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Smart Agriculture in the Digital Age: A Comprehensive IoT-Driven Greenhouse Monitoring System

A. Simo, S. Dzitac, A. Duţu, I. Pandelica

Attila Simo[1*], Simona Dzitac[2], Amalia Duţu[3], Ionuţ Pandelica[4]
[1*]Politehnica University Timişoara, Timişoara 300223, Romania
Corresponding author: attila.simo@upt.ro
[2]University of Oradea, Oradea 410087, Romania
[3]National University of Science and Technology Politehnica Bucharest, Romania
[4]Bucharest University of Economic Studies, Faculty of International Economic Relations, Romania

Abstract

The integration of Internet of Things (IoT) technologies in agriculture has emerged as a transformative force, revolutionizing traditional farming practices and driving efficiency and sustainability. This paper presents the development and implementation of a cost-effective greenhouse monitoring system utilizing LoRaWAN technology for data communication. The system's design, deployment, and performance are discussed in detail. Key components include an array of sensors for monitoring environmental parameters and LoRaWAN for long-range, low-power communication. The low-cost nature of the system challenges the notion that advanced agricultural technology is prohibitively expensive, making it accessible to farmers of varying scales. The system's affordability and real-time data accessibility make it a valuable tool for precision agriculture, contributing to improved crop yields and resource management.

Keywords: Smart Agriculture, Internet of Things, LoRa, Digitization.

1 Introduction

In recent decades, technological advances have generated significant transformations in a variety of industries, and agriculture is no exception. The concept of smart agriculture has come to the fore in response to the increasingly complex challenges involved in food production in a world characterized by population growth, climate change and the need for efficient management of natural resources. The integration of technology into the agricultural sector is being pursued to enhance both the quantity and quality of crops.

Smart agriculture is defined by the use of technological innovations such as big data analysis, the Internet of Things (IoT) and Artificial Intelligence to revolutionize and optimize the entire agricultural production chain. Smart agriculture can be defined as an agricultural management model based on the integration of advanced technologies into traditional production processes. This approach focuses on increasing efficiency and productivity, minimizing risks and sustainable use of resources. Using Internet-connected devices and sensors, as well as advanced analytics algorithms, smart agriculture enables real-time monitoring of field conditions, optimization of irrigation, and precise application of fertilizers and pesticides.

One approach to modernizing agriculture involves integrating traditional agricultural practices with innovative technologies such as the Internet of Things (IoT) and wireless sensor networks. The wireless sensor network is responsible for collecting data from a diverse range of sensors and transmitting it to the primary server through a wireless protocol. Several supplementary factors exert a significant impact on productivity. Throughout the cultivation process, the crop is susceptible to predation by diverse wildlife species and avian populations, alongside the presence of insects and other detrimental organisms. However, the implementation of suitable insecticides and pesticides can effectively mitigate these challenges. The erratic nature of monsoon precipitation is contributing to a reduction in agricultural yield, which, in conjunction with water scarcity and excessive utilization, poses a potential hazard.

The term "smart agriculture" remains unfamiliar to a significant portion of farmers [1]. Examples of technologies commonly employed in agricultural settings include precision irrigation [2] and precise plant nutrition [3], as well as climate management and control in greenhouses [4] [5]. All of these components operate in conjunction with specialized software to supervise and control a farm or greenhouse with the objective of optimizing its productivity. Precision agriculture employs Global Positioning System (GPS) technology to generate comprehensive field maps, monitor the whereabouts of equipment, and accurately administer fertilizers, pesticides, and seeds. This practice mitigates the squandering of resources and improves agricultural productivity [6]. Satellite-based remote sensing technology facilitates the acquisition of high-resolution imagery pertaining to agricultural fields, thereby enabling farmers to effectively monitor the health of their crops, evaluate water stress levels, and identify occurrences of disease outbreaks [7]. Smart irrigation systems employ a combination of sensors, weather forecasts, and soil moisture data in order to enhance the efficiency of water distribution. The aforementioned practices contribute to the conservation of water, the prevention of excessive irrigation, and the preservation of soil health [8]. Unmanned aerial vehicles (UAVs) outfitted with advanced camera systems and multispectral sensors offer the capability to capture high-resolution imagery and collect data for the purposes of crop monitoring, yield estimation, and pest detection [9]. Internet of Things (IoT) devices, such as soil moisture sensors, weather stations, and livestock wearables, facilitate the collection of real-time data pertaining to environmental conditions. This data acquisition capability empowers individuals to make informed decisions regarding irrigation, fertilization, and livestock management [10].

Agriculture plays a pivotal role in human civilization as it serves as the primary means of sustenance and exerts significant impact on the economy. Farmers continue to employ traditional agricultural techniques that have been passed down through generations, leading to a diminished output of crops. In recent years, there has been significant research and investigation into the integration of different technologies in the field of smart agriculture. The integration of contemporary scientific and techno-logical advancements is imperative for optimizing productivity. It is foreseeable that the implementation of IoT technology in agriculture will result in a reasonable in-crease in productivity. This can be achieved through the monitoring of various factors such as soil quality [11], temperature and humidity levels, precipitation levels [12], fertilizer effectiveness, water tank capacity, and theft detection [13].

The agricultural industry is currently undergoing a fourth revolution, commonly referred to as "Farming 4.0" or “Agriculture 4.0”, due to the integration of information and communication technologies (ICTs) in preparation for the forthcoming era of agriculture [14]. In recent years, there has been a notable increase in the number of studies, projects, and literature focused on smart agriculture, resulting in the dissemination of knowledge and information.

The concept of a smart greenhouse pertains to the facilitation of necessary modifications and reorientation of agricultural systems to effectively sustain their development and ensure food security amidst the challenges posed by climate change [15]. A smart greenhouse is a technological approach that facilitates the management of necessary interventions to modify and maintain the environmental conditions. The policy aims to accomplish three primary objectives: fostering a long-term and environmentally responsible growth in agricultural output, enhancing the ability to withstand the

impacts of climate change, and reducing greenhouse gas emissions to the greatest extent feasible. The smart greenhouse holds considerable importance in the World Food Organization's strategic objectives pertaining to enhancing resource mobilization and crop productivity. The initiative is in accordance with the food vision of the Food and Agriculture Organization (FAO) and supports the organization's objective of enhancing the productivity and sustainability of agriculture [16]. The popularity of the Internet of Things (IoT) is growing steadily as a method of inter-connecting diverse devices and gathering data. The Internet of Things (IoT) is employed in conjunction with its associated frameworks to effectively manage and engage with data and information. Internet of Things (IoT) agricultural systems find application in diverse domains such as irrigation management, soil management, precision agriculture, and intelligent farming. This technological advancement has enabled farmers to increase their profitability by effectively protecting crops from pest infestations during the early stages of detection [17]. The objective is to effectively steer the field of agriculture towards achieving higher levels of production at reduced expenses, while simultaneously improving the overall quality of output, by means of gathering and utilizing accurate and specific information. For example, the implementation of remote sensors in agricultural fields provides farmers with precise cartographic representations of the terrain and the available resources within a given area [18]. Moreover, it possesses the capability to forecast forthcoming weather pat-terns through the assessment of variables such as soil temperature and humidity. The implementation of Internet of Things (IoT) in agriculture facilitates the ability to make more informed assessments regarding agricultural productivity. Furthermore, the collection and analysis of data play a crucial role in the monitoring of agricultural pests and the accurate determination of pesticide quantities required to prevent their inappropriate usage [19]. The application of comparable pragmatic and logical methodologies can be employed in the collection and analysis of data pertaining to irrigation water. The monitored parameters of intelligent agricultural systems exhibited variability across different studies. As per the findings of the authors in reference [20], a significant portion of the endeavors employed sensors for the purpose of monitoring variables such as temperature, humidity, soil moisture, and light intensity. The thermal conditions of the soil exert a substantial impact on the quantity of agricultural yield. Changes in soil temperature have a significant impact on both soil moisture levels and nutrient uptake. Furthermore, the utilization of air temperature measurements can serve as a valuable means for monitoring the environmental conditions of crops cultivated in both open fields and greenhouses. The detection and measurement of relative humidity levels can be facilitated through the utilization of various sensors, including the air humidity sensor, soil humidity sensor, and relative humidity sensor. Humidity exerts diverse influences, both direct and indirect, on plant leaf growth, pollination, and photosynthesis. Regarding soil moisture, it is employed in the assessment of soil's water content and quality. The relationship between the resistance of the soil moisture sensor and the moisture content in the soil is inversely correlated. This correlation plays a crucial role in determining the growth rate of plants. The consideration of soil moisture content is integral to the management of water resources and implementation of relevant automated protocols across the entire field. The intensity of light directly influences the process of photosynthesis, thereby exerting an impact on the growth of agricultural crops. Furthermore, the measurement of pH is essential in the context of irrigation practices, as it aids in the accurate assessment of the nutrient composition of the soil. Moreover, the velocity of wind and the quantity of precipitation are commonly employed as variables in the regulation of water flow and the prediction of precipitation likelihood.
Despite the potential benefits of IoT devices in providing valuable information on various physical aspects to enhance cultivation techniques and crop productivity in agriculture, there are still several challenges and limitations that IoT-based agricultural systems face. The authors of [21] have identified a series of significant challenges that are associated with the implementation of smart agriculture applications. The challenges have been categorized into distinct groups based on their respective characteristics, as depicted in Figure 1.

Smart agriculture, while promising numerous benefits, also faces several concerns and challenges that need to be addressed for its widespread adoption and sustainable development. Some of the key concerns in the field of smart agriculture: data security and privacy [22], cost of technology adoption [23], data interoperability, reliability and connectivity [24] [25] [26], energy efficiency [27], environ-

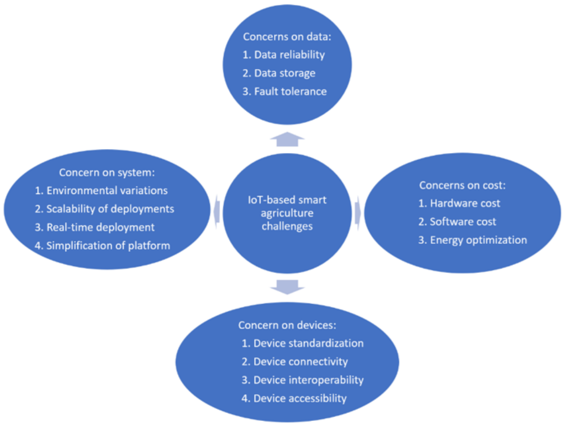

Figure 1: Categories of challenges in smart agriculture applications based on IoT

mental impact [28], regulatory and legal issues, scalability and standardization [29] [30]. Our research collective has been dealing with this problem for some time, our concerns being more and more directed towards small farmers, basically in the western part of Romania [31][32].
This paper makes a significant contribution to the development of smart green-houses by introducing a cost-effective, multisensory IoT monitoring solution. This solution is now enabled by LoRaWAN data transmission, primarily because some of the greenhouses are situated far away from the offices. Initially, in [31] a first version of the device was presented, that transmitted the recorded data via WiFi technology. As the project continued to expand and the interest of the participants increased, a need arose for a device that could transmit data over large geographical area with low energy consumption. With the aid of this innovative solution, we can effectively monitor key environmental parameters, leading to enhanced greenhouse climate control. Furthermore, we can keep a close watch on the electrical energy consumption of greenhouse equipment, thereby enabling us to implement energy-saving measures and reduce overall energy usage within the greenhouse.

2 Solution Architecture

A new architecture (Fig. 2) compared to the one presented in [31] was designed, in the sense that everything was adopted for the recorded data to be transmitted over long distances, using LoRaWAN. We are talking about 7 greenhouses located on an area of 3.64 km^2. The collected data must be sent from each greenhouse to the offices where the data is analyzed, and decisions are made.

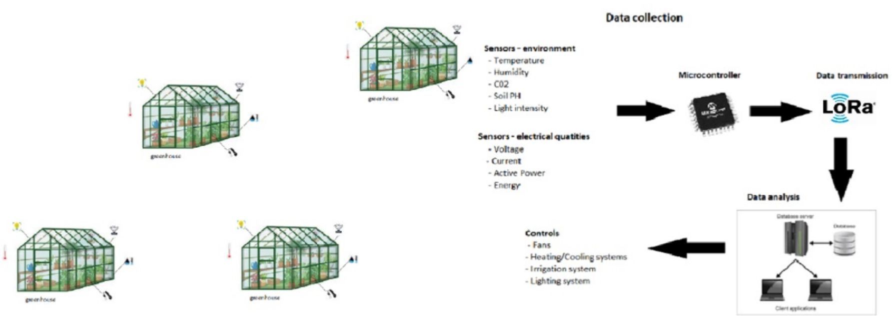

Figure 2: Solution architecture

2.1 LoRaWAN Network Deployment

The successful deployment of a LoRaWAN over a large geographical area (3.64 km^2) is a crucial element in realizing the full potential of IoT applications. This part of the paper details the intricacies of deploying a LoRa network infrastructure to cover a vast and diverse study area, emphasizing the technical considerations, methodologies, and challenges encountered during this phase of the project. The deployment process commenced with an exhaustive site survey and planning stage. Our objective was to identify strategic locations for LoRaWAN gateways that would maximize network coverage while considering environmental and logistical factors. Geographic Information System (GIS) data played a vital role in guiding our placement decisions, taking into account elevation, terrain, and potential sources of interference. We installed four LoRaWAN gateways at predetermined locations based on the findings from the site survey. The gateways were strategically placed on elevated structures, utility poles, and building rooftops, to maximize their line-of-sight range. The number of gateways deployed was determined by careful coverage analysis, and we ensured uniform distribution across the geographical area. Kerlink Wirnet Station Gateways (868 MHz Frequency Band) were used for network development, registered on on-premises The Things Network (TTN) network server.
Selecting the appropriate antennas for the gateways was a critical consideration. We evaluated various antenna types, considering factors such as gain, beamwidth, and polarization, to optimize signal propagation. Antenna configurations were fine-tuned to align with the network's specific coverage objectives, ensuring minimal signal attenuation and interference. To connect the gateways to the central network server, we established reliable backhaul connections. The choice of backhaul technology varied based on the availability of infrastructure at each gateway location (Ethernet, GSM). A dedicated LoRaWAN network server was established, on-site, to efficiently manage and process data from multiple gateways. This server was designed for scalability, accommodating the potential growth of the network over time. End-devices, comprising a diverse range of IoT devices, were registered with the Lo-RaWAN network. Each device was configured with the necessary session keys, ensuring secure and authenticated communication. A comprehensive testing regime was undertaken to validate network coverage, signal strength, and performance.

3 Monitoring Devices Development

The goal of this research project was from the very beginning the development of a multisensory device, at an affordable price for any farmer who wants to adopt new technologies in their current activities. The first version of this device, presented in [31] offered a solution for this problem. In [31], a multisensory device was presented with the help of which very good results were obtained. Later, there were requests that raised the issue that the data collected in the greenhouses should be sent over long distances. In many cases these greenhouses extend over large geographical areas, and in this areas is no wired Internet connection, and WiFi technology can only cover the area with a very high density of base stations, therefore the costs are very high.

3.1 Multisensory monitoring device

The primary objective of this device is to offer real-time data while simultaneously generating a historical record of data. This functionality aims to assist farmers in making informed decisions concerning the growth of plants within greenhouses, optimizing the timing of interventions and actions. The device is capable of monitoring the subsequent parameters: temperature, humidity, Carbon Dioxide, light intensity, pH.
In contrast to the device described in [31], the sensors remained unchanged due to the favorable outcomes achieved:

- Soil pH Sensor (Fig. 3a);
- BH1750 Ambient Light Sensor (Fig. 3b);

- SHT31 Humidity Temperature Sensor (Fig. 3c);
- SHT31 Humidity Temperature Sensor (Fig. 3c);

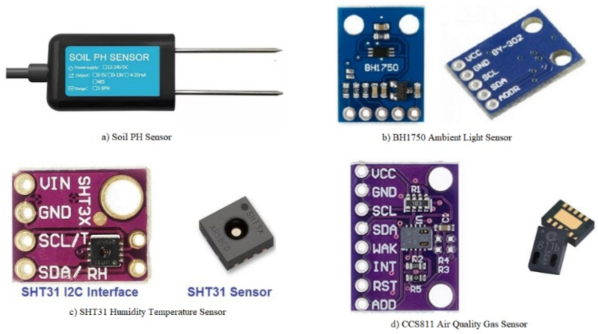

Figure 3: Sensors – environment monitoring device

A significant modification was implemented on the development board (controlled by an AT-mega328P microcontroller), wherein the ESP8622 was replaced with a Lo-RaWAN Shield

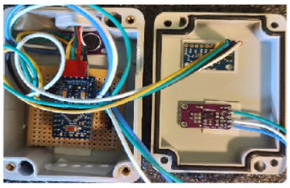

Figure 4: Environment monitoring device – prototype

The device acquires data from all sensors at regular intervals of 13 minutes. Subsequently, it compiles the gathered data into a package and communicates it to the network server via the LoRa communication module. This transmission occurs once every 15 minutes. Following the established protocols, the data is transmitted to the application server (inflaxDB), where it may be effectively viewed and subjected to analysis through a user-friendly interface.
The monitoring device from the perspective of electrical parameters monitoring has not undergone changes compared to those presented in [31]. The following parameters are monitored: electrical voltage, electrical current, electrical active power, electrical energy. This is done using components:

- ZMPT101B AC Voltage Sensor Module
- SCT-013-030 Non-invasive AC Current Sensor

This device (Fig. 5), akin to the environment monitoring device, is also constructed around a development board including an ATmega328P microprocessor. The At-mega328P microcontroller is tasked with the acquisition of data from the sensors and subsequent processing of the data. Subsequently, the data is transmitted to a LoRa Shield, a module that assumes the responsibility of delivering the data to a data server for the purpose of analysis.

4 Results

In the first phase, the multisensory solution was tested in laboratory conditions. The results being encouraging, as a next step the device was mounted on a farm where it was tested in real conditions. It is important to note that our objective was to create a comprehensive monitoring solution that caters to the requirements of small-scale farmers. This solution focuses on digitizing data pertaining to greenhouse operations on their farms, with the aim of enhancing efficiency in terms of both production and electricity usage. The collected data are deemed satisfactory since the devices function as intended,

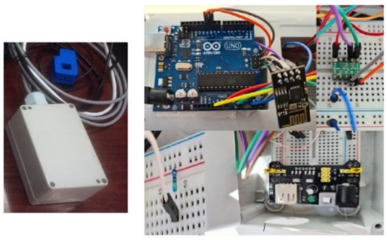

Figure 5: Electrical quantities monitoring device

providing the requisite data for subsequent actions. When examining the domain of agriculture, it becomes apparent that a crucial requirement for farmers is the ability to trans-fer acquired data over long distances while minimizing electrical energy use. The device described in [31] was utilized to meet the specified requirements, with the incorporation of LoRA communication technology.
The data recorded and transmitted about the electrical parameters are presented in figures 6-9. The consumption pattern and voltage variations can be observed during the presented period (22 h), 14 June 2023.

Figure 6: Electrical voltage

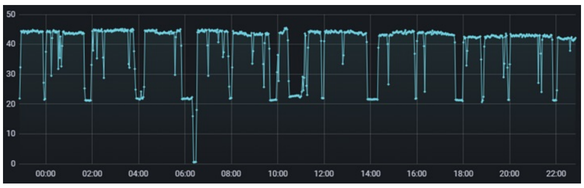

Figure 7: Electrical current

The data collected by environmental sensors can be seen on figures 10-12, for a period of 5 days.

Based on the recorded measurements (fig. 10), the soil's pH falls within the range of 6.8-5.4. The graph indicates that on June 15, an intervention was conducted on the pH levels using specialized solutions with the objective of reducing its value. The graphs illustrate that the temperature exhibits its minimum value during the night hours, while indicating the possibility of an increase over the course of the day. As the ambient temperature rises, there is a corresponding increase in humidity levels, resulting in a greater need for operation for fans during this time to facilitate the air circulation. The act of applying a fine mist of water onto the flowers serves to regulate the relative humidity within a range of 60 to 70 percent. Based on the recorded measurements spanning a duration of five days, the temperatures observed fall within the range of 22 to 30 degrees Celsius. Additionally, the humidity values during this period range from 54% to 72% (see Figure 11). The concentration of carbon dioxide (CO_2) falls within the range of 800 to 1400 parts per million (ppm), as indicated by the measurements presented in Figure 12.
The cost of the devices has decreased, with the LoRa Shield being less expensive than the ESP8266; this is even though there have been significant alterations made to the communications side. However, it is important to note that in order to construct a LoRaWAN network, a significant financial investment is required; despite this, the venture is more financially rewarding than the construction of a WiFi network. By directing our attention solely to the value of the individual components, specifically Table 1 and Table 2, it becomes apparent that the overall investment is relatively modest, yet still produces desirable results.

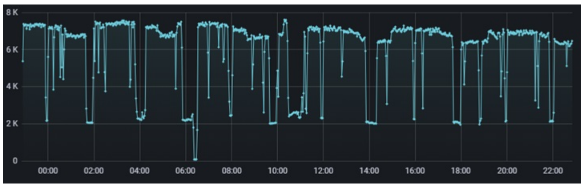

Figure 8: Electrical active power

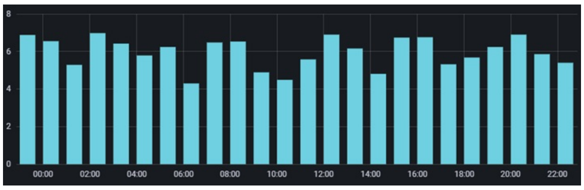

Figure 9: Electrical energy consumption

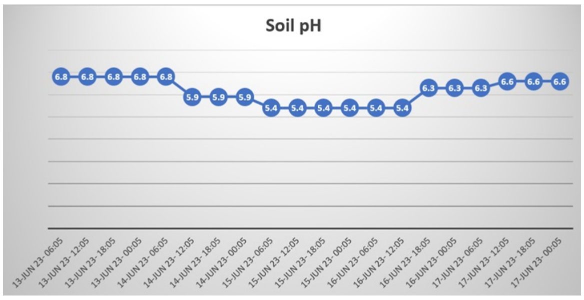

Figure 10: Soil pH measurements

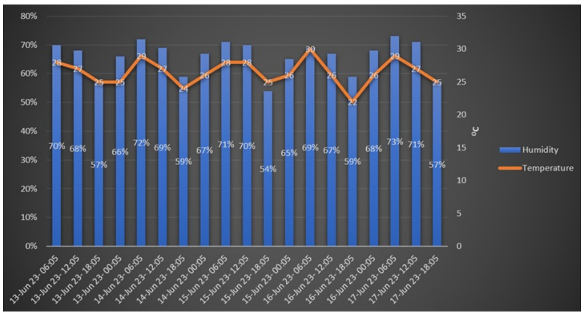

Figure 11: Humidity and temperature measurements

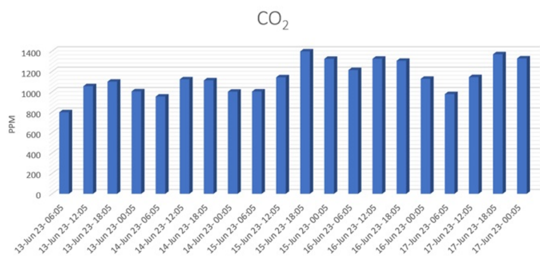

Figure 12: CO_2 measurements

Table 1: Electrical quantities monitoring device components and device final price

No.	Components	Quantity
1.	Developing board with ATmega328P	1
2.	LoRa Shield 868 MHz	1
3.	ZMPT101B AC Voltage Sensor Module	1
4.	SCT-013-030 Non-invasive AC Current Sensor	1
5.	Power supply	1
6.	Bidirectional BUS Logic converter	1
7.	Resistor 10K	2
8.	Resistor 100ohm	1
9.	Capacitor 10uF	1
10.	Connecting Wires	22
11.	Breadboard	1
Total price		142 Euros

Table 2: Environment parameters monitoring device components and device final price

No.	Components	Quantity
1.	Developing board with ATmega328P	1
2.	LoRa Shield 868 MHz	1
3.	Soil pH Sensor	1
4.	BH1750 Ambient Light Sensor	1
5.	SHT31 Humidity Temperature Sensor	1
6.	CCS811 Air Quality Gas Sensor	1
7.	Connecting Wires	16
8.	Breadboard	1
Total price		173 Euros

We conclude that the price of the devices is reasonable, even for smaller farms, and that the data recorded by the devices can be used for in-depth analysis and pro-cess optimization and improvement.

5 Conclusions

The primary aim of our research was to investigate whether a low-cost greenhouse monitoring system for large geographical area covering, tailored to the requirements of modern agriculture, could provide tangible benefits in an era increasingly defined by data-driven decision-making and sustainability imperatives. Our conclusions resoundingly affirm that not only does this system offer good results but also it represents a transformative force in the contemporary landscape of greenhouse management.

First and foremost, the low-cost nature of our monitoring system challenges traditional notions that cutting-edge agricultural technology is prohibitively expensive. By harnessing the power of IoT, we have created an affordable yet highly effective solution that democratizes access to sophisticated greenhouse monitoring capabilities. This democratization opens doors for small and resource-constrained farmers to leverage data-driven insights and optimize their agricultural practices.

The heart of our system, embedded with an array of sensors, seamlessly tracks critical environmental parameters including temperature, humidity, light intensity, soil moisture, CO_2 levels and air quality. In addition, it provides a clear picture of electrical energy consumption. The resulting data streams empower greenhouse operators with granular insights into the growing environment, facilitating precise control and adaptability. The system's real-time monitoring capabilities emerged as a linchpin in ensuring optimal crop conditions, leading to improved crop yield and quality. Furthermore, the integration of IoT principles has not only extended the monitoring system's capabilities but has also simplified remote management and data accessibility. With the IoT era's connectivity and cloud-based

features, our system enables real-time data visualization and remote control from anywhere with an internet connection. This convenience not only empowers greenhouse operators but also ensures rapid response to emerging issues, reducing the risk of crop loss and resource wastage.
Our low-cost greenhouse monitoring system was rigorously tested and proven to be both robust and reliable. It withstood the demands of continuous operation and demonstrated its suitability for deployment in various greenhouse environments. The system's ease of installation and user-friendly interface further enhance its appeal for widespread adoption. As we conclude this research endeavor, it is evident that our low-cost greenhouse monitoring system has effectively harnessed the power of IoT to redefine greenhouse management in contemporary agriculture. It has showcased its capacity to optimize resource utilization, enhance crop yields, and provide accessible data-driven insights that are crucial in today's competitive agricultural landscape.
As future directions, our team will continue to focus on developing data analytics and machine learning models to analyze the vast amount of data collected by green-house monitoring systems. These models can provide predictive insights, optimize resource usage, and enable early detection of plant stress or disease.

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See above.

Author contributions

The authors contributed equally to this work.

Conflict of interest

The authors declare no conflict of interest.

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