Harnessing the power of IoT: a survey of Internet of Things applications in greenhouse agriculture

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Published in:
2024 IEEE 30th International Conference on Telecommunications (ICT)

DOI:
10.1109/ICT62760.2024.10606131

Publication date:
2024

Document Version
Author accepted manuscript

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***Abstract*— The Internet of Things (IoT) technology is now widely used in virtually all industries, including agriculture, and is adopting IoT technology. Through their IoT technology, greenhouse agriculture has entered an era of precision farming like never before. This survey is made on the recent progress in greenhouse agriculture with IoT, and the architecture of IoT is illustrated further with its application in greenhouse agriculture. For instance, the chapter investigates various disciplines like Monitoring and Control Systems, Smart Irrigation Systems, Environmental Data Collection and Analysis, and Crop Health Monitoring. It should also be noted that the many advantages IoT brings to greenhouse farming in the way of increased yield and quality of crops, greater efficiency in the use of resources, and reductions in labor and operational costs are also taken into consideration. Not with these benefits, problems like information security and privacy, integration, and interoperability issues still exist. The last part of the discussion will be about the future vision: what changes can we expect in IoT-based greenhouse farming and what new trends are emerging. The survey offers essential lessons about the cost-effectiveness and sustainability of IoT in improving production and productivity in greenhouses.**

Keywords*— *Internet of Things (IoT), Greenhouse Agriculture, Precision Farming, Monitoring and Control Systems, Smart Irrigation Systems, Environmental Data Collection and Analysis, Crop Health Monitoring

I. INTRODUCTION

Greenhouse farming is a very resource-consuming farming method [1]. The growing environmental issues and the high demand for agricultural products have turned the production and use of resources into a primary concern for agriculture businesses. One of the greenhouse's main benefits is controlling and altering climate variables, creating a controlled and green atmosphere, which causes the production of goods of high quality, and simultaneously, the output is increased. Despite this, it requires advanced knowledge, and more often than not, it requires higher expenses than conventional farming [2].

The decision-making process becomes more intricate when aiming to maximize production while considering the prices and production costs associated with high-value crops [3]. The Internet of Things (IoT) is recognized as a crucial factor in revolutionizing the agriculture industry, enabling automation and data-driven methods at a reasonable expense [4].

The Internet of Things is a term used to denote the wireless connection of devices/computers to the Internet. It also encompasses other protocols and technologies, such as Bluetooth, near-field communication, and wireless communication [5]. These protocols allow direct communication between devices without needing human-to-human or human-to-computer interaction. Information is stored and processed and can be acted upon. In the future, this trend of wireless connection will be an integral part of automation and is likely to enable advanced applications through the collection of an immense amount of data from varied sources, with the use of intelligent technologies (sensors, devices, software) to provide new services across many sectors.

IoT is also defined as the internet-working of hardware, software, actuators, sensors, network connectivity, and access points embedded with electronics. These allow data collection and exchange between objects. The inclusion of IPv6 makes it possible to aggregate objects on the Internet and uniquely and universally identify them, regardless of existing protocols. It also provides end-to-end direct connectivity for any device, enabling even better monitoring of the real world at a low cost. Again, IoT is not specific to a single application domain but has considerable implications for the future and has been expanding rapidly in many market segments, including greenhouse agriculture.

According to Al-Fuqaha et al. [6], the Internet of Things is a worldwide network architecture that can self-configure. It effortlessly integrates virtual and physical objects into information networks by giving them identities, characteristics, and personalities through intelligent interfaces. Often, these things are an integral part of a smart environment or system. This concept is innovated from the conventional system of physical computation and digital simulation, reflecting a more general fusion of the digital and physical world. However, it is limited by the available technology.

IoT endeavors to proactively assimilate more information about the world and the environment around us, enabling greater visibility. It employs intelligent things to enable innovative applications and aims to create a more context-aware environment that increases the user's situational awareness. To fully understand the impact of the Internet of Things on greenhouse agriculture, one must first understand the traditional methods and be meticulous in determining precise problems that the IoT attempts to resolve [7]. Traditional greenhouse agriculture has been proven to have some significant limitations. One of these limitations is that a physical presence is required to perform any actions on the plants. When a farmer needs to monitor the condition of the crops, he must physically walk to each location and visually inspect for any problems. Physical attendance is inherently slow and time-consuming. However, the farmer does not influence the fluctuations in environmental conditions. It is often necessary to manually interfere in regulating light exposure for crops and regulating soil pH levels, which might result in inadequate efficiency [8]. Another factor to consider is obtaining access to the necessary data for these modifications, which may be challenging due to the inaccessibility of specific locations or the protracted data collection process.

Nevertheless, identifying such crop problems is undeniably a drawback of conventional greenhouse farming. Typically, the farmer becomes aware of the abnormality in the produce only after it has been destroyed. The process of upgrading is likely to incur significant costs, and despite the substantial investment, there is still a risk of losing the product. As a result, the Internet of Things (IoT) will significantly transform the methods used in greenhouse farming in response to these issues. The Internet of Things enables highly automated systems and remote monitoring to collect and store data in real-time environmental conditions [9]. An example of an application is a device that measures the soil's pH level. At that point, the gadget is implanted into the soil, and the data is transmitted to a computer that the farmer may conveniently access as required.

II. THE ARCHITECTURE OF THE INTERNET OF THINGS (IOT)

The architecture of the Internet of Things can be divided into three layers: perception, which deals with recognition, is the initial layer; network, which is accountable for the transmission and reception of data, is the intermediate layer; and application layer, specifically designed for agricultural applications, is the final layer [10].

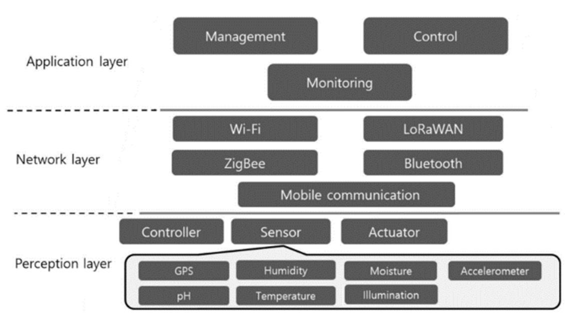

Fig 1 The Internet of Things (IoT) architecture consists of three main layers: the application layer, the network layer, and the perception layer.

The second layer of this level consists of sensor nodes strategically located in numerous locations, such as livestock, agricultural equipment, greenhouses, crops, and farms. These nodes are responsible for promptly detecting and gathering measurements. Data from the website is sent to the gateway over a Wireless Sensor Network (WSN), assisting with agriculture-related tasks, such as monitoring, control, surveillance, and self-contained machinery. The Internet of Things architecture consists of three main layers: the application layer, the network layer, and the perception layer as shown in Fig 1.

A. *The Perception Layer*

The core role of the perception layer in IoT is to give real lives and symbols to physical things like farms, crops, ranch animals, and the entire mother farming machinery [11]. The sensing element consists of various sensors, smart agricultural operators, Wireless Sensor Networks (WSNs, and other electronic components like Actuators, Controllers, and RFID Technology. For instance, these electrodes have led to recent agricultural advancement in the sector by constantly tracking these parameters. Temperature, humidity, wetness, pressure, pH, ultrasonication, and acceleration are some of the sensors used in my project [12]. The Internet of Things (IoT) is a sophisticated and integrated sensing technology that includes Wireless Sensor Networks , Near Field Communication (NFC), Radio Frequency Identification (RFID), Image Processing, and Global Positioning Systems (GPS) [13]. Wireless Sensor Networks have shown their value in many practical applications by introducing monitored systems' better temporal and spatial features. Integrating adaptable and autonomous (traits) in agricultural will become possible through this. A WSN (wireless sensor network) involved in IoT-based agriculture repeats the phrase: a network consisting of sensor nodes deployed in multiple areas to collect and process data relevant to various farming activities. Wireless Sensor Networks can send data across varied distances with minimum chances of wires through the uninterrupted transmission of digital signals to a central decision point [14]. It follows the sensory data collection route through the processing layer to the transmission one. The data is appropriated and collated into a database for data analytics [15].

B. *The Network Layer*

One of the fundamental components of computer networking is the network layer that ensures the effective routing and transmission of the data packets regardless of the proximity of the networks. The network layer is responsible for transmitting real-time data, feeding the application layer from the perception layer through telephony, LAN, and the Internet [16]. The transportation layer uses a microprocessor or microcontroller to transfer data from perception to the application layer, using various methods like IEEE-802.11, Bluetooth, Wi-Fi, 4G/5G, NFC, GSM, ZigBee, and GPRS. The network layer is responsible for data transmission from the perception to the application layers. Ultimately, it facilitates the transmission of control signals from the application to the perception layer to operate selected devices.

C. *The Application Layer*

The Internet of Things application layer, which uses data processed at the network layer, is the highest level of architecture [17]. It is a sophisticated processing device. Numerous intricate systems are included in this layer, including those that oversee and manage farms, plants, animals, and equipment, detect illnesses and infestations, provide early warnings, manage agricultural data, and operate autonomous machinery. Furthermore, the application layer primarily handles data management and analysis, system assessment, future trend projection, decision-making based on past data sets, and sending user suggestions. Therefore, by quickly correcting any agricultural issues and improving production efficiency—which will raise farmers' income—it is possible to decrease the harm.

III. Application of IoT in Greenhouse Agriculture

Traditionally, greenhouses have used soil moisture sensors to optimize irrigation scheduling and prevent waterlogging and/or drought, although these have been underutilized in many cases. IoT systems can utilize environmental data to calculate plant water needs and transpiration rates, considering the type of plant and its growth stage [18]. Water status can be measured, and appropriate actions can be taken using simple rule-based decision systems, more complicated algorithms, and plant-based sensors. Remote monitoring enables the evaluation of crop reactions, facilitating the improvement of irrigation programs. It can monitor and regulate the utilization of water by plants.

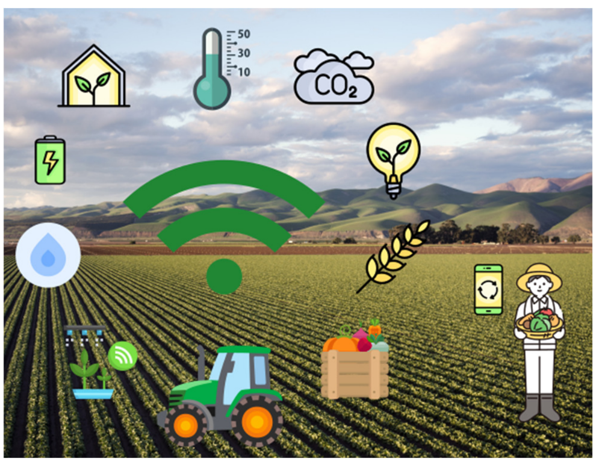

Fig. 2 Internet of Things in agriculture

Implementing Internet of Things technology in greenhouse agriculture entails monitoring and regulating environmental variables to guarantee the most favorable conditions for plant development as shown in Fig 2. The spectrum of control systems can vary from primary analog controllers that monitor single heating equipment to intricate systems that regulate the environment by utilizing data from various sensors. These systems employ calculated algorithms to make automated climate control decisions to restore the greenhouse to its target state when it deviates. IoT systems can still use said devices; however, the interconnectivity and automation of these devices separate them from existing automated systems. IoT devices can gather more accurate environmental data and control said devices more precisely and energy-efficiently.

A. Monitoring and Control Systems

Greenhouses are closed environments designed to provide optimum growing conditions for plants. As such, they rely highly on various equipment to control the internal environment in response to external conditions and plant needs. Greenhouse control systems are employed to manage a variety of internal greenhouse conditions. These include heating, cooling, ventilation, shading, carbon dioxide (CO2) injection, and lighting systems [19]. Traditionally, control systems have been implemented as stand-alone systems, each with its control unit. While these traditional systems have the benefit of simplicity, they are often inefficient and not cost-effective. Monitoring and Control Systems. The goal of any control system is to manipulate the environment in such a way as to bring about a desired change. An effective control system will do this based on knowledge of the system it is controlling.

Greenhouse agriculture involves quantitative measures of environmental or crop characteristics, such as ambient air temperature, soil pH, or plant growth rate, to indicate the status of the controlled thing. A slow growth rate may indicate inadequate light for plants. By manipulating a control on the light system, the system can try increasing the light level and observe the effect on the plant growth rate measure. This kind of system is known as a feedback control system and is quite advanced compared to many greenhouse control systems. Usually, the control system is an open loop, with the grower changing the environment and observing the effects on the crop. The problem with this method is that it is often difficult to determine whether a change has helped or hindered crop productivity, and changes can be made arbitrarily. Nevertheless, even with open-loop control, monitoring the crop and the environment is essential to determining the crop's success and the control system.

B. Smart Irrigation Systems

Smart irrigation systems in greenhouse agriculture also play a crucial part in water conservation. The smart irrigation system uses weather and soil moisture data from sources on the Internet, such as a weather station or a satellite link [20]. It collects the data from the integrated controllers and makes automatic irrigation adjustments to decrease water usage. Smart irrigation systems use collected data to determine plant transpiration rates, anticipate system run times, and assess water loss percentages. This technology is crucial in greenhouse agriculture, as precise watering affects growth rate and marketable yield for hydroponic plants, ensuring efficient and accurate irrigation. Overwatering can lead to poor root development, leaf and fruit disease (i.e., Botrytis, Pythium), and nutrient leaching while underwatering can lead to plant stress and loss in yield. The automatic adjustment of a smart irrigation system can prevent these problems and save water by applying the least amount for the most significant yield. This increase in water use efficiency benefits both the grower and the environment. A study states that smart irrigation systems use 30-80% less water than well-managed conventional scheduling. This same study simulated smart irrigation methods in California and estimated a potential water savings of 440,000-1,150,000 acre-ft/year, or 542 million to 1.4 million gallons per year for every 100 acres farmed.

C. Environmental Data Collection and Analysis

At the most superficial level, sensors are connected to a computer, which stores the data and produces a graphical output. More advanced systems are capable of analysis and decision-making. An IoT system developed at the University of Georgia, US, sought to create an environmental control system for the greenhouse production of fruit and vegetables [21]. The system used several off-the-shelf microcontrollers and wireless communication to interface various sensors and control devices at two research sites. Collecting data on temperature, light, and soil EC for various crops led to automated software control at a site, resulting in improved crop quality and a 24% reduction in energy consumption due to better utilization of a more energy-efficient cooling system. The simulation showed a potential 40% saving in heating energy due to tighter control of the night temperature set point, but this was not tested due to concerns about nighttime electricity costs at that location.

Environmental factors such as air temperature, humidity, soil temperature and moisture, light, and carbon dioxide levels that affect plant growth are fundamental to any agricultural endeavor. In simpler terms, they are the ingredients to the recipe for crop growth. For greenhouse crops, the indoor environment is the medium where the growers must provide the optimal combination of these ingredients to produce the best crop. Monitoring incoming solar radiation is also important in predicting plant growth and the energy needs of the greenhouse. With the many required monitoring devices, automating the collection of this data is highly desirable.

D. *Crop Health Monitoring*

An automated mosaic image capture and image transfer system was also developed in Japan to monitor rice plant growth using an unmanned tractor and a Zigbee wireless communication network as shown in Fig. 3 [22]. The system can schedule when to capture image data depending on the weather conditions. The images assess rice plant health by measuring the Normalized Difference Vegetation Index (NDVI).

Fig. 3 Assessment of Rice Plant Health Through Imagery

One such example is the monitoring of sugarcane to detect an outbreak of yellow-leaf disease using computer vision methods. A machine learning algorithm was used to classify images of sugarcane into those containing symptoms of the disease and those without. The algorithm achieved an accuracy of 90%. The images were captured using an IoT device consisting of a GPS-enabled smartphone and a custom-designed attachment to protect the camera from direct sunlight. This method eliminated the need for the researchers to revisit the location of the sugarcane for inspection, as the IoT devices could be left in the area and the images sent remotely. The device attachment and power supply were rugged and weatherproof, making it suitable for long-term deployment in the field.

Diseases and pests significantly impact the quality and quantity of agricultural produce. Traditional crop monitoring involves human visual inspection. A potential solution to this problem is to use computer vision methods to detect patches caused by diseases or pests automatically. IoT devices can then be instructed to apply targeted treatment to affected areas.

IV. Benefits of the Internet of Things in Greenhouse Agriculture

In a study conducted in the Netherlands, Wageningen UR Greenhouse Horticulture applied a wireless sensor network for an experiment to grow roses. The experiment was to grow the roses at two different temperatures. The goal was to determine if the roses could be stored for extended periods if grown at a higher temperature, even if this meant more energy would be required to develop them. The network consisted of 200 sensors measuring temperature, humidity, and leaf water potential. The network produced a reliable dataset that provided insight into the relationship between the growth of the roses and the factors influenced by temperature. This insight could have never been realized without the help of the sensors, and it allowed for conclusions to be made without speculation. A similar experimental setup using manual measurements would require much effort and be impractical. This experiment shows the potential benefits of IoT for microclimate management and how it can allow growers to make more informed decisions.

The greenhouse environment's increased crop yield and quality provide an ideal crop growth atmosphere. However, maintaining perfect conditions can be costly and time-consuming. Greenhouse operations are based a lot of the time on grower experience and manual adjustments and decisions. Implementing IoT can significantly improve both the yield and quality of crops grown. Sensors can measure CO2, water, light intensity, temperature, humidity, and ranges [17]. Micro-climate management can be established and maintained for each crop species. If a crop is more valuable, more can be invested to provide the perfect conditions for growing. The result of improved monitoring and decision-making will be crops of more consistent quality.

A. *Increased Crop Yield and Quality*

Smart technology has revolutionized farming by reducing the need for farmers to overcompensate with heating and cooling systems to maintain optimal crop growth conditions, thereby reducing the output of excessive energy. Smart systems could automate the control of the greenhouse environment by using real-time data from temperature, humidity, and light sensors to change heating, cooling, and shading systems to maintain optimal conditions for crop growth. Responding directly to environmental changes would help reduce energy consumption in greenhouses and lower the overhead costs for growers. Delphi, a company based in the Netherlands, has already developed such a system, which created a climate computer that controls heating, cooling, CO2 dosing, and venting, specifically for greenhouse environments. This system has decreased energy usage by more than 25% and has a proven track record of increasing fruit and vegetable crop quality and yield. Should smart systems such as these be mass-produced and implemented in greenhouses, a significant improvement in quality and yield would be achieved from increased energy efficiency [23].

Protected environment agriculture is a method used in farming to protect crops from undesirable conditions such as inclement weather, pests, and diseases. It also helps to provide an optimal environment to maximize crop yield. Greenhouses are a typical example of protected environment agriculture, providing an enclosed space with a controlled environment to grow crops. Greenhouse agriculture allows farmers to have greater control over crops; however, it often requires a large amount of input in the form of energy and resources to regulate the environment within the greenhouse, where the IoT can play a significant role in changing how greenhouse agriculture is approached and improving the efficiency and productivity of greenhouses.

B. Resource Efficiency and Sustainability

The work on precision agriculture and resource sustainability seems to contrast with the IoT application in agriculture, which tends to increase crop yield through more efficient utilization of resources. With IoT, it is possible to create smart systems that can manage precise resources and increase yield, which contradicts the common understanding that more products can only be achieved by more resource use. The resource constraints in the form of availability and cost are also a concern for reaching the desired crop yield increase. IoT can play a role in resource management as production using the right resources can be more expensive than the resources themselves. The advancement of IoT, particularly in autonomous systems, can lead to the development of a more efficient and superior substitute system, which can replace the old system with improved output [24].

In an agricultural context, resource sustainability is more related to the efficient use of inputs such as water, labor, energy, and fertilizer, which leads to economic sustainability. It is essential to increase the efficiency of input use considering the output. Hence, agriculture can contribute to achieving national economic growth and sustain its existence. Ideally, it will be possible to improve economic value and natural resource sustainability simultaneously. However, a trade-off arises when more efficient input use (resulting in lower input use per product) leads to less employment and less income for the resource owner. Precision agriculture is a method to enhance resource efficiency by managing field variability. It involves using tools to measure variations and apply the correct treatment at the right time. In advanced nations, satellites or UAVs monitor the field, allowing for more accurate and timely treatment.

C. Reduction in Labor and Operational Costs

Automating the management and monitoring of a greenhouse will likely lead to a decrease in the demand for manual labor. Sensors can detect environmental changes, and settings can be adjusted automatically. For example, an optimal plant-growing setting involves monitoring the soil moisture for each plant and changing the watering schedule accordingly. A sensor can detect the moisture content in the soil, thereby ensuring precise management of water resources. The system can be completely automated, collecting data and adapting watering schedules without human involvement. It is particularly advantageous when connected to an Internet-based weather forecasting system, as it can conserve water and effort by adjusting plant watering schedules in anticipation of rain. A user interface is often developed to enable remote monitoring and control of IoT devices, allowing farmers to manage their crops without being on-site. External services can sometimes be hired to manage and monitor crops using data collected from IoT devices on the customer's site [25].

V. CHALLENGES AND FUTURE PERSPECTIVES

Data security and privacy concerns with modern-day technology are rapidly increasing, and efforts for future sustainability are becoming increasingly prevalent. IoT technology is expected to become a viable substitute for current technologies in greenhouse agriculture. However, concerns about data imperceptibility and privacy uncertainty raise questions about the success of implementing IoT in greenhouse agriculture, as it is uncertain where private data is stored and who can access it [26]. An experiment on IoT technology for a smart irrigation system showed the potential benefits of using sensors to monitor soil moisture. However, the experiment used general Internet resources to acquire cloud storage and servers, and only basic security measures were taken. It took less than 24 hours to breach the system during a dummy cyber-attack. Such data security and privacy issues can significantly hinder the development of IoT technology for greenhouse agriculture as it may lead to industry reluctance to utilize IoT. This means that for the future of IoT in greenhouse agriculture to be successful, there must be a clear incentive or mandate on how IoT technology can be developed and implemented while maintaining data security and the privacy of the end users.

A. Data Security and Privacy Concerns

Sensitive data exchanged and stored in a cloud environment can be at risk due to the use of internet connections, making it easier for malicious intents to access it. Data breaches can take many forms, such as loss of data integrity, where the data is altered and is no longer valid; loss of data confidentiality, where hackers steal the data for their gain or render it inaccessible; and service availability issues, where the data is intact but the service to retrieve it is sabotaged [27]. These can be significant problems, especially regarding critical data for greenhouse farming, as they can impact decision-making and result in losses. Measures and countermeasures are usually costly and cannot guarantee zero risk of data breaches. For example, employing someone solely responsible for managing and monitoring data traffic requires extensive knowledge of IT and cybersecurity, but even then, it is not guaranteed. The best practice is still to avoid using internet connections for IoT implementation. However, if necessary, the best choice is to use cost-effective encryption methods and to avoid storing sensitive data whenever possible.

B. Integration and Interoperability Issues

Many potential environmental and productivity gains can be made from using IoT. However, several significant barriers are preventing widespread adoption. One of the most significant issues is the lack of interoperability between different systems and devices. The current obstacles in developing IoT platforms often hinder farmers from efficiently utilizing different IoT technologies, including water and fertilizer dosing systems and climate control systems, which are essential for automating greenhouse operations [28]. It impedes the attainment of potential agronomic benefits, as various systems must work together to obtain the desired outcomes. Interoperability difficulties can potentially trap farmers in technologies that may become obsolete. As a result, farmers may be left with an outdated and irreparable asset incompatible with more advanced technologies. These issues are recognized by industry, and a great deal of research is currently going into developing IoT standards and a common platform from which all companies can work. Once the previously discussed issues have been addressed, and there is a high level of IoT system integration onto farms, there is likely to be a fundamental shift in how agricultural research and extension is conducted. In the current context, agricultural scientists often develop new technologies and practices to increase productivity and environmental sustainability. These are then taught to farmers who, it is hoped, will adopt the new technologies. The adoption rates are often low, as farmers face many barriers to understanding and implementing new practices. With smart connected devices, it will become possible to conduct research that provides recommendations directly to the control systems, which will then implement the treatments automatically. The outcomes can then be compared with the existing practices, and it will be much easier to determine the cost benefits and environmental impacts of adopting the new practices. This type of research will be highly appealing to the industry as it will provide clear evidence of the profitability and sustainability of new practices.

C. Advancements and Future Trends in IoT for Greenhouse Agriculture

With rapid technological advancements, IoT for greenhouse agriculture is also expected to grow. IoT-based systems for greenhouse agriculture are currently mere automatons that make the system work without human intervention. These systems are expected to become decision-making support systems capable of providing the correct information to stakeholders at the right time. For the decision to be perceived as correct, it is suggested that IoT-based systems consider expert knowledge and results extracted from evidence-based research in agriculture. Modern IoT systems are also expected to target multiple levels of automation, especially in crop and environment sensing; perception-based decision-making capability is likely to aid in better yield of crops, and the quality of such decisions can be evaluated based on performance indicators. The current aim is to convert greenhouse agriculture into a wholly contained system, employing sophisticated technology to guarantee a regulated environment for the cultivation of crops. From a materials and energy perspective, it is possible almost to scale agriculture to a cellular level, creating and individually packaging the perfect environment for each crop. Reducing the scale of agriculture will reduce biological diversity and access to wild crops but may increase the overall quality and yield of crops grown. IoT will be essential in this transition, and an adaptable decision-making support system will be necessary to see when products exist; technologies such as RFID/MEMS for individually tagged food products will strongly impact agriculture [29].

VI. CONCLUSION

IoT is commonly used to monitor environmental conditions, greenhouses, livestock, irrigation systems, and soil. The application of communication technologies in Internet of Things-based agriculture is examined, including Wi-Fi, LoRaWAN, Bluetooth, ZigBee, and mobile communication. By choosing sensors and networks based on transmission range, power consumption, and cost while taking the working environment into consideration, farmers can achieve high efficiency and cheap expenses. IoT devices need to be secure in inclement weather and have reliable network and data security. By lowering labor costs and input requirements, IoT is anticipated to improve quality and productivity in agriculture while also addressing current issues and boosting agricultural profitability. Nonetheless, all agricultural management requires a technology that incorporates Internet of Things (IoT) capabilities, and local networks must prevent network conflicts.

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