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Internet-of-Things for Smart Agriculture: Current Applications, Future Perspectives, and Limitations

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Abstract

The increasing global population has led to a higher demand for food production, while a decrease in rural labor and a rise in production costs present complex challenges for the food industry. Smart agriculture is a farm management concept that considers the deployment of Internet of Things (IoT) to address current food production challenges. In this regard, the agricultural sector is becoming increasingly data-focused, and requires data and technologies that are more precise, advanced, and cutting-edge than in the past. IoT enables agriculture to become data-driven, resulting in timely and more cost-effective farm intervention while reducing environmental impact. This review provides an analytical survey of the current and potential applications of IoT in smart agriculture to overcome challenges posed by spatio-temporal variability under varying environments and task diversity. This review also discusses the challenges that may arise from IoT deployment and presents an overview of the existing applications and those that may be developed in the future.

Keywords

Smart Agriculture, Internet of Things (IoT), Precision Farming, Data-Driven Agriculture, Agricultural Technology, Sustainable Food Production

1. Introduction

The International Telecommunication Union defines IoT as "a technology that primarily enables interconnections between a human and an object, an object and another object, as well as between humans themselves." IoT is a transformative technology that has the potential to revolutionize the computing industry and enable novel modes of data exchange and communication in the future [1] [2]. The technology functions through the integration of advanced sensor systems, including intelligent sensors, radio-frequency identification (RFID) devices, global positioning systems (GPS), infrared sensors, remote sensing (RS) equipment, as well as mobile communication networks and other related communication infrastructures [3]. IoT represents a wireless network of autonomous objects that can be configured independently [2]. The primary goal of IoT is to establish a large-scale network that interconnects different sensor devices, such as GPS, remote sensing (RS), radio-frequency identification (RFID), and laser scanners, to enable a smooth exchange of information. This network can contain numerous embedded intelligent devices, commonly referred to as "smart things," which can autonomously gather data about themselves, their environment and other smart objects, and transmit this information to other systems and devices via various channels, such as networks, Bluetooth, near-field communication (NFC) and sensor data, without the need for human intervention [1]. As a result of these benefits, IoT technology is extensively utilized in numerous sectors such as smart cities, smart healthcare, smart homes and buildings, energy, transportation, waste management and monitoring, and agriculture [3] [4]. **Figure 1** shows various IoT sensors powered with solar-charged batteries implemented in experimental and commercial fields to monitor agricultural parameters such as microclimate, soil temperature, soil moisture, leaf wetness, and light conditions.

Figure 1. An example of IoT deployment in agricultural fields for live monitoring of air and soil parameters.

Food security is a primary concern for most countries due to population growth, ongoing depletion of natural resources, scarcity of arable land, and increased frequency and intensity of natural disasters. Many researchers are conducting studies to address these issues so as to increase agricultural productivity. In this context, IoT and big data analysis are intended to enhance the operational efficiency and overall productivity of the agriculture sector [5]. IoT enables agricultural automation, resulting in increased agricultural output [4]. Additionally, IoT can potentially increase crop production by reducing waste generation, streamlining operational procedures, and establishing a safe food supply chain [6]. The main objective of this review paper is to consolidate the existing applications of IoT in smart agriculture, the availability of sensors and equipment in IoT, and research gaps from previous studies by identifying current challenges and proposing future research prospects.

2. Use of IoT for Digitalization of Agriculture

IoT technology has introduced a new era of digitalization in agriculture. It has been adopted in multiple agricultural processes, such as farm management [7], farm monitoring [8], livestock monitoring [9], irrigation control [10], greenhouse environmental control [11], autonomous agricultural machinery [12], and drone-based surveillance [13]. Farmers can monitor their farm conditions in real-time through wireless sensors and mobile networks, and manage their operations efficiently. Furthermore, the integration of IoT technology enables farmers to gather relevant data that can be utilized to produce yield maps, facilitating the production of high-quality crops at a lower cost via precision agriculture (PA) [14]. The incorporation of IoT technology has enabled various digital agricultural applications, including soil and plant monitoring, tracking and tracing, crop growth observation and selection, PA, irrigation assessment support, greenhouse production and its monitoring and control systems, food supply chain monitoring, as well as biomass measurement of plants or animals. Figure 2 shows a typical IoT-based data collection system for live monitoring of agricultural parameters. The system includes solar-powered sensors and transmitters, multi-channel gateways, cloud storage, and web or mobile applications.

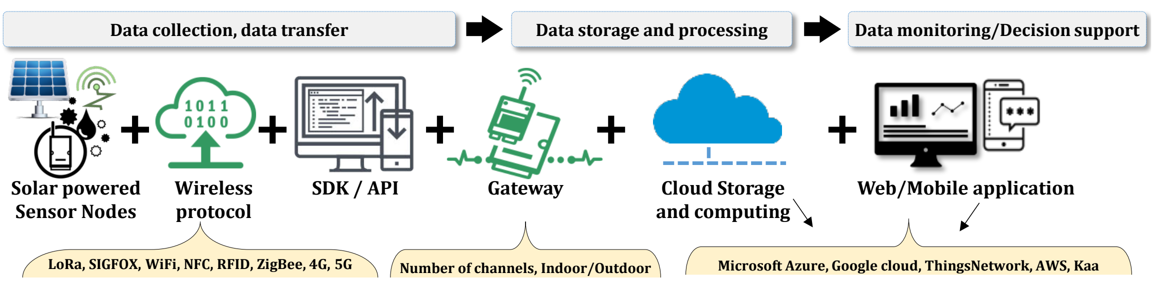

Figure 2. Overview of a typical IoT-based data collection for live monitoring of agricultural parameters.

It is worth mentioning that IoT has a broad application range, including the ability to track and regulate real-time environmental variables such as humidity, temperature, shock, and vibration during the transportation of products [15]. Furthermore, IoT has the ability to predict a product's condition and demand on shelves or inside refrigerators and provide end-users with information regarding the product's origin and properties. In the agricultural sector, IoT has the potential to foster the growth of a well-informed, connected, adaptable, and advanced rural community. Inexpensive electronic devices can facilitate human interaction with the physical environment under the IoT framework, and the computing power and software available on the internet can deliver valuable analytical information [16].

Environmental applications of IoT technology include the creation of detailed real-time maps of air and water pollution, noise levels, temperature, and hazardous radiation [17] [18]. It can also collect and store environmental data, check compliance of ecological variables with local regulations, issue alerts, or send recommendations to citizens and authorities [19]. Upon data transmission to the cloud, authorities can utilize predictive models to anticipate changes in environmental factors, locate and monitor sources of pollution across temporal and spatial dimensions. This analytical approach can facilitate quicker and more effective decision-making, aiming to safeguard the health and well-being of all members of society [20]. IoT agricultural applications, smartphone-based agricultural applications, and sensor-based agricultural applications are the categories that fall under the term "agriculture apps." In recent years, wireless sensor networks (WSNs) have enabled IoT applications for smart agriculture. Some examples of these applications include irrigation sensor networks, frost event prediction, PA and soil farming, smart farming, and unsighted object recognition [21]. IoT is utilized for numerous tasks in the agricultural industry. The following four categories can be used to broadly classify these tasks: (a) management systems, (b) monitoring systems, (c) control systems, and (d) unmanned machinery, as displayed in **Figure 3**.

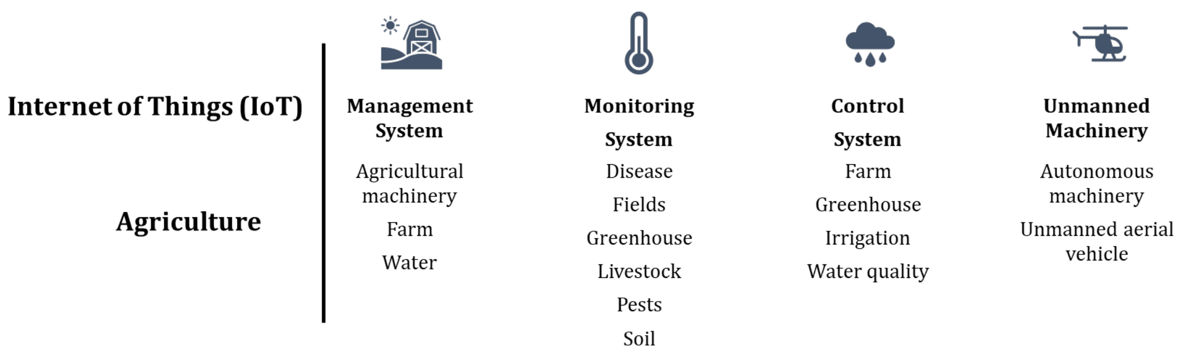

Figure 3. The paradigm of applications, facilities, and sensors utilized by smart agricultural monitoring systems with the current availability of applications.

3. IoT for Agriculture

3.1. IoT-Based Sensing and Monitoring

Sensors, harvesting equipment, smartphones, cellular communication, advanced machines, and cloud computing (CC) are significant components of IoT technologies commonly used in agriculture. The hardware setup shown in **Figure 4** is an IoT-based data collection, monitoring, and control system that benefits from low-cost and modular components for research purposes in digital agriculture. The system was designed by Adaptive AgroTech and are being been deployed at the pilot scale in the experimental fields of Universiti Putra Malaysia for (i) soil and crop monitoring, including soil moisture levels, temperature, and nutrient levels, which are used to optimize irrigation practices and adjust the application of fertilizers to improve crop yields, (ii) livestock monitoring, including live assessment of livestock health and ensuring their well-being by means of sensors that can monitor heart rate, body temperature, and movement patterns to detect any abnormalities or signs of illness, (iii) weather monitoring, including weather conditions such as temperature, humidity, and precipitation levels, which are required to predict weather patterns and plan accordingly to minimize crop damage, (iv) the detection of pests and diseases, including constant monitoring of crops for signs of infestation or disease, as well as early detection and treatment to prevent widespread damage and reduce the need for pesticides, and (v) water management, including monitoring water usage and ensuring efficient irrigation practices to reduce wastage of water and improve crop yields. It should be noted that there is a wide variety of sensors used in agriculture, such as visual, multispectral, thermal, light detection and ranging (LiDAR), hyperspectral, heavy metal detection sensors, biosensors, gas sensors (to detect the presence of gas), and many more. Table 1 shows current IoT-based sensor applications in smart agriculture.

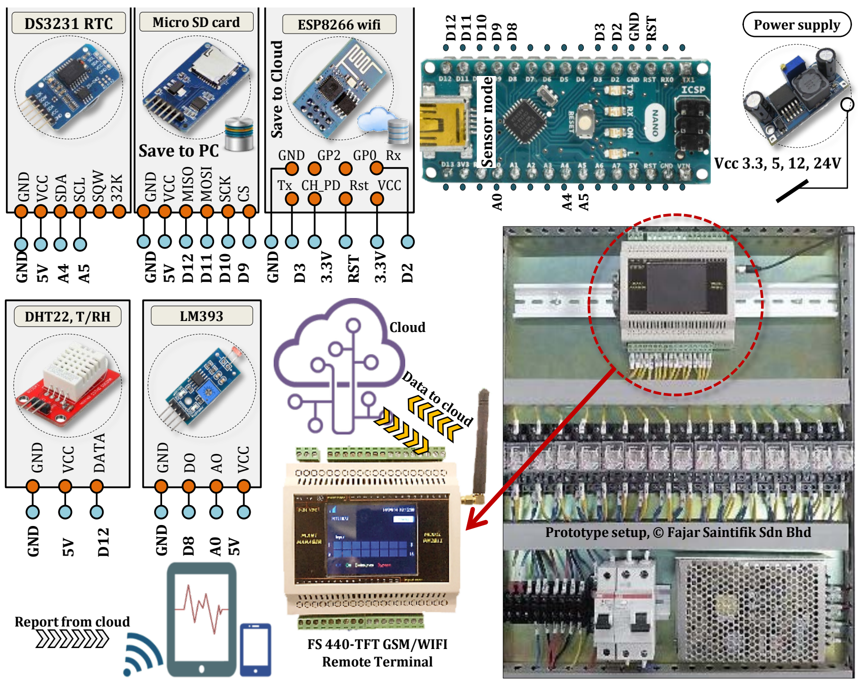

Figure 4. Hardware prototype used for IoT-based monitoring and control of microclimate inside a tropical greenhouse at Universiti Putra Malaysia.

Table 1. IoT-based sensors in smart agriculture with potential use for increased agricultural production.

Sensor	Operation
Acoustic	Weeding, harvesting, and farm management, Low cost and quick response capabilities with convenient devices such as smartphones [22]

Continued

Electromagnetic	Records conductivity, electrical responses, transient electromagnetic responses, and adjusts variable-rate applications, Electrical circuits can assess soil particles' conductivity or charge accumulation capability via contact or non-contact methods [23]
Soft water level-based	Monitors hydrological behavior, such as flow and water level, with strict time-step acquisitions (SWLB) [24]
Optoelectronic	Differentiates plant types, discerns weeds and other plants, including wide-row crops, Characterizes vegetation and soil based on reflection spectra [25]
Electrochemical	Determines soil nutrient levels and pH by assessing the soil characteristics, Supersedes time and cost-consuming chemical soil assessments, Precise measurements of soil salinity, pH, nutrients (macro and micro) [26]
Telematic	Universally used communication equipment, Precise agricultural-based toolkit, collects information from inaccessible remote areas, reports machine status, identifies locations, and locates travel routes, automatically stores and records agricultural-related data [27]
Ultrasonic ranging sensors	Low-cost, user-friendly, and customizable, Tank monitoring, spray distance measurement (e.g., controlling boom height and width for uniform spraying, detecting objects, and avoiding collisions), and monitoring crop canopies [28] [29]
Remote/Proximal	Collects, manages, analyses, and stores geographical and spatial data, including various environmental and climatic parameters, Forecasts and evaluates multi-factors that include yield assessment, crop evaluation, land degradation, and pest management using satellite or UAV platforms [30]
Mechanical	Evaluates soil compaction or mechanical resistance to detect variable compaction, these sensors penetrate the soil, measuring forces using load cells or strain gauges [31] [32]
Ambient light	Monitors the photosynthetic light intensity level, Allows for investigations on the impact of light intensity on temperature of greenhouse environment [33]
Optical	Measures soil organic matter, moisture, color, availability, and compositions of minerals contents, including clay, using light reflection, Conducts assessments on soil light reflection at selected parts of the magnetic field [34]
Soil moisture	Measures the soil moisture content, which is affected by changes in soil dielectric permittivity. The sensor generates a voltage that is proportional to soil dielectric permittivity, as it averages the water content throughout its entire length, obtains information on the ideal level of soil moisture for each plant species, Information about soil moisture content is monitored in greenhouses in order to regulate irrigation [35]
Turbidity	Measures water turbidity level and quantifies total suspended solids in water by determining the amount of light transmitted and the amount of scattered light [36]

Continued

Light detection and ranging (LiDAR)	Calculates the ranging distance at each data point using an image camera, Segmentation, land mapping, 3D farm models, determination of soil type, yield prediction, soil loss, and erosion monitoring, Monitors dynamic parameters, *i.e.*, leaf area and fruit sizes [37] [38]
Rain	Detects rain pressure, and can potentially determine the strength of the rainfall [13]
Airflow	Measures soil permeability and moisture content, Identifies and distinguishes different soil structures and types, enables measurements to be taken in a static or dynamic position while in motion [16]
Mass flow	Yield monitoring, provides yield data by measuring grain flows, *i.e.*, when passing through combined harvesters [16]

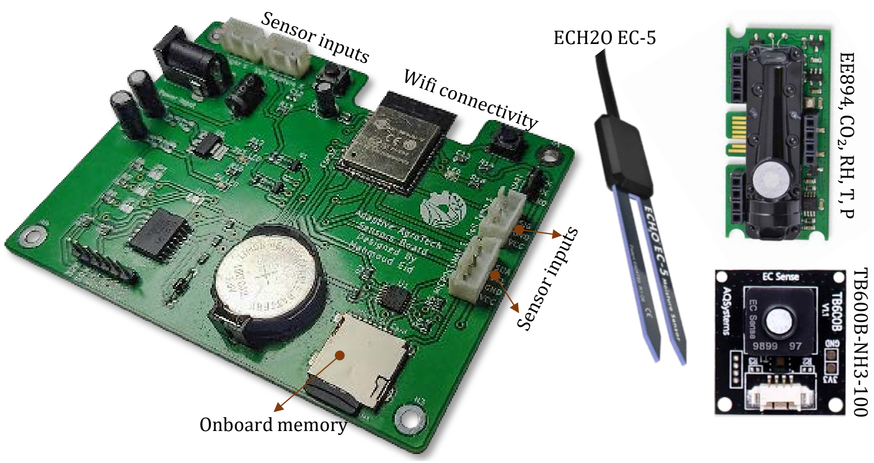

Figure 5. A WiFi connectivity board with analog and digital sensor probes for collecting agricultural parameters including CO_2, NH_3, microclimate, and soil moisture. (Source: Adaptive AgroTech)

Despite the lack of reliable infrastructure, phones are still the most popular way to communicate in rural locations. Smartphones, a potent communication technology, are widely used to inform the community if a contractor is needed. Smartphones have become more affordable due to recent technological breakthroughs, making them more appealing, especially to farmers in remote regions. Moreover, the inclusion of features such as GPS, microphones, cameras, accelerometers, proximity sensors, and gyroscopes has caught the attention of information technology specialists that are focusing on creating increasingly engaging smartphone services to fulfill the varying needs of farmers [39] [40]. Various new tools and methods for strategically implementing smartphone technology in agriculture have been created. **Figure 5** presents some examples of application sensing using smartphones. Smartphone technology is being widely utilized in countries such as China, India, Turkey, Ghana, Kenya, Nigeria, Uganda, Mali, and Zimbabwe to bolster agricultural production and economic growth [41]-[45]. **Figure 6** categorizes sensors related to smartphones, *i.e.*, accelerometer [46], image sensor

[47], global positioning system [48], microphone [49], gyroscope [48], inertial sensor [50] and barometer [51].

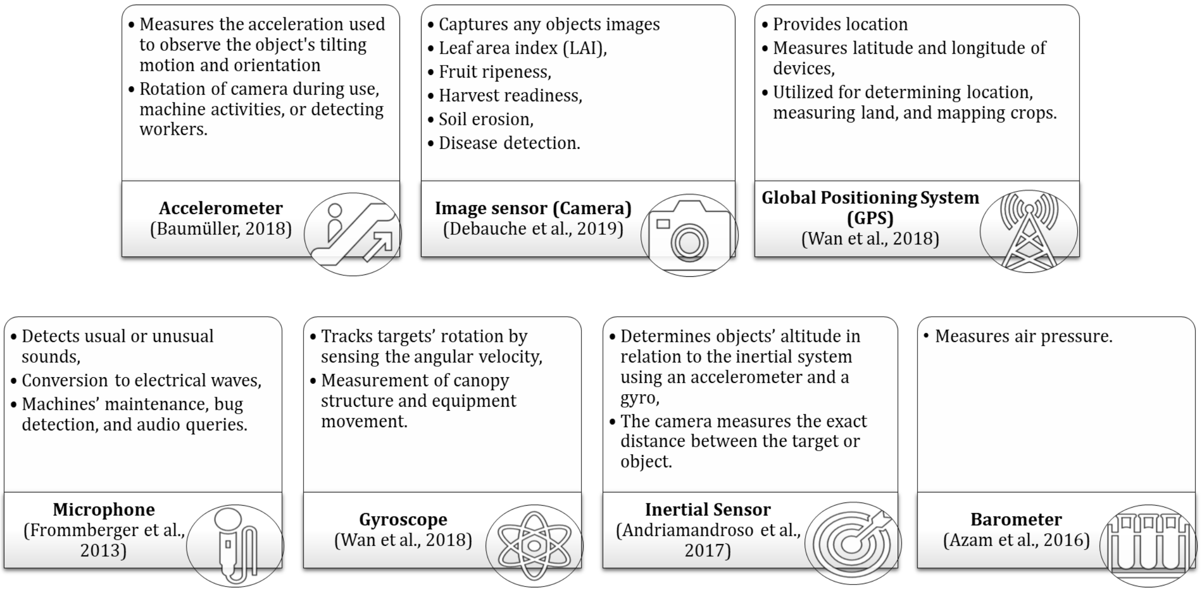

Figure 6. Applications for smartphone sensors in modern agricultural practices.

3.2. Mobile Applications to Support IoT Monitoring and Automation

Integration of mobile applications has emerged as a significant trend in recent times. As a result, more and more businesses are exploring the possibility of forming strategic alliances with other application service providers to provide professionals with the choice of utilizing the entire infrastructure supporting their applications, resulting in superior outcomes and higher productivity levels. Table 2 lists several smartphone applications developed for agriculture. The Land-Potential Knowledge System (LandPKS) framework is given in Figure 7.

Table 2. Smartphone applications that support various agricultural functions/operations.

Mobile application	Function	Feature
LandPKS [52]	Soil assessment	Weather patterns, topography, relatively static soil properties, and land management practices have long-term implications, designed to assist farmers in gaining a better understanding of their land's potential and their ability to adapt to and mitigate the effects of climate change.
PETAFA [53]	GIS	Offers Normalized Difference Vegetation Index (NDVI) on multiple crops across different growth stages, also provides packaged soil analysis with geo-references.
PocketLAI [54]	Irrigation	Determines plant water requirements by computing its Leaf Area Index (LAI). It acquires images at 57.5 degrees under the hood using a moving camera and accelerometer sensor while the operator turns the device about its axis of rotation.

Continued

AMACA [55]	Machinery or devices	Estimates mechanical and implantation costs that are significant crop expenditures for various field operations. It follows the cutter-driven Quality Function Deployment (QFD) method to ensure that the final product satisfies the user's needs.
eFarm [42]	GIS	It is a crowd sourcing and human perception platform that captures geo-tagged information on agricultural land at the parcel level. It is particularly useful for mapping, sensing, and modeling agricultural land systems.
Ecofert [56]	Fertilizer management	Ecofert is a software tool that aids in optimizing fertilizer utilization by identifying the optimal fertilizer composition that aligns with the nutritional requirements of diverse crops. Furthermore, it incorporates the market costs of fertilizers in providing recommendations to farmers.
AgriMaps [57]	Land management	This application adopts a site-specific, evidence-based approach to suggest management practices for croplands. Compared with similar applications, it offers a broader range of geospatial information and facilitates the visualization of spatial data.
SWApp [58]	Irrigation	The creators of this application aimed it toward arid areas, where irrigation issues are more prevalent. The application offers an affordable, dependable solution for tracking soil moisture and considers historical weather data.
SnapCard [59]	Chemical spraying	This application was created to conduct field analysis of spray collectors using imaging analysis. It utilizes various sensors found in mobile devices and employs five imaging techniques to measure droplet deposition and size.
Weedsmart [60]	Weed management	This application offers a means to enhance weed management in pastures. By evaluating pasture farming systems through a series of nine questions, it can determine herbicide resistance and the risk of weed seed bank.
Village Tree [61]	Pest management	This application offers intelligent solutions for pest management by gathering reports of plant pests. It utilizes a crowd sourcing mechanism to transmit location-based information and images, alerting other cultivators susceptible to the same issue.
cFertigULF [62]	Fertigation	This application quantifies fertilizer and water needs of major crops using various growth systems and fertilization methods. It enables the precise application of nutrients and water in greenhouse farming.

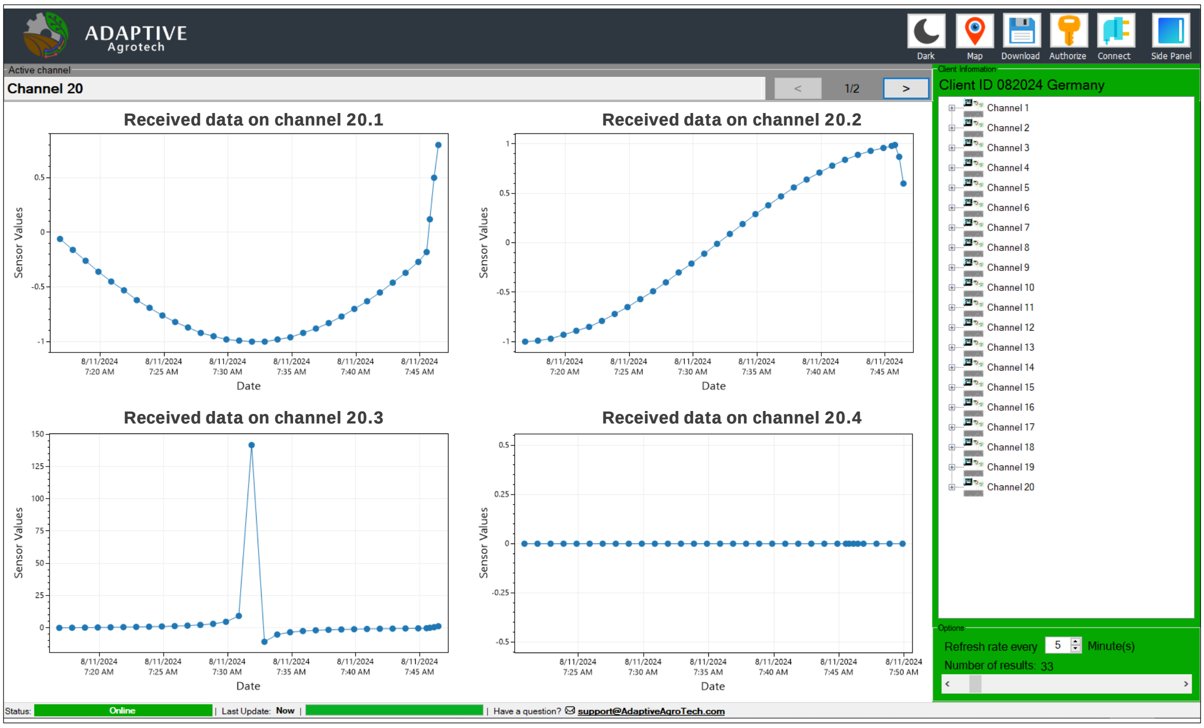

Figure 7. Screenshot of an IoT application for simultaneously plotting and downloading multiple sensor data that are stored on cloud (Unpublished data).

3.3. IoT Integration with Mobile Robots and Drones

The integration of IoT with mobile robots has provided new opportunities for PA. By leveraging IoT technologies, mobile robots can be equipped with various sensors and connected to the cloud for real-time data processing and analysis. This technology enables farmers to monitor crop and soil conditions more accurately and timely, improving yields and resource efficiency. For instance, mobile robots equipped with soil moisture sensors and GPS receivers can help farmers precisely irrigate crops where water is scarce, thereby reducing water wastage and increasing crop productivity. Similarly, drones equipped with multispectral cameras can collect data on plant health and help farmers detect early signs of disease or stress, allowing for prompt intervention and mitigation [63]. Additionally, IoT-enabled mobile robots can also help farmers to automate labor-intensive tasks such as weeding, pruning, and harvesting. For example, robots equipped with computer vision and machine learning algorithms can detect and classify different types of weeds and apply targeted herbicide sprays, reducing the use of herbicides and minimizing crop damage. Similarly, mobile robots with robotic arms and sensors can harvest fruits and vegetables accurately and consistently, reducing labor costs and improving harvesting efficiency. As IoT technologies advance, mobile robots are expected to become an indispensable tool for PA, enabling farmers to optimize their operations and enhance sustainability [64]. Farmers and growers rely on Unmanned Aerial Vehicles (UAVs) for crop growth assessment and ecological landscape monitoring. UAVs can efficiently administer water and pesticides for crops on rough terrain. Robots and drones have demonstrated superior speed and accuracy compared to conventional spraying equipment. Recent developments in swarm technology and task-based control have enabled multiple groups of robots and drones equipped with different tools and sensors to collaborate and offer farmers an all-inclusive land management capability. Along with the use of drones, the adoption of robotics in agriculture has increased productivity and crop yield; furthermore, pesticides are decreasing due to the use of robots for weeding and spraying. Therefore, the environment will be less polluted due to the prevention of agrochemical leaching with precise and timely applications [65] (Khan *et al*., 2020).

3.4. Cloud Computing and Data Analytics

IoT and data analytics are crucial tools for successful smart farming. The integration of these technologies plays a pivotal role in determining the effectiveness of smart farming systems. Applications of IoT and data analytics are diverse, and it is essential to identify the most suitable approach for smart farming. Cloud computing platforms offer farmers a repository of knowledge-based information and experience regarding different agricultural techniques and equipment. In order to make this plan more practical, it can be expanded to include access to customer databases, supply chains, and billing systems [66]. Cloud-based services have numerous benefits but also pose new challenges. First, smart farming involves developing and implementing a broad range of sensors, each with its unique data format and meaning. Second, decision support systems are usually tailored to a particular application, whereas farmers may need access to different systems depending on their specific needs, such as monitoring soil health. Therefore, cloud-based decision support systems should be capable of managing a wide range of data and their formats and customizing them for specific purposes [16]. The PA market is constantly developing, allowing farmers to adopt data-driven solutions. Although the potential for data analytics in agriculture is boundless, significant advantages exist, including increasing innovation and productivity, greater understanding of environmental challenges, reducing waste and improving profits, and improving supply chain management. A summary of smart agriculture data analytics is provided in **Table 3**.

Table 3. Comparative analysis of the smart agricultural system.

Features	Approach/Technique	Benefit
Big data	Big data virtualization	Reducing the risk of data errors, improving storage capacity, enhancing data processing speed, and increasing data availability [67].
	Precision agriculture, analytical method and applied economics	Climate forecasting, crop yield, crop selection, disease prediction, irrigation systems, agricultural policy, and trade [68].
	Predictive modelling	Revolutionize livestock production through real-time data and innovative processes [69].

Continued

Big data analytics and meta data	Digital agriculture	The system aids farmers throughout the growing season with tasks such as weather prediction and pest control [70].
	Global positioning system, yield monitoring and mapping, information management and variable rate technology	Accuracy in agribusiness [71]
	Predictive analytics, recommendation systems, data mining and time series analysis using big data approach	Maximize output while decreasing manual tasks [72]
	Precision agriculture	Provide farmers with technical assistance for simulating complex models on a large scale [73]
	Classification and clustering	Measure soil moisture, plant stem diameter and environmental conditions [74].
	Sensor cloud infrastructure and mobile services	Used for farmland monitoring to ensure continued viability [75]
Cyber-physical system and cloud computing	Precision regulation modelling and agriculture cyber-physical system	Regulations pertaining to water and fertilizer are enhanced [76]
	Fog computing and real-time processing	Efficient use of cloud resources, network bandwidth, and power makes this technology ideal for real-time cloud applications [77]
Data aggregation	Data aggregation at layer 1 (sensor network), layer 2 (base station—Internet), and layer 3 (response center—SQL server)	Top-level data analysis is simplified [78]
Data analysis and data warehousing	Crop yield prediction and precision agriculture	An agricultural data management system improves crop yield prediction and production efficiency [79]
	Photovoltaic systems covering multi-time scale coupling and multi-system correlation	Increases crop yield through the use of renewable energy models [80]
	Apache Hadoop framework and its core elements	Apache Hadoop, a big data framework, is useful for handling large datasets generated from precision agriculture [81]

Continued

Data analytics, data mining and IoT	Centralized control unit for sensors	Minimizes power consumption for devices with IoT [82]
	K-means and K-medoid clustering algorithms	K-medoids clustering surpasses k-means on the agriculture dataset, indicating its effectiveness for agricultural data analysis [83]
	Video surveillance approach, transmission, and analysis approach	The application is made of IoT, cloud computing, and analytical tools. It creates a hybrid data storage system [84]
IoT	Controlled environment agriculture	The agricultural device is designed to be user-friendly It can be used in agribusiness, regardless of scale, ranging from small to large [85]
IoT and nano technology	Web-based automatic control system	Automates the process of irrigation and plant monitoring in a terrace garden [86]
IoT, cloud computing and big data	Global positioning system and geographic information system	Optimizes crop yield and reduces wastage [87]
	Cloud-based real-time data gathering and processing	Discusses the issues of cyber security in smart farming in greater detail [88]
	Cluster analysis approach	Helpful information acquired through front-end visualization technology [89]
IoT, cloud computing and cyber physical system	Non-orthogonal multiple access	The system can accommodate numerous user devices concurrently while maintaining a high data transmission rate and enabling widespread connectivity [90]
IoT, data visualization	Nonlinear autoregressive model and wireless sensor network	Able to accurately track environmental conditions such as humidity, temperature, and soil moisture [91]
IoT and wireless sensor network	A cloud-based IoT architecture	The efficiency, productivity, and profitability of agricultural production systems through wireless sensor networks would promote digital agriculture [92]
	Wireless sensor network and remote monitoring system	Collecting real-time farm construction environment data [93]
	Precision agriculture and IoT	This solution addresses the issue of a limited energy supply by utilizing renewable energy sources [94]
	Global positioning system, real-time kinematic sensing	Provide positional precision (cm) for agricultural tasks [95]
Photovoltaic agriculture, IoT and big data	Node sensors and web application	Optimal irrigation for farming crops [96]

Continued

Wireless sensor network and data analytics	Decision support system, wireless visual sensor network and Bluetooth 4.0	Bluetooth 4.0 is a messaging protocol capable of compressing data and producing high-quality images that are well-suited for outdoor environments [97]
	Image processing	Prevents data loss and collusion and increases the lifetime of wireless sensor network [98]
	Renewable energy, machine learning, web and mobile-based applications and motion detection devices	Discourses the usage of water in agriculture [99]

4. Data Transfer in Digital Agriculture

Accurate communication and prompt information reporting are two essential features in advanced agriculture. Multiple factors must be connected and involved to achieve effective and significant results. The dissemination of reliable communication is critical for agricultural development, and telecommunication operators play a vital role in this process. Developing a highly effective management system is also necessary to expand IoT and increase general knowledge to improve the agricultural industry. When selecting a communication method, it is crucial to consider several factors, including coverage, energy consumption, reliability, and cost [16].

4.1. Cellular Network and LPWAN

Increasing the cellular communication mode from 2G to 5G may be appropriate, depending on the task and available bandwidth. In addition, the dependability and accessibility of cellular networks are essential considerations in rural areas. Information transmission via satellite is another effective option to address this issue. However, the cost of this communication mode can be prohibitively expensive, making it unsuitable for small- and medium-sized farms. Selection of a suitable communication model will depend on the operational requirements. For example, some farms require sensors that can process data at a slower rate but must operate continuously for an extended period, requiring a longer battery life. In this scenario, the latest version of the Low-Power Wide Area Network (LPWAN), which has a longer battery life, more comprehensive connection range, and more affordable price point (between USD2 and USD15), is considered an excellent alternative to cellular networks [100]. Currently, LPWAN networks are highly suitable for crop and pasture management, and their success has led to their use in various other agricultural applications [101]. Wireless sensors can be categorized into three groups in agricultural applications based on their communication information rate and power consumption, as summarized in **Figure 8**.

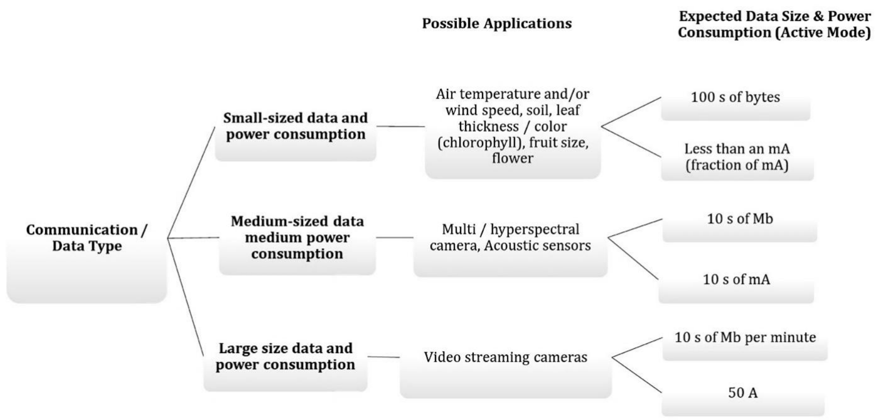

Figure 8. Data and power specifications of wireless sensors often used for modern farming.

4.2. Radio Communication Protocols

Communication protocols are sets of rules and standards that define how devices communicate with each other in a networked environment. In smart agriculture, communication protocols are essential to ensure that sensors, actuators, and other devices can exchange information and data effectively and securely. The choice of communication protocol in agriculture depends on the application's specific requirements, such as the range of communication, power consumption, data rate, and security. By selecting a suitable communication protocol, smart agriculture systems can be optimized for efficiency, productivity, and sustainability. There are several communication protocols used in smart agriculture, including i) Bluetooth, ii) Zigbee and iii) LoRa. Bluetooth is a wireless communication protocol essential for connecting small devices across short distances. IoT agricultural devices like the Farm Note Air gateway and Color Sensor are compatible with Bluetooth-enabled sensors. Given its widespread use, Bluetooth is currently being evaluated as a possible tool for multi-level farming operations [102]. Zigbee is a wireless communication protocol that was designed to serve as a replacement for non-standard equipment and has a wide variety of applications. Devices based on this protocol can be categorized as routers, coordinators, or end devices, depending on the application's specific requirements. Additionally, Zigbee networks can support three distinct topologies, including Cluster Tree, Star, and Mesh, as described by [103]. In agricultural applications, Zigbee can be particularly useful in greenhouse environments that require short-range transmissions due to its characteristics. During parameter observations, real-time data can be transmitted from sensor nodes to the terminal server via Zigbee, as noted by [104]. The Zigbee module can also transmit data to support operations such as fertilization and irrigation. LoRa uses radio frequency. This low energy-consuming architectural technology, presented in **Figure 9**, uses a proprietary chirp spread spectrum technique that allows communication distances to range over 15 km with a novel collision handling protocol. The modeling is easily deployed and maintained. Two LoRa devices must operate and share the same channel bandwidth, spreading factor, and coding rate for communication. It is advised to use it for low-speed and low-data transmission. LoRa is ideal for rural areas to adopt PA as it offers flexibility in architectural design. Hence, there is no need for complex or power-demanding routing and popular wireless technologies like Bluetooth and ZigBee. It allows sensor nodes to communicate directly with the data collection point and is acknowledged sequentially upon transmission. Some agricultural usage for modeling the probe includes air temperature, leaf wetness, and humidity [105].

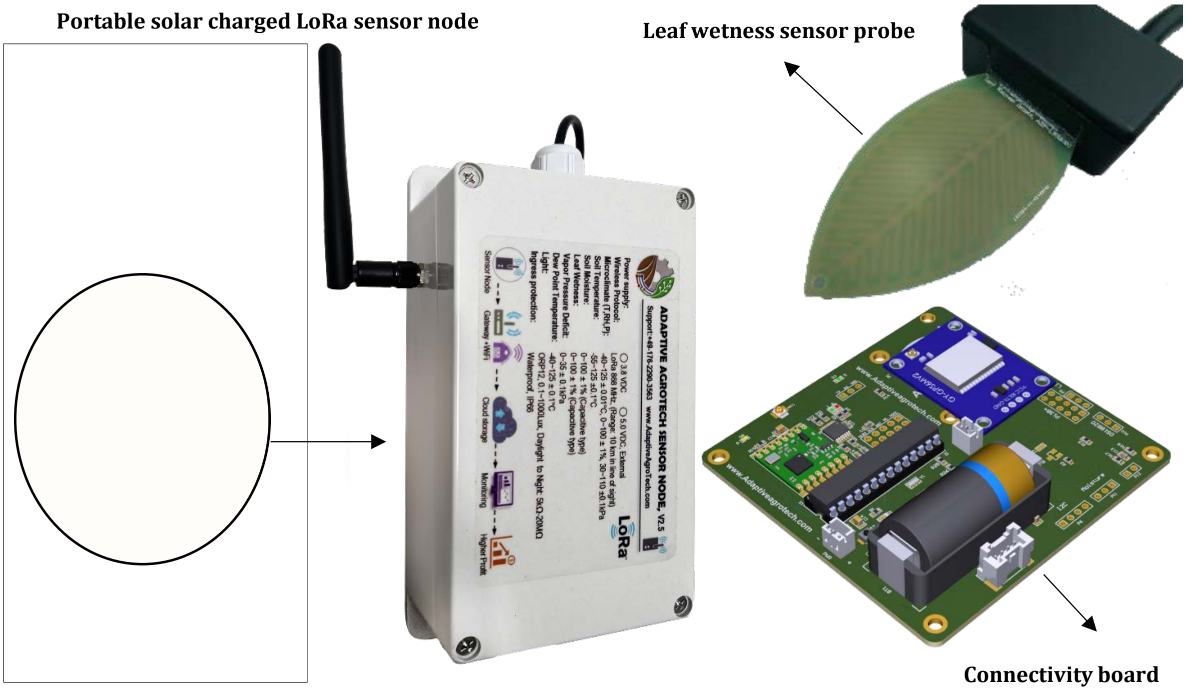

Figure 9. A portable LoRaWAN leaf wetness sensor node with a modular solar-charged battery. (Source: Adaptive Agro-Tech)

5. Advantages of IoT-Based Automation in Agriculture

Internet access has been increasingly available over the past two decades, resulting in numerous benefits for individuals and organizations worldwide. The most notable advantage is the ability to access and produce data and services in real time. IoT has emerged as a promising technology for bringing similar advantages to everyday objects, enabling the extension of human perception and the ability to modify the surrounding environment [1]. The environmental and agricultural sectors are particularly suitable for IoT solutions as they require continuous monitoring and control over large areas. When coupled with machine learning algorithms, the collected data can provide predictions, opening up new opportunities beyond basic automation and facilitating planning and decision-making by owners, managers, and policymakers. Utilizing IoT together with blockchain in the agricultural sector offers a variety of benefits and advantages, some of which are as follows: (1) Increased efficiency of agricultural inputs such as soil, water, fertilizers, pesticides, and more [66], (2) Cost reduction through timely application with the right amount of inputs [66], (3) Improved profitability for farmers through efficient and timely application of inputs [106], (4) Improved sustainability on two levels: environment protection and food security and resource sufficiency with a transparent supply chain between farmers and consumers [107], (5) Aid in achieving the food safety mission [108], (6) Playing a vital role in environmental protection [106], (7) Transparency and traceability accessible for producers and end-users on food quality, standard compliance, shipping, storage duration, and more. Logistics and supply-chain information can be organized efficiently [107], and (8) Prevention of fraudulence or data hacking from blockchain systems that prohibit data tampering, creating a secure system. Data stored in a blockchain will not be compromised or altered, including stored or transactional data. Food fraudulence can be mitigated with a blockchain-powered IoT [107].

6. Current Challenges of IoT in Agriculture

In the agricultural sector, IoT adoption is affected by obstacles such as an infrastructure limitation, high costs for equipment and installation, and data security concerns [109]. The lack of adequate communication infrastructure in remote areas where farms are typically located makes it difficult for farmers to connect to the internet and access crop data in real time. This challenge renders an advanced monitoring system ineffective and limits the potential benefits of IoT technology. Infrastructural challenges include developing and implementing IoT-connected architectures incorporating innovative technologies like cloud and fog computing and network virtualization. The cost of equipment needed to implement IoT in agriculture is high; outfitting fields with sensors alone costing over a thousand US dollars. Moreover, automated machinery is costlier than manually operated machinery due to the cost of farm management software and cloud access to record data. While investing in these technologies is crucial for farmers to earn higher profits, the initial investment required to set up IoT technology at farms is difficult to make [110]. Security concerns arise due to the enormous amount of data collected by IoT agricultural systems, which can be challenging to protect [111]. As IoT devices interact with older equipment and have access to the internet, there is a risk of unauthorized access to drone mapping data or sensor readouts through public connections. Farmers need basic training on the use of Human Interface Devices (HID), such as computer or tablet and an understanding of the operations of an IoT system. It is also necessary to provide proper education on the unique IoT deployment on their farm [112]. IoT devices or sensors are intelligent, and they consume less energy with potentially less storage, which is beneficial when faced with redundant and fabricated data transfer. IoT-based equipment or devices in smart agriculture systems are designed for different farming activities, which may result in device incompatibility. This issue can be resolved by integrating blockchain for decentralized management rather than relying on centralized management from IoT in smart agriculture [113].

Other problems that may affect the implementation of an IoT-based agriculture system include hardware, data analytics, maintenance, and mobility [111] [114].

The choice of IoT devices presents a hardware challenge. Water quality, humidity, chemical, air pressure, and temperature sensors are needed for efficient IoT applications. Machine learning, deep learning, and prediction algorithms are used to analyze IoT data, which sometimes can pose an interoperability challenge to data analytics. Maintenance is crucial, with regular sensor inspections required, especially in farm areas. The mobility issue is related to network connections such as 4G, 5G, WiFi, 6LowPan, and LoRa that connect sensors spread across a large farm region. Table 4 summarizes recent studies on IoT-based smart agriculture based on objectives, technological approach, challenges, and benefits.

Table 4. Recent studies on IoT-based smart agriculture.

Reference	Objective	Technological approach	Challenges	Benefits
[115]	Crop productivity	Big data storage and data analytics, IoT, data mining and cloud computing	-	i) Network architecture, platform and design help to access IoT ii) Improves crop productivity iii) Provides an overview of IoT applications, sensors, protocols, and data-enabled technologies
[116] Rajaram & Sundareswaran (2020)	Water management	Bluetooth, Wi-Fi, RFID, Zigbee and Raspberry Pi	i) Human interaction ii) Labor cost. iii) Water consumption	i) Can facilitate identification of moisture, humidity and temperature thresholds ii) Allows consistent management within the entire study region
[117]	Irrigation monitoring	WSN, data analytics, node sensors and web application	-	i) Facilitates optimal irrigation of crops
[6]	Crop management	Raspberry Pi, mobile technology and Wi-Fi	i) Low or high watering	i) Facilitates monitoring of weather conditions ii) Cost-effective iii) Allows automatic disease monitoring
[35]	Crop and irrigation management	Mobile technology, GPRS, Wi-Fi, Raspberry Pi and Zigbee.	i) Unstable weather ii)Water shortage iii) Irregular water usage	i) Improves crop yields ii) Low installation cost

7. Future Directions

Implementing IoT-based communication technology and sensors is crucial to increase agricultural production in a sustainable manner. Cloud computing, unmanned aerial vehicles, and wireless sensors have been proven to benefit long-term agricultural production. Smart devices can automate various cyclic tasks in crop production, such as irrigation, soil sampling and mapping, fertilizer application, pest and disease control, yield monitoring, forecasting, and crop harvesting, thereby improving crop quality and growth potential. Agriculture is expected to become an advanced industry in the future with an IoT-based system integrated with Artificial Intelligence (AI), big data and robotic capabilities. This integrated system will combine various agricultural tools, equipment, and techniques that can be utilized for various management activities in agriculture, from sowing to yield forecasting.

7.1. IoT and Wireless Sensors (IoTWS)

Strategically installing IoTWS across farms, farmers may have access to the most recent information and knowledge, enabling them to make required adjustments and ultimately resulting in greater crop yields. IoT can potentially be at the forefront of farming operations for sustainable agriculture. It can potentially play a leading role in agricultural practices contributing to sustainable agriculture. This includes water conservation, energy, and crop transportation optimization, agricultural equipment maintenance and operating warnings, and updated market prices. Determining crop needs during each growth phase can make these tasks more efficient and productive. It has proven innovative and will give farmers unprecedented control over their land and assets.

Furthermore, significant advancements in wireless sensor networks and 5th generation (5G) smartphone communication technology can shape the upcoming internet technology, providing growers with important real-time updates anywhere. According to a business report, it is projected that by 2025, over 75 million internet-connected agricultural devices will be in operation. Additionally, it is projected that by 2050, the average farm will generate 4.1 million data points on a daily basis [118].

7.2. Smartphone and IoT

Smartphones and IoT can potentially revolutionize agriculture in developing nations by improving market access and solving problems. These technologies can help bridge the gap between rural and urban farmers, benefiting the next generation of agricultural workers. In developing countries, previous agricultural-related smartphone services have been limited to simple functions due to the lack of delivery technologies [45] [119]. However, with the fast-paced evolution of smartphones and IoT, there is an opportunity to develop more complex services that provide users with a broader range of devices to disseminate information. Furthermore, expanded smartphone networks can now collect and process large amounts of data to help farmers and facilitate social networks for sharing information and learning.

7.3. Communication/Connectivity

The success of IoT in agriculture will primarily depend on the expansion of connectivity. This includes essential value-added services that have a broad perspective in the telecommunications industry and have the potential to significantly impact the entire supply chain [120]. While almost all telecommunication operators worldwide provide connectivity facilities, such public services represent only a tiny portion of the advanced agriculture market. Smartphone operators must offer a range of advanced services to fulfill the needs of growers, especially in remote regions where these services are highly valued. Additionally, operators must provide end-to-end solutions, not just connectivity, as many community members may not be highly educated or fully understand new technologies. This will improve the market share of smartphones and telecommunication operators.

7.4. Artificial Intelligence

Artificial Intelligence (AI) is being used to extract valuable insights from data, such as identifying trends and making predictions. In agriculture, AI has been applied to identify genes that produce high-yielding crops suitable for different locations across climatic regions worldwide. Additionally, AI algorithms can also help identify the demand for certain goods in the market, providing farmers with valuable information that can be used to strategize for subsequent cropping cycles. The latest advancements in AI will allow growers to accurately classify the value of their crop produce, eliminating less profitable produce even before planting.

7.5. Blockchain in IoT (BIoT) in Agriculture

BIoT is an upcoming scheme for agricultural operations that assures data integrity and provides maximum storage fault tolerance for data routing or communication concerning IoT and agriculture. It is also claimed that BIoT routes data securely with low energy consumption. Integrating BIoT securely eliminates redundant data and enables verification without human intervention while securing systems intelligently [107] [113] [114]. Some of the standard applications of BIoT are the Bitcoin system [121] (Choi *et al.*, 2019) and AgriBlockIoT for traceability in the agri-food chain. Another research study in rice value chain management has illustrated rice grain traceability/blockchain to evaluate efficiency, security, and quality during transportation processes [114]. With BIoT in agriculture, smart contracts can be developed. Smart contracts are pre-written codes by software developers that simplify secured transactional processes, allowing immediate transactions without human intervention if the requirements are met. The stock market based on the agricultural supply chain can determine price fluctuations. Pavocoin is an example of an agricultural cryptocurrency that serves as a secure payment gateway [107].

8. Conclusion

Smart farming has emerged as a solution to the challenges faced by the food industry due to the increasing demand for food production, decreasing rural labor, and rising production costs. With the increasing focus on data in the agricultural sector, IoT has made agriculture more data-driven, leading to cost-effective and timely farm production and management while potentially reducing environmental impacts. This review has highlighted the unique challenges that spatial data, highly varying environments, task diversity, and mobile devices present in smart agriculture, as well as the potential solutions and application domains. The existing and future applications of IoT in agriculture have been discussed, and opportunities for IoT in agriculture towards smart farming have been identified. The results of this review could provide a roadmap for researchers to explore further the potential of IoT in agriculture and develop innovative solutions to meet the challenges of smart farming. Further investigation and research need to be done to determine how the newest tools and technologies can help farmers in developing countries. The developers of smartphone and IoT technology also need to ensure that their services meet a wide range of user needs rather than concentrating too much on new machinery that may not be available due to limited resources and underserved growers. Additionally, edge computing technologies must ensure ease of access, processing, good storage, and data protection, especially in crowd data mechanisms, autonomous decision-making tools, open-sourced blockchains, and data transmissions. Since the prospects of technology in the agriculture industry are increasing, sustainability aspects such as energy conservation, carbon-efficient equipment, proper electronic waste (e-waste) disposal channels, and construction of IoT devices from biodegradable materials must be taken into consideration.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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