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Original Article

Advancements in Smart Agriculture (IoT): Architecture, Devices, Communication Standards, Applications and Challenges

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Abstract - *The agriculture domain deals with various procedures that consume a lot of effort and cost, but their outcomes may be affected due to several factors, i.e., weather conditions/soil attributes/irrigation, water level/land location (rural area/urban area/underwater/surface), etc. In order to enhance agricultural production with optimal operational cost, there is a need to automate these processes, as well as to estimate the critical factors. The Internet of Things (IoT) is an emerging technology that can be used to transform traditional agricultural activities in order to enhance the farming experience. It has various applications in the agriculture domain. All the applications may have different hardware and software requirements, and these applications may consume different network resources (i.e. energy, bandwidth, internet, wireless links, etc.) to complete different operations. There is a need to optimise all these parameters to ensure higher network performance. This paper outlines a structured five-layer IoT layered architecture and examines factors influencing resource consumption at different IoT layers. This study examines the significant impact of IoT on agriculture, focusing on challenges and solutions to traditional farming methods. Furthermore, this paper offers a comprehensive analysis of widely used IoT devices and wireless communication standards relevant to the field of agriculture. It focuses at three key smart farming applications: soil health monitoring, crop monitoring, and pest and disease control, with a focus on energy efficiency while also covering other relevant application areas. Additionally, the paper addresses the challenges that come while implementing smart agriculture and explores strategies to turn them into opportunities. Finally, the study delves into energy-efficient algorithms and techniques, going over the most recent smart farming research that is reshaping traditional agricultural practices to produce optimal, technology-driven* systems.

Keywords - *Internet of Things, Smart agriculture, Precision farming, Energy efficiency.*

1. Introduction

The agriculture sector encompasses a wide range of activities that can be quite time-consuming and demand significant manpower, effort, and resources. To successfully grow high-quality crops, it's essential to manage multiple operations efficiently. Conventional agriculture majorly struggles with issues like efficiency and sustainability. It often leads to inefficient resource management because farming uses many resources like water, fertilisers, and energy, which are difficult to optimise [1, 2]. Conventional farming requires excessive human intervention to complete processes, which results in increasing labour costs and dependency. Lack of real-time farm monitoring makes it difficult to monitor large agricultural areas [3]. Ultimately, decision-making is then based on intuition and experience instead of data-driven insights, which leads to worse outcomes and results in making decision-making error-prone [4]. Hence, modern solutions are required to improve conventional farming methods in terms of efficiency and sustainability. One effective solution to these problems is IoT. The term "Internet of Things" refers to a network of physical objects, commonly known as "things," that are equipped with embedded technology. This technology enables these objects to establish communication, perceive their surroundings, and engage in interactions with their internal states as well as the external environment. According to research, this innovative technology allows for the seamless connection of different objects, regardless of their location or time [5, 6].

1.1. Contributions of the Research

- Architecture and resource utilization: This study presents a structured representation of the five-layer IoT architecture based on existing literature, with the aim of providing a clear understanding of the functionality and role of each layer in smart agricultural applications.
- Comparative Analysis of IoT Communication Technologies: This study provides a comparative analysis of IoT communication technologies for smart

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agriculture based on key technical parameters, including power consumption, communication range, data rate, frequency, modulation, bandwidth, and network topology.

- Application-level comparative analysis with energy focus: This paper covers a comparative review of IoT-based applications in Soil Health Monitoring, Crop Monitoring, and Pest and Disease Control, while presenting a general overview of other smart agriculture applications.
- Challenges, opportunities, and future directions: The paper systematically reviews different technical, economic, and socio-environmental barriers to smart agriculture adoption in low-resource settings, and discusses how these challenges can be turned into opportunities through appropriate architectures, energy-aware solutions, and supportive policies. Finally, this review summarizes the recent smart farming research and provides an insight into the future directions of designing scalable, energy-efficient IoT frameworks and cross-layer architectures to support smart agriculture.

1.2. Smart Agriculture

Increase in population, decrease of resources, shrinking of arable land, and unpredictable weather patterns all contribute to the global problem of food insecurity. The agricultural industry is now embracing "smart agriculture," a method of increasing production and optimizing operations through the use of IoT.

This method promotes ecologically responsible practices while transforming farming through the use of digital tools and realtime data analysis to monitor plant health in various cultivation methods [7-9].

A layered architecture of agriculture-IoT is represented in Figure 1, and the layers of the agriculture IoT network are described in Table 1, the smart farming architecture consists of the object, perception, network, application, and end-user layers [10, 11]. These layers respectively represent field entities, collect real-time data, transmit signals, process information according to user requirements, and enable users to monitor system status.

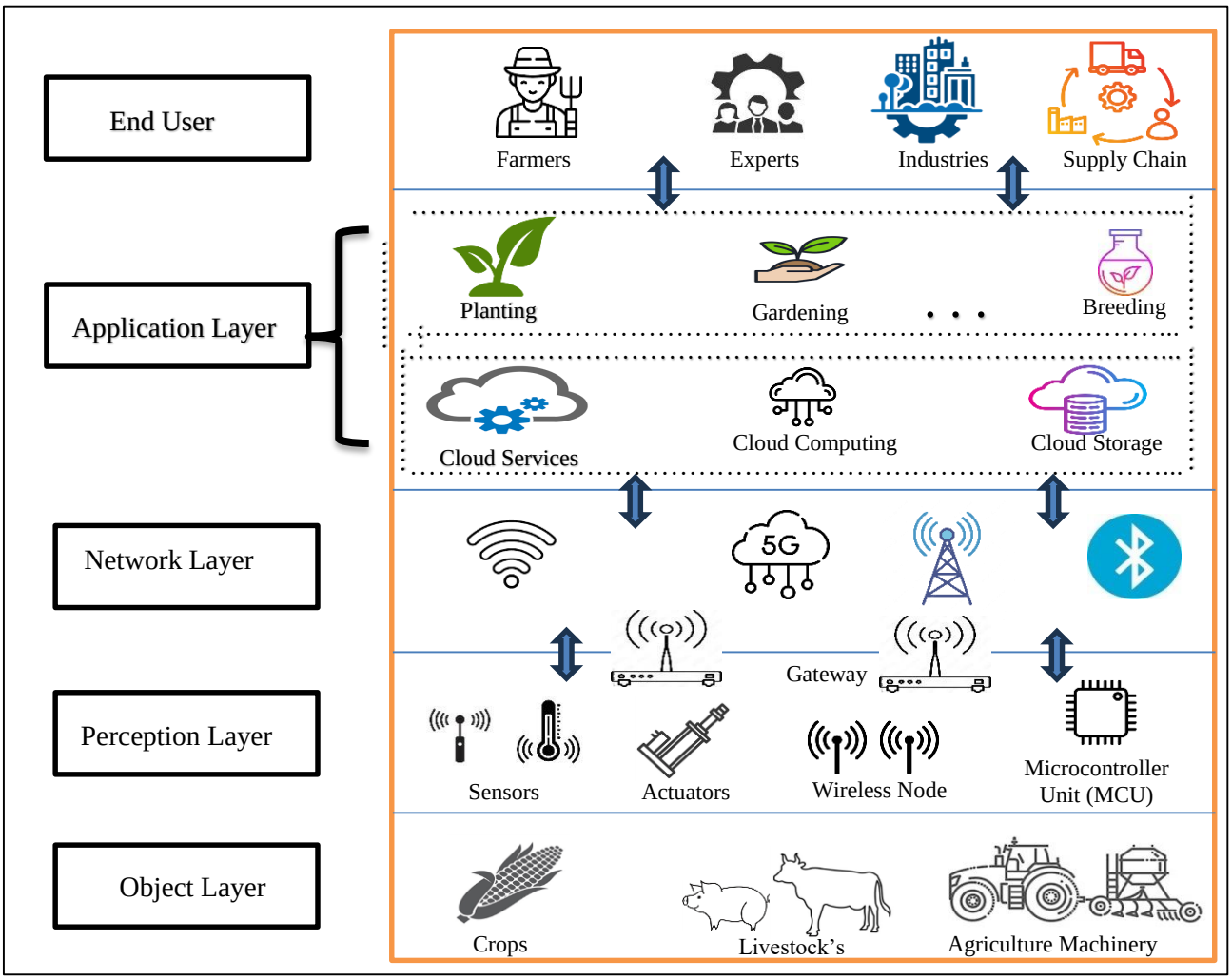


Fig. 1 A Layered architecture of agriculture-IoT [11-14]

Table 1. Layers in agriculture IoT network

Layers	Description
Object Layer	It is used to define objects present in the field like crops, livestock and agricultural machinery [14].
Perception layer	It is used to manage the end devices (sensors/actuators) deployed over the coverage area to collect the parameters in a real-time environment [13].
Network layer	It is responsible for routing/transmitting the data over the network, and it may also initiate cross-layer operations. Network performance may vary due to the behaviour of the routing protocol [12].
Application layer	This layer acts as an interface between applications and end users. Users can utilize different applications to monitor climate conditions/ tracking of agriculture vehicles/animals, or equipment's wear & tear/measurement of different gases/stock monitoring, etc. [14].
End User Layer	It is the model's highest layer and is designed to benefit the user or consumer. This layer enables users to view the system status, analyse, or process data in order to control and monitor their model through an interface. The farmer is the end-user in agricultural models [11].

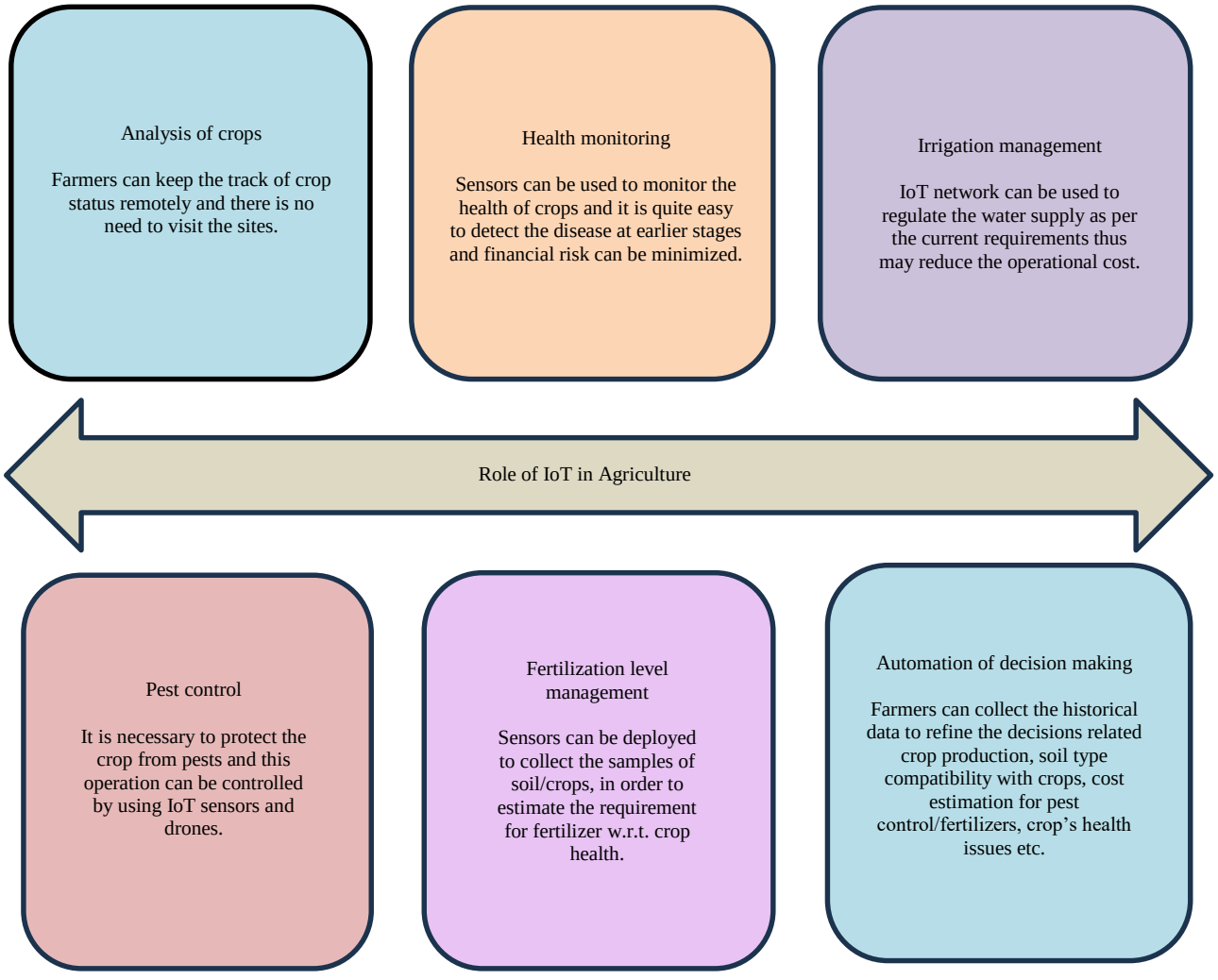


Fig. 2 Role of IoT in agriculture

Efficient resource utilisation in agriculture IoT is of utmost importance due to various factors. It aids in the efficient utilisation of water, fertilisers, and pesticides, resulting in waste reduction and cost reduction. The role of IoT in agriculture is very important as it resolves the conventional agriculture problems. Figure 2 describes the role of IoT in agriculture [15-23], Table 2 represents the factors influencing resource consumption at different IoT layers, and Figure 3 represents the issues and solutions of conventional agriculture activities.

Table 2. Factors influencing resource consumption at different IoT layers

IoT Layers	Causes for resource consumption
Application layer	Data payload size and communication protocol overhead [19]
Network Layer	Routing-path construction, management, and selection [20]
Perception Layer	Sensor data acquisition and wireless communication [20]

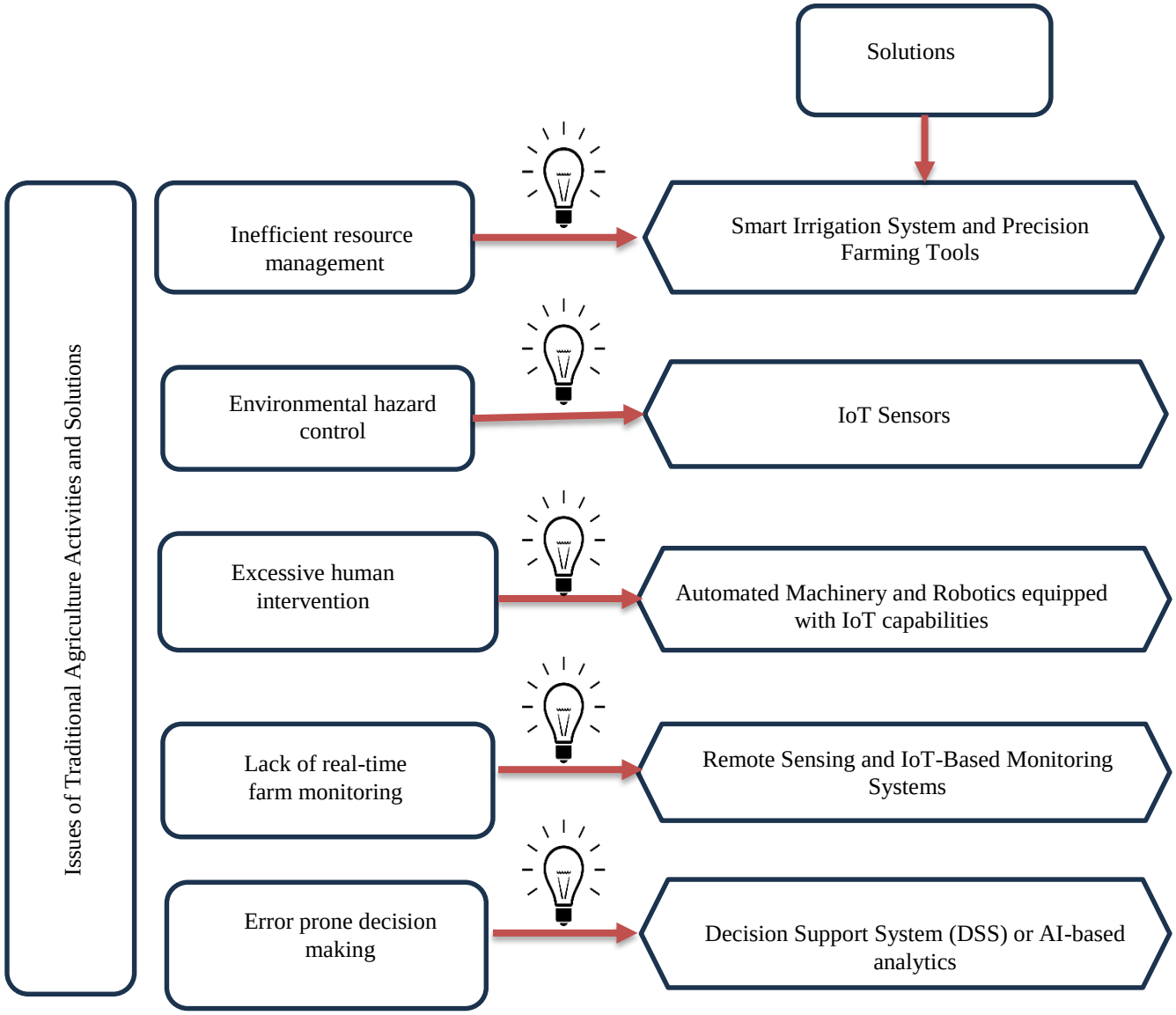


Fig. 3 Issues and solutions of traditional agriculture activities

2. Devices and Wireless Communication Standards

An IoT agriculture sensor is a compact and intelligent device designed to detect and quantify actual environmental conditions within the agricultural sector [24]. Through the use of real-time data and practical insights, IoT devices and sensors are transforming smart agriculture. This helps farmers to maximise crop yields, minimise resource consumption, and improve farm management in general. With these advanced tools, it's easy to track the health of the soil, weather and the crop, leading to more accurate interventions and more efficient use of resources. There are different types of sensors/devices which can be deployed over agricultural land to collect the various types of data and [25-35]. Table 3 describes the commonly used IoT devices, while Table 4 represents a list of sensors and their application area in agriculture.

Table 3. Commonly used IoT devices

Device	Operation	Benefits
Data logger	Data collection from sensors.	Real-time data analysis.
Asset tracker	Tracking of livestock.	GPS location can be traced.
Moisture measurement sensor	Humidity measurement with respect to crop requirements.	Humidity can be controlled.
Temperature measurement sensor	Temperature measurement.	Temperature can be regulated dynamically.
Water level measurement sensor	Irrigation cycle management.	Irrigation requirements can be predicted.
Gas analyzer	Measurement of CO_2 and O_2 concentrations in the environment.	Enables CO_2 monitoring and oxygen-level assessment to support environmental monitoring and air-quality management.
Wind speed monitor	Measurement of wind speed/direction w.r.t. weather conditions.	Real-time tracking of the wind conditions over the coverage area.
Light sensors	To track the intensity of light.	By measuring the sunlight's intensity, crop growth/health/condition can be predicted.
Soil measurement sensors	To analyse the soil properties with respect to crop requirements.	Farmers can analyse the different parameters, i.e. soil temperature/PH value/conductivity/NPK value, etc., in a real-time scenario.
High-Resolution cameras	Real-time picture capture, enabling rapid evaluation and decision-making.	Monitor crop growth, detect pests, and assess overall field conditions.
Unmanned Aerial Vehicle (UAV) sprayers	Drones with the ability to store liquid and nozzles for precise spraying.	Pesticides, herbicides, and fertilisers can be applied precisely with this tool.
Radio Frequency Identification (RFID) tags	Track and manage assets.	Utilised to track and identify livestock.

Table 4. List of sensors and their application areas in agriculture

Article	Sensor Name	Sensor Applications									
		Fertilizer Administration	Irrigation Monitoring Systems	Forecasting and Harvesting	Crop Disease Detection	Quality Monitoring	Processing Monitoring	Climate Conditions Monitoring	Logistics Monitoring	Fire Detection	Yield Monitoring
[36, 37]	Soil Moisture Sensor	×	✓	✓	×	×	×	×	×	×	×
[39, 40]	Soil pH Sensor	✓	×	×	✓	×	×	×	×	×	×
[41]	CO_2 Sensor	×	×	×	×	✓	✓	✓	×	×	×
[42]	Light Sensor	×	×	×	×	✓	×	✓	×	×	×
[43]	Water Level Sensor	×	✓	×	×	×	×	×	✓	×	×
[44]	Flexible sensor	×	×	×	×	×	×	×	×	×	✓
[45, 46]	Flame Sensor	×	×	×	×	×	×	×	×	✓	×
[41]	Livestock Sensor	×	×	×	×	×	×	×	✓	×	×
[47]	Temperature & Humidity Sensor	×	✓	✓	×	✓	✓	✓	×	×	×
[48]	Plant Disease Sensor	×	×	✓	×	×	×	×	×	×	×

The effectiveness of IoT devices and sensors in agriculture is primarily based on the wireless communication standards that are used. Protocols like LoRaWAN, Sigfox, NB-IoT, and Zigbee are very important for transmitting data from sensors that monitor soil moisture, weather conditions, and crop health. These standards support reliable, long-range, and energy-efficient connectivity, enabling immediate data analysis and decision-making. By incorporating strong

wireless communication, agricultural IoT solutions can greatly improve productivity and sustainability. Low-Powered Wide Area Network (LoRaWAN): It is capable of transmitting data over long distances using low-powered IoT devices through gateways [23]. SigFox: It utilises bi-directional signalling along with binary phase-shift keying modulation [25]. NarrowBand-IoT (NB-IoT): It is based on cellular technology for data exchange with a higher data rate, and it is more efficient as compared to LoRaWAN/SigFox [26]. Zigbee is a wireless protocol that creates personal area networks for low-cost IoT devices, not directly connecting to end users on the internet [49, 50]. Table 5. describes agriculture wireless communication standards used in smart agriculture.

Table 5. Agriculture wireless communication standards

	LoRaWAN	**Sigfox**	**NB-IoT**	**Zigbee**
Power consumption	Very low In Active mode- 20-40 milliamperes (mA)	Extremely low In Active mode- ~50 (mA)	Low to moderate In Active mode- 100 -250 (mA)	Low In Active mode- 20-40 (mA).
Range	Urban: ~10km Rural: ~10-40km	Urban: ~3-10km Rural: ~30-50km	Urban: ~1km Rural: ~10km	10-100m
Data Rate	0.3 to 50 kbps	~100bps Uplink ~600bps downlink	~20-250kbps Uplink ~250Kbps downlink	250kbps
Frequency	Unaccredited ISM band 915MHz (North America), 868MHz (Europe)	Unaccredited ISM band	Accredited LTE band	Unaccredited ISM band
Modulation	Chirp Spread Spectrum (CSS)	Binary Phase-Shift Keying (BPSK)	Quadrature Phase Shift Keying (QPSK)	Offset Quadrature Phase-Shift Keying (OQPSK) & BPSK
Bandwidth	50 kbps	100 bps	200 kbps	~ 250 kbps
Topology	Star	Star	Cellular Network Topology	Mesh

3. Applications of Smart Agriculture

3.1. Soil Health Monitoring

In smart agriculture, IoT technology is used to monitor the health of soil by placing sensors in the field to track parameters like pH, temperature, nutrients, humidity, moisture, and wireless communication. With the help of this real-time data, farmers can make better decisions, leading to disease-free, healthier crops and making optimal use of resources [59, 61]. A system is designed which uses solar- powered devices, deployed in the field area to monitor soil temperature, moisture, conductivity, and CO_2 levels. The designed system is successfully tested in the field area and results in good performance in data collection, power efficiency and wireless range [51]. Subsequently, a general framework to monitor soil health and crop yield is proposed, which aims to help farmers and researchers to develop better soil monitoring solutions [52]. Additionally, a 3D-printed device called Argo-toolbox is designed by the authors to monitor various parameters, and results show that the designed system has proven to be accurate and cost-effective, giving farmers and other people involved in agriculture easy access to it [53].

A cell-phone-based IoT system is designed by the authors in order to monitor soil moisture to help with irrigation. The system has been successfully used in South Carolina for three years. Farmers can see the data regarding soil moisture on their phones or computers and can make a decision whether to water the crop or not [54]. Furthermore, to measure gases like CO_2, O_2, NOx, CH_4, CO, H_2, and NH_3, along with soil parameters like pH and moisture, the author discusses a realtime remote monitoring system. The system successfully helps farmers to make decisions like whether soil is ready for planting or not, and also determines proper fertiliser application, and crop yield prediction [55, 56]. Another IoT - enabled model called IoT-enabled Soil Nutrient Classification and Crop Recommendation (IoTSNA-CR) is presented, which helps farmers to monitor soil nutrients and, based on the value, recommend suitable crops. Use of IoTSNA-CR tool helps farmers to increase yields while decreasing fertiliser usage and keeping soil healthy with little investment of time and money [57]. One more system using Raspberry Pi and IoT technology, developed at IITM Pune by the authors, which allows users to view information through their mobile application. Results show that the system accuracy is very high and closely matches the traditional measurement methods. The authors aim to add cameras and a GPS system to their existing system [58]. Moreover, a project is made by authors which uses low-cost sensors to monitor soil parameters and provide real- time data to farmers, aiding them in improving their water management practices to prevent crops from being over- or under-watered [60]. Table 6 describes the comparison of Soil Health Monitoring Systems on the basis of parameters like real- time monitoring, soil moisture monitoring, temperature monitoring, nutrient monitoring, wireless communications, data visualisation, mobile app visualisation and humidity monitoring.

Table 6. Comparison of soil health monitoring systems

Article	Parameters							
	Real-Time Monitoring	Soil Moisture Monitoring	Temperature Monitoring	Nutrient Monitoring	Wireless Communication	Data Visualization	Mobile App Notification	Humidity Monitoring
[51]	✓	✓	✓	✓	✓	✓	×	✓
[52]	✓	✓	✓	×	✓	✓	×	✓
[53]	✓	✓	✓	✓	✓	✓	×	✓
[54]	✓	✓	✓	×	✓	✓	✓	×
[55]	✓	✓	✓	✓	✓	✓	×	✓
[55]	✓	✓	✓	×	✓	✓	×	✓
[57]	✓	✓	×	×	✓	✓	✓	×
[58]	✓	✓	✓	×	✓	✓	×	✓
[59]	✓	✓	✓	✓	✓	✓	×	✓
[60]	✓	✓	✓	✓	✓	✓	×	✓

3.2. Crop Monitoring

Crop monitoring is very important in smart agriculture, providing real-time insights into soil health, crop growth, and environmental factors. By using this kind of information, the farmers/ experts can make decisions about irrigation, fertilisation, and pest control, leading to enhanced resource utilisation, increased crop yield and minimised ecological footprint. In [62], the authors reviewed significant advancements in Agriculture -Internet of Things (Ag-IoT) from the past decade. It highlights the lack of adequate sensors for real-time nutrient monitoring and the system's complexity due to varied data and platforms. To tackle these issues, the author proposes possible solutions, which are enhancing communication technology, investigating alternative power sources for crop monitoring, and improving sensors and actuators.

Subsequently, an automated monitoring and crop recommendation system is used to demonstrate how Artificial Intelligence and the Internet of Things (AIoT) can be integrated into hydroponic agriculture. Results highlight the capacity of AIoT to improve agricultural productivity and sustainability, with forthcoming efforts aimed at optimisingdata acquisition and system accuracy [63].

Additionally, a low-cost smart weather monitoring system is designed by the authors to monitor real-time meteorological conditions while transmitting weather data to the farmer's mobile device, facilitating enhanced decision-making to maximise yield [64]. Moreover, an integrated system is designed that can detect crop health by analysing multi-spectral images captured by an IoT-enabled UAV. The evaluation of the system's performance involved the application of diverse machine learning techniques, which were then compared to established disease detection methods [65]. Subsequently, by demonstrating how effective machine learning methods are in enhancing soil nutrient management, enabling informed choices regarding crop fertiliser use, and evaluating crop quality from the consumer's point of view, the authors contribute to the field of Internet of Things (IoT) enabled agriculture [66].

Additionally, machine learning techniques are also used for estimating nitrogen content in MD2 pineapple crops using multispectral images, IoT-integrated sensors, and SPAD chlorophyll measurements, which can help in improving agricultural productivity, lowering costs, and reducing environmental and health risks, making nitrogen management more sustainable [67]. Similarly, in [68] authors highlight the key characteristics of strawberry crops in which the data are processed and transmitted in real time using communication protocols, allowing the devices to manage information from various sensors. Another work presents the deployment and implementation of a cost-effective greenhouse monitoring system utilising LoRaWAN technology for data transmission.

The system incorporates various sensors to track environmental conditions and utilises LoRaWAN for efficient long-range, low-power communication [69]. Further, a detailed framework for the implementation of IoT technology within the agricultural sector of Bangladesh is presented. The framework combines IoT, data mining methods, and cloud

monitoring systems to enhance productivity, optimise water management, and facilitate real-time crop forecasting. Thorough experimentation is carried out, resulting in the proposed model attaining an accuracy of 87.38% in predicting data harvest [70]. In another work, researchers created a dashboard that improves crop yield and allows for educated decision-making [71]. Similarly, a structured questionnaire is distributed to 550 farmers with a response rate of 90.91%. It is found that there is a strong relationship between farmers' knowledge of IoT technologies and their perception of its benefits [72]. Lastly, authors in [73] present an Internet of Things - Smart Farming Framework (IoT-SFF) by using big data analytics and geospatial analysis. The IoT-SFF model improves the prediction rate by 97.7 per cent, achieves an accuracy rate of 94.5 per cent, reduces the average error by 38.1 per cent, and reduces costs by 34.4 per cent, according to the simulation results. It also increases crop yield by 92.4 percent. Table 7 represents the comparative analysis of smart agriculture systems for crop monitoring and includes various parameters such as sensor types, data collection frequency, data transmission, power source, data storage, user interface, integration, durability, etc.

Table 7. Comparative analysis of smart agriculture systems for crop monitoring

Articles	Sensor Types	Data Collection Frequency	Data Transmission	Power Source	Data Storage	User Interface	Integration	Durability	Cost	Scalability	Accuracy	Performance
[62]	Temperature, Humidity, Soil Moisture	Continuous	Wi-Fi	Solar	Cloud	Web and Mobile App	High	Medium	High	High	High	High
[63]	pH, EC, Temperature	Continuous	Wi-Fi	AC Power	Local and Cloud	Mobile App	High	High	Medium	High	High	High
[64]	Temperature, Humidity, Rainfall	Intermittent	GSM	Solar	Local	SMS Alerts	Medium	High	Low	Medium	Medium	Medium
[65]	Multispectral Images	Continuous	Wi-Fi	AC Power	Cloud	Web Dashboard	High	Medium	High	High	High	High
[66]	NPK Sensors, Soil Moisture	Continuous	Wi-Fi	Solar	Cloud	Web and Mobile App	High	High	High	High	High	High
[67]	Multispectral Images	Intermittent	Wi-Fi	Battery	Local	Web Dashboard	Medium	Medium	Medium	Medium	High	High
[68]	Temperature, Humidity, pH	Continuous	Wi-Fi	Solar	Cloud	Web and Mobile App	High	High	Medium	High	High	High
[69]	Various Sensors	Continuous	Wi-Fi	Solar	Cloud	Web and Mobile App	High	High	High	High	High	High
[70]	Temperature, Humidity, Soil Moisture	Intermittent	Wi-Fi	AC Power	Local and Cloud	Web and Mobile App	Medium	Medium	Medium	Medium	High	High
[71]	Temperature, Humidity, Soil Moisture	Continuous	Wi-Fi	Solar	Cloud	Web and Mobile App	High	High	Medium	High	High	High
[72]	Various Sensors	Intermittent	Wi-Fi	Solar	Cloud	Web and Mobile App	Medium	Medium	High	Medium	Medium	Medium
[73]	Multispectral Images	Intermittent	Wi-Fi	Battery	Cloud	Web Dashboard	High	Medium	High	Medium	High	High

3.3. Pest and Disease Control

Smart agriculture relies on efficient pest and disease control to keep crops healthy, maximise yields, and reduce the use of harmful chemicals. In [74], a Parallel and Distributed Simulation Framework (PDSF) that incorporates the IoT is proposed for agricultural monitoring and pest control. In terms of performance metrics, the proposed system is 98.65% better. In [75], using state-of-the-art technology for early Red Palm Weevil (RPW) detection and management, the authors present a novel approach to sustainable palm tree cultivation. The approach uses geospatial data, computer vision, deep learning, and the IoT to successfully identify and categorise palm trees infested with RPW. Further, the [76] study demonstrates that providing long-term solutions and positive social and environmental impacts, smart farming greatly improves rice production. Another study shows the use of Convolutional Neural Network (CNN) and Transition Probability Function (TPF) to analyse pest photos for precise insecticide dosing.

The suggested TPF-CNN method outperforms other intelligent methods in terms of accuracy and processing speed, particularly when compared to Artificial Neural Network (ANN), K-Nearest Neighbour (KNN), and Support Vector Machine (SVM) and other similar algorithms [77]. Additionally, in [78], the objective of the researcher is to create a model that can classify and identify pests by analysing data collected from IoT devices. Adaptive Honey Badger Algorithm (AHBA) parameters are fine-tuned after the Yolov3 object detection analysis of images. A faster rate of data collection and more trustworthy technical support are two outcomes of this approach. Subsequently, the Late Blight Management Decision Support System (DSS) is built and tested in the cloud using the IoT.

The proposed system is able to achieve more widespread accessibility and cost-effectiveness compared to cutting-edge DSS solutions [79]. Moreover, using the IoT and deep learning, researchers intend to build a smart, long-term framework. An automated system gathers data on the health of millet crops through sensors, stores it on a server in the cloud, and then uses a Raspberry Pi to detect diseases using an improved deep learning model [80]. Further, a deep learning-based approach for cotton leaf disease detection is proposed using fine-tuned Transfer Learning (TL) algorithms.

The proposed approach is used to develop a web-based application for real-time cotton disease prediction, and then the model is utilised to create a web-based application that could predict cotton diseases in real-time [81]. In [82], researchers detail the experimental testing of a gas-sensing array that detects a commercial organophosphate pesticide using a hybrid nanomaterial. The eventual goal is to incorporate it into a full-fledged smart farming tool similar to the "gaiasense" system. Additionally, an Improved MaskFaster Region-based Convolutional Neural Network (IMFR-CNN) aims to enhance applications for detecting insect-infested plants within the realm of Cloud Computing (CC). The evaluation of the IMFR-CNN model revealed a peak accuracy of 99.0%, surpassing alternative approaches. Lastly, in [84], an IoT-based smart agriculture model collects data using k-means clustering and routes and selects cluster heads using Adaptive Mud Ring Optimisation algorithm (AMRO). Cloud-based hybrid Artificial Neural Networks (ANNs) predict crop diseases. It conserves energy, speeds data transmission, and improves soil and plant growth.

3.4. Other Applications

3.4.1. Smart Irrigation

A smart irrigation system is one of the applications of IoT technology in smart agriculture that helps farmers to reduce their water usage. Sensors track the weather, soil moisture, temperature, and humidity in real-time. When farmers have this information in advance, they can water crops just when they need it, which means less water waste and better crops all around. In order to save labour, the system can use the data to automatically turn irrigation on or off. In general, smart irrigation helps increase productivity, sustainability, and efficiency in agriculture [85, 86].

3.4.2. Livestock Monitoring

Livestock monitoring enables the management of farm animals' locations, health, and activities in real-time. With the help of wearable tech, farmers can monitor their animals' vitals and behaviour in real time. Devices like temperature sensors, heart rate monitors, and GPS trackers provide valuable data. This information enables real-time alerts, which are beneficial for detecting illness symptoms, tracking eating habits, and preventing theft or loss. Livestock monitoring enhances productivity and welfare by allowing for timely and informed decision-making. By applying data-driven insights, it improves overall farm management and reduces the need for manual labour [87-89].

3.4.3. Climate Monitoring

Climate monitoring is important for smart farming. This includes the collection of real-time data of key environmental parameters such as humidity, temperature, precipitation, wind speed and solar radiation with meteorological stations and IoT sensors. The collected data helps farmers to understand local weather patterns and gives them understanding about when to irrigate the farm or what will be the scheduling for planting. Therefore, having timely access to reliable climate information helps to support better crop management which reduces the risk of losses related to weather and results in increase of agricultural productivity. Lastly, it also promotes more sustainable farming practices [90].

3.4.4. Supply Chain and Storage Monitoring

The monitoring of the supply chain and storage is an important application of smart agriculture as this application is accountable for ensuring the quality and safety of agricultural products while they are being transported and

stored. Various sensors like temperature, humidity etc are enabled by the IoT and installed in locations like cold storage units, warehouses and transportation vehicles. With the help of these sensors the analysts are able to measure critical parameters such as temperature, location and humidity etc. This setup allows for the early detection of issues such as spoilage, delays and incorrect handling, allowing for timely corrective actions. With the help of sensors, the storage conditions of perishable goods such as meat and dairy can be monitor which help in maintaining suitable conditions and thus extending their shelf life. As a result, supply chain monitoring enhances food safety, reduces wastage, and improves the overall efficiency of farm-to-market operations [91, 92].

3.4.5. Aerial Crop Monitoring with Drone Technology

One of the most emerging applications of smart agriculture is aerial crop monitoring through drones that help in monitoring the crop and field conditions in smart agriculture over large areas. The monitoring with a drone is possible because they are equipped with advanced cameras and sensors by which it is possible to capture aerial information. This information includes pest infestations details and disease, identify crop stress and variations in irrigation. Using this information, farmers can identify affected areas and apply fertilizers, irrigation, or pesticides as required. Researchers in this domain found that drone monitoring reduce human tedious work and can cover more areas in less time. Drones provide more detailed information as compared with the traditions field inspection which help in making timely decisions. Hence, the use of drones can help to improve crop productivity, reduce unnecessary input use, and contribute to more sustainable agricultural practices [93, 94].

3.4.6. Smart Greenhouses

Smart greenhouses use IoT-based technology in order to create and maintain more suitable conditions for crop growth. For this, different sensors are installed inside the greenhouse to collect information on various parameters like temperature, humidity, soil moisture, light intensity, and CO_2 concentration. This information therefore is used to control lighting, ventilation, irrigation, and temperature according to the needs of the crops. This ongoing monitoring helps to keep the growing environment stable, which can reduce unnecessary water and energy use. It also supports better crop growth and quality while allowing cultivation throughout the year with less dependence on manual monitoring and intervention [94, 95]. In conclusion, today IoT-based applications are being used across various stages of agricultural production and management. Application like soil monitoring helps farmers in providing the information about nutrient levels and soil conditions, while on other hand crop monitoring help in tracking plant growth and identify signs of stress. Sensor-based pest and disease monitoring can also support early detection and timely action. Similarly, smart irrigation systems help farmers to manage water more efficiently, and livestock monitoring provides useful information about animal health, movement, and behaviour. Climate monitoring assists farmers in responding to changing weather conditions, whereas smart greenhouses provide better control over the growing environment. Drones in addition support crop surveillance by covering large areas and identifying problems that may not be easily observed from the ground. IoT technologies are also being applied to storage and supply chain monitoring to maintain product quality during transportation and storage. Hence, the integration of these applications through farm management platforms can provide farmers with a more centralized source of information, supporting better planning and data-based decision-making.

4. Challenges in Smart Agriculture

Smart farming in low-resource regions faces various challenges such as limited internet connectivity, shortage of technical expertise and most important the high initial cost of agricultural equipment and technologies. This is why adoption of technologies by the farmers is very challenging task. Also, this is noticed that in some areas, due to less awareness and resistance to new technologies further slow the transition toward digital farming. In addition, poor policies, lack of training and market access problems can also limit the effective use of smart farming solutions. Moreover, environmental factors like extreme weather and difficult geographical terrain may also affect the deployment and operation of these technologies. Thus, these issues need to be overcome by affordable and reliable technologies, adequate training, better infrastructure and more institutional support. On other side, Smart farming in areas with limited resources faces several challenges which make the adoption of modern agricultural technologies really very difficult. One important reason is the low and uncertain income of the small and marginal farmers in the developing countries. As a result, the high initial cost of IoT devices, sensors, drones, automated equipment, and AI-based platforms can be difficult for them to manage. However, even if farmers are interested to adopt these technologies, they may not have access to the loans, insurance, subsidies and other financial support needed to invest in them. Infrastructure, in contrast, is another major issue in rural and remote areas. Working of IoT based farming systems is affected by poor internet connectivity, limited network coverage, unreliable supply of electricity and low bandwidth.

Many devices need to be charged or maintained regularly and need to be connected to data, which can be difficult in areas without access to a reliable power grid. Moreover, it is possible that different devices may also use different communication standards, which may lead to compatibility issues when several technologies need to work together. Subsequently, the performance of smart farming systems can be affected by the environmental conditions like extreme temperatures, heavy rain, dust, humidity and other harsh conditions. These conditions can damage sensors or affect the

quality of the data they collect. Thus, incomplete or inaccurate data might reduce the reliability of data analysis and may affect the performance of AI-based models used for crop monitoring, disease detection and farm management. Another big problem is that many farmers have little technical knowledge and digital skills.

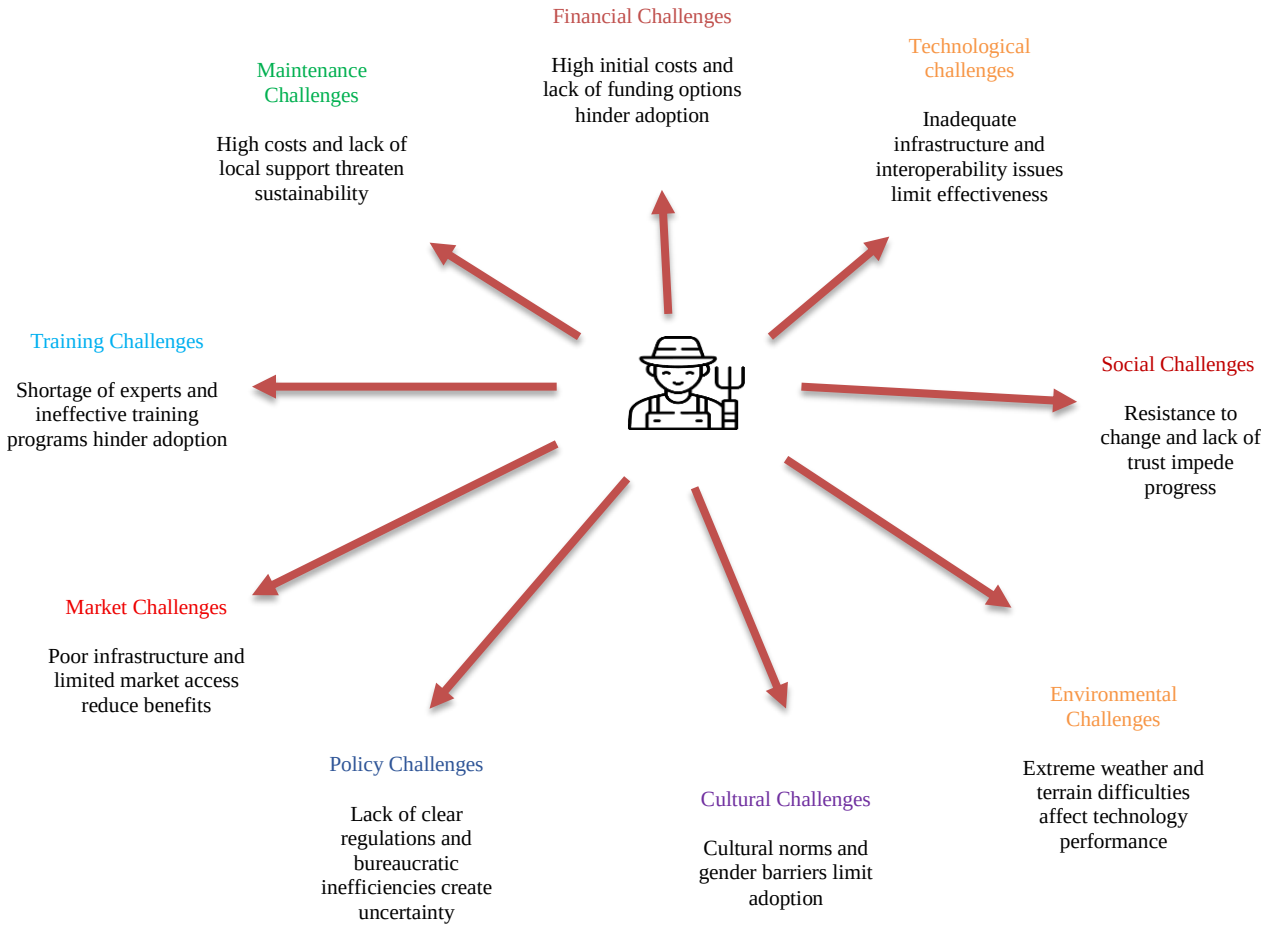


Fig. 4 Challenges in smart agriculture adoption

Farmers may have difficulty in installing, operating, troubleshooting, and maintaining advanced technologies without adequate training and technical support. Language barriers and lack of locally relevant training materials can compound this difficulty. Hence, for successful smart farming adoption, cost-effective technologies, dependable infrastructure, suitable financial assistance, farmer education and continuous technical assistance are needed. These challenges are interrelated and cannot be solved by technology alone. To successfully implement smart agriculture, affordable and flexible technologies, reliable infrastructure, farmer training, supportive policies, data protection and active participation from local communities are needed. Such integrated approach can help rural farmers to adopt smart technologies and to use them effectively for long-term agricultural development. Another worry is the sustainability of smart farming projects in the long run. A lot of pilot projects are funded by donors or external sources and can die when donor funding ends. This can happen where local farmers and institutions are not adequately involved in the design, management and ownership of the system. Hence, the smart agriculture solutions should be developed for long-term financial and technical sustainability.

4.1. Turning Challenges into Opportunities in Smart Agriculture

IoT and AI-enabled smart agriculture provides new opportunities for farmers facing many challenges in resource-constrained settings, such as high costs, no internet, limited education, and unpredictable weather. When used properly, these technologies give direct answers to the problems encountered by farmers in their daily tasks, leading to easier,

more productive and sustainable farming. First, most farmers do not have the money to buy expensive machines or systems. However, new models like Farm-as-a-Service enable them to leverage technology without having to buy it upfront. They can afford to rent expensive tools when needed instead of owning them. These systems also help farmers save on resources by giving precise advice on when and how much to water or fertilize, which saves money and increases profits. Technologically, you need not be stopped by a bad internet connection or a power outage. Many of today's Internet of Things devices are energy efficient and can run on solar power. Some are even smart enough to process data on the farm, no need for the cloud or a constant connection. That means farmers in far-flung villages can access smart systems without all-out internet access. Many farmers have limited digital skills, so smart farming platforms use local languages, simple visuals, and voice commands to improve accessibility and trust. Some farmers are even using cell phones to get advice from artificial intelligence fitted to their crop and region. Once farmer starts reaping the benefits, others are more likely to follow suit. The environment has many real risks, like unpredictable rain and bad soil. But intelligent systems can detect and react to such changes in real-time. Farmers can also plan ahead with soil sensors and AI models to predict weather, watering only when necessary or planting when it will be most appropriate. Even in adverse weather conditions, greenhouses managed by IoT systems can ensure year-round food production. Policy and governance are important. Digital platforms can offer farmers direct access to subsidies, markets, and traceable records, though government assistance is still catching up. Blockchain and cloud platforms can also boost trust by tracking the origin, cultivation, and quality of food. Rural markets and supply chains are often disrupted, but smart agriculture can help. GPS trackers, real-time temperature sensors, and mobile apps help farmers track their produce during storage and transportation, which minimizes waste and increases the chances of getting a fair price. Artificial intelligence can even tell you the best time to harvest and sell based on market trends. Training does not need to occur in a classroom, which is a good thing. Now farmers can learn on their phones through short videos or interactive guides.

AI tools such as transfer learning can give useful insights even with limited data, which is ideal in areas where records are hard to come by. Lastly, maintaining these technologies can be simplified, as many devices now provide alerts when maintenance is required. Others can be repaired by trained local technicians or farmer cooperatives, without the need for outside help. New approaches, such as federated learning, can keep data secure while reducing internet usage by training AI models on local devices.

5. Recent Contributions of Various Researchers in the Smart Agriculture Domain

A major emphasis of recent smart agriculture advancements is on the utilisation of innovative algorithms, methodologies, and protocols to enhance energy efficiency. There have been significant advancements in optimisation algorithms, such as genetic algorithms, which have led to more efficient lighting in plant factories. Cross-layer and clustering protocols promote data transmission efficiency, and federated learning-based monitoring systems ensure resilience and consistency. While improving routing and clustering, deep learning optimises sensor node activity. This improves energy-efficient smart farming while lowering costs and increasing productivity.

Table 9 represents the recent contribution of various researchers in the smart farming domain, including contributions, merits, demerits and outcomes. Based on the recent contribution Figure 5 indicates that out of the three systems, Energy Efficient IoT Smart Farming (EE-IoT-SF), Renewable Energy-IoT-Smart Farming (RE-IoT-SF), and Monitoring and Management-IoT- Smart Farming (MM-IoT-FM). EE-IoT-SF has the lowest residual energy. This shows that by integrating monitoring and efficient management protocols or renewable energy sources, IoT smart farming setups can drastically cut energy consumption. When it comes to conserving energy, every system offers its own distinct advantages that contribute to the long-term viability and effectiveness of smart agricultural technologies. Table 9 represents the major contributions of various researchers in smart farming.

Table 9. Contribution of various researchers in the smart agriculture domain

Author(s)	Contribution	Merits	Demerits	Outcomes
Z. Gupta et al. [100]	Offers a LoRa and SigFox-based IoT network that optimises sensor transmission according to energy levels.	Optimising data transmission rates increases sensor life and throughput.	Energy - saving protocols may cause latency.	Simulations show improved network performance and sensor longevity, making it a viable solution for Resource - Constrained agriculture, especially large-scale deployments.
Bouali et al. [101]	Research integrates solar energy with IoT-based agriculture systems to improve water use and reduce fossil fuel use.	Up to 71.8% water savings, Cost-effective and Optimises irrigation with Big Data Analytics.	Effectiveness limited by low sunlight or power reliability.	Field tests show resource savings and sustainable agriculture potential in underprivileged areas.

P. Supanirattisai et al. [27]	Proposes a LoRaWAN-based IoT solution for agriculture to monitor and manage environmental conditions and support crop growth.	Offers low power consumption, cost-effectiveness over Wi-Fi, long-range transmission up to 1700 meters.	Battery performance may affect field devices.	The system delivers reliable farm monitoring and control by controlling temperature and humidity with low power consumption.
G. Moloudian et al. [102]	Studied the role of Various energy harvesting methods.	RF - based charging for IoT devices.	Higher implementation cost.	Highlighted the usage of renewable energy sources and RF-based charging for IoT devices.
K. Aggarwal et al. [103]	Investigated the issues related to resource consumption.	Analysis covers various energy-efficient solutions.	It does not explore the energy consumption at different IoT layers.	Study found various facts that can cause excessive resource consumption, i.e. coverage area, network topology design, behaviour of routing protocols, type of harvesting schemes, etc.
S. Mishra et al. [104]	Uses multilayer data transmission.	Supports multi-sensor-based routing paths.	The developed solution is only for LoRaWAN.	Energy-efficient routing.
R. Deepa et al. [105]	Smart irrigation.	Energy-efficient irrigation.	Less Compatible With 2G/3G networks.	Optimization of operational cost.
A. Mittal et al. [106]	Regulator to manage sleep/wake cycle of intermediate nodes.	Secure transmission using Ultra-low power IoT devices.	Higher implementation cost.	Optimal energy consumption.
D. Ghosh et al. [107]	Microcontroller-based surveillance.	Hybrid renewable energy - based smart irrigation.	Maintenance cost.	Energy-aware smart farming.
A.K. Rao et al. [108]	Energy - efficient routing solution.	Energy-efficient routing with minimal overhead.	Developed solution is only for LoRaWAN.	Optimal energy consumption.
Z.Y. Hasan et al. [109]	Efficient data aggregation.	Optimization of network energy consumption.	Did not compare the proposed solution with other standards.	Optimal consumption of network resources.
Waluyo et al. [110]	Agricultural land surveillance using fuzzy logic.	Energy-efficient solution.	Used only a trapezoidal composite fuzzy rule.	Reliable communication over a scalable network.
A.C. Nguyen et al. [111]	Resource management using a Q-learning approach.	UAV-based solution.	Operational Cost.	Energy-efficient transmission.
Bouali et al. [101]	Integration of cloud platform with IoT network over farm land.	Open - source solution.	A complex solution requires cloud connectivity.	Efficient usage of for renewable network energy resources operations.
R. Dhaya et al. [112]	Optimization of network resources.	Optimal resource allocation.	Single protocol-based solution.	Energy-efficient production process.
S. Debdas et al. [113]	Environment monitoring system.	Accuracy of forecasting.	Implementation costs high.	Automation of decision -making process.
S. Popli et al. [114]	NB - IoT - based solution for urban farming.	Optimal energy consumption.	Single protocol-based solution.	Energy efficiency.
P. Supanirattisai et al. [27]	A cloud platform for an IoT network.	Efficient power utilization.	Cloud platform connectivity.	Energy efficiency.
R. Sokullu [115]	An IoT network to analyse agricultural	Analysis of energy consumption causes.	Computational Cost	Energy consumption.

	land statistics.			
R. Hartono et al. [116]	Prototype model for the growth of crop production.	Low - cost prototype for agriculture.	Lack of real-time implementation.	Optimization of energy consumption/operational cost etc.
Srinivasan et al. [117]	A genetic algorithm for optimal cluster head selection has been introduced.	The use of incremental learning resulted in lower power consumption during model updates.	Performance in non-uniform or obstacle-rich terrains is not covered.	Significantly reduced energy consumption and improved event detection precision.
Nandal et al. [118]	Developed an energy-efficient information aggregation protocol for WSNs in agriculture.	Hierarchical lustering leads to significant reductions in energy consumption.	Multi - level clustering may cause computational overhead.	Increased energy efficiency over traditional LEACH and TEEN protocols.

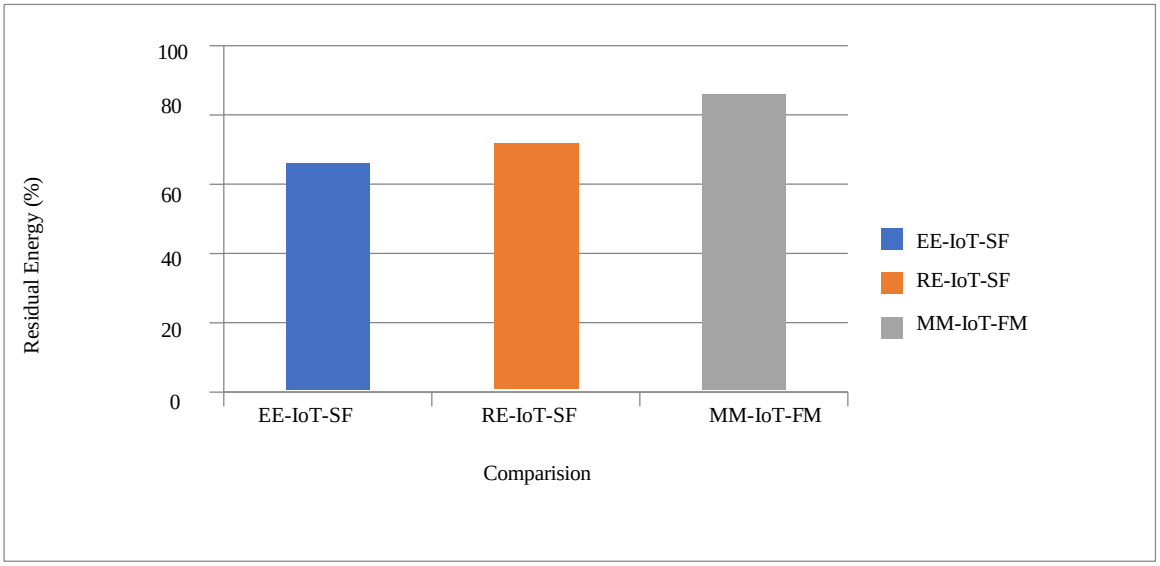


Fig. 5 Residual energy comparison in IoT smart agriculture systems

6. Conclusion

In the case of the traditional farming process, farmers are facing various challenges related to the different activities like resource management, accurate prediction of environmental hazards, farm management, manual decision making, human intervention, livestock monitoring etc. All these facts can be considered as barriers for using cutting-edge technologies. These challenges can be sorted out by the process of automation. In this paper, the impact of advanced technology in the agriculture domain is investigated. Study shows that it is feasible to adapt the smart solutions to enhance the farming experience, and the cost of operational, production, and maintenance can be optimised.

The study discusses IoT communication technologies such as LoRaWAN, Sigfox, and NB-IoT, highlighting their different technical characteristics and their relevance to smart agricultural applications. These technologies can be selected according to specific communication requirements. IoT networks also support various types of sensors to measure the vital parameters associated with the farming process (i.e. Gas/Temperature /Moisture/Water level/Wind speed/Light & Soil mineral, etc.) and types of IoT sensors in agriculture may vary with respect to the nature of farming. This paper highlights the importance of smart agriculture applications in improving agricultural efficiency and sustainability. These applications include soil health monitoring, crop monitoring, pest and disease detection and many more.

The study shows how soil monitoring maximises nutrient use, crop monitoring increases yields, and pest detection reduces losses and pesticide use through comparisons of different technologies. Moreover, the study discusses different challenges to the adoption of smart agriculture and delves into how those challenges can be turned into opportunities. In addition, studies concentrating on residual energy are a focus of recent smart farming contributions that have prioritised energy efficiency. Based on the findings, smart farming setups that utilise the IoT can drastically cut energy consumption by combining monitoring systems with efficient management protocols or alternate energy sources. In the future, this study will help to shed light on the architecture of the IoT and its

critical uses in smart agriculture. It will be helpful for researchers to guide the development of energy-efficient and optimised solutions for various farming processes, leveraging cutting-edge IoT network technologies and addressing a variety of IoT network configurations. Also, this paper can serve as a foundation where various researchers can get a detailed knowledge of the major application areas of smart agriculture.

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Appendix

Table 8. Comparative analysis of pest and disease detection technologies in smart agriculture

Article	Sensor Types	Methods for Detection	Algorithms /Models	Power Source	User Interface	Integration	Durability	Data Storage	Scalability	Accuracy	Performance
[75]	Multi-level sensors	Sensor-based pest detection	Not mentioned	Solar energy	Dashboard interface	IoT sensors, distributed processing	High	Cloud storage	High	98.65%	Realtime monitoring, low latency
[76]	Acoustic sensors, UAV images	Sound-based pest detection and mapping	Inception V3, YOLOv8	Solar power and batteries	Dashboard and app interface	IoT, geospatial data, AI	High	Cloud and geospatial storage	High	100% (InceptionV3 classification on test data)	High efficiency, realtime mapping
[77]	IoT sensors, UAVs, Remote sensing data	Disease monitoring, yield estimation	CNN, Random Forest, RNN, LSTM	Renewable energy	Web interface	IoT, AI, UAV integration	High	Cloud and remote storage	High	80-98%	High precision in rice yield estimation
[78]	Soil NPK sensors, cameras	Image processing for pest identification	TPF-CNN	External power	Dashboard, app interface	IoT sensors, AI integration	Moder ate	Cloud storage	High	90%	Quick decision-making support
[79]	IoT sensors, cameras	Image-based pest identification and classification	YOLOv3, Adaptive Honey Badger Algorithm (AHBA)	External power	Not mentioned	IoT sensors, AI integration	High	Cloud storage	High	Not mentioned	Realtime pest classification
[80]	Weather sensors	Environmental condition-based model	BlightMote forecast system	Battery - powered	Cloud-based dashboard	IoT sensors, cloud, forecast models	High	Cloud storage	High	Not mentioned	Realtime decision support
[81]	Various sensors, Raspberry Pi	Image-based disease detection (blast, rust)	Customized CNN	Renewable energy	Dashboard interface	IoT sensors, CNN integration	Moderate	Cloud and local storage	High	98.80%	Realtime disease monitoring
[82]	Not specified	Image processing of leaf diseases	VGG-16, VGG-19, Inception -V3, Xception	Not mentioned	Web interface	AI models, deep learning	Not mentioned	Cloud storage	High	98.70%	High image processing performance
[83]	Gas sensors, nanoparticles	Gas sensing for pesticide detection	PCA for gas-analyte differentiation	External power required	Not mentioned	IoT and local processing	High	Not mentioned	ot mentione	Not mentioned	High for pesticide detection

[84]	Not mentioned	Pest detection	Mask FRCNN, MobileNet	Battery - powered devices	Mobile app interface	Cloud computing, AI	High	Cloud storage	High	99%	High accuracy and performance
[85]	IoT sensors	Disease prediction	K-means, Adaptive Mud Ring Optimization, ANN	Renewable energy	Not mentioned	IoT network, cloud integration	High	Cloud storage	High	Not mentioned	Optimized for energy efficiency