing productivity, conserving water and energy, and minimizing environmental impacts. The implementation of these technologies has significantly enhanced farming operations[22]. The vast amounts of data generated in smart farming provide farmers with comprehensive insights into current agricultural conditions, enabling informed decision-making[23]. Real-time programming, based on AI principles, is integrated into IoT devices to support farmers in making the best choices[24].

Agriculture 4.0, representing the current era of farming, integrates advanced technologies such as IoT, big data analytics, AI, cloud computing, and remote sensing. The advent of cost-effective sensors and network platforms has significantly advanced agricultural practices. These technologies aim to optimize production efficiency, reduce energy and water consumption, and minimize environmental impact[22]. AI principles enable real-time computing, which is incorporated into IoT systems to help farmers make more informed decisions[24]. Intelligent farming facilitates remote plant monitoring and leverages modern technologies to support precision agriculture. The automation of sensors and machinery has enhanced farming efficiency, benefiting crop yields and harvesting[25]. This technological revolution replaces traditional manual farming with automated systems, fundamentally transforming agricultural practices[26].

2.1 IoT in smart farming

IoT is an innovative technology that enables remote connectivity for devices in smart farming. Its influence has extended across numerous sectors, including healthcare, commerce, communication, energy, and agriculture, enhancing efficiency and effectiveness in each industry[25,26].

Modern agriculture is automated effectively and accurately with the least amount of human intervention by using IoT, an innovative technology[27]. Precision agriculture (PA) is made easier by the deployment of technologies for wireless communication, sensors, and remote sensing. Wireless communication is necessary for transmitting data to data processing centers to improve agricultural production as well as quality. Agriculture will be successful in terms of consistent connectivity only when its limited resources are used effectively, which is made possible by wireless communication[28]. Agricultural fields are typically found in isolated locations with inconsistent connectivity to the internet. The deployment of a WSN is necessary to overcome these constraints. In a WSN, the sensor node and the communication protocol for sending agricultural field data to a location where the internet connection is reliable enough to support communication with the cloud server are incorporated with open-licensed band communication protocols[29]. Small, energy-efficient nodes that collect data for a range of uses constitute a component of a WSN. The IoT for agriculture depends heavily on WSN localization. Agricultural applications are making extensive use of small, inexpensive devices with minimal power consumption and limited computational power. Requirements for sensor node deployment in fields include the estimation of the number of sensor nodes and their position using localization methods including time on arrival, time difference of arrival, and received signal strength indication (RSSI)[30]. To tackle the issues of power consumption and transmission range, as was previously said, adopting appropriate wireless communication is essential. In accordance with frequency range, network size, topology, etc., several communication systems are presented in Table 1.

Agricultural IoT encompasses several key components, including sensor-equipped devices, internet connectivity, wireless communication technologies, and data collection and transmission. Effective deployment of IoT systems relies heavily on wireless communication technology, which can be categorized based on spectrum, transmission range, and application scenarios. Various common sensors are utilized in smart agriculture depending on specific operational needs and are shown in Figure 3[31].

These sensors continuously monitor crops with high precision, detecting any adverse conditions early in the crop cycle. Modern farming now employs smart equipment for tasks ranging from seeding to harvesting, storage, and transportation. This precision monitoring has enhanced the profitability and efficiency of

Table 1 Technical specifications of communication protocols

Particular	Short range protocol						Long range protocol		
	NFMI	Bluetooth	ZigBee	Wi-Fi	Terahertz	RFID	LoRa	SigFox	NB-IoT
Modulation	D8PSK	GFSK, DPSK, and DQPSK	BPSK/OQPSK	BPSK, QPSK	BPSK/OQPSK	GFSK	CSS	BPSK	QPSK
Interference immunity	Low	Low	Medium	Low	Medium	TCP/IP	Very High	Very High	Low
Localization	Not supported	Not supported	Not supported	Not supported	Not supported	Not supported	Not supported	Yes (RSSI)	Yes (TDOA)
Standardization	IEEE 1902.1	IEEE 802.15.1	ZigBee Alliance	IEEE 802.11ah	IEEE 802.15	ISO/IEC 1802.11	LoRa-Alliance	SigFox company with ETSI	3GPP
Maximum data rate	596 kb/s	1-3 Mbps	20 and 40 kbps	150 mbps	550 kbps	640 kbps	50 kbps	100 kbps	200 kbps
Bidirectional	Yes/ Half-duplex	Yes/ Half-duplex	Yes/ Half-duplex	Yes/ Half-duplex	Yes/ Half-duplex	Yes	Yes/ Half-duplex	Limited/Half-duplex	Yes/ Half-duplex
Message/day	470 max	358 max	64 (max. MAC payload in 200 series chip)	620 max	unlimited	350 max	Unlimited	140 (UL), 4 (DL)	Unlimited
Payload length	512 bytes	256 bytes	256 bytes	243 bytes	256 bytes	256 bytes	243 bytes	12 bytes (UL) 8 bytes (DL)	1600 bytes
Coverage	140 dB	125 dB	145 dB	110 dB	153 dB	161 dB	157 dB	160 dB	164 dB
Power Consumption	Around 185 mW	Around 215 mW	Around 36.9 mW	10-30 mA	Medium	10-100 mW	Low	Low	Very low
Security	128 bits AES	64/128 bits AES	128 bits AES	Medium	High	Medium	Low	Low	Very High
Bandwidth	400 KHz	1 MHz	Equal to 2 MHz	1 MHz	100 GHz		250 and 125 kHz	100 kHz	200 kHz
Frequency	2.0-2.5 kHz	2.40 GHz	868/915 MHz and 2.4 GHz	900 MHz and 2.4 GHz	0.3 to 10.0 THz	110.0-134.2 kHz	ISM Band 433, 868, 915 MHZ	ISM Band 433, 868, 915 MHZ	Licensed LTE Frequency
Technology	OFDM	FHSS	DSSS	OFDM	FHSS	OFDM	Proprietary	Proprietary	Open LTE
Spectrum	Unlicensed	Unlicensed	Unlicensed	Unlicensed	Unlicensed	Unlicensed	Unlicensed	Unlicensed	Licensed
Topology	Point-to-point	Scatter-net Topology	P2P, tree, star, mesh	one-hop	Point to Multi-point	WiMAX	Star	Star	Star
Downlink Data	0.8 Mbps	1 Mbps	0.5 to 20 kbps	150-400 kbps	150-350 kbps	250 -550 kbps	0.3-50 kbps	0.1 kbps	Rate 0.5-200.0
Uplink Data Rate	1.5 Mbps	3 Mbps	40 kbps	650-780 kbps	200-600 kbps	450-790 kbps	0.3-50 kbps	0.1 kbps	0.2-180.0 kbps
Range	30 m	10-50 m	100 m	100 m	10-100 m	100 m	5 km (urban) 20 km (rural)	10 km (urban) 40 km (rural)	1 km (urban) 10 km (rural)
Duty Cycle Restriction	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Output Power	20 dBm	20/4/0(Class 1/2/3) dBm	−20-0 dBm	14 dBm	19 dBm	33 dBm	14d Bm	14 dBm	23 dBm
Battery Lifespan	5-10 years	10 years	10 years	10-15 years	10 years	5-10 years	10 years	10 years	15 years

Source: References [38-48].

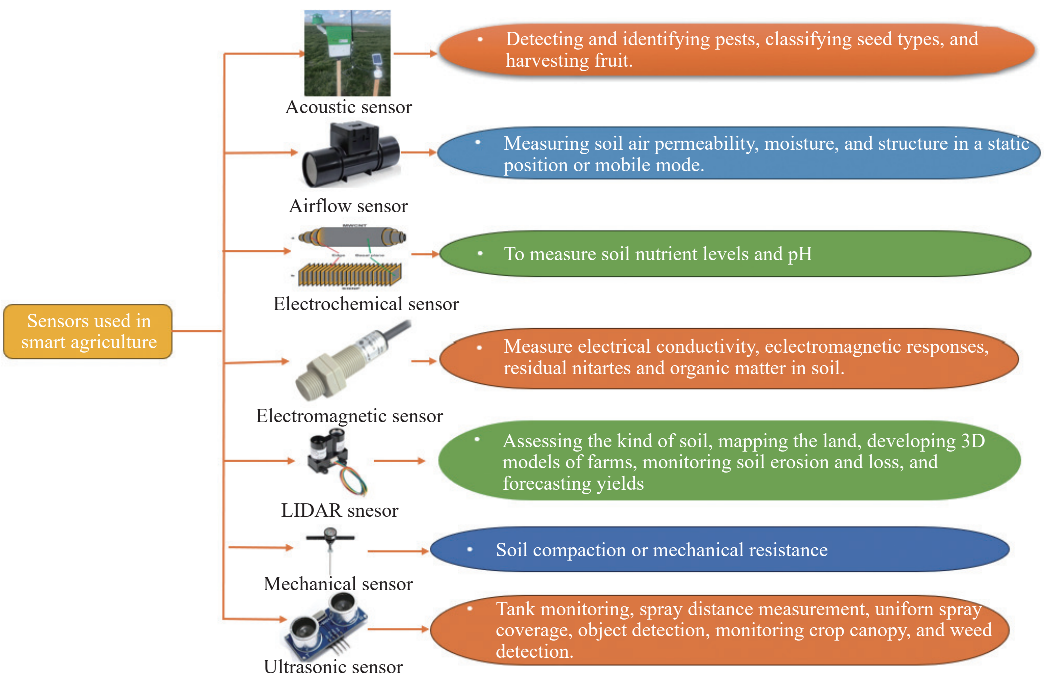

Figure 3 Commonly used sensors and their application purposes in smart agriculture

agriculture through the strategic use of diverse sensors. Additionally, rapid-collection sensors provide site-specific crop information, available online for further analysis. The timely use of sensors has made agriculture both smart and cost-effective[32]. Sensors are integrated into robotic weeders, unmanned aerial vehicles, and automated harvesting tools to gather data at frequent intervals. Nevertheless, the vast scale of agriculture imposes significant demands on technological advancements to ensure sustainability and minimize environmental impact. Farmers can utilize wireless communication to obtain information about crop needs and requirements remotely, even when not physically present in the fields[33].

Sensors provide continuous and precise monitoring of crops, detecting potential issues both before and during the growing period. Modern farming employs smart devices for a wide range of tasks, including crop seeding, harvesting, storage, and transportation. The use of various sensors has significantly improved operational efficiency and profitability through accurate monitoring. Additionally, fast-collecting sensors deliver crop- and site-specific data, which is readily accessible online for further analysis. These sensors, such as those measuring photoelectric, electromagnetic, conductivity, and ultrasound, assess soil texture and structure, nutrient levels, vegetation, humidity, vapor, air quality, and temperature. Remote sensing data helps in identifying crop varieties, classifying weeds and pests, detecting crop and soil stress, and monitoring drought conditions. Factors like soil moisture, nutrient availability, sunlight exposure, humidity, rainfall, and leaf color all affect plant health. Micro-irrigation systems conserve water and energy while maintaining optimal temperature and light conditions for plants. Various sensors are utilized in both indoor and outdoor agricultural settings. When sensor readings exceed predefined limits, the microcontroller intervenes to perform necessary actions until parameters return to optimal levels[34]. Sensing devices often incorporate multiple sensors, including those for temperature, humidity, soil patterns, airflow, CO_2, pressure, light, and moisture. Key attributes of these sensors include computational efficiency, versatility, durability, memory, coverage, and reliability[35]. Modern wireless sensors are crucial for monitoring crop conditions and addressing other agricultural needs. These autonomous sensors can be integrated with heavy machinery and advanced agricultural tools, such as temperature and humidity sensors for data collection and light intensity sensors used in various robots during operations[36].

For successful integration of IoT into smart agriculture, advancements in communications technology are crucial for the development of IoT devices[23,37]. These advancements are vital for enhancing IoT systems. Current communication solutions can be categorized into three types: protocol, spectrum, and topology.

2.2 Protocols

Recently, researchers have developed several wireless communications protocols for smart agriculture. These enable the components of a smart agriculture operation to communicate, exchange data, monitor and manage farming conditions, enhance yields, and increase yield efficiency. Depending on their communication range, generally used in lower power protocols in smart agriculture and may be divided into short range and long range categories (Figure 4). Intelligent farming cannot be achieved without wireless communication technology. SigFox, Bluetooth, ZigBee, LoRa, Narrow Band IoT (NB-IoT), and Wireless Fidelity (Wi-Fi) are only a few examples of advanced wireless communication technologies and systems that are currently extensively used in agriculture. Their primary uses include intelligent irrigation, identification of pests, environmental management in greenhouses, sensing of soil, plant protection, and so forth[38]. They can protect crops from pests and nutrient deficiencies, automate lighting and watering, avoid forest fires, and stop oxygen deficiency in fisheries. Yavasoglu et al.[39] used wireless communication in robots for in-line inspection over a long range.

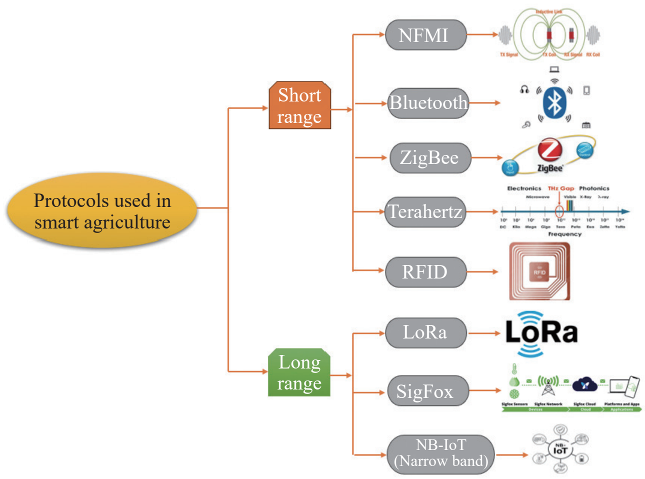

Figure 4 Protocols used for Internet of Things in smart agriculture

2.2.1 NFMI (Near-field magnetic induction)

Near-field magnetic induction (NFMI) is a relatively close communication (NFC) technology which is operated over a limited range. The near-field limit is defined as ($\lambda/(2\Pi f)$), and it depends on frequency f (or wavelength). The magnetic field energy also has a relatively faster decay rate (as r^{-6} with distance r), which further reduces its range. In comparison to short-range RF technologies, NFMI has several desirable features, such as better penetration performance and higher power efficiency, and it does not hinder the functioning of other wireless networks like Wi-Fi and BLE. In 2009, IEEE developed the 1902.1 standard, which defines a low-frequency NFMI, communication protocols known as RuBee which is operated in a range from 30 kHz to 900 kHz. The primary purpose is to accommodate to lower rate data applications with 5-10 years coin-sized battery[40]. A common frequency range for NFMI for short-range applications is 13.56 MHz, which is closer to the near-field limit and range of 3.7 m and 0.1-2.0 m, respectively. A transmission rate of 400 kbps per frequency channel is achieved in frequency band. There may be 10 frequency channels, with time division multiplexing enabling each and every channel to be further divided into 10 sub-channels[41].

2.2.2 Bluetooth

Communication can be exchanged over short distances using the wireless technology known as Bluetooth (BT). It operates at 2.4 GHz on the ISM band. The data transfer rates for the most recent Bluetooth version 5.2 are more than 50 Mbps. In general, Bluetooth is used to exchange data in different types of end devices. Generally, it is operated in a frequency spectrum which is uniformly distributed over the world, is extremely resistant to interference, and is therefore ideal for several devices. The primary uses of Bluetooth in agriculture are for intelligent irrigation and environmental monitoring. Kim et al.[42] studied a method that uses BT for irrigation applications to preserve water and improve production. Kim et al.[43] Bluetooth is a wireless communication protocol that allows for real-time field data collection for irrigation. Li et al.[44]

developed a customized software to employ BT technology for monitoring temperature and relative humidity in greenhouses. By increasing the lettuce height, leaf number, fresh weight, and dry weight, the integration of BT modules in an integrated control technique enables the accurate monitoring of greenhouse irrigation systems based on soil and weather data[45]. The integrated control method utilizing BT technology also shows a 90% saving in water usage and electricity estimation compared to traditional methods such as timer control techniques.

2.2.3 ZigBee

ZigBee is a wireless technology which is operated at 2.4 GHz in the ISM (Industrial, Scientific, and Medical) band with a transmission rate of 25-250 kbps and works on IEEE 802.15.4 standard. It is usually used for sensor control in narrow areas. It is used in various agricultural fields because of its lower price and power consumption, better transmission, simple operation, and many applications in wireless sensors. The autonomous drip irrigation techniques consist of a wireless network of ZigBee and a fuzzy controller[46-48]. In greenhouses, ZigBee technology was implemented to gather real-time environmental data like humidity, temperature, and light[49]. The system gathers data including temperature, soil moisture, and several other parameters, and then feeds this data to fuzzy controller to determine when to irrigate. Its various advantages include a short duty cycle, simple interconnection, low power requirement, and low power processing capability node, which are appropriate for precision agriculture (PA) applications involving periodic data updates, such as monitoring the quality of water, fertilizer and pesticide control, and irrigation supervision[50]. According to Bodunde et al.[51] and Dasgupta et al.[52], the technique is highly utilized for intra-sensor communication in agricultural or irrigation systems because of its low consumption of electricity and short duty cycle. Furthermore, Raheemah et al.[53] used the ZigBee wireless protocol to study a route loss model in a mango greenhouse. These studies show ZigBee's adaptability and efficiency in a range of agricultural applications. Key factors like temperature, humidity, CO_2 levels, and solar radiation were considered in an investigation on greenhouse climate management[54]. Utilizing ZigBee technology, these factors were monitored and controlled, leading to optimal plant development and 22% and 33% reductions in energy and water use, respectively. Additionally, to monitor and control greenhouse climatic conditions, a combination of Global System for Mobile Communications or General Packet Radio Service (GSM/GPRS) and ZigBee technology was used[54].

2.2.4 Wi-Fi

Wi-Fi is operated at 2.4 GHz with a frequency band of 5 GHz which is based on IEEE802.11. The most recent Wi-Fi-7 technology, introduced in 2022, is operated in the frequency bands of 2.4, 5, and 6 GHz[55]. A popular wireless technology, Wi-Fi is typically used for internet access because of its variety of bandwidths, negligible power consumption, higher rate of transmission, and ability to communicate across longer distance. Wi-Fi is frequently used in agriculture for various purposes including remote communications, video surveillance, and wireless sensing, and for observations of environmental factors including humidity, temperature, and soil salinity. Lloret et al.[56] studied a Wi-Fi based sensor network which helps farmers determine when to irrigate their farmland. The Wi-Fi-based, flexible, limited-bandwidth technology is acceptable for agricultural monitoring and control of long-distance and remote areas[57]. It is used to collect information over 15 km with a low power consumption[58].

2.2.5 Terahertz Technology

The amount of wireless data communication has increased significantly as information technologies have advanced. According to Cherry[59], cellular data transmission doubles every 18 months. During 2016-2021, mobile data and video transmission increased by seven times and three times, respectively[60]. In view of the above scenario, the communication technologies which operate on high-level frequency bands are no longer exceptional, such as communications with millimeter waves at frequencies lower than 100 GHz[61]. However, these technologies still face challenges in supporting transmission of data at the rate of terabits per second (Tbps) as well as the information exchange of million dollars of gadgets for communication. To transfer higher-level data such as Tbps, communication devices like terahertz have been suggested due to their ability to provide higher bandwidth, ultra-high bandwidth, minimum time, and quick higher level of data transfer. The frequency range of terahertz (THz) waves is 0.1 to 10.0 THz. In terms of the entire visible spectrum, terahertz lies in between the microwave band and infrared bands. Terahertz waves have spectral resolution as well as microwave-band absorbing and penetrating capabilities. Terahertz communication has a large amount of bandwidth that supports ultra-high communication rates using transmission waves for wireless communications like terahertz. One of the alternative radio technologies is the terahertz communication system for achieving 6G Tbps communication rates, which is used in photorealistic communications, transforming information with ultra-high capability, microwave communications and limited range ultra-high transmission range. Late blight and fusarious in potatoes and cereals of different types was determined by THz-TDS technology, and phytopathogen presence or absence was detected. The latter may be used to assess the extent and severity of tissue damage to plants[62]. According to Wei et al.[63], the protein content in soybeans was determined specifically and precisely using THz technology. The results indicated the potential of combining dimensional reduction methods with THz technology for quantitative assessment of protein in soybeans.

2.2.6 Radio Frequency Identification (RFID)

The performance of many agricultural operations is expected to be enhanced by RFID, which is entering a new phase. The most recent developments provide a multitude of chances for agricultural study, deployment, and innovations. This is the result of declining ownership costs, the design of ever-smaller sensing devices, advancements in radio frequency technologies, and the development of digital circuitry[64]. RFID has a greater scanning range than barcodes and can be read from up to 100 m away. RFID scanners can read tags significantly more quickly, up to 100 tags per second (though new advancements promise up to 1000 tags per second). RFID is used for monitoring data of temperature, gas concentrations and humidity, microbial contamination of packaged foods, food traceability, livestock, and precision farming. Vellidis et al.[65] used RDIF for irrigation scheduling. The device could detect the status of water levels in the soil as well as soil and air temperature inside the canopy with few exceptional concerns for the 2004 growing season. Quino et al.[66] developed a system for acquiring inventory data in nurseries by scanning tags, which is 95% more efficient than other tag designs. Evaluating a holistic system in for-profit nurseries is a future task for this development.

2.2.7 LoRa

LoRa is a standard wireless communications technology (varied from USA, Japan, China, and EU). It transmits data at a rate of 10 kbps for long transmission range, which is operated in ISM band (EU: 433 MHz and 868 MHz; US: 915 MHz). It is used in agricultural operations because of its lower power consumption, high range of transmission, affordable price, and adaptable installations. In order to generate a cost-effective sensor system capable of monitoring agriculture on a huge scale, Swain et al.[13] connected LoRa to particular lower power hardware platform. A remote-manipulation-capable, low-power LoRa enabled a greenhouse environmental monitoring system[67]. Lighting, cooling, and irrigation can all be managed by devices, which also collect and monitor data on soil and environmental elements. LoRa offers a bidirectional solution for communication between machines (M2M) that is similar to cellular or WiFi technology. It provides an affordable way to link mobile or battery-operated devices to the network or other endpoints. The LoRa wireless protocol was employed by Gil-Lebrero et al.[68]for monitoring bee colonies in isolated regions and to facilitate communication between the bee nodes and a distant local server.

2.2.8 SigFox

The low power wide area network (LPWAN) includes SigFox and LoRa technologies. The LPWA networks an innovative form of communication designed to overcome the drawbacks of conventional wireless communication technologies, including WiFi, GSM, Bluetooth, ZigBee, and LTE. LPWA networks are used by about 25% of the 30 billion IoT devices online[69]. LPWA networks are commonly used in agriculture, smart city applications, animal monitoring, logistics, infrastructure monitoring, IoT personal use, etc. SigFox is a French company that Ludovic Le Moan and Christophe Fourtet founded in 2010. SigFox operates at 100 bps and employs ultra-narrow band (UNB) modulation with differential binary phase-shift keying. The sub-band employed in the 868 MHz frequency band has a 1% duty-cycle constraint. Within an hour, a SigFox system can send information for 36 s. The lower power consumption, higher receiver sensitivity, and cheap design of the antenna are some of the major advantages that allow UNB to enable Sigfox, which helps to lower noise levels[70]. When designing IoT networks, SigFox is mostly employed when the amount of data is low (between a few bytes and a few hundred KBs), the operational area is wide (a few kilometers), and the power consumption is low (a few mA). SigFox employs DBPSK (Differential Binary Phase-Shift Keying) modulation, demands that messages have a fixed bandwidth of 100 Hz, and transmits them at a speed of 100 bps. Without an ISM license, SigFox operates on the 868 MHz band in Europe and the 915 MHz band in North America[71]. It is possible for the developed device to transmit more than a thousand Sigfox transmissions when it is powered by a coin-cell battery (90 mAh).

2.2.9 NB-IoT

The 3GPP standardization group has standardized the NB-IoT protocol for mobile communications, which has a 180 kHz bandwidth. Applications for the IoT must meet specified characteristics, including longer range, lower date transmission, and lower energy consumption and cost effectiveness. Some applications require long-range communications, but extensively used short range radio technologies (like ZigBee and Bluetooth) are insufficient. Cellular network-based solutions like 2G, 3G, and 4G can offer extensive coverage, but they use a lot of power from the device[72]. With legacy GSM and long-term evaluation (LTE) technology, it is nevertheless built to work excellently in coexistence. A 180 kHz minimum system bandwidth is needed for communication in both the uplink and downlink. Environmental data is collected by sensors and then transmitted to the NB-IoT module via the RS485 interface; this data transmission network includes the internet network and NB-IoT netwrok. The NB-IoT network transmits data from the NB-IoT terminal to the internet network; the application server’s functions include collecting, saving, and visualizing data before making appropriate decisions based on data analysis[72].

2.3 Spectrum

Every radio device communicates over a specific frequency band. Unlicensed spectrum bands have been developed by the Federal Communication Commission for unlicensed operations in the fields of science, industry, and medicine[73]. Devices requiring lower power and short-range communication commonly use these spectrum bands. Thus, several widely used technologies for the smart agriculture industry from wireless automation and UAVs to communications technology like Wi-Fi and Bluetooth use unlicensed spectrum bands[73]. Furthermore, there are several difficulties of using unlicensed bands, including ensuring the quality of service, the expense of building the initial infrastructure, and the interference caused by the large number of IoT devices[74]. In most cases, mobile networks are allocated a licensed spectrum. It provides more efficient and reliable connection traffic, improved service quality, safety, wide coverage, and cheaper starting infrastructure costs for consumers. Furthermore, there are several restrictions on the utilization of permitted frequency bands, such as higher data transfer costs and reduced efficiency of IoT devices[75]. Unlicensed spectrum bands have very low efficiencies but excellent data rates and longer transmission range (millimeter wave range). However, one significant drawback is that the data rate is significantly impacted by weather conditions, particularly rain[76,77].

2.4 Topology

The organization which develops IoT system for smart agriculture use identifies the communication frequency band and IoT device operating protocol. The two major node types in network topologies for smart agriculture are generally sensor and backhaul nodes[78]. Short communication ranges, low data rates, and excellent energy efficiency are key features of IoT sensor nodes. IoT backhaul nodes, on the other hand, frequently require long transmission ranges, high bandwidth, and high data rates. Figure 5 shows a schematic small network topology developed for monitoring and keeping track of various aspects of a smart farm. The device is made up of the following parts:

1) IoT sensor nodes receive data from the agriculture field, including soil moisture, relative humidity, temperature, nutrients present in the soil, pest images, and the quality of the water, and then send the received information to IoT backhaul devices. IoT sensor nodes can be established as RFDs (reduced-function devices), which can only interact with FFDs (full-function devices) depending on the operating intent and deployment location. To save energy and lower capital costs, these nodes are unable to connect with the other RFDs.

2) In addition to functioning as IoT sensor nodes, IoT backhaul nodes operate as interfaces, transferring data from other IoT nodes to the control center. To interact with other FFDs and RFDs, IoT backhaul nodes are frequently developed FFD devices.

3 Microcontrollers

Microcontroller-based IoT technologies have been used in various industrial sectors such as wearable devices that allow for remote user activity monitoring[80]. Since it can gather data from sensors, evaluate that data using machine learning tools like genetic algorithms and neural networks, and provide the final control instructions, the microcontroller might be considered the “brain” of the system[81]. The microcontrollers in these systems perform data collection, data exchange, and data processing as their primary tasks. The microcontrollers are further utilized to link devices made by various manufacturers. The commonly used microcontrollers include Arduino[82], Raspberry Pi microcontroller board[83], and an 8-bit microcontroller[84] to power lightweight sensors; these are listed in Table 2. However, when developing a smart microcontroller, the following three considerations should be kept in mind: First, the microcontroller needs to be modified. In certain applications, both the hardware and the software might be modified. Second, the microcontroller must possess intelligence. It needs to be able to do logical control and data mining. Third, the microcontroller should be scalable. They may work together to complete a complex task.

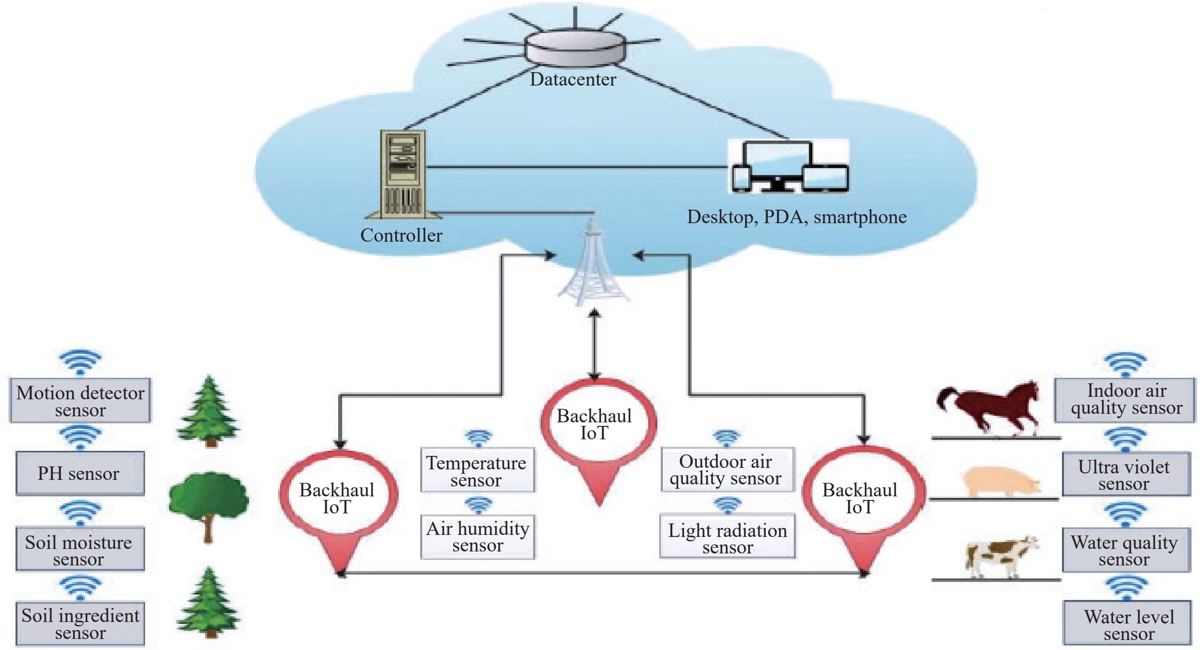

Figure 5 An illustration of the typical IoT-based smart agriculture topology[79].

Table 2 Some common microcontrollers used in agriculture

Microcontrollers	Application	Case study	Reference
Arduino UNO ATmega328	Agriculture	An Arduino-based smart farming system is designed to track the condition of field crops using sensors that can provide real-time field data.	[85]
Arduino UNO ATmega328	Agriculture	This technique uses data from soil moisture sensors to irrigate the soil, thereby preventing both over- and under-irrigation. The issues with manual irrigation of plants might perhaps be resolved by this method.	[86]
Arduino UNO ATmega328	Agriculture	For the green wall to develop in optimal conditions, monitors weather parameters, i.e., temperature, relative humidity, sunshine hours, soil moisture, and water flow.	[85]
Raspberry Pi	Agriculture	Raspberry Pi sends and stores data while taking into consideration a defined time span and the information’s accuracy.	[87]
Raspberry Pi (Stereo Pi)	Agriculture	A microclimate sensor, along with a Raspberry Pi for imaging, was utilized to monitor crop growth during a spring wheat breeding trial for automated phenotyping purposes.	[88]
Raspberry Pi 3 and Arduino Mega 2560	Agriculture	Developed autonomous robot for weeding, watering plants accurately, and sowing seeds.	[89]
8-bit AVR microcontrollers	Agriculture	With the help of these processors, multiple data can be processed quickly in a single command.	[90]
8-bit AVR microcontrollers	Agriculture	On 8-bit AVR microcontrollers, the suggested LEA and HIGHT with CTR mode methods enhance performance by 6.3% and 3.8%, respectively.	[91]

4 Common IoT technologies in smart agriculture

There are several IoT applications for agriculture such as monitoring, tracking, traceability, and greenhouse production groups. In the following subsections, the entire results are depicted.

4.1 Monitoring

Several variables that affect agriculture and production can be tracked and gathered in the agricultural sector, including soil moisture, humidity, temperature, pH level, etc. The following techniques are being used to monitor various smart agricultural sectors.

4.2 Crop farming

Air temperature, soil moisture and humidity, precipitation, solar radiation, pest activity, salinity, soil nutrient composition, etc. are some important characteristics that have a significant impact on this sector’s agricultural process and production efficiency. Farm Fox is a tool that collects and analyzes farming soil structure in real-time and then distributes the data to farmers and owners using the Internet. One study found that the condition of the soil can be continuously tracked to give timely advice to farmers looking to boost agricultural productivity[88]. Additionally, there is a weather radar, an IoT device that enables autonomous regulation of temperature and humidity parameters. When the temperature or humidity increases beyond a set threshold, this device will automatically activate the warning mode, employing a light indicator, and transmit information to the farmer[92].

4.2.1 Aquaponics

Aquaponics is a combination of hydroponics and aquaculture in which fish effluent is used as a source of nutrients for plants. Constantly monitoring factors like water quality, water level, temperature, salinity, pH, sunshine, etc. are among the most crucial tasks in such farms[93]. Additionally, the system has a function for automatic fish feeding that will increase fish production as well as a management system for water metrics that will maintain the stability of the fish habitat. The findings indicate that the IoT system performed continuously and produced real-time monitoring information.

4.2.2 Forestry

For survival, humans depend on forests. In addition, forests support over two-thirds of all animal species and are key to the carbon cycle. In addition to safeguarding watersheds and reducing flooding, forests also help to slow down global warming. The key aspects of a forest that need to be monitored are the components of the soil, temperature, humidity, and concentrations of various gases, including methane, oxygen, ammonia, and hydrogen sulfide. A system was designed to monitor environmental parameters such as wind speed and direction, temperature, humidity, barometric pressure, and disaster management in a severely burned peatland rainforest. IoT devices, powered by solar energy, communicate with the monitoring center via a LoRa network to enhance system viability[94].

4.2.3 Livestock farming

The process of managing farm animals within an agroecosystem—such as cattle, pigs, sheep, goats, and poultry—is aimed at enhancing land use, supporting production, and obtaining products like meat, eggs, milk, fur, and leather. The specific variables for study in this area depend on the type and number of animals involved. VetLink is a support system designed to assist in the identification, management, and treatment of cattle diseases, providing remote guidance for farmers in areas where veterinary services may not be readily available[95]. To ensure timely disease diagnosis and animal health, Ma et al.[96] proposed a passive temperature measurement device and animal monitoring system. Additionally, Lee et al.[97] introduced an IoT-based detection system for large pig farms, which tracks individual pigs' behaviors—including eating, resting, and activity—by attaching an IC tag to each animal. Data collected from these sensors is integrated with analytics programs to generate insights into pig health.

4.3 Tracking and tracing

To meet customer demand and enhance profitability, modern agriculture must ensure that the products sold are safe and easily traceable. This

approach will bolster consumer confidence in food safety and address health-related concerns. Several tracking-based issues, including the following, have been put out for the smart agriculture sector:

The SISTABENE monitoring system was developed by Tradigo et al.[98] and provides tracking and tracing of agricultural goods and commodities, including dairy and vegetables. This technique supports end customers in tracing the origin of food and assists suppliers in monitoring the production process and distribution network problems. It is a blockchain-based system for tracking the food supply chain[99]. It aids in tracking and tracing the production process of agrifood supply chains and locating the source of farm products. The agricultural systems for tracking and tracing agricultural goods enable customers to know the full history of the commodity. Consumers and other stakeholders may learn about the origin, location, and history of items owing to these systems' ability to monitor and trace part of the data gathered across the supply chain, as shown in Figure 6.

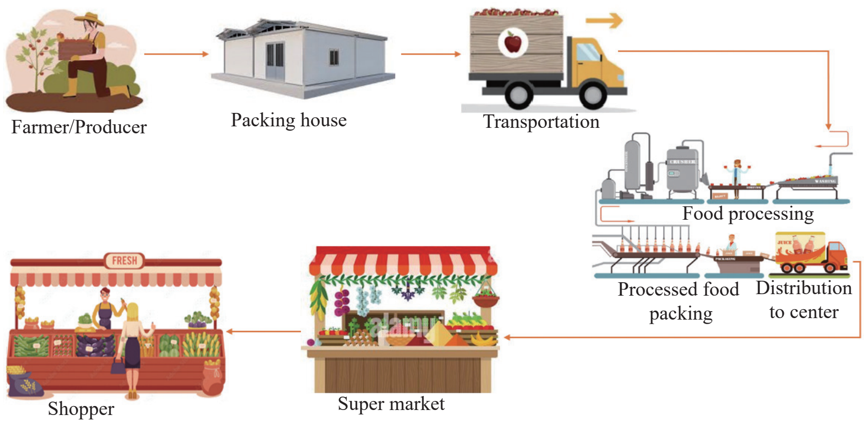

Figure 6 Modern agricultural tracking and tracing supply-chain system for smart agriculture

4.4 Smart precision farming

Advancements in Global Positioning System (GPS) technology have driven significant progress across various scientific and technological domains. GPS provides critical information, such as location and time, that is essential for device identification. It has been successfully integrated into numerous industries, including smartphones, automobiles, and IoT ecosystems. However, GPS is primarily effective for outdoor and sky-based systems. With the growing demand for identification and navigation systems within homes and urban environments (Figure 7), the development of an advanced Global Navigation Satellite System (GNSS) has been proposed to address this need[100]. Additionally, GPS and GNSS technologies have been utilized to create precise mapping systems for agricultural fields and farms. Therefore, farm machinery and equipment may operate autonomously.

The use of drones in agricultural operations, including spraying, fertilizing, planting seeds, assessing and mapping, and monitoring crop development, is one of the most significant uses of smart precision farming. Kim et al.[101] studied the use of drones in smart precision farming, considering control technologies and potential developments in UAV applications. A technology for detecting and classifying agricultural products was developed by Zhou et al.[102] using camera systems, image processing algorithms, and mechanical actuators. The experiment findings for agricultural items, such as oranges and tomatoes, provide a classification success rate of over 95%, and the sorting time for each product is less than one second. The classification of various agricultural goods may be accomplished using this technique, which is adaptable. Kurtser et al.[103] suggested a method for calculating grape production. The recommended solution integrates an RGB-D camera mounted on a moving robot platform with a grape bunch size estimate algorithm. According to the experimental findings, the average error is between 2.8 and 3.5. The findings show that this approach may be used to assess the productivity of large grape fields.

Figure 7 IoT-based platform for efficient input management in smart farming

4.5 Greenhouse production

A novel data collection technology called WSNs is currently gaining extensive use in the agricultural sector, especially in greenhouses. Improved conditions for agricultural development may be easily achieved by controlling the greenhouse environment. By improving production management, WSN use in greenhouses can increase yields and quality. Production management choices as well as recommendations could potentially be developed based on the enormous amount of data that WSN has gathered[104]. In the past few years, WSNs have gained significant applications in agriculture, including environmental factor monitoring, vegetable growth, insect pest management, and irrigation[105]. Plants are raised in greenhouses where environmental factors such as moisture, soil nutrients, light, temperature, etc. are all properly controlled, as shown in Figure 8. Therefore, by simply providing optimal climatic conditions, greenhouse technology enables humans to grow any plant at any time[106].

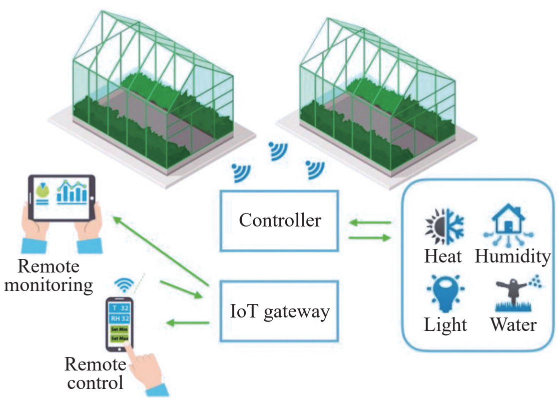

Figure 8 An Internet of Things application for monitoring greenhouse agricultural conditions

Geng et al.[107]conducted research on an environmental monitoring system for multipoint monitoring in large greenhouses. This method employs a drive system to enable the sensor system to travel to various areas in greenhouses rather than utilizing numerous sensors at various locations. The results of the study showed that the recommended method can efficiently monitor several sites in a large greenhouse, thus offering a temperature control solution with energy-saving features for intelligent greenhouses[108]. Two intelligent control strategies were put forth in this study: active disturbance rejection control and fuzzy active disturbance rejection control. The results of the experiments showed that the suggested method reduces the greenhouse's overall energy usage by almost 15%. To save energy and increase crop output, Subahi et al.[109] developed an intelligent IoT system used to monitor and regulate greenhouse temperatures. The research studies for the Kingdom of Saudi Arabia, where daytime high temperatures can exceed 50°C, show the effectiveness of the suggested treatment, including energy savings and plant growth rate prediction.

5 Challenges and future research directions

The extensive adoption of IoT in the agriculture sector faces several challenges, primarily related to economic efficiency and technical problems. These issues, along with the regulations that will shape the implementation of IoT in agriculture, present significant obstacles to its extensive use.

5.1 Economic efficiency

In agricultural economics, a key concern is the low rate of return on investment projects, which involves various risks due to environmental factors. To balance the costs of technological implementation with potential profits, it is essential to analyze the benefit-cost ratio of new technologies in agriculture. Implementing IoT in agriculture incurs several costs, which can be divided into two categories: 1) initial system setup costs and 2) ongoing operational costs. Initial costs include hardware purchases such as IoT devices, gateways, and base station infrastructure. Operational costs encompass registration fees and labor associated with running IoT devices, as well as additional expenses for energy, maintenance, and data exchange between devices, gateways, and cloud servers. According to Turgut and Boloni[110], for successful IoT implementation, the advantages to customers (who must understand the benefits and potential of the technology) must outweigh the physical and privacy-related costs.

5.2 Technical problems

5.2.1 Interference

IoT systems that employ both long and short spectrum bands might be hindered by the installation of many IoT devices for smart agriculture, as illustrated in Table 1. Interference has the potential to lower IoT network dependability as well as affect overall performance. De Lima et al.[111] studied a wide range of hardware that can connect to the Internet quickly and with a large bandwidth. IoT networks' entire interference issue will be resolved.

5.2.2 Security and privacy

One of the major concerns with using IoT in smart agriculture is security, which includes protecting data and systems from cybersecurity risks. Due to their limiting capabilities and capabilities in terms of system security, IoT devices cannot perform complicated encryption techniques. As a result, IoT systems may be accessed through the Internet to acquire access to the system, and IoT gateways can also be targeted by denial-of-service attacks[112]. Additionally, data manipulation attacks on cloud servers have the potential to interfere with farms' autonomous farming operations by carrying out illegal activities. Attackers may also have influence over cloud infrastructures[113]. Neshenko et al.[114] identify data security as a key barrier to IoT adoption in smart agriculture. Specifically, service providers collect, process, and utilize data from IoT devices on farms for commercial purposes to varying extents, raising concerns around data security. Consequently, one of the critical policy challenges is the legitimacy and legal status of agricultural data[115].

5.2.3 Reliability

Most IoT devices will likely be used in fields and farms. Stressful working conditions might cause unanticipated manufacturing breakdowns and accelerate the quality deterioration of IoT devices. IoT gadgets and systems need to be mechanically safe to endure climate variability, including high temperatures, high humidity, heavy rain, and flash floods. In our opinion, to increase the endurance of electronics, new materials and technologies should be further investigated[116].

Several challenges must be overcome before IoT can be adopted. Service providers can reduce costs by more effectively utilizing farm data. However, farmers need to enhance their skills to implement IoT solutions, boosting agricultural efficiency and productivity. Researchers also need to continuously explore optimal solutions to ensure IoT systems' privacy, security, and device robustness. These challenges present important research opportunities and will be crucial for adoption of IoT in the smart agriculture sector.

6 Government initiatives on IoT and agriculture

The government has undertaken several initiatives related to IoT in agriculture. Three Technology Innovation Hubs (TIHs) have been set up each at IIT Ropar, IIT Bombay, and IIT Kharagpur for carrying out research, translation, and technology development using IoT and agriculture. Some applications of IoT in agriculture under research at these centers include precision farming, agricultural UAV, livestock tracking, climate monitoring, smart greenhouse, and AI-integrated computer imaging. The major activities are as follows:

1) To create comprehensive solutions in agricultural technology for forecasting crop yield during the growing season.

2) To design aerial robotic systems for monitoring soil parameters, conduct drone-based imaging, and perform drone-assisted spraying.

3) To develop a predictive data analysis model that enables intelligent decision-making using environmental factors (temperature, rainfall, humidity, wind direction and speed), soil properties (moisture, temperature, electrical conductivity, pH, NPK, sulfur), and leaf wetness.

In 2018-2019, a program called "Innovation and Agri-Entrepreneurship Development" was launched under the Rashtriya Krishi Vikas Yojana (RKVY) to foster innovation and agripreneurship. Its goal is to provide financial support and enhance the incubation ecosystem within the agriculture and related sectors. Numerous start-ups are working on projects across areas such as agro-processing, food technology and value addition, AI, IoT, ICT, blockchain, precision farming, digital agriculture, agricultural logistics, value and supply chain management, online platforms, agricultural extension services, farm mechanization, organic farming, natural resource management, renewable energy, waste conversion, animal husbandry, fisheries, dairy, and secondary agriculture. To date, 1102 start-ups in these sectors have been selected, with Rs. 66.83 core disbursed in phases. These start-ups underwent a two-month training at agribusiness incubation centers before receiving financial support[117].

7 Conclusions

The promotion of IoT deployment in the agriculture sector has produced several concerns that have been closely investigated. Due to its distinctive capability of real-time monitoring, the IoT is revolutionizing all applications. By using distance sensors and wireless connectivity protocols, IoT in agriculture can increase crop yields. Various wireless communication protocols such as WiFi, ZigBee, SigFox, LoRa, RFID, NFMI, Terahertz, and NB-IoT were summarized and their applications in various fields were also studied. These protocols in smart agriculture can effectively and efficiently address environmental data, water saving, monitoring of animal behavior, accuracy, power efficiency, and cost reduction. These wireless protocols increase the crop yield significantly more than traditional farming methods. Microcontrollers are used to gather data from sensors, evaluate that data using machine learning tools like genetic algorithms and neural networks, and provide the final control instructions. The most commonly used microcontrollers are Arduino (to develop autonomous machines), Raspberry Pi (to store data) and 8-bit microcontroller (to process data). Next, this paper discussed several developed wireless communication technologies and showed how they had significantly enhanced farming operations. Several studies have been conducted on the use of IoT in smart agriculture with the goals of increasing efficiency, reducing the need for human labor, and increasing production efficiency. For most farmers, especially small- and medium-scale farm owners, IoT solutions need to be inexpensive, but there are still several issues that need to be solved. The use of IoT technology for smart farming is unavoidable and will increase productivity, provide clean and green foods, support food traceability, decrease the need for human labor, and increase production efficiency. However, security technologies still need to be continually improved. Researchers expect that these techniques will be used in agricultural applications in upcoming research, allowing for fully intelligent and automated farming. The following conclusions were drawn from the above study:

1) With the continuing advances of computers and software, sensor and wireless communication protocols help to resolve several issues such as labor shortage, timely application, etc., directly contributing to increased agricultural yields.

2) IoT-enabled devices in smart agriculture help to monitor environmental parameters such as temperature, humidity, rainfall, soil moisture, etc. CO_2 levels in farmland and the evapotranspiration rate can also be measured accurately for crop health surveillance.

3) Different protocols have unique applications which are useful in various fields in agriculture, as well as in home automation, smart lighting, traffic management, war field, etc.

4) Using these sensors and protocols contributes to the automization of the agriculture sector, which helps to improve and optimize agriculture overall.

5) Various activities and schemes have been implemented by the government of India for smart agriculture.

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Authors' contribution

Conceptualization, original draft preparation, methodology and writing, review and editing: Gatkal N R, Nalawade S M, Ramesh K. Sahni; Resources: Bhanage G B, Walunj A A, Kadam P B; Drafting, review and editing and funding acquisition: Musrrat Ali.

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