Recent Advancements in IoT for Agriculture: A Comprehensive Review of Enabling Technologies and their Applications

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ABSTRACT

Over the last several decades, many technological advancements have been made. Internet of Things (IoT) technology has captivated many people and solved real-world issues. It incorporates cutting-edge technologies including smart sensors, wireless communication technologies, predictive analysis, cloud computing, remote sensing technology, image processing, and blockchain technology to enhance existing processes and provide value to customers. Their extensive use in agriculture has resulted in improved solutions and control over agricultural processes in the areas of water management, disease and pest control, farm animal management, and climate monitoring and forecasting. This review provides an up-to-date overview of IoT technology and its applications in the agriculture industry.

General Terms

Internet of Things, Smart Agriculture, Artificial Intelligence

Keywords

Wireless Technology, Sensors, cloud computing

1. INTRODUCTION

The increasing population has set an alarm for food insecurity and economical imbalance. There is also a chance that people will become undernourished and have a lesser chance of accessing a few vital nutrients. This could be addressed by increasing production; however, the related resources are becoming scarce [19]. In India, the economic security mostly depends on the agricultural sector. As of now, 58% of the Indian population is supported by agriculture. It also faces degradation of land and groundwater resources, which affects the rate of growth of total factor productivity [74]. New tools of science and technology have to be used appropriately to overcome the existing issues and increase productivity with the available resources and maintain the fertility of the soil in long run. Currently, the impact of technology on agriculture is unavoidable. The major technological advancements experienced in agriculture are mechanization, the introduction of chemicals, and the application of modern genetics. Recently precision agriculture, industrial automation, automated irrigation systems, and remote monitoring of crops using sensors are the new technologies that help in managing farming, crops, and livestock management problems [135]. Precision agriculture uses different technological tools for data collection and optimizes the inputs to the fields based on specific conditions. It enables continuous monitoring of various influencing factors to crop growth and reduces resource wastage. In industrial automation, robotics and other automated processes are used to carry out precision field seeding, planting, fertilizing, spraying pesticides/herbicides, and harvesting crops [115]. This automation helps in increasing efficiency on farmlands. Automated irrigation systems deal with how water is supplied to crops. It aims at improving the efficiency of water distribution, preserving the water resources, and the quality and quantity of agricultural production. Advanced irrigation systems provide water when it's needed most without wasting any resources. Crop sensors are also proliferating nowadays which enables remote monitoring of crops from anywhere in the world using an app or web browser. Drones and satellites can also be used for observing large-scale and inaccessible terrain farms. Crops can also be modified genetically to suit the benefit of the consumer and the farmers. The qualities required are pests and diseases resistant nature, tolerance to herbicides, expected nutritional value, withstanding adverse weather conditions, etc [42]. The automated process implementation in agriculture could achieve global reach and enhanced sophistication with the usage of the Internet of things. It is a network of objects that are connected, and exchange data with other devices and systems over the internet. It has an everlasting future and will become the base of regular life. Hence this paper aims at providing a review of the technologies of IoT that would enable an efficient agricultural process and help in increasing productivity and inducing a conducive environment for efficient resource utilization [126].

2. INTERNET OF THINGS

Internet of things (IoT) is a revolutionary technology that allows components to communicate with each other over the internet, allowing them to perform functions such as sensing, storing, processing, analyzing, actuation, command, and control. They are made up of various layer architectures, beginning with the edge technology layer at the bottom and ending with integrated application layers at the top [29]. The data is collected via sensors at the bottom layer, which are connected to a node/device. Using Gateway, RFID, GSM, Wifi, 3G/4G, UMTS, Bluetooth, Zigbee, and infrared technologies, data is sent to the Gateway/network layer [89]. The next tier is data storage and management on cloud servers, where big data analytics tools analyze the accumulated vast data and give useful insights and patterns. Stakeholders can receive appropriate notifications and take actions based on analysis [25]. The entire workflow is shown in Fig.1.

In agriculture, a variety of IoT devices have been developed to address the challenges of unpredictably changing weather and environmental conditions, animal diseases, pests, and price volatility in agricultural markets. Temperature, rainfall, humidity, wind speed, insect infestation, and soil content data are collected and sent to the cloud via IoT devices like allMETEo, Smart Elements, Pycno, Arable, and Semios [67]. These data may be utilized to make choices and automate processes for better resource management, increasing productivity, yields, and profitability [16, 17. Few IoT systems such as are Farmapp, Growlink, and GreenIQ used to manage greenhouse environment conditions [15]. In livestock management, smart IoT sensors (collar tags) like Allflex and Cowlar are used to measure health, temperature, activity, and nutrition [19]. IoT devices and sensors are used by FarmLogs and Cropio to remotely monitor the farm, as well as vehicle tracking, storage management, and logistics [28, 48] [20]. The devices used for a variety of applications are listed in Table.1. The major application areas in agriculture are depicted in Fig. 2

3. CRUCIAL TECHNOLOGIES OF IOT IN AGRICULTURE

3.1 Sensors technology

The front end of an IoT network comprises sensor technologies. It has expanded in sensitivity and precision to the extent and is widely used in environmental protection and monitoring, as well as disease prevention and treatment [11]. Temperature sensors, infrared sensors, ultrasonic sensors, pressure sensors, proximity sensors, and touch sensors are examples of sensors. It transforms a physical property from the surrounding environment into an electrically measurable signal [60]. Optical, electrochemical, and dielectric sensors are available to measure the soil properties. They are designed to determine the clay, organic matter, and moisture content of the soil. Electrochemical sensors are used to measure the gas components, pH, and soil nutrient levels. Dielectric sensors help to identify the moisture level and pH in the soil [64]. Pesticide usage can also be optimized by using suitable sensors. Camera sensors can be used to identify the pests and locate the same for spraying pesticides specifically. There are also sensors to monitor the livestock. GPS satellites are also used to identify the exact geospatial location [39].

3.2 Wireless Communication Technology

Wireless communication protocols are used to send data over a long distance utilizing wireless communication technology. IoT requires standards to provide low power, low rate, and transmission over wireless personal area networks (WPAN) along with IPv6 support [22]. The general classification of wireless communication technology is shown in Figure 3.

3.2.1 Short-range wireless communication technologies. Radio frequency identification (RFID), Bluetooth, and other technologies that employ short-range magnetic pulses to transmit signals at distances of 10 to 50 metres. Bluetooth-based greenhouse environment monitoring and control system was designed by Singh et al., [117]. RFID-based livestock identification and traceability control application [75].

3.2.2 Medium-Distance Wireless Communication Technologies. Wi-Fi (IEEE 802.11 a/b/g/n) and ZigBee (IEEE 802.15.4 standard) are wireless communication protocols that employ radio frequencies (RF) or infrared (IR) waves to transmit data at distances of up to 100 metres [16]. Sivasankari et al. [119] created a Wi-Fi-based wireless sensor network (WSN) to remotely monitor the state of agriculture's environment. For greenhouse climate management, Sabri et al. [111] built a ZigBee-based WSN. Al-ali et al. [10] presented a Zigbee-based automated plant watering system based on WSN.

3.2.3 Long-Distance Wireless Communication Technologies. There are several low power wide area technologies, which employ radio waves to transmit data across distances of up to 10 km. The major available technologies are listed as follows. Weightless is a lightweight, open standard protocol that enables very lesser overhead, and exchange of data to a single base station (gateway, star topology) [95]. SigFox is another protocol that consumes much power and relies on specific hardware for implementation. It was initially designed for unidirectional traffic (sensor posting the sensed values) and later extended with the bidirectional operation [53]. LoRa supports long-range transmission with much less power. However, it doesn't natively support IP but has the security provision [69]. NB-IoT enables wide-area (indoor) at a very low cost per device. Used mostly in building automation and asset tracking [83]. LTE-M is a simplified version of 4G LTE that enables low power consumption, extended coverage and a reduced transmission rate of 1Mbps compared to the LTE. EC-GSM-IoT is based on enhanced GPRS that enables data rates between 70 Kbps and 240 Kbps [85]. Telensa is a proprietary LPWAN protocol that concentrates mainly on smart city applications and has a coverage

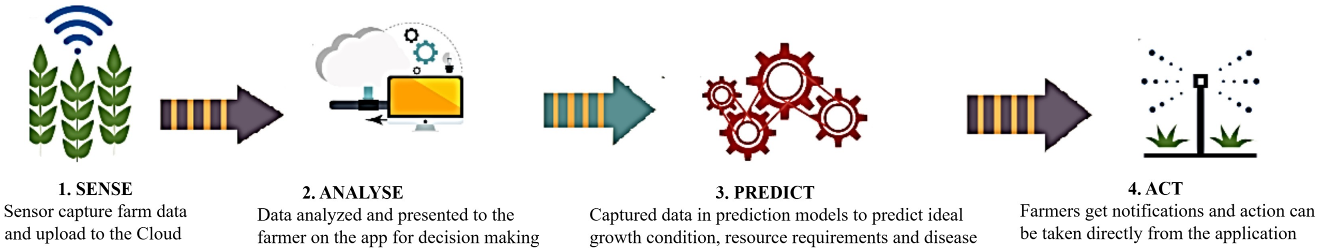

Fig. 1: Overview of IoT workflow

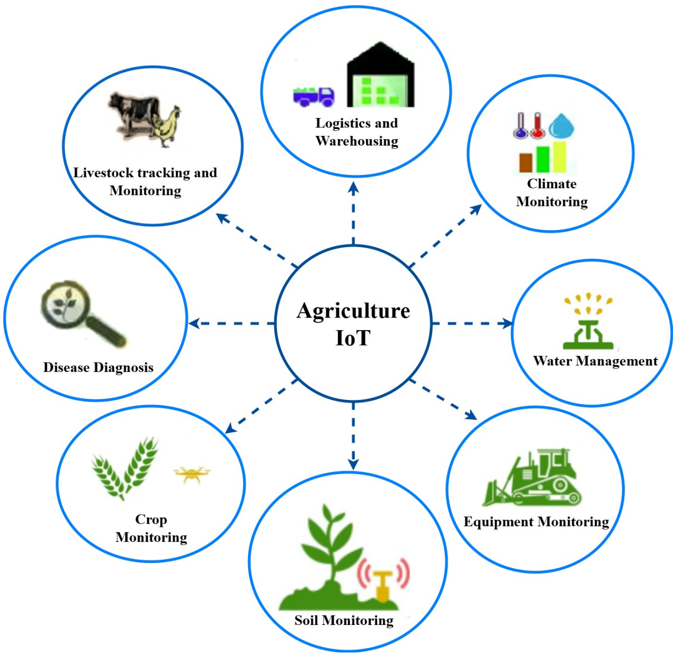

Fig. 2: Application of IoT in Agriculture

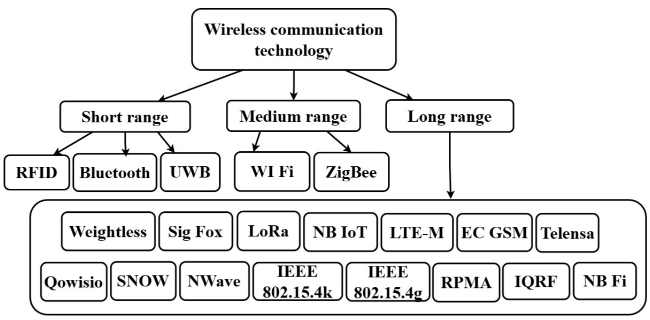

Fig. 3: Classification of Wireless communication Technologies

range of over 2 to 4 km [33]. SNOW is a technology that uses the unoccupied frequency guard bands between TV channels and enables 50 Kbps transmission rate over a range of 1.5 km [17]. Nwave is a commercial LPWAN technology that enables data transmission at a rate of 100bps between mobile devices over a range of 10 km in urban environment [33]. IEEE 802.15.4k is a standard for low energy, critical infrastructure monitoring applications that enables the transmission rates of up to 50 Kbps over a range of 3 km [107]. IEEE 802.15.4.g is a wireless smart utility networks that enables the transmission rates of up to 800 Kbps over a range of 10 km [38]. Random Phase Multiple Access (RPMA) operates over the 2.4 GHz ISM band and supports a transmission rate adaptation strategy too. IQRF deals with devices, gateways, and applications addressing scenarios, with a data rate of 250 Kbps and a coverage range of 500 m [54]. Narrowband fidelity (NB-Fi) provides robust and reliable interaction between devices and base station. It also aims at providing lesser deployment cost and time [127]. Feng et al. [44] developed an IoT application based on Code Division Multiple Access (CDMA) wireless communication protocols to collect data on plant growth and environmental parameters and transmit it to a processing centre, allowing crop and environmental conditions to be monitored remotely. Gutiérrez et al. [51] used the General Packet Radio Service (GPRS) module and WSN to construct an autonomous agriculture irrigation system based on soil moisture and temperature data. Ahmed et al. [9] proposed a LoRa wireless protocol-based star topology network to monitor greenhouse environmental factors. Monica et al. [88] presented a GSM-based smart agriculture system that uses data from smart sensors to automate watering.

3.3 Global Positioning System (GPS) Technology

GPS identifies the precise location based on the real-time position of the satellite. It is used in an IoT sensor layer for precision fertilization and spraying in agriculture and in diverse settings including navigation, agriculture, environmental monitoring, industrial, and healthcare [99]. A GPS-based robot with a database management system has been designed for intelligent decision-making in a smart irrigation system [66].

3.4 Remote Sensing technology

Remote sensing applications such as Unmanned Aerial Vehicles/Drones are significant in precision agriculture. It is used for phenotyping plants and agricultural monitoring, Agri-IoT assists farmers in making decisions about disease incidence using unmanned observation planes and real-time meteorological data [106]. Drone-based IoT in precision farming enables on-demand visual imaging information on the crop details such as plant growth

Table 1. : IoT Devices and Their Applications in Cloud-based Systems

IoT Device	Applications	References
Bitponics	Integrated cloud-based hydroponic automation providing reviews and recommendations based on logged data of water, air, temperature, humidity, brightness, and pH.	[67]
Niwa	Indoor smart hydroponic system - automatically creates the perfect climate for plant variety and can be monitored and controlled remotely.	[108]
Edyn	Solar-powered smart garden monitor system to monitor and track environmental conditions and automatically controls them based on data collected by the sensor, and adapts to every change in the weather forecast.	[67, 108]
Botanicalls	IoT device enables the communication between plants and humans, to call and text message people to request assistance.	[72, 108]
Parrot Pot	Bluetooth 4.0 enabled an inbuilt sensor that monitors and analyses sunshine, ambient temperature, fertilizer, and soil moisture before sending data to the user's smartphone or tablet.	[8]
PlantLink	Indoor/outdoor wireless sensors track plant conditions, schedule automatic watering times, and send alerts.	[67, 108]
HarvestGeek	Greenhouse monitoring and automation system to monitor and control environmental conditions and send alerts such as email or push notifications on smartphones.	[112, 108]
Rachio	Irrigation controller to automate sprinkler controller based on weather conditions obtained from local weather stations and remotely controlled from anywhere in the world.	[6, 67]
Daisy	Automatic plant watering device for indoor and outdoor plants based on soil humidity, temperature, and brightness.	[49]
ripeSense	Ripeness indicator label that changes color to indicate the ripeness of fruit enabled by IoT and AI.	[116, 76]
Yuktik	Sensor-based smart solutions for environment sensing, Crop Disease Prevention, Smart Greenhouse, Post-Harvest Monitoring and Management.	[91]
MooCall Calving sensor	Non-invasive tail-mounted motion sensor to measure tail movement and contractions of a calving cow to predict accurately the calving time.	[68]

and diseases [102]. UAVs were used in the detection and monitoring of sheath blight disease in paddy [134].

3.5 Software Applications

Different agricultural processes are supported by IoT platforms such as software tools/applications. AgTech Finder provides high-performance computational algorithms, a sensor network, communication between mobile devices, cloud computing, and analytical procedures to manage massive amounts of data and provide decision support systems (`http://www.agtechfinder.com`). CropX is an adaptive irrigation software application that allows farmers to boost crop yields while saving water and energy at the lowest feasible cost (`http://www.cropx.com`). GEA FarmView visualizes a multitude of sensor data from farms and aids in animal monitoring, whole herd grazing patterns, and heatmaps (`http://www.iotag.com.au`). Ovass, a Geospatial Analytics platform,

Fig. 4: Predictive Analysis process

uses satellite images and Artificial Intelligence for crop monitoring and vegetation detection (`http://www.ovass.com`). SenseAg uses analytic tools to assist farmers in making informed irrigation decisions and offers timely information (`http://www.devpost.com/software/seneag`. FluroSense is an AI-based precision system that uses stress detection and nutrient management to improve crop performance (`http://www.flurosat.com`). Agri-Webb is a Livestock Farm Management Software that helps farmers keep track of their records, meet audit and certification requirements, and boost production (`http://www.agriwebb.com`). Kenyan farmers use MbeguChoice to choose the best drought-tolerant seed sources (`http://www.mbeguchoice.com`). Agricolus Farmer is a software application that leverages the FIWARE infrastructure to integrate Hardware and Software together in a decision-making process to help farmers [42].

3.6 Predictive analysis

In IoT predictive analytics deals with the prediction that is associated with the control of appliances involved in the scenario. The input to the predictor will be the collective data gathered from various sensors located in the farm fields and the other areas related to the same. It enables the analysis of the elements involved in the process and helps in upgrading the same in near future. The process flow in the predictive analysis is provided in Fig 4. The process starts with data gathering which involves the collection of reliable data. It is ensured by following a strategy to fill the missing values, drop the redundant contents, and remove the noise effectively. Then the data clusters are formed to use the dataset in an efficient way. Followed by that the data is passed through the predefined rule set to remove noise and any other irrelevant or redundant content. It provides minimum support mining and enables a reduction in execution time and the number of rules required. Then outlier processing is performed to identify the presence of any new patterns and address the existing issues. Conclusive statement gathering involves knowledge building, knowledge classification, knowledge validation, and knowledge verification. This helps in taking decisions even during different scenarios [96].

3.7 Cloud computing

The data generated by an IoT-enabled farm is huge, and cloud computing allows us to store and save it in a distant database. Big data technologies could be used to analyze these records to identify insights and patterns in the machine and human behavior. The IoTCloud architecture includes APIs that allow sensors to publish data to the cloud and clients to subscribe to that data. Phytech, Paraimpu, Arkessa, AMEE, Yaler, Axeda, Connecterra, ThingWorx, GroveStreams, Exosite, and Carriots are some of the IoT clouds that have been created for the deployment of smart, connected devices [109]. They provide real-time data analysis solutions for transmitting and receiving data from cloud services in real-time, as well as a framework for developing and deploying applications on public or private clouds.

3.7.1 Infrastructure as a service (IAAS). Cloud-based service that comprises storage, networking, and virtualization and is available on a pay-as-you-go basis. Microsoft Azure, Amazon Web Services (AWS), Digitalocean, Linode, Rackspace, Cisco Metapod, and Google Compute Engine (GCE) are all examples of cloud computing services [125].

3.7.2 Platform as a Service (PAAS). Hardware and software can be delivered through the Internet. UBIDoTS, IBM Bluemix, Amazon IoT, Nimbits, Xively (Pachube) platform, ThingSpeak and idigi platform are examples of PaaS [46, 13].

3.7.3 Software as a service (SAAS). A software/application that is made available via the Internet by a third party. Examples such as Salesforce, Google Apps, Dropbox, ZenDesk, Slack, Hubspot [129].

3.8 Artificial Intelligence

For the early diagnosis of agricultural diseases, IoT is integrated with modern techniques such as artificial intelligence [90, 21]. Agarwal et al., [7] developed a neural network-based detection and classification method for potato leaf diseases. Biwas et al. [27] suggested a system for determining the severity of potato late blight disease using neural networks and image processing techniques. Predic et al. [104] presented a data mining model based on meteorological and microscopic data to predict the change of spores from a normal to an active pathogenic state for fruit tree infection. Katsoulas et al., [65] designed a web-based decision support system (DSS) aimed at predicting the likelihood of a fungal disease outbreak in a greenhouse. DSS has been built for apple orchards [87] and pear orchards [84]. Ali et al. [14] established a farm management information system using IoT that efficiently analyzed wheat crop profitability. It provides ideal solutions for lowering input costs and increasing profitability. Mohanraj et al. [86] presented an e-Agriculture application-based architecture composed of KM-Knowledge base and monitoring modules with information from market pricing, geospatial data, and weather forecast, measuring plant development at different levels.

3.9 Blockchain Technology

Blockchain technology provides a secure way to store and manage data through the entire transactions across a peer-to-peer network [5]. The database generated throughout the entire value-added process of an agricultural product is helpful for developing data-driven mobile applications to optimize farming [130]. Many models have been proposed based on IoT and blockchain technology to have smart farming practices. Jamil et al. [59] developed a lightweight blockchain-based architecture for smart greenhouse farms, IoT sensors act as a private local blockchain managed by a centralized authority. Ferrandez et al., [45] proposes a model that combines agricultural expert knowledge, blockchain for value chain planning, and IoT protocols to ensure tamper-proof traceability in the agricultural sector. Lin et al. [81] proposed a model based on blockchain, associated with Information and Communication Technologies; data from a real-time water quality monitoring system is backed up locally and added to the blockchain Information Communication Technology (ICT). The e- agriculture system model with blockchain infrastructure for usage at a local and regional scale information exchange throughout the agricultural sector. In Taiwan [37], Farmland irrigation associations use blockchain to archive the data collection and better interact with the public, to create transparency and encourage contribution to irrigation management and increase water resource use efficiency. Madhu et al., [82] designed an IoT farm robot and a blockchain mobile app to minimize environmental impact, boost customer satisfaction, ensure supply chain transparency, and provide financial gains for farmers. The crop monitor app alerts farmers to take timely actions in unfavorable conditions.

3.10 Agriculture IoT Use-case

Farmers seeking to proactively address issues before they impact profits can leverage the advantages of smart farming. IoT plays a pivotal role by employing interconnected devices to provide real-time information on crucial factors such as soil conditions, humidity, and water levels. Several agriculture IoT applications have been successfully implemented, including field and livestock monitoring, aerial surveillance with drones, smart irrigation controllers, aerial seeding techniques, pest detection using infrared sensors, automated crop readiness detection and harvesting methods, and motion detection cameras.

3.10.1 Greenhouse Monitoring System. The greenhouse monitoring system utilizes different sensors based on temperature and humidity, light, carbon dioxide concentration, soil temperature, and pH. Zamora-Izquierdo et al. [133] developed low-cost soil-less culture greenhouse monitoring system based on edge and cloud computing. Models based on plant development and environmental characteristics have been developed to estimate crop output for improved greenhouse management [100, 132, 50]. Sung et al. [122] designed an NB-IoT-based greenhouse temperature intelligent control system. Liao et al., [79] developed a smart irrigation system using real-time soil moisture data to estimate dynamic crop water use demand (WUD). The central irrigation controller used this information to achieve precise irrigation depth in each event during a greenhouse experiment with drip irrigation for tomatoes in northern China. The study emphasizes the importance of water-saving irrigation scheduling and provides insights for developing an efficient automated irrigation system.

3.10.2 Farm Management system. Various farm management systems have been established utilizing IoT to optimize resource utilization in agriculture [62, 43, 113, 80]. Smart FarmNet, an IoT platform, analyses and recommends crop performance based on data from the environment, soil, irrigation, and fertilization [4]. Abdullah et al. [3] presents AgriSys, a smart agriculture system that proactively analyzes and intervenes in the agricultural environment to maintain optimal conditions. AgroMobile for agricultural cultivation and marketing, as well as crop image analysis for disease detection using image processing [103]. Agri-Info is an agriculture service that manages several sorts of agriculture-related data, including crop, weather, soil, pest, fertilizer, productivity, irrigation, livestock, and equipment [118]. Elsheikh et al., [41] introduced an intelligent system, the Agriculture Land Suitability Evaluator (ALSE), designed to assess the suitability of land for various crops in tropical and subtropical regions. ALSE utilizes geo-environmental parameters to identify the most appropriate land for different types of crops. Roy et al. [110] presents AgriSens, an IoT-based dynamic irrigation scheduling system for efficient water management in irrigated crop fields. It offers real-time, automatic, and dynamic irrigation treatments for different crop growth phases, achieving significant results in various performance metrics and climatic conditions.

3.10.3 Crop-Field Monitoring and Irrigation Automation system. Crop fields may be monitored and watered automatically utilizing established models that employ a diverse set of sensors and actuators, with decisions made by a computer, based on moisture and temperature data detected [31]. To schedule irrigation in cotton, Kamienski et al. [63] developed an IoT-based smart water management platform (SWAMP) enabling precision irrigation in agriculture. Payero et al. [98] devised a method for monitoring soil moisture in a wheat field based on a network of sensors. Pongnumkul et al. [101] proposed the concept that allows users to remotely monitor and control the system using an Android mobile app. Abba et al. [2] designed an intelligent drip irrigation system that uses water level sensors to assist in decreasing water waste without requiring human intervention. Bandara et al. [23] suggests an innovative irrigation control method for green roofs that relies on predicted evapotranspiration. The system has the capability to forecast evapotranspiration and determine the appropriate irrigation amount accordingly. Jin et al., [61] introduces a novel approach that integrates deep learning and image processing for weed identification. Using a trained CenterNet model, it detects vegetables by drawing bounding boxes and identifies remaining green objects as weeds. This focused approach streamlines the identification process, specifically targeting vegetables while excluding various weed species. Studies have been conducted on a disease forewarning model specifically designed for groundnut and castor crops [70].

3.10.4 Aid Pest Management. Insufficient pest control practices can result in disappointing and financially unproductive harvests. The traditional approaches employed by farmers to detect insect infestations are not only labor-intensive but also consume a significant amount of time. Additionally, these methods may fail to identify issues until they have reached a critical stage, exacerbating the overall impact on crop yields and profitability [30]. IoT sensors play a crucial role in providing instantaneous updates on crop health and detecting the presence of pests in real time [20, 19, 35, 71]. These advanced technologies offer a comprehensive view of the pest landscape. Conversely, high-resolution sensors focus on recording the plant's spectral signature, measuring the amount of light energy emitted, providing a nuanced understanding of the crop's condition. [97] Farmers opting for IoT devices in pest management carefully consider factors that contribute to the likelihood of infestations. This proactive approach enables them to make informed decisions based on timely and accurate information, enhancing overall crop protection and yield [34]. Utilizing IoT sensors offers a valuable means of gathering data on general pest behavior patterns within a farm, enabling users to assess the effectiveness of existing pest control measures. These sensors go beyond mere data collection by providing predictive analyses, allowing farmers to proactively prepare for potential increases in pest prevalence associated with specific weather patterns [114].
Smart farming gadgets equipped with IoT sensors also offer insights into the efficacy of current pesticide applications. By continuously monitoring and analyzing the data, farmers can make informed decisions about how, when, and where to apply pest management tactics. This dynamic approach ensures that adjustments are made in real time based on regular, up-to-date information, allowing for a more strategic and proactive implementation of smart farming practices, as opposed to relying on luck or unforeseen circumstances.

3.10.5 Animal Farming. Monitoring and location of farm animals, animal breeding, feed management, disease diagnosis, and warning are examples of IoT applications in animal farming [52]. IoT aids in the understanding of an animal's physiological and nutritional needs, as well as it's capacity to adjust to external environmental changes [93]. IoT systems have been devised to monitor water quality indicators such as dissolved oxygen content, water temperature, and pH value in aquaculture to assure aquatic animal growth [55, 124]. Animal husbandry using an IoT system has been developed to monitor vital signs, behavior, and breeding environment data [92]. Yazdanbakhsh et al. [131] presented an intelligent livestock monitoring system employing animal-mounted sensors to monitor the health of each animal automatically and constantly. Cecchi et al. [32] developed an innovative smart sensor system for real-time monitoring of beehive conditions. The system measures hive weight, bee sounds, temperature, humidity, CO2 levels inside the hive, and external weather conditions. This multisensor platform, designed for field-deployed beehives, integrates data to offer insights into the colony's status, its interaction with the environment, and the impact of climatic conditions.

3.10.6 Agri-food Supply Chain Traceability. Food safety and quality may be ensured at every stage of the manufacturing process from the field to the customer, using IoT-based Agri-food Supply Chain Traceability [78, 77]. IoT integration with blockchain technology digitizes transactions or "blocks" that are cryptographically protected at each step [12]. RFID, GPS, and smart sensors assist in field monitoring and information sharing [47]. In an intercontinental transit of fresh fish from South Africa to Europe, RFID sensors with temperature and relative humidity detection capabilities were employed [1]. In the safe and quality mangosteen [128], traceability in the cold meat chain [123], and storage and transit of chilled tilapia [36], White wine traceability was improved by combining RFID technology with WSN [26]. Qian et al. [105] developed Wheat Flour Milling Traceability System (WFMTS), that utilizes 2D barcode and RFID technologies to ensure flour quality and safety. Sun et al. [121] built an anti-counterfeiting system that uses GPS encrypted Chinese-sensible coding and GPS technology to determine the provenance of agricultural products.

3.10.7 Improving Water Usage. In agriculture, achieving optimal water usage is vital to prevent both overwatering and underwatering, which can negatively impact crop production and soil health. IoT technology, by detecting soil moisture, helps farmers effectively address challenges associated with drought and overwatering [31].

3.10.8 Agricultural Drones. Drones for agricultural surveillance can significantly boost farm crop yields while lowering the cost of roaming the fields or shooting from an aeroplane. Drones are frequently used to survey fields and determine soil chemical composition, field status, crop spraying, and irrigation. Higher output and more effective use of land, water, and fertiliser are among the advantages for farmers [40]. Higher yields: Yield-limiting problems can be identified using drones equipped with machine vision and specific algorithms. Drones contribute to time savings in agricultural surveys by minimizing the reliance on human labor, covering up to 10 times more ground in equivalent timeframes. This efficiency is particularly advantageous for large farms or those with intricate geography or natural obstacles such as streams and hedges [120]. It plays a crucial role in helping farmers assess the actual health of their crops by measuring factors such as the amount of sunlight absorbed by plants in different sections of a field and analyzing the chemical composition [24, 56, 18]. Swift remedial measures can be deployed to counteract bacterial or fungal infections [94]. Water efficiency and environmental benefits are notable advantages of thermal cameras in agriculture. These cameras have the capability to identify temperature variations, distinguishing between adequately watered, cooler sections of a field and dry, hot spots. Farmers can leverage this information to make informed decisions about adjusting irrigation practices, optimizing water usage, and ultimately promoting more sustainable and resource-efficient agricultural practices.[58]. In the field of 3D mapping, drones have

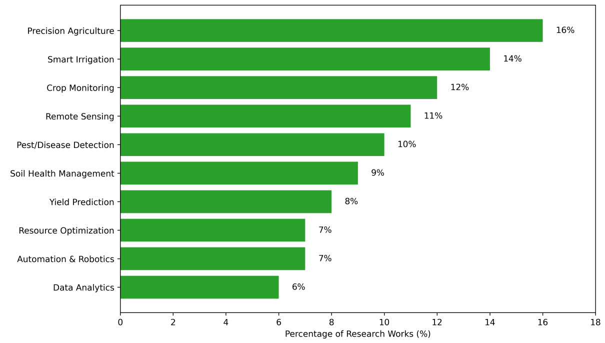

Fig. 5: Percentage of Research Topics in IoT Agriculture papers (2011-2024)

emerged as crucial tools for generating accurate and regularly updated maps of land impacted by human activities, weather variations, or natural disasters [73]. Their capability to provide precise spatial data contributes significantly to monitoring and managing changes in land conditions. The Agriculture Drones Market is anticipated to experience substantial growth, with an estimated size of USD 1.79 billion in 2023. Projections suggest a robust upward trajectory, reaching USD 3.76 billion by 2028, reflecting a notable Compound Annual Growth Rate (CAGR) of 16.05% during the forecast period from 2023 to 2028 [57].
Figure 5 illustrates the percentage distribution of research topics covered in IoT-related agricultural studies from 2011 to 2021. Precision agriculture, smart irrigation, and crop monitoring lead in focus, indicating a strong emphasis on optimizing inputs and improving yield through technology-driven methods.

4. CONCLUSION

The integration of the Internet of Things (IoT) has fundamentally reshaped traditional agriculture, ushering in an era of greater efficiency and productivity. By embedding smart sensors and interconnected devices throughout the farm ecosystem, IoT-enabled systems have optimized cultivation techniques, boosted both yield and quality of produce, lowered operational costs, and improved energy utilization. When combined with machine-learning algorithms, the vast volumes of data generated by these devices yield actionable, data-driven insights that empower farmers to make timely, informed decisions. IoT also facilitates early detection and predictive management of crop diseases and pests—minimizing losses and promoting healthier harvests.
Looking ahead, the convergence of IoT with artificial intelligence (AI) and blockchain promises to unlock new applications and research avenues that advance sustainable agriculture. As AI models grow more sophisticated, they will deliver ever more precise forecasts for yield optimization, resource allocation, and disease prevention. Meanwhile, blockchain can bolster transparency and security across supply chains—ensuring food safety and fostering trust between producers and consumers.
Future work must prioritize the development of robust, cost-effective, and user-friendly IoT solutions tailored to the heterogeneous needs of farms, including smallholder operations. Addressing data security, privacy, interoperability, and rural connectivity will be critical to accelerating adoption. Moreover, integrating next-generation networks (5G) and edge-computing platforms will enable real-time analytics and more autonomous field operations. Continued innovation at the intersection of IoT,

AI, and blockchain will drive the transformation of agriculture into a more sustainable, resilient, and efficient enterprise—an outcome essential to global food security and environmental stewardship.

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