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IoT-Based Precision Farming Robot for Agricultural Automation

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Abstract

As the world turns to new technologies and applications, advancing agricultural development goals is essential. The Internet of Things is essential for smart agriculture. IoT sensors are capable of providing farmland data. This study offers an automated IoT and smart farming system. An IoT-based agricultural monitoring system uses wireless sensor networks to collect data from multiple sensors placed on multiple nodes and transmit data using wireless protocols. The use of IoT has, to a large extent, influenced the efficiency of farming activities by providing accurate use of resources in farming. These smart farming systems are interconnectivity devices such as the moisture in the soil, weather stations, and automated irrigation systems, whereby farmers are able to receive real-time data. It helps farmers in achieving the best practices in crop management; they use water in an efficient way, use fertilizer, and even control pests. However, mechanization also received an improvement through the use of machine learning algorithms and artificial intelligence, which have extended the functionalities of smart farming systems. Such technologies can process a sizable amount of data to estimate crop yield, diagnose crop diseases in their early stages, and give a particular course of action appropriate for a definite field or crop.

Keywords: Agriculture IoT, Embedded Systems, Precision Agriculture, Robotics, Smart Farming, Wireless Sensor Networks.

Introduction

The proposed method utilizes the Internet of Things (IoT) to monitor agricultural fields. In the recent past, the application of artificial intelligence (AI) and machine learning (ML) has taken agriculture to another level. Such elaborate systems can process information originating from different sources, such as satellite imagery, data from soil sensors, as well as weather forecasts, for farmers' use. For example, with recent advancements in smart technologies, self-driving tractors and drones for crop surveillance are changing the micro of farming. These innovations not only enhance productivity but also help in tackling some of the problems related to the shortage of labour in several agricultural fields, which, in turn, helps shape a sustainable, technology-based future in agricultural practices (1, 2). Blockchain technology has been identified in the recent past as having the potential to change the landscape in the agricultural supply chain. This technology plays the role of an open and secure ledger, which assists in food safety and distribution, as well as in combating unfair trade practices. Blockchain has the potential to be utilized on the farm in tracking a product from farm-gate to dinner plate, giving consumers a 'back story' on their food. From the same technology, fraud in the sector can be minimized, payments can be made easier, and efficiency in the agricultural sector can be enhanced. Further, using smart contracts within blockchain platforms, a number of procedures can be automated, such as crop loss insurance or making direct sales from producers to consumers, exempting middlemen, which cuts down the profits of farmers (3, 4). The two other serious breakthroughs in agricultural technology are vertical farming and controlled environment agriculture (CEA). The latter makes it possible to cultivate crops throughout the year in Southern cities, ensuring high efficiency of space utilization and minimizing transportation expenses. Vertical farming involves growing crops on several levels, where the crops are typically grown in aeroponic

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or hydroponic systems. Contrary to other cultivation techniques, which may require a lot of water and pesticides, this method allows detailed monitoring of growth conditions, enabling farmers to achieve high yields of crops and simultaneously produce standardized crops that are marketable. This is particularly beneficial in growing cities, where arable land is shrinking, making vertical farming and CEA techniques viable solutions to food security issues due to their proximity to consumers and positive environmental impact (5). The integration of IoT not only increases the ability to monitor and manage agricultural fields but also introduces a level of precision that was otherwise impossible. Real-time data on soil moisture, temperature, and crop health gives farmers the chance to make informed decisions on the efficient use of resources to maximize yield. Additionally, the control of irrigation and fertilizing systems can be achieved through IoT-enabled devices, which means that human input in this process is minimized, reducing wastage. These systems are vital for food security needs, as climate change affects agricultural production rates in the future. The use of AI in conjunction with blockchain and vertical farming concepts marks a significant step toward the future of sustainable agriculture (6). The agricultural sector has several issues, such as a declining labor force, volatile weather conditions, and stiff competition. To efficiently address these issues, technologies like the IoT and robotics have been introduced as modern tools in farming. Concentrating on these innovations in excessive and precision agriculture, it is performed better than the traditional way of farming, where the resources are efficiently used and maximally produced (7). The objective of this survey is to analyze currently available two types of technologies, namely IoT devices and farming minidomes, their application in agriculture and challenges, and prospects for these technologies. IoT is said to be a collection of devices that are interconnected and can gather and share information over the internet. Within agriculture, IoT platforms translate into the collection of sensors, data capture, and robots, which give useful information to farmers about environmental parameters like temperature, soil moisture, and humidity. The essentially guided processes improve management of water and nutrient application and pest control, thereby reducing the risk of guesswork and improving effectiveness. In farming tasks, attention-grabbing performance aimed at improvement of IoT platforms becomes an essential point. Water levels in the ground can be tracked and weather predictions made on that platform in order to inform the farmers and assist them to manage water usage better with the weather, as Microsoft Azure IoT does, for example. There is a precise application of International Business Machines Corporation (IBM) Watson IoT analytics and solutions in pest and disease prediction and prevention using IoT, which allows addressing problems promptly and effectively. So, using Google Cloud IoT, a lot of agricultural data is stored and processed to determine the growth rate as well as the health status of the crops. On the other hand, despite the various behaviors that appeal to the use of IoT in agriculture, it has turned out that over 70% of smallholder farmers in developing world countries have no access to these systems because they are too expensive. Although there is a definable rationale for such claims on cost (8), there is an equally convincing push for low-cost IoT solutions that can target small as well as medium farms. Robotics represents the next agrarian mechanization stage, which enables a higher degree of automation for agricultural cyborgs that can carry out operations like planting, weeding, fertilizing, and harvesting more effectively. These robots normally have crop health monitoring areas and help reduce the manual farming activities. Agriculture is a multidisciplinary arena where robotics is actively used. These include, but are not limited to, the Ecorobotix weeding robot with integrated machine vision, which is able to spray herbicides only around the weeds and not over the whole field, conserving chemicals. The See and Spray Unit also focuses on the weeds, making the herbicide application more accurate and environmentally friendly. Furthermore, cake-decorating robotics from Agrobot Co. are able to tell when vegetables and fruits such as tomatoes and apples are ripe and as such only harvest them when they are at their optimal ripeness to avoid wastage. Robotics can provide solutions for labor shortage problems in agriculture, especially in seasons with a high call for physical human labor. On the flip side, a major drawback for small-scale farmers remains the initial investment and operation costs of acquiring and using these robots (9). The use of IoT and robotics in agriculture can be of great use; however, there are a number of barriers to their widespread adoption, especially by the smallholders. Using advanced AI algorithms and ML models, the data processing system uses sensor data and multispectral images to process and make a precise decision. Image analysis is performed using Convolutional Neural Networks (CNNs) to classify plants into categories like healthy or stressed as well as to detect plant stress, diseases, and nutrient deficiencies. Environmental parameters such as trends in the soil moisture can be predicted with regression models (linear regression and decision trees) and used to pre-emptively manage water resources. Anomaly detection algorithms are additionally used to analyze real-time sensor data and identify anomalies, including sudden temperature or moisture changes, for which immediate alerts are raised to take corrective action. The benefits of the proposed IoT-based agricultural robot are distinct from those available in current technologies. While systems such as Ecorobotix concentrate mostly on weeding, Agrobot's harvesting robots meld together multiple functionalities like seeding, irrigation, and soil health monitoring into one system. Moreover, existing IoT-based solutions, like IBM Watson IoT or Microsoft Azure IoT, offer robust data analysis platforms; however, these services are costly to set up in cloud computing and lack direct connection to autonomous robotic systems. To address these gaps, this system combines low-cost IoT devices with edge computing near where the data is collected to overcome relying on expensive cloud infrastructure and enable real-time decision-making. Smallholder farmers, especially in developing economies, find such systems and agricultural robots too costly. Smallholder farmers are unable to work with the cost of acquiring sensor devices and cloud platforms. Without the possibility of procuring such solutions at subsidized terms or with the help of specific financing, the outreach of such technologies is limited in several regions. Infrastructure poses a further obstacle. For instance, IoT systems and robots require electricity and the internet, without which it would not be possible to provide care for the crops and animals (10). Unfortunately, these are mostly unavailable in rural developing regions, making investment in IoT-based systems impossible. Environmental factors such as hostile natural terrains, different weather patterns, and various soil conditions can also lower the effectiveness and dependability of the robotic systems. However, there is very little literature that is focusing on these practical issues. The upcoming phase of the agricultural transformation is likely to be fuelled by the growth of AI, ML, and autonomous systems. AI algorithms are currently being designed for the task of plant disease diagnosis, enabling the robots to carry out pest control and crop protection protocols better. Another area that's gaining traction is called swarm robotics, whereby several tiny robots perform the same task, such as planting, weeding, and harvesting. This strategy will allow for the breakdown of the tasks performed by one large and costly machine to several small, low-cost machines that share information and synchronize their operations. Nevertheless, it has not been feasible so far, as the volume of studies to be carried out comparing swarm robotics and conventional machinery practices is rather low. Also, the application of 5th Generation (5G) in IoT should be mentioned as an encouraging change because it accelerates device communication and enables the devices to work faster and with higher accuracy (11). Unfortunately, an understanding of developing countries is that there is yet insufficient 5G infrastructure in place to support this healthy trend. The IoT and robotics have shown great potential in transforming the agricultural sector, but still, there are major barriers concerning the accessibility of these technologies to the smallholder farmers. Issues pertaining to cost, energy fatigue, infrastructural development, and job loss have to be solved through continuous research and development. But more research will be required to optimize the cost-performance of these technologies in order to ensure that they are suitable for a variety of farming practices. It is expected that the march of AI, swarm robotics, and 5G will address these issues and therefore promote the adoption of smart agriculture worldwide. Build a battery-powered, intelligent agricultural robot to perform various farm tasks

(12). It should examine the soil's moisture content and the surrounding area's humidity. Following the determination of the soil's moisture level, excavate the ground to the necessary depth and distribute the appropriate number of seeds using water. After the seeding operation, level the mud. It should be simple to use and safe to handle. These robots employ the features of AI and ML to identify the kind of soil and crops grown and the environmental conditions and make efficient real-time decisions to increase the yield. These technologies being developed are aspects that hold the potential to solve at least some of the labor scarcity problems, do away with wastage of resources, and aid in the adoption of sustainable farming.

Methodology

All these features that have been discussed as characteristic of smart farming are consistent with the concept of IoT: IoT is thus well suited for smart farming. Being aware of the great opportunities that IoT technologies will open in the field of smart farming, IoT is slowly but steadily advancing in the sphere of agriculture (13). Define the requirements and goals of the agriculture system, including the capability to measure meteorological conditions, control the water supply, or identify pathogens. Find out how big the coverage area of the system is, as well as how far the range will spread. What one should concern him/her with are the supply power, the connectivity, and the scalability. Hardware Setup The use of integrated Wireless Fidelity (Wi-Fi) and Bluetooth features in the Espressif 32 (ESP32) board will make the system practical; real-time video surveillance and data processing will be integrated on the board, and the ESP32 board will be the central processing unit from where control algorithms will be executed and communication with the cloud will be managed. The system will utilize Light Detection and Ranging (LIDAR) for precise terrain mapping and multispectral cameras for monitoring plant health and stress or disease detection and is managed by additional Node Micro Controller Unit (NodeMCU) boards or similar IoT platforms for data acquisition from multiple sensors. Soil moisture sensors will measure water levels, and pH/electrical conductivity sensors will measure soil nutrient content, which information will be measured in real time. Carbon dioxide (CO_2) sensors will record air quality, and The Digital Humidity and Temperature (DHT-11/DHT-22) will record environmental conditions. In order to ensure that there will be an uninterrupted power supply, particularly in remote areas, solar power will be installed. With these advanced sensors, they will be certain of monitoring the farm ecosystem in detail. Battery backup systems will allow operations at times of low sunlight. This combination of renewable energy and efficient battery management makes the system environmentally friendly and reliable for long-term use (14).

Sensor Data Acquisition

The enclosed environment in which these additional advanced sensors, such as temperature, humidity, CO2, soil nutrients, pH/EC, and multispectral imaging cameras, are brought in will address this challenge. Inter-Integrated Circuit (I^2C), Serial Peripheral Interface (SPI), General-Purpose Input/Output (GPIO), and other interfaces will be used for sensors to communicate (15); regular sensor calibration routines will increase data acquisition accuracy, self-diagnosis will detect erroneous data, and redundant sensors will be used for cross-verification.

Data Processing and Analysis

Real-time data processing will happen on-site, using edge computing and AI algorithms. Tensor Flow will be used to develop AI models that will analyze multispectral images and sensor data for the early detection of diseases, nutrient deficiency, and water stress. Actionable insights for irrigating in the most effective way, applying pesticides, and fertilizing will come from predictive analytics. Local data processing will be done on ESP32 board and heavy data load will be transferred to Firebase for analysis of the data and historical trends (16). The advanced AI algorithms and ML models are used for the data processing system, analyzing the sensor and multispectral images with precision on decision-making. Image analysis is achieved using CNNs to detect plant stress and diseases; environmental parameters such as soil moisture trends are predicted using regression models, such as linear regression and decision trees, allowing for proactive resource management. And nutrient deficiencies by categorizing plants into healthy or stressed. Environmental parameters such as soil moisture are real-time predicted using regression models, such as linear regression and decision trees, allowing for proactive resource management. Anomaly detection algorithms also observe real-time sensor data to discover peculiarities, like sudden temperature or moisture shifts, and right away generate alarms for corrective action. K-Means and other clustering techniques group plants according to their health in outbreaks and then allow targeted intervention in certain field areas. By merging historical and platform data, predictive scalability models predict crop yields, possible disease outbreaks, and irrigation needs. The models have been developed with the help of Tenreal-timelatforms, which guarantee scalability and reliability. With the aid of edge computing on the ESP32 board, data is processed locally, minimizing Firebase and long-duration time actions, like adjusting irrigation without relying much on decisions, services. Then, the processed data is uploaded to cloud platforms such as Firebase for the long duration storage to carry out trend analysis and make calculated decision. This robust method enhances this system's utilization of resources at the maximal level and its overall agricultural sustainability.

Communication and Connectivity

For long-distance communication, the system will exploit Low Power Wide Area Network (LPWAN) technologies like long-range wide area network (LoRaWAN) (17). A mesh topology will be used in the communication network to exchange seamless data among the IoT nodes and maintain scalability. Message Queuing Telemetry Transport (MQTT) protocols will be used to transmit data, keeping the integrity and confidentiality of farm data. Real-time Surveillance: For live video streaming through Wi-Fi or other communication protocols, video cameras will be connected to ESP32 board to achieve live video streaming through ESP32-Camera (ESP32-CAM) module, and the ESP32-CAM module will output high-definition live video for remote monitoring crop health and field conditions. To provide aerial surveillance over large farm areas quickly, drones equipped with multispectral sensors are used. To complement ground level monitoring, a pan-tilt camera module will capture images at various angles. (18). Actuation and Control: Intelligent actuators interfaced with the NodeMCU will activate irrigation pumps, fans, and pest control systems through predictive control and status assessment sensors integrated into the systems. Relay modules will be provided to the actuators to switch devices such as motors and valves, and ultrasonic sensors will be used for precise measurement of water level and obstacle detection. The LM series of integrated circuits (ICs), LM2596 motor pump is used in the irrigation system and will adjust the water flow rate according to the real-time soil moisture data (19). Data Storage and Visualization: Sensor data and video streams will be stored in Firebase real-time databases or local systems; graphical dashboards will present heatmaps derived from multispectral imagery depicting areas of crop stress or possible pest infestations. Farmers will benefit from advanced trend analysis tools to monitor environmental changes (20), crop health, and system performance that will inform decision-making.

Proposed Design

The system architecture is modular, while installation and application of the system will be centered on a mobile or web app that integrates most of the control and monitoring functions. This is an agricultural robot that has been built to be lightweight and also compact in size for easy navigation through the crops without damaging the crops or the soil structure. The robot is equipped with 4 wheels, which are also rubberized, to enable it to move over uneven surfaces of agricultural fields. Its movement mechanism facilitates sharp turns as the wheels are driven independently; thus, no complex movement systems, including differential gears, are required, making the whole design cost-efficient. The aforementioned robot is fitted with a seed dispensing unit, powered by a direct current (DC) motor that regulates the displacement of seedlings into the soil. Besides this mechanism assisting in accurate plant depth, which is key in ensuring developed plant roots that aid in better nutrient and water uptake, it also assists in water saving. There are two primary working modes available for this device: manual and autonomous. In the mobile app, the operator controls the robot by moving it and turning it in the required direction. At a certain position, the autonomous mode of the robot is turned on and the seeding mechanism comes to rest. The robot moves along a specified trajectory in series while seeds are sown. At the end of the path, the robot is immobile while the operator lifts it and moves it manually into the subsequent row as shown in Figure 1.

Implementation and Block Diagram

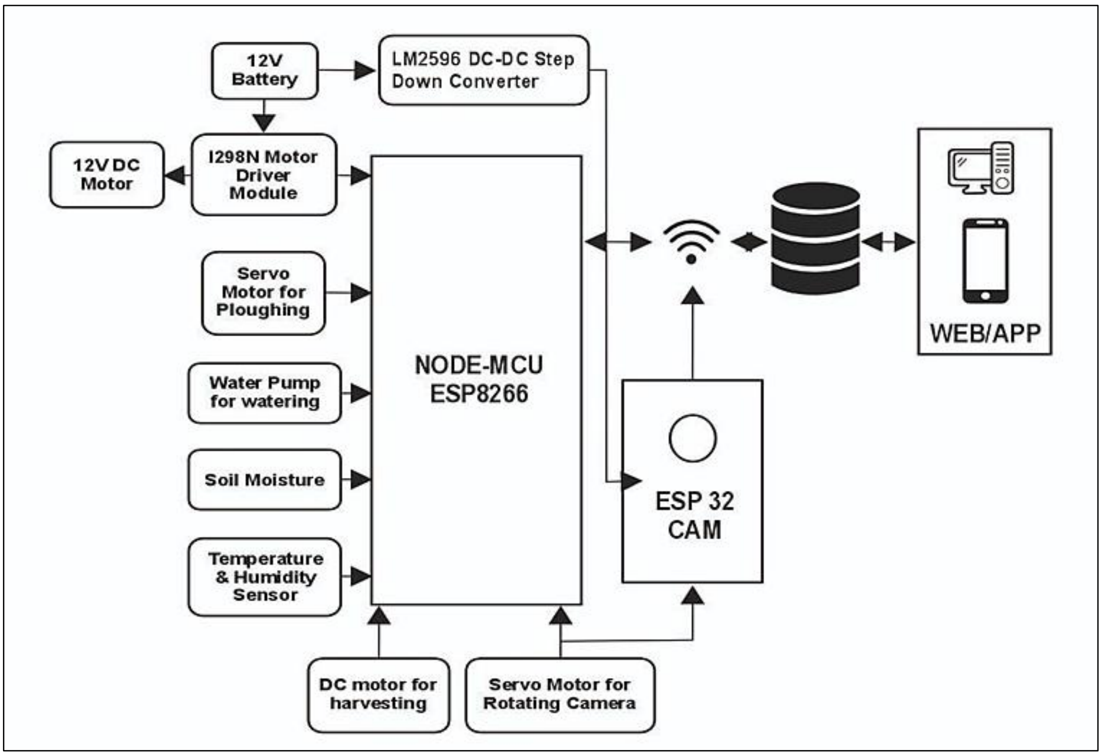

Figure 1: Block Diagram of the System (21)

Working Principle

Mobility System

The IoT-integrated agricultural bot is a ground-breaking invention that employs the use of sophisticated technology to ease the different procedures in agriculture, as shown in Figure 2. With the integration of Firebase for Unity communication and a combination of various hardware components, this offers farmers one effective tool in raising productivity and yield. This brief outline will explore each one of the components and talk about its functions in this context (22).

Seeding Mechanism

The seeding mechanism is a critical component responsible for accurate and controlled seed placement. A servo motor drives this mechanism, ensuring a consistent and even distribution of seeds across the field. The NodeMCU (23) orchestrates the servo motor to activate the seeding mechanism when the website interface assigns a seeding task.

Ploughing Mechanism

The ploughing system, which mimics the conventional Plow system, has ice cream sticks connected to a servo motor as its driving mechanism (24). When the bot is in the forward and backward motion, the servo motor swings the sticks from, thus doing the work of tilling and aeration of the soil. This is coordinated by the NodeMCU to make sure that ploughing happens at the same time with the movement of the bot.

Watering System

LM 2596 motor pump holds a very special importance in controlling the flow of water to the soil. This component is designed to manage the water distribution in a way that will guarantee the crops proper irrigation. In another way, with the use of a soil moisture sensor, the NodeMCU measures the level of moisture that is necessary for the plant, and it is able to control the rate of watering.

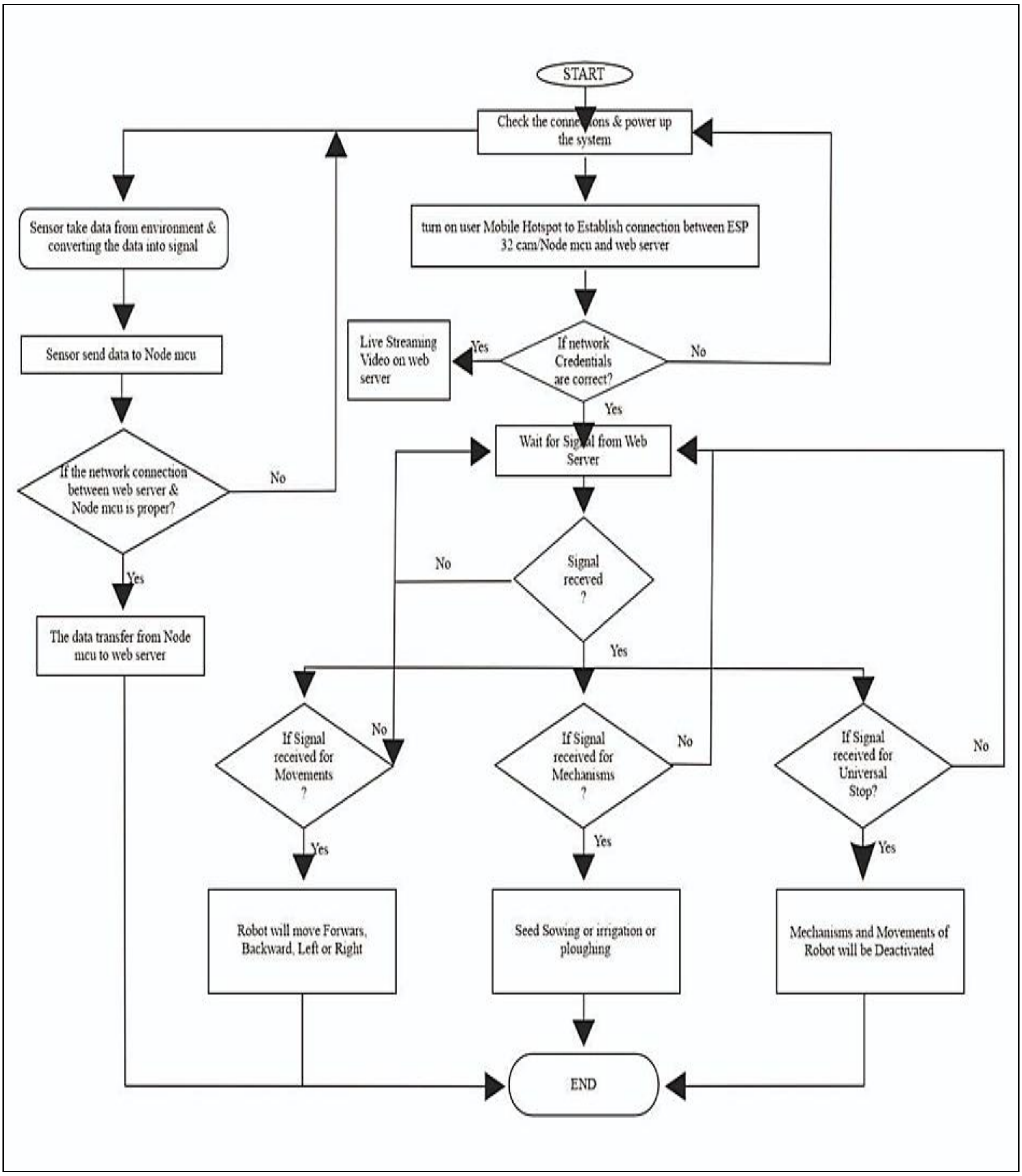

Figure 2: Flow Chart of Block Diagram (25)

Soil Monitoring

Temperature and moisture content in the soil must be kept track of because they give information on the environment affecting plant growth. DHT-11 sensor monitors the mentioned parameters to give timely information to farmers on which crop to grow and how to grow it (26). The NodeMCU continually records data from the sensor and sends it to the website interface with the help of Firebase.

Live Surveillance

The ESP32-CAM module comes with an Internet Protocol (IP) address for broadcasting it by incorporating it into a normal network. In this work, both the ESP32-CAM module and the desktop computer with the established web server are connected to the same access point. The user, who we presuppose is an observer, establishes a connection with an access point (AP) through his or her computer (27). The addition of the Pan Tilt Module to the ESP 32 Cam brings out one of the most important aspects of the security and remote surveillance system. The camera is set to capture a video stream of the field, and farmers can visually inspect the fields remotely (28).

IoT Integration via Firebase

Firebase is a combination of Google's many services in the cloud, including instant messaging, user authentication, a real-time database, storage, hosting, and so on. This study primarily uses its user authentication and real-time database functions, supplemented by instant messaging, to complete the event notification and Short Message Service (SMS) notification functions (29). The integration with Firebase is the backbone of the system's communication. This cloud-based platform serves as the intermediary between the website interface and the NodeMCU. The farmer initiates tasks and commands, which Firebase receives in real time. The NodeMCU continuously monitors the Firebase database, fetching new tasks and executing them promptly (30).

Results

The testing of the IoT-based agricultural robot resulted in the following quantitative results. The performance of the robot was evaluated according to its effectiveness in monitoring environmental parameters, automating farming tasks, and providing real-time data visualizations as shown in Table 1, Figure 3 and Figure 4.

Environmental Monitoring

Table 1: Data Collected by Sensors during a 7-day Test Period

Parameter	Average Value	Minimum Value	Maximum value
Soil Moisture (%)	45	30	70
Air Temperature (°C)	28.5	24	33
Humidity (%)	65	50	80
CO2 Levels (ppm)	450	400	500
Soil pH	6.8	6.2	7.5

Automated Task Performance

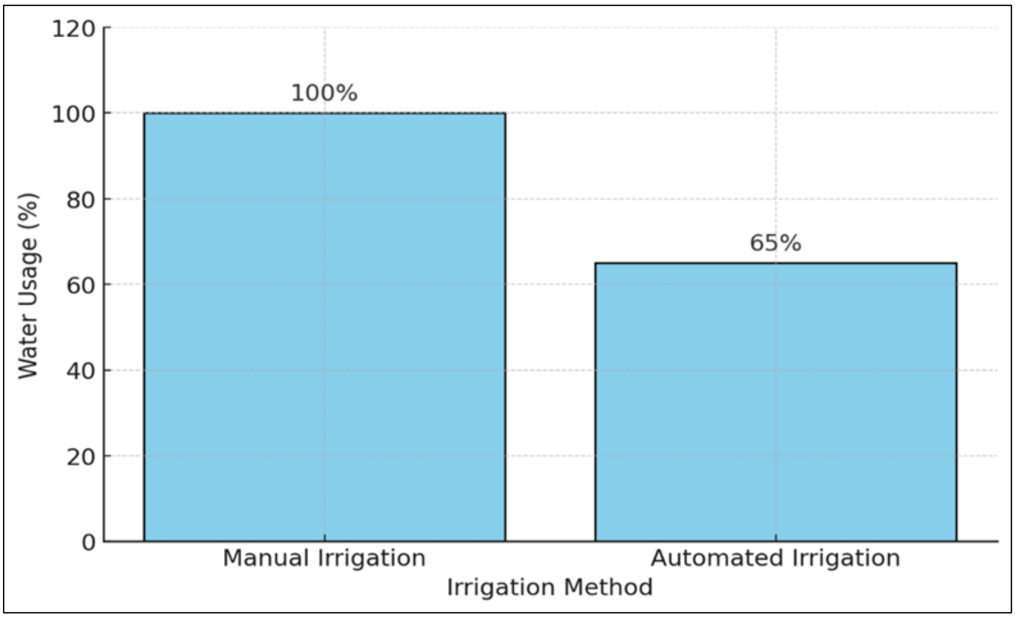

Figure 3: Comparison of Water Usage in Manual vs. Automated Irrigation

The IoT-enabled robot demonstrated a marked efficiency in water conservation by saving 35 percent more water compared to conventional irrigation methods. Real-time soil moisture monitoring and automatic irrigation are used to achieve this level of efficiency.

Crop Health Analysis

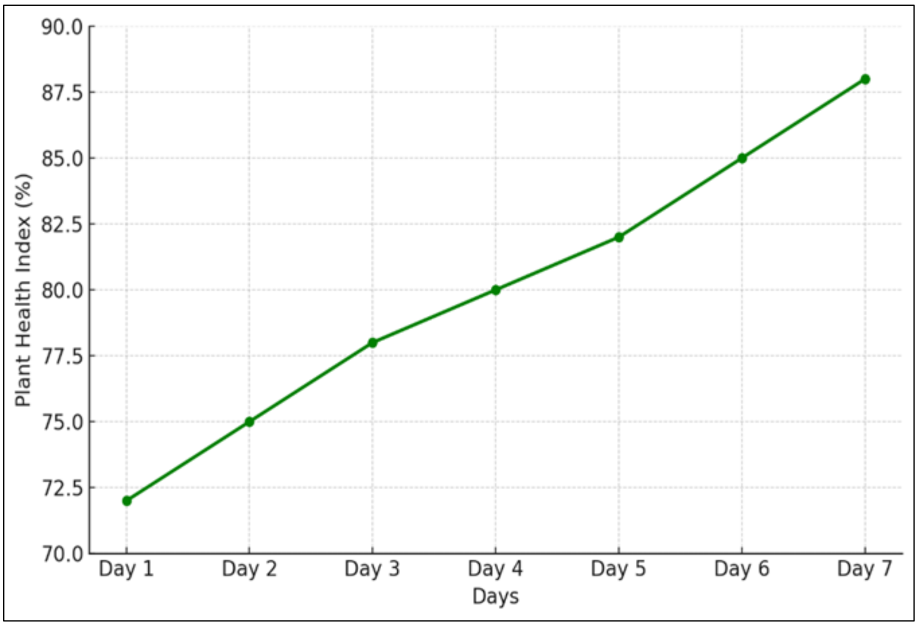

Figure 4: Plant Health Index Derived from Multispectral Imaging over a Week

The observations showed that the system's ability to early detect stress in 12% of plants was a key to keeping the crops healthy as a whole. The robot was able to identify plants with nutrient deficiencies or symptoms of disease onset, using real-time data from multispectral imaging. The early intervention allowed resources, such as fertilizers or pesticides, to be targeted onto affected regions of the field, rather than across the whole field. Through addressing these issues in a timely manner, the system did not only prevent possible yield loss but also prevented resource wastage and increased the sustainability of farming practices.

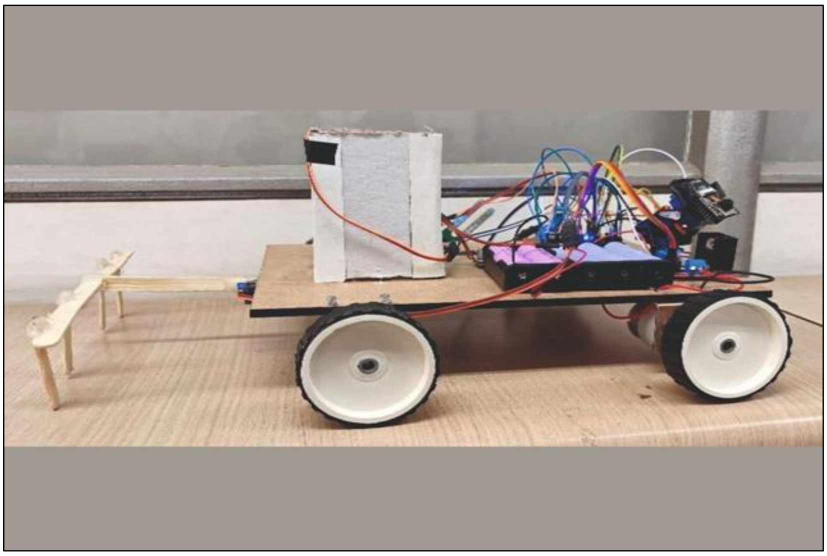

Figure 5: Side View of Robot

The agricultural robot that is integrated with the IoT is one of the significant tools of contemporary farming. This way the use of real time video streaming increases the operational efficiency of the robot and its decision making as well. The robot is embodied with high-resolution cameras and sensors that help the robot to capture accurate images of the fields as shown in the Figure 5.

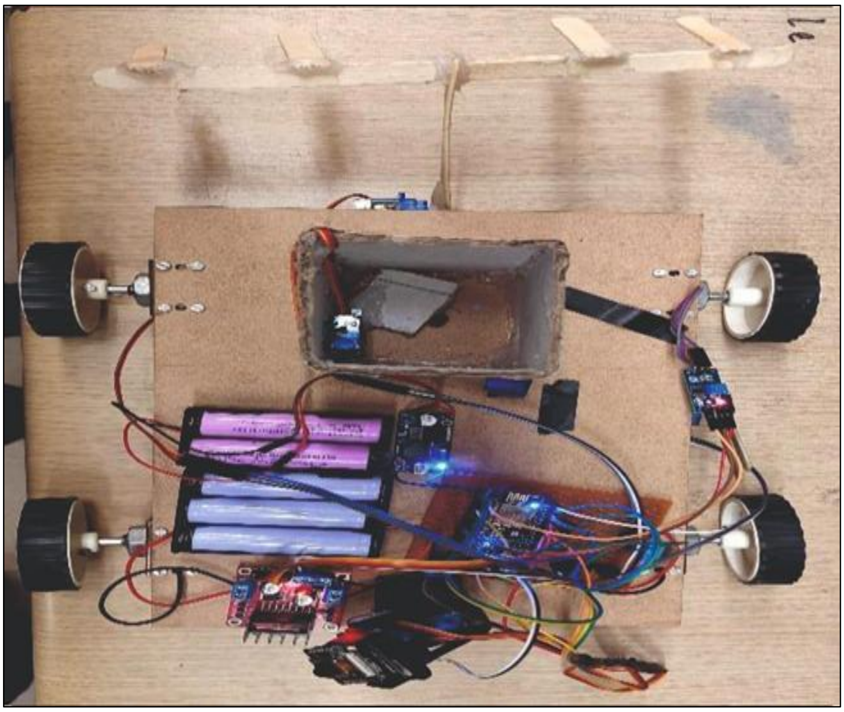

Figure 6: Top view of Robot

Figure 7: Robot and Live video

The live video feed gives as shown in Figure 6 the farmers a type of live control panel where they can control the plant production depending on the data given. The robot has motion capability and can stream live video, the live video to provide a real-time prospect of the agricultural environment that makes it easier for the farmer to get views of crops, monitor plant status, and examine for signs of trouble such as pests or diseases. With the help of AI and ML, the images are being processed. It is useful for pinpointing the particular sections that need attention; in addition, it is helpful for developing recommendations concerning the improvement of crop management as shown in Figure 7.

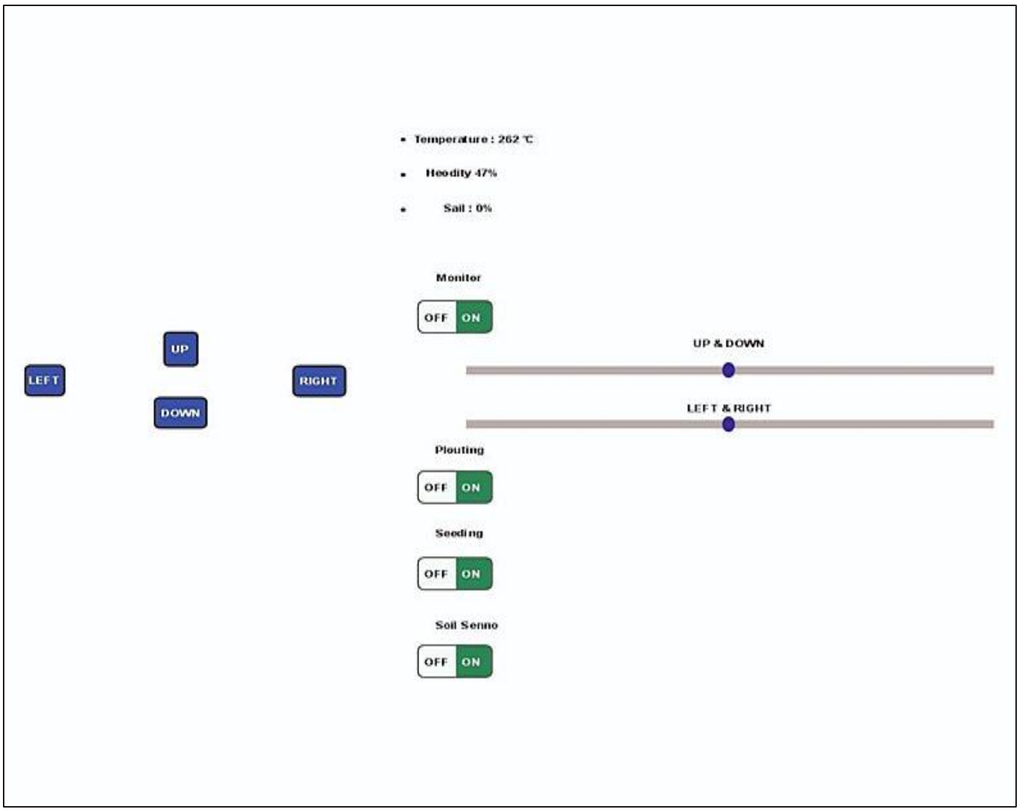

Figure 8: Quick and Prompt Management of the Crop

The physical attendance in the fields is not compulsory. It is especially advantageous in vast tracts of farmland where quick and prompt management is called for if the crop is to be saved from an unhealthy or poor yield as shown in Figure 8. The integration of the robot with the live video technology is a giant leap towards all round improvement of precision agriculture by encouraging farmers as shown in Figure 9. Proactive approach in farm management through use of live video for better production and productivity.

Figure 9: Real-time Data Base

Discussion

The development of IoT, AI, and robotics in agriculture brings to light fundamental changes in modern agricultural practices. A combination of these technologies creates precision agriculture systems that increase productivity and sustainability of farming. The Economic Development and Research Foundation (EDRF) proposed IoT-based agricultural robot shows in general how real-time data collection through sensors (soil moisture, temperature, humidity, etc.), In conjunction with AI-based decisions, it claims that farmers can improve their practices by making better data-driven choices that enhance production and yield. It utilizes an efficient strategy that focuses on saving water and fertilizers while reducing pollution. Additionally, processes such as irrigation and seeding that are labour-intensive are now fully automated, thus enhancing efficiency and reducing the burden posed by shortage of labor. Taking into account autonomous mobility and controlled seeding, robotics allows operations to be done with limited human involvement and increases the precision of farming activities. Automated tilling mechanisms tend to favor soil management and in turn complement studies that support mechanization of arable farming. AI-enabled robots designed to carry out targeted pest control have low requirements for chemicals and enhance environmental safety. However, there are barriers to this mass adoption. Initial investments and technological barriers act as a blockade, especially to smallholder farmers in developing areas, to the disadvantage of small-scale farmers. Infrastructural deficiencies such as poor internet and electricity further complicate the situation. These issues have to be addressed through efficient infrastructural investments and direct funding for agriculture. By increasing the degree of transparency and efficiency in agricultural supply chains, Blockchain technology helps in providing value. It ensures secure monitoring from the farm to the consumer, enhances food safety, and minimizes fraud. Systems of Smart Contracts on the blockchain have the ability to carry out automated processes such as crop loss insurance claims and cut down the supply chain by allowing producers to directly sell to consumers, thus making it easier for farmers. There are solutions to space limitations and food security problems posed by Vertical farming and CEA, which are useful in urbanization. These methods allow for the growth of crops through a controlled environment throughout the year and enable better management and less water usage along with lower pesticide application. These technologies have great promise but are beset with barriers, particularly for smallholder farmers due to financial costs and logistical factors. Government-subsidized equipment and community-based technological centers could serve to fill this gap. Using simple interfaces and maintenance will make the adoption of technology easier for farmers with minimal technological know-how. Fabrication of 5G systems could allow faster data transfer and increase the efficiency of agricultural robots, thus enhancing the reliability of the IoT system. However, 5G technology is not yet available in most places and investment is needed if a larger benefit is to be gained. The factors of cost, infrastructure, and accessibility have to be dealt with if the changes that IoT, AI and robotics can bring to agriculture are to be realized. It is suggested that more concerted efforts including governments, technology developers and other stakeholders are necessary for smart farming to achieve its objective for the enhancement of food security worldwide. The proposed IoT-based agricultural robot shows promise in enhancing farming practices but faces several limitations. Cost constraints arise from the high initial investment in hardware like multispectral cameras and LIDAR sensors, which can be prohibitive for smallholder farmers, especially in developing regions. Scalability challenges involve the need for advanced communication infrastructure to support larger farms, increasing complexity and costs. The environmental impact of electronic waste and the reduced effectiveness of solar power in low-sunlight areas are concerns. Real-world deployment challenges include reliance on internet connectivity and electricity, which may not be available in remote areas, and the complexity of use for farmers with limited technical knowledge. Field conditions, like extreme weather and uneven terrain, can affect the robot's durability. Data accuracy may be impacted by sensor wear or calibration issues. To address these limitations, solutions like cost reduction, enhanced training, localized energy solutions, improved durability, and scalability enhancements are essential. To address these limitations, some solutions to these are cost reduction, better training, local energy solutions, improved durability, and scalability improvements.

Conclusion

The real time tracking and monitoring of agricultural bots through IoT has a potential in shaping agro-business in the future. There are some benefits which can be stated when dealing with such systems, such as being efficient and productive, while adopting eco-friendly farming techniques. The greatest redeeming feature of IoT technology is the implementation of real time tracking and monitoring of agricultural bots while being controlled from a distance. This helps farmers to track the location, status, and activities of their bots in real time thus maximizing productivity and minimizing human labor and associated dangers to the employees. In addition, IoT systems help farmers in collecting and Analyzing data of the soil moisture content, temperature, humidity of the air and that of the crops hence making it possible to make decisions on irrigation, fertilizers, pesticides and management of pests. Real time tracking can help response to issues, take advantage of them and therefore lead to better crop yield with less wastage of resources. The use of tracking based on the IoT is also consistent with environmental and energy conservation since water and power will be used sparingly, thus good agricultural practices will be observed with little impact to the environment. There are, however, some constraints like the cost of installation, safety and confidentiality concerns, and the provision of reliable connectivity especially in isolated areas. Solving these problems needs integration between tenure and technology

Future Prospect

The next few years of IoT-based tracking and monitoring systems for agricultural activities showcases a lot more possibilities, as AI and ML technology improves the targeting and customization of crop treatments. Bots that improve themselves may come about, that utilize data in improving their operations. Blockchain technology has the potential to enhance the transparency of the food chain and as a result increase consumer safety and information. IoT systems will readily address climate change threats, promoting such agricultural practices as vertical farming and hydroponics. It is about everybody – farmers, researchers and tech partners that can make the food system more innovative and solve the food security problem. The forthcoming advancements will also feature 5G networks and edge computing to help reduce the time taken to transmit data, and nano-technology for small scale sensors that monitor and evaluate the health of the plants from the outset. It is likely that they would be welfare-free where only a few individuals would be required to operate the automated farms, whereas increasing barriers to food and demand for the marketplace IoT may strengthen logistics and distribution of the farm-to-table system. Such innovations are bound to revolutionize agriculture as they will enhance productivity, sustainability and effectiveness.

Abbreviations

IoT: Internet of Things, AI refers to Artificial Intelligence, ML: Machine Learning. IBM: International Business Machines Corporation, LPWAN: Low Power Wide Area Network, LoRaWAN: Long Range Wide Area Network. MQTT: Message Queuing Telemetry Transport, CEA: Controlled Environment Agriculture. 5G: 5th Generation, DHT-11: Digital Humidity and Temperature Sensor, SPI: Serial Peripheral Interface, GPIO: General-Purpose Input/Output, NodeMCU: Node Micro Controller Unit, DC: Direct Current, LIDAR: Light Detection and Ranging, CO2: Carbon Dioxide, pH/EC: Potential Hydrogen/Electrical Conductivity, ESP32: Espressif 32.

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Author Contributions

Nilkamal P. More. Supervised the study, validated the results, and contributed to manuscript writing. V.Venkataramanan conceptualized the study, designed the methodology, and conducted data analysis Mohammed Owaish Kumar assisted with data collection, curated the dataset, and contributed to reviewing the manuscript. Mohammed Saqlain Padaya contributed to data collection, performed preliminary data analysis, and helped draft sections of the manuscript. Fihaan Solanki assisted in data interpretation, provided critical manuscript revisions, and reviewed the final draft for accuracy. All authors approved the final version of the manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Ethics Approval

Ethical approval was not required for this study.

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