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ARTICLE

IoT-Enabled Plant Monitoring System with Power Optimization and Secure Authentication

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ABSTRACT

Global food security is a pressing issue that affects the stability and well-being of communities worldwide. While existing Internet of Things (IoT) enabled plant monitoring systems have made significant strides in agricultural monitoring, they often face limitations such as high power consumption, restricted mobility, complex deployment requirements, and inadequate security measures for data access. This paper introduces an enhanced IoT application for agricultural monitoring systems that address these critical shortcomings. Our system strategically combines power efficiency, portability, and secure access capabilities, assisting farmers in monitoring and tracking crop environmental conditions. The proposed system includes a remote camera that captures images of surrounding plants and a sensor module that regularly monitors various environmental factors, including temperature, humidity, and soil moisture. We implement power management strategies to minimize energy consumption compared to existing solutions. Unlike conventional systems, our implementation utilizes the Amazon Web Services (AWS) cloud platform for reliable data storage and processing while incorporating comprehensive security measures, including Two-Factor Authentication (2FA) and JSON Web Tokens (JWT), features often overlooked in current agricultural IoT solutions. Users can access this secure monitoring system via a developed Android application, providing convenient mobile access to the gathered plant data. We validate our system's advantages by implementing it with two potted garlic plants on Okayama University's rooftop. Our evaluation demonstrates high sensor reliability, with strong correlations between sensor readings and reference data, achieving determination coefficients (R^2) of 0.979 for temperature and 0.750 for humidity measurements. The implemented power management strategies extend battery life to 10 days on a single charge, significantly outperforming existing systems that typically require daily recharging. Furthermore, our dual-layer security implementation utilizing 2FA and JWT successfully protects sensitive agricultural data from unauthorized access.

KEYWORDS

Plant monitoring; agriculture; food security; environmental monitoring; IoT; power management; AWS; secure access; JWT

1 Introduction

As the world becomes increasingly interconnected, food security has emerged as a paramount global concern, posing a severe threat to the sustainability of societies. Securing sufficient, safe, and nutritious food access stands as a key aspect of the United Nations' Sustainable Development Goal (SDG) 2 [1]. It aims to achieve the goals of ending hunger, achieving food security, enhancing nutrition, and fostering sustainable agriculture [2]. One of the key challenges farmers face is accurately monitoring and optimizing environmental conditions for crop growth [3].

Traditional methods of monitoring plant growth and environmental conditions often rely on manual inspections, which can require a significant amount of time and effort. For instance, visual inspections require regularly checking plants for health issues, but this method can miss early problems and provide no quantitative data. Measuring soil moisture with hand-held probes requires frequent visits and only gives localized information. Similarly, taking temperature readings with thermometers needs regular checking and doesn't capture fluctuations well. These limitations can result in sub-optimal growing conditions and potential crop losses [4].

Moreover, the lack of real-time data on plant growth and environmental conditions hinders farmers' ability to make decisions based on accurate information and respond promptly to changes in the growing environment. This can lead to inefficient resource utilization, like overwatering or under-fertilizing, which not only affects crop yields but also contributes to environmental degradation [5]. Advanced technologies are needed for accurate, real-time monitoring of plant growth progress and surrounding environment, enabling farmers to optimize their farming practices and improve crop yields sustainably [6–8].

To tackle these issues, the adoption of Internet of Things (IoT) technology in agriculture has garnered considerable interest in the last decade. IoT-based monitoring systems have transformed the agriculture industry by enabling farmers to gather real-time data on essential environmental parameters like temperature, humidity, and soil moisture, crucial for optimal plant growth [9–11]. These systems employ an array of sensors and wireless communication technologies to gather and transmit data continuously, offering farmers valuable information on the health and performance of crops [12–14]. By leveraging these data and further processing them using cutting-edge artificial intelligence (AI) and machine learning techniques, farmers can optimize resource management, leading to increased crop yields [15].

This paper introduces an innovative IoT application specifically developed for monitoring plant agriculture systems. Its goal is to assist farmers in monitoring and tracking essential environmental conditions crucial for optimal plant growth. Our proposed system incorporates power management configurations to periodically measure various environmental parameters while reducing power consumption. The collected data is securely transmitted to Amazon Web Services (AWS) for storage and analysis. In addition, plant photos are captured using the remote camera and sent to the cloud. Through a specialized Android application on their mobile devices, users can observe and check the gathered plant information.

To ensure security in the plant monitoring system, we consider secure authentication for accessing the sensor data. The application incorporates Two-Factor Authentication (2FA) and JSON Web Tokens (JWT) mechanisms. The 2FA requires users to provide an additional verification step beyond username and password to access the application, enhancing security. Additionally, JWT enhances the security of token-based authentication by introducing an expiration time to the tokens, minimizing the vulnerability associated with token reuse.

To evaluate the system, we deploy applications on two potted garlic plants located on the rooftop at Okayama University to verify its functionality. Our findings demonstrate the effectiveness of the IoT-based monitoring system, showcasing precise sensor readings, extended battery life, and secure access restricted to authorized users.

In summary, this work introduces an IoT-enabled plant monitoring system to solve key agricultural challenges. It uses a portable, weatherproof design with cost-effective components like the Raspberry Pi Zero and affordable sensors. Data is managed with AWS EC2 and Django for efficient processing and storage. Security is ensured with 2FA and JWT. The system is simple, scalable, and secure, making it ideal for improving long-distance communication, energy efficiency, and protection against water damage in agriculture. Furthermore, this system aligns with several SDGs, contributing to sustainable agriculture and environmental protection.

- **SDG 2: Zero Hunger.** By providing farmers with real-time data on environmental conditions, our system helps optimize plant growth and increase agricultural productivity. This can lead to higher yields and more efficient use of resources, contributing to food security.
- **SDG 7: Affordable and Clean Energy.** Our system incorporates power management configurations to reduce energy consumption. By optimizing power usage, it supports the goal of affordable and clean energy.
- **SDG 9: Industry, Innovation, and Infrastructure.** The integration of IoT technology in agriculture represents a significant innovation. It enhances the infrastructure for data collection and analysis, promoting sustainable industrialization and fostering innovation.
- **SDG 13: Climate Action.** Efficient resource management and reduced energy consumption contribute to lower greenhouse gas emissions. This aligns with efforts to combat climate change and its impacts.
- **SDG 15: Life on Land.** The system supports sustainable land management practices, helping to maintain healthy ecosystems and biodiversity.

Following this introduction, the paper is organized as follows: Section 2 presents a review of IoT applications in agriculture, discussing relevant literature regarding the proposed project and addressing associated challenges. Section 3 introduces the proposed IoT application for plant monitoring system, emphasizing its incorporation of power optimization and secure authentication functionalities. Section 4 evaluates the effectiveness of the proposal through practical implementation on two potted garlic plants. Section 5 concludes this paper by summarizing the findings from implementing and evaluating the proposed IoT application for plant monitoring systems. It also suggests areas for future research.

2 IoT in Agriculture and the Challenges

This section explores the use of IoT applications within the agricultural domain, discuss relevant works while also addressing the challenges associated with their implementation.

2.1 IoT for Agricultural Applications

IoT has emerged as a transformative technology in agriculture, offering a suite of tools that can revolutionize traditional farming practices. At its core, IoT in agriculture involves the use of smart sensors, drones, satellites, and other connected devices to collect and transmit data about various aspects of the farming process [16]. This data can be integrated with other sources, such as weather forecasts and historical data, to provide farmers with practical insights and recommendations.

In the agricultural context, IoT devices can monitor a wide array of parameters: soil moisture, pH, nutrient levels, temperature, humidity, wind speed, light intensity, and more. These sensors can be deployed in fields, greenhouses, storage facilities, and even on livestock. The data they collect is transmitted in real-time to cloud platforms, where it is processed using analytics and machine learning algorithms. The resulting insights help farmers understand their operations at a granular level, predict outcomes, and take proactive measures [15].

Numerous studies have explored the use of IoT-based systems for various agricultural purposes, including irrigation, precision farming, crop monitoring, energy supply for agriculture and environmental control. Water scarcity makes smart irrigation a key IoT application. In [13], Lean et al. developed a smart farming system using Raspberry Pi. It monitors and controls essential plant growth factors like irrigation, temperature, humidity, soil moisture, and light intensity. They connected sensors to a GrovePi board, making it easier to integrate multiple sensors. The system includes a smartphone app made with MIT App Inventor for simple sensor monitoring and drip irrigation control. One standout feature is its ability to adjust watering automatically based on real-time soil conditions, reducing water waste and supporting healthy plant growth. However, the study focuses on a small-scale prototype and may encounter challenges like network connectivity, power management, and data security in real farming environments.

In precision farming, farmers can optimize inputs such as fertilizers, pesticides, and water based on the specific needs of individual plants or sections of a field. In [17], Ahmed et al. proposed scalable network architecture aims to efficiently monitor and control agricultural operations in rural areas while reducing network latency compared to existing IoT solutions. It incorporates a cross-layer-based channel access and routing solution for sensing and actuating, enhancing energy efficiency, delay, and throughput performance. Integration with the WiLD network further improves end-mile connectivity. Additionally, the implementation of fog computing minimizes delay and conserves bandwidth. Besides, they suggested to incorporate security part. Security measures are crucial to prevent data tampering and ensure privacy across fog, cloud, and Internet entities, safeguarding the integrity of individual devices.

Similarly, in [18], Nguyen et al. explored the development and implementation of an Internet of Plants (IoP) system for remote monitoring of various environmental factors crucial to plant growth, such as soil moisture level, water level, temperature, and humidity. They employed ESP32 devices, which are low-cost, low-power, and highly integrated microcontrollers with built-in Wi-Fi and Bluetooth connectivity, to create a small-scale IoP system suitable for organic gardens. The collected data was then transmitted to open-source IoT platforms, such as Thingsboard, for storage and visualization. However, the indoor testing environment with wired electricity limits the direct applicability of the system to real-world agricultural settings. In practical agricultural environments, factors such as the availability of power sources, the need for wireless connectivity, and the ability to withstand harsh outdoor conditions must be considered.

In [19], Selmani et al. contributed to the ongoing discourse surrounding Agricultural Cyber-Physical Systems (ACPS) by focusing on integrating solar photovoltaic energy as a renewable source. It presented a new approach to improve ACPS design and decision-making. The design supported photovoltaic irrigation systems and included an inference engine considering resource availability. Through developing an event-driven system with low-cost devices and a micro-service architecture, the paper showcased effective photovoltaic energy use. It also demonstrated real-time remote management, especially for irrigation tasks. A successful case study in an experimental greenhouse provided evidence of the approach's cost-efficiency and task management effectiveness. It is important to note that conducting the experiment outdoors provides a more realistic simulation of natural agricultural conditions.

Crop health monitoring through IoT is becoming increasingly popular. Additionally, there is a growing trend towards integrating IoT technologies with machine learning algorithms for data analysis and decision support in agriculture. In [20], machine learning was applied to IoT data analytics in agriculture, presenting a promising avenue for enhancing crop production and quality. The research focused on predicting apple disease in Kashmir valley's apple orchards using IoT data analytics and machine learning techniques. Real-time data collected from wireless sensor/IoT nodes serve as input for a linear regression model, facilitated the development of a user-friendly application for farmers to monitor their orchards in real time. Following data collection, analysis, and logging in a Postgres database, machine learning techniques, particularly simple linear regression, are applied to predict disease status and treatment requirements in advance. By analyzing factors such as temperature and leaf wetness, the system predicted disease outbreaks early, enabling farmers to take prompt action to protect their crops.

Security is a critical concern in IoT-based agriculture systems due to the sensitivity and value of collected data, as well as the diversity of devices involved. In [21], blockchain approach was implemented to secure the connection between the server and IoT devices in a smart climate agriculture system. This ensured the security and integrity of data. The technology facilitated tracking and tracing transactions through devices. By implementing blockchain technology, secure transmission was achieved for receiving data from devices, delivering data to users, and storing it securely. Reference [22] adopted a similar approach using blockchain to enhance the security and privacy of smart farms.

Moreover, Reference [23] demonstrated the effectiveness of incorporating the Expeditious Cipher (X-cipher) lightweight encryption protocol into the message queuing telemetry transport (MQTT) protocol to create secure communication channels in precision agriculture. This approach successfully addressed the primary security threat by protecting sensor data from unauthorized access and modification, while also ensuring the integrity of irrigation decisions. The implementation of such security measures is crucial for maintaining the accuracy and reliability of data-driven decision-making in precision agriculture, ultimately leading to improved crop outcomes.

Environmental control in greenhouses heavily relies on IoT. In [24], Dan et al. introduced a smart greenhouse system designed to optimize plant growth by adjusting temperature, humidity, and light levels. Leveraging IoT and fuzzy logic, the system provided precise control and communication using ZigBee technology. It was cost-effective, easy to set up, and expandable as needed. Integrating IoT and fuzzy control with remote capabilities via GPRS. This system enabled remote access to greenhouse data, allowing users to monitor conditions from anywhere. Additionally, the system established a dual-input temperature and humidity fuzzy neural network control model, enabling comprehensive control of environmental factors, including CO_2 levels, for simplified plant growth management. Fuzzy logic facilitated precise environmental control without requiring intricate knowledge of system details.

With the advent of low-power wide-area network (LPWAN) technologies, such as long range (LoRa) and narrowband internet of things (NB-IoT), researchers have explored their potential for large-scale IoT deployments in agriculture. In [25], Klaina et al. explored the assessment of large-scale farm monitoring scenarios utilizing LPWAN technology and near-ground sensor nodes. It focused on enhancing agricultural operations through interactions between tractors, farmers, and infrastructure. Here, LPWAN technology proved better than ZigBee, especially in large, uneven fields, providing stronger coverage and better connections whether the sensors were fixed or moving with tractors and farmers.

In [26], Soy et al. looked into using the emerging concept of the Internet of Vehicles (IoV) to develop an integrated tracking system for agricultural vehicles and machinery, utilizing two prominent LPWAN technologies: LoRa and NB-IoT. They made special tracking units for both LoRa and NB-IoT connectivity and tested them to see how well they worked, serving as reference hardware for coverage analysis. They also did computer simulations to double-check their results using a tool called XIRIO online radio planning tool maps. Based on what they found, they suggested ways to enhance the feasibility of tracking agricultural vehicles in smart farms using LPWAN.

In [27], Foughali et al. developed a system to manage Late Blight disease in potato and tomato crops using five Waspmote IoT sensor nodes. These nodes collected data on temperature, humidity, and leaf wetness, crucial for disease monitoring. They communicated via ZigBee using the XBee802.15.4 SMA 5dBi module. The system utilized the Ubidots platform for data management and included notifications based on the SIMCAST model to alert farmers of disease risk factors. However, the study focused specifically on Late Blight and used a limited number of sensors for monitoring agricultural conditions.

These diverse studies demonstrate how IoT is being effectively applied across various agricultural domains. By providing real-time, location-specific data, IoT empowers farmers to make data-driven decisions, automate tasks, and intervene proactively. This technology is not just enhancing productivity but also promoting more sustainable, resilient farming practices. However, despite the promising potential, the adoption of IoT in agriculture also faces various challenges, which will be discussed in the subsequent sub-section.

2.2 Challenges in Implementing IoT in Agriculture

The adoption of IoT in agriculture poses several challenges that require attention [28,29]:

1. **Environmental Factors.** Agricultural environments can pose challenges, including exposure to extreme temperatures, moisture, dust, and other environmental factors that could affect the performance and longevity of IoT devices and sensors. Designing robust and weather-resistant hardware and enclosures is essential to ensure reliable and long-lasting operation in these conditions.
2. **Connectivity.** Many agricultural areas, particularly remote rural regions, lack reliable and consistent internet connectivity, which is crucial for IoT devices to transmit data to cloud platforms or local gateways. Ensuring adequate network coverage and bandwidth is essential for seamless data transmission and real-time monitoring.
3. **Remote Camera.** Incorporating remote cameras into agricultural IoT systems introduces its own set of challenges. The application of remote camera technology in agriculture in developing countries like India presents unique challenges and considerations. In rural India, where smallholder farming is prevalent, infrastructure limitations significantly impact the deployment of IoT cameras. Unreliable electricity supply is a major hurdle, necessitating robust battery systems or alternative power sources like solar panels, which add to the overall cost and complexity. Internet connectivity, crucial for transmitting image and video data, is often sporadic or absent in remote agricultural areas, limiting real-time monitoring capabilities.
4. **Power Management.** IoT sensors and devices deployed in agricultural fields often rely on batteries or solar power sources. Efficient power management strategies and energy-harvesting techniques are necessary to ensure long-term operation and minimize the need for frequent battery replacements or maintenance.

5. **Data Management and Analysis.** The large volumes of data generated by IoT sensors and devices in agricultural settings require robust data management and analysis capabilities. Effective data storage, processing, and visualization tools are needed for extracting meaningful information and enabling decision-making based on data.
6. **Security and Privacy.** As IoT systems in agriculture handle sensitive data related to crop yields, farm operations, and potentially personal information, robust security measures are necessary to protect against cyber threats, unauthorized access, and data breaches. Privacy concerns regarding the collection and use of data must also be addressed.
7. **Cost.** Implementing IoT solutions in agriculture can be capital-intensive, particularly for small-scale farms or resource-constrained regions. Ensuring cost-effectiveness while maintaining system performance and reliability is a significant challenge.

Table 1 compares the proposed system with existing works in terms of application, collected data, data management, IoT nodes, connectivity, waterproof sensors, power efficiency, security, and user engagement. This work introduces an IoT-enabled plant monitoring system designed to tackle critical challenges in agriculture. The solution features a portable and weatherproof hardware design, optimized power management, and cost-effective components like Raspberry Pi Zero and affordable sensors. Data is managed using AWS EC2 and Django, ensuring efficient processing and storage. Robust security measures, including incorporating 2FA and JWT for secure authentication, safeguard sensitive data. The system's simplicity, scalability, and secure access make it ideal for addressing agricultural needs, such as enhancing long-distance communication, improving energy efficiency, and providing protection against water damage.

Table 1: Comparison of our proposed scheme and several existing schemes

Scheme	[18]	[20]	[21]	[22]	[23]	Our proposal
Application	Monitoring two potted garlic plant at outdoor	Predicting of apple scab at outdoor	Handling the process of watering plants at indoor	Triggering a quick device alarm at indoor	Controlling irrigation at indoor	Monitoring two potted garlic plant at outdoor
Collected data	Temperature, humidity, and soil moisture	Temperature and leaf wetness	Temperature, soil moisture, light intensity, and humidity	Temperature, humidity, and light exposure	Temperature, humidity, and soil moisture	Temperature, humidity, soil moisture and plant photos
Managing data	Thingsboard	Personal computer	IoT cloud platform	AWS	ThingSpeak	AWS
IoT nodes	ESP32	IRIS mote	Arduino	ESP32	NodeMCU ESP8266 and Raspberry Pi	Raspberry Pi Zero
Connectivity	Wi-Fi	Zigbee	Wi-Fi	MQTT	MQTT	Wi-Fi and GSM
Waterproof sensor	No	No	No	No	No	Yes
Power efficiency	No	No	No	No	No	Employing power management

(Continued)

Table 1 (continued)

Scheme	[18]	[20]	[21]	[22]	[23]	Our proposal
Security	No	No	Secure access using blockchain	Secure access using blockchain	Secure channel using Expeditious Cipher (X-cipher)	Secure authentication using 2FA and JWT
User engagement	Web-based	Desktop-based	Android app	Web-based	Web-based	Android app

3 IoT-Enabled Plant Monitoring System Proposal

This section presents detailed design proposal of the proposed IoT-enabled plant monitoring system, which incorporates power optimization and secure authentication features.

3.1 Overview

Fig. 1 provides an overview of the proposed system architecture [30]. The system that has been developed is intended to provide real-time information regarding the growth and well-being of plants, featuring waterproof cases, power optimization, and secure authentication. It consists of five main components: remote camera, power source, sensor module, *AWS* cloud platform, and Android application for user monitoring.

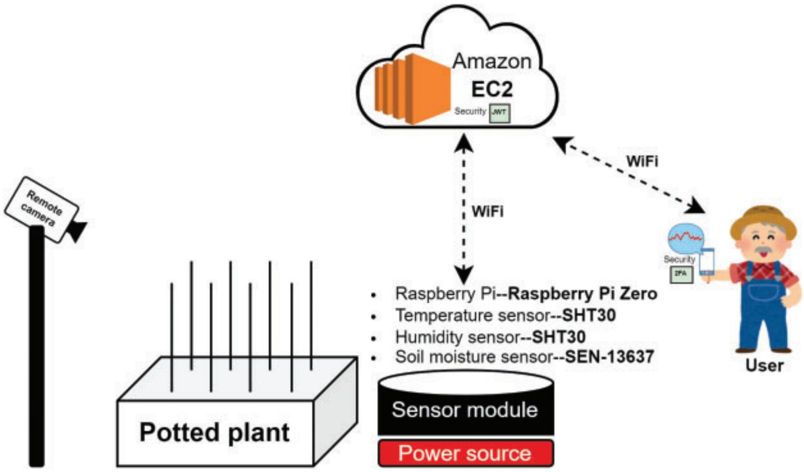


Figure 1: The proposed IoT-enabled approach to plant monitoring system

In the agricultural setting, a remote camera is strategically mounted to capture periodic images of the plants. The power source is designed to support the sensor module, particularly in environments with limited access. The sensor module is responsible for measuring critical environmental parameters that influence plant growth, such as temperature, humidity, and soil moisture. The collected data is then securely transmitted to the AWS cloud platform. On the user end, farmers can access the collected data through the Android application, enabling them to monitor environmental conditions in real-time and secure.

3.2 Remote Camera

The remote camera has the responsibility of periodically capturing images of the plants to provide a comprehensive view of both the plants and their immediate surroundings. We utilize the FieldCam FC-1000 for a dedicated agricultural monitoring task. This camera is specifically designed for remote surveillance of outdoor environments [31].

The camera comes with features such as auto-focus, adjustable resolution, and low-light capabilities to ensure optimal image quality in various lighting conditions. It captures and transmits the photos of the potted plant every 1 h. These captured images are timestamped and transmitted to the FieldShare cloud platform for further analysis and storage using 4G cellular connectivity. Fig. 2 illustrates the FieldShare dashboard used for viewing and managing the photos collected of the plant.

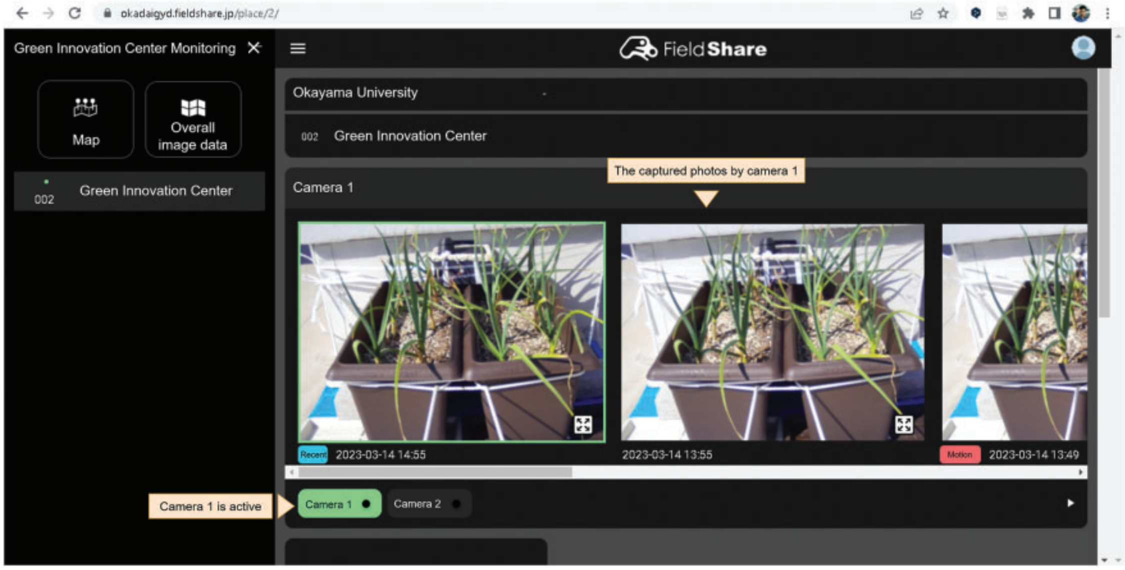


Figure 2: Dashboard displays images of the garlic plants collected

The camera is housed in a weatherproof enclosure to protect it from environmental factors such as rain, dust, and extreme temperatures. The power for this specialized camera is provided by a set of twelve AA batteries.

3.3 Power Source with Optimization Solution

The power source is a critical component of the system, ensuring a reliable and continuous power supply for the hardware components. In agricultural settings, power accessibility may be limited, and the system needs to operate autonomously for extended periods.

To ensure consistent and reliable power in outdoor environments, the system is equipped with a *Cheero Power Plus 5* mobile battery to effectively power the sensor module. This battery offers a capacity of 100,000 mAh. It also provides a maximum output of 2.4 A, suitable for meeting the power requirements of devices such as the *Raspberry Pi Zero*, ensuring stable performance even in demanding conditions.

However, mobile batteries may experience voltage fluctuations depending on their charge level, which can potentially damage the *Pi Zero*. To address this concern, additional power management module is employed to regulate the voltage and current supplied by the mobile battery. This module effectively prevents under-voltage and over-voltage situations, thereby safeguarding the reliable operation of the system.

In outdoor environments with limited accessibility, effective power management is crucial to ensure the continuous operation of an IoT-based agricultural monitoring system. To optimize energy efficiency and reliability, the system employs several strategies:

1. Turning the *Pi Zero* on Every 10 min. The power management module is programmed to turn on the *Pi Zero* every 10 min to collect and process sensor data. After that, it goes back to sleep, conserving power by only running when needed. This approach reduces energy consumption while still providing regular updates on sensor readings like temperature, humidity, and soil moisture.
2. Closing Unnecessary Apps. To save even more energy, the system shuts down any apps or background processes that aren't essential. This helps extend battery life and ensures that the system focuses its limited power on important tasks like monitoring and data collection.

3.4 Sensor Module with the Waterproofing Design

The sensor module is responsible for measuring critical environmental factors that impact plant growth. It includes sensors for temperature, humidity, and soil moisture. This provides precise and real-time data on the conditions affecting the plants.

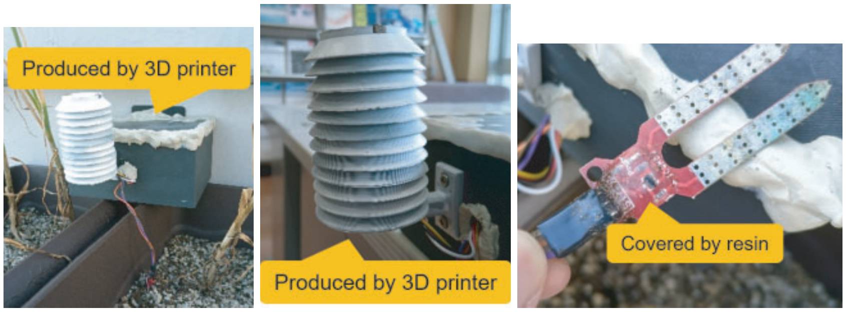
Table 2 outlines the specifications of the sensors chosen for this study. These sensors were installed in the potted garlic plants and connected to a microcomputer, specifically the *Pi Zero*. The temperature and humidity sensors are placed in close proximity to the plants to measure the ambient conditions, while the soil moisture sensor is inserted into the soil to measure the moisture content at the root level.

Table 2: Characteristics of the sensors in use

Attribute	SHT30	SEN-13637
Operation	Temperature & humidity	Soil moisture
Power usage	2.15 to 5.5 V	3.3 to 5 V
Operational limits	Temp: -40°C to $+125^{\circ}$C Humi: 0% to 100%	0 to 880
Communication	I2C	ADC

After connecting the sensors to *Pi Zero*, a *Python* program is launched to start gathering data from them. After that, it timestamps the collected data and sends it to *AWS* for further processing. This entire process, encompassing data collection, timestamping, and *AWS* transfer, is seamlessly automated by the *Python* program operating on the *Raspberry Pi Zero*.

Due to their placement in outdoor environments, the sensors are susceptible to damage from water and other environmental factors, potentially resulting in inaccurate readings and reduced system performance. These sensors play a vital role in monitoring various environmental variables such as temperature, humidity, and soil moisture in outdoor settings. To prevent potential damage and ensure consistent data collection, the sensor module is housed in a secure, waterproof, and dustproof enclosure. This enclosure is compact, lightweight, and designed for easy installation, providing adaptability to a wide range of monitoring needs. Fig. 3 displays the waterproofing cover for the sensor module, temperature and humidity sensor, as well as the soil moisture sensor.



(a) (b) (c)

Figure 3: Waterproofing cover (a) sensor module (b) SHT30 (c) SEN-13637

We utilize sensor covers for the SHT30 and SEN-13637 sensors to shield them from direct sunlight, rain, and other environmental factors. Specifically, the 3D-printed cover for the SHT30 sensor, which measures temperature and relative humidity, is designed according to the Stevenson model [32]. This model is widely recognized as a standard for meteorological enclosures. This design allows proper ventilation while shielding the sensor from direct exposure to precipitation and solar radiation, ensuring more accurate measurements [33]. Lastly, the sensor cover is coated in white spray to enhance its reflection of sunlight and heat, effectively reducing the impact of radiant heating on the sensor readings.

3.5 AWS EC2 Platform

The proposed system utilizes Amazon Web Services (AWS), specifically its Elastic Compute Cloud (EC2), which provides flexible cloud-based computing resources [34]. The *EC2* instance was configured with specific security groups to allow SSH and HTTP traffic. Secure access to the instance was ensured by implementing SSH with public key authentication, which enhances security by using cryptographic keys for authentication rather than plaintext passwords.

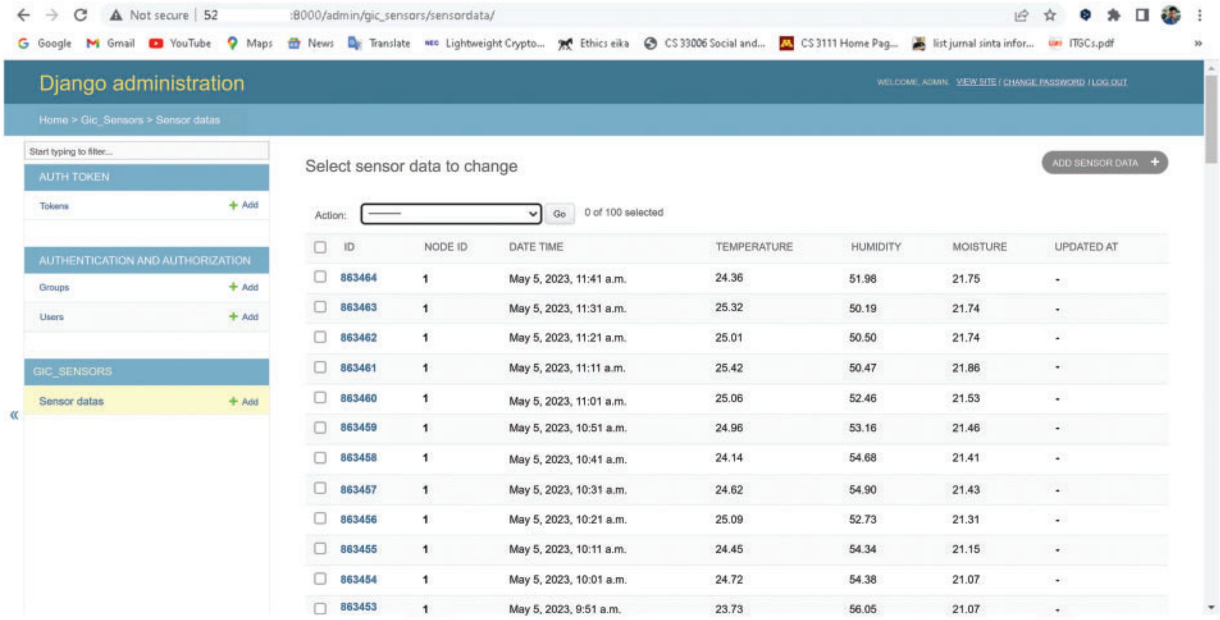
AWS EC2 offers scalable computing capacity in the cloud, enabling the deployment of complex data analysis applications. The *EC2* instance can be easily scaled up or down based on the computational demands of the application, providing flexibility and cost-effectiveness. After collecting data from the *Raspberry Pi Zero*, the *EC2* instance proceeded to process and store the data in a *MySQL* database for future analysis and use.

Using AWS for data storage in agricultural monitoring systems offers many advantages. However, it also presents potential vulnerabilities related to access control, data exposure, insecure APIs, and third-party integrations. Since sensitive environmental and operational data is collected from IoT devices, these vulnerabilities could lead to data breaches or service disruptions. To mitigate these risks, it's essential to implement strong security practices.

Besides, we develop a web application using *Django* to receive and store environmental sensor readings. *Django* is a well-known Python web framework celebrated for its emphasis on rapid development and its clean, pragmatic design principles [35]. We created an API endpoint using Django's built-in REST framework, allowing the *Pi Zero* to transmit sensor data to the web platform [36].

After setting up the Django application, users could immediately begin receiving and processing sensor data. The application featured a user-friendly interface for visualizing the collected sensor data using interactive charts and graphs. It also included data filtering features, allowing users to analyze specific date ranges or sensor types.

Fig. 4 illustrates the Django dashboard admin interface. The dashboard of the application, accessible via the Django admin panel, offered a summary of the gathered data. It enabled administrative tasks such as managing users, sensors, and data visualization settings. Users could access the dashboard by entering the EC2 instance's public IP address followed by ":8000" in the browser's URL field.



Select sensor data to change

0 of 100 selected

☐	ID	NODE ID	DATE TIME	TEMPERATURE	HUMIDITY	MOISTURE	UPDATED AT
☐	863464	1	May 5, 2023, 11:41 a.m.	24.36	51.98	21.75	-
☐	863463	1	May 5, 2023, 11:31 a.m.	25.32	50.19	21.74	-
☐	863462	1	May 5, 2023, 11:21 a.m.	25.01	50.50	21.74	-
☐	863461	1	May 5, 2023, 11:11 a.m.	25.42	50.47	21.86	-
☐	863460	1	May 5, 2023, 11:01 a.m.	25.06	52.46	21.53	-
☐	863459	1	May 5, 2023, 10:51 a.m.	24.96	53.16	21.46	-
☐	863458	1	May 5, 2023, 10:41 a.m.	24.14	54.68	21.41	-
☐	863457	1	May 5, 2023, 10:31 a.m.	24.62	54.90	21.43	-
☐	863456	1	May 5, 2023, 10:21 a.m.	25.09	52.73	21.31	-
☐	863455	1	May 5, 2023, 10:11 a.m.	24.45	54.34	21.15	-
☐	863454	1	May 5, 2023, 10:01 a.m.	24.72	54.38	21.07	-
☐	863453	1	May 5, 2023, 9:51 a.m.	23.73	56.05	21.07	-

Figure 4: Django application dashboard for admin

It's essential to note that the developed web application operated in development mode. It utilized HTTP, an unsecured protocol. Therefore, information exchanged between the client and server in this mode was not secured and susceptible to interception by third parties. However, since the application is still in development, enabling HTTPS is not recommended during this stage.

To ensure the security of data transactions while the application is in development mode, we considered securing user authentication and access control. The application leverages JSON Web Token (JWT) authentication and Two-Factor Authentication (2FA) mechanisms, which are discussed in the next section. JWT authentication is a secure and stateless method of authenticating users by encoding their identity and access privileges in a digitally signed JSON object called a token. 2FA enhances security by necessitating users to provide an additional form of verification, like one-time code sent to their mobile device, alongside their password. These mechanisms help protect sensitive data and prevent unauthorized access to the application during the development phase.

3.6 Data Visualizaton on Mobile Apps

The proposed IoT-based plant agriculture monitoring system includes a user-friendly Android application that allows farmers and other agricultural users to easily monitor and track conditions surrounding their plants. The Android application communicates with the *AWS EC2* instance to retrieve the collected plant data, including sensor readings.

To develop the web application, we utilized *Bubble*, a no-code platform that enables rapid prototyping and application development, reducing development time and costs [37]. *Bubble* enabled rapid development of a customized dashboard presenting real-time sensor data in an intuitive and user-friendly format.

The "GIC Project" application utilizes *Bubble's API Connector* to interface with the *AWS EC2 API* for retrieving sensor data. Through the developed mobile apps, users can access real-time data from plant sensors and track historical trends directly on their mobile devices. The application includes essential user authentication functionalities like login and logout.

To utilize the GIC Project application on mobile phone, it must first be exported as an Android Application Package (APK) file. Bubble offers an option to export the app as an *APK*, necessitating the prior installation of *Android Studio* on the computer. Through *Android Studio*, the exported *APK* can be signed and prepared for installation on phone devices. Once installed, the application becomes accessible from any Android smartphone or tablet with an internet connection, enabling users to monitor sensor data remotely.

Fig. 5 shows the installed *APK* of the GIC Project application alongside its main menu interface. Upon launching the application, users are presented with real-time sensor readings for essential environmental factors: temperature, humidity, and soil moisture. This makes it easy for users to understand the current environmental conditions affecting plant growth.

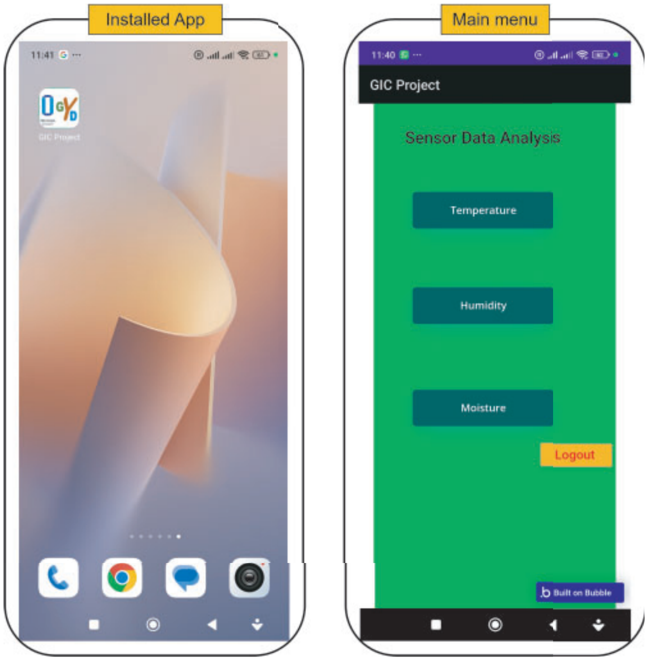


Figure 5: "The GIC project app" runs on the android platform

To operate the application, users simply navigate through the intuitive interface by selecting specific sensor categories from the main menu. For example, tapping on "Temperature" will bring up detailed charts showing the temperature trends over time, while selecting "Moisture" displays both current readings and historical data in a graphical format. Each data visualization is designed to provide instant clarity, helping users easily interpret the current environmental conditions. Users can view historical data and trends for each monitored parameter over different time periods (e.g., past

24 h, past week, past month). This feature enables users to identify patterns, compare data across different time intervals, and make informed decisions based on long-term observations.

To ensure secure user authentication and access control, the application leverages JWT authentication and Two-Factor Authentication (2FA) mechanisms, which are discussed in the next section.

3.7 Secure Authentication

IoT implementations for plant monitoring systems face significant security challenges that could compromise both operational integrity and data reliability. The primary security risk derives from unauthorized access to IoT devices, which is particularly concerning as these devices typically operate in remote or exposed environments, making them vulnerable to unauthorized access attempts. This vulnerability could enable attackers to disrupt data collection processes or manipulate environmental sensor data, potentially leading to incorrect system responses such as improper irrigation or environmental control decisions.

Another critical threat lies in data compromise, where intercepted or altered sensor data potentially harming the monitored plants through mismanaged care routines. The integrity of sensor data transmission is crucial, as compromised data can lead to systemic failures in plant care and monitoring processes. Considering that this system utilizes HTTP for communication, it's important to note that password-based authentication and sensor data could be vulnerable to interception.

Tokens offer a distinct advantage over passwords as they are not directly tied to sensitive user credentials. Typically longer and more complex, tokens significantly enhance security compared to traditional passwords. By adopting tokens, this approach reduces dependence on user-managed passwords, effectively mitigating risks associated with interception. As a result, this proposal introduces a more secure authentication method for securely accessing sensor data and facilitating communication with cloud resources.

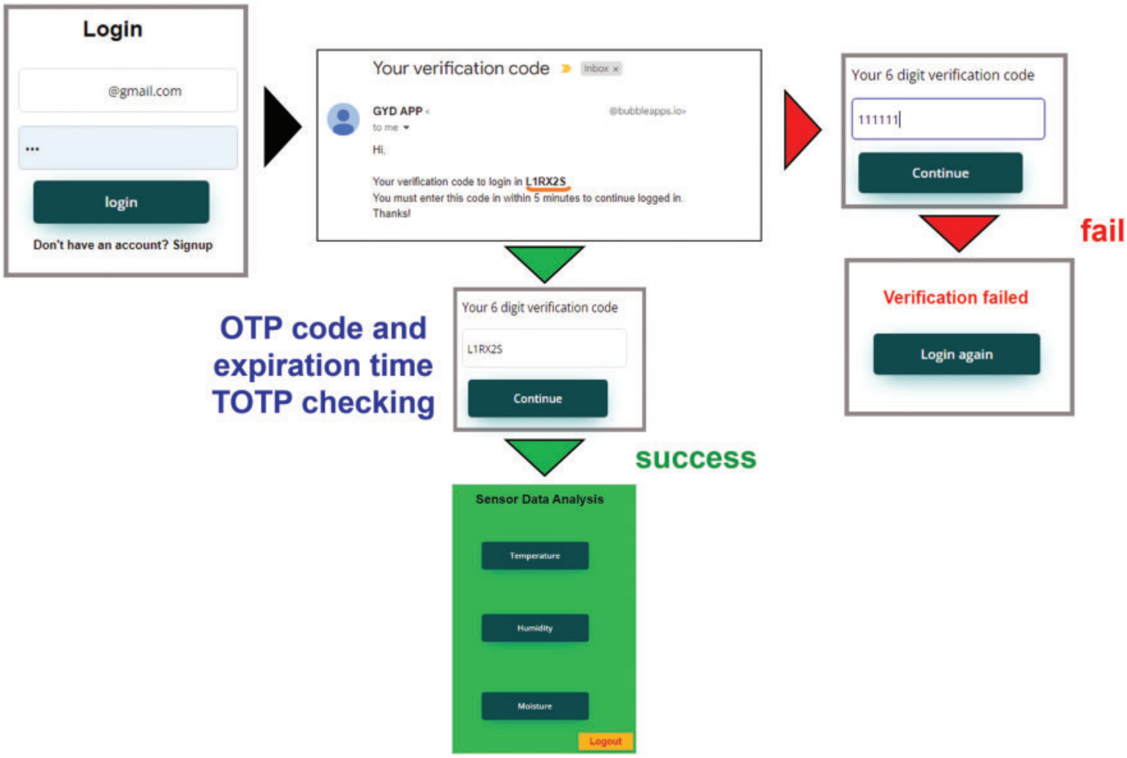
The system only allows legitimate users and devices to communicate, ensuring the integrity of operations. Access to sensor data via the Android application is restricted to authenticated users, enhancing data integrity and system reliability. In this study, we are exploring the simultaneous adoption of Two-Factor Authentication (2FA) and JSON Web Tokens (JWT) mechanisms. 2FA mitigates the risk of unauthorized access to IoT devices, while JWT secures communications and ensures data integrity by verifying the authenticity of each transmission.

3.7.1 Implementation of Two-Factor Authentication (2FA)

To strengthen security, the proposed solution incorporates 2FA. It requiring users to provide two forms of verification during the login process:

1. **Username and Password.** In the first step, users utilize the conventional username and password combination. Subsequently, upon launching the application, users input their data, which must correspond to the information registered in the database.
2. **Time-Based One-Time Password (TOTP).** Following the initial step, the subsequent stage involves the generation of a TOTP. This TOTP is produced on the server and remains valid for a specific duration within one authentication session.

For practical implementation, the bubble low-code platform provides an intuitive environment for seamlessly designing and integrating 2FA. Upon login attempts, users will receive a one-time verification code to their registered email, valid for three minutes to enhance security. Fig. 6 illustrates the successful and unsuccessful user login with 2FA added.



Hi,

Your verification code to login in L1RX2S
You must enter this code in within 5 minutes to continue logged in.
Thanks!

Figure 6: User login with 2FA

3.7.2 Implementation of JSON Web Tokens (JWT)

Incorporating token expiration is essential for addressing vulnerabilities linked to token misuse. By implementing a relatively short expiration period, the potential for attackers to exploit stolen tokens is substantially minimized.

JWT include a built-in mechanism for specifying token expiration via the "exp" (expiration time) claim in the token's payload. During user authentication, the server establishes an expiration timestamp within the JWT. This timestamp indicates when the token will lapse and become invalid.

Upon receiving the JWT, the client securely stores it for subsequent API requests. When the token expires, users must re-authenticate to acquire a new token. This process effectively reduces the window of opportunity for attackers to misuse stolen tokens.

In this study, we employ access tokens and refresh tokens for implementation purposes. The access token authenticates the user and provides them with limited-time access to protected resources. Meanwhile, the refresh token is utilized to acquire new access tokens once the original one expires. When the access token expires, the client forwards the refresh token to the server for validation. Subsequently, a new access token is generated without requiring the user to re-enter their credentials.

We detail the procedures in the following steps:

1. **User logs in.** After successful authentication, the server generates both an access token and a refresh token. The access token is promptly forwarded to the client for immediate utilization.
2. **Access token usage.** The client includes the access token in its API requests to gain access to protected resources.

3. **Access token expiration.** The access token is configured to be valid for a duration of 30 min. This duration was chosen based on AWS best practices for handling sensitive data, which recommend access token lifetimes between 15 min and 1 h [38]. Upon expiration of the access token, the client utilizes the refresh token to initiate a request for a new access token.
4. **Refresh token exchange.** The client forwards the refresh token to the server for verification.
5. **Issuing new access token.** If the refresh token is deemed valid, the server proceeds to generate a new access token, which is then provided to the client.
6. **Repeat process.** The client maintains the usage of the new access token until its expiration, thereby initiating the repetition of the cycle.

4 Evaluations

This section examines the effectiveness of the implemented system through a study involving two potted garlic plants situated on the rooftop of Okayama University. Each pot contains 5 seeds. We selected garlic for this study due to its popularity among home gardeners and small-scale farmers. Garlic is favored for its ease of cultivation, minimal attention requirements, and cost-effective harvest, making it a preferred option over some other crops. Fig. 7 shows the implementation of the proposal.

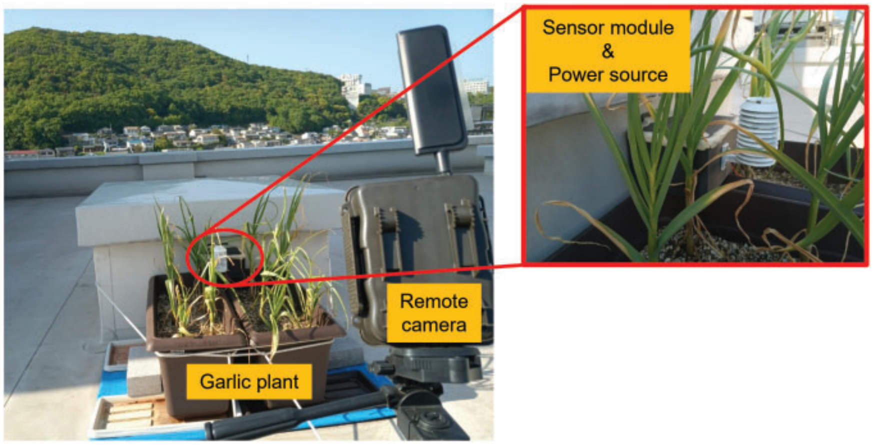


Figure 7: Implementation to two potted garlic plants

The hardware components of the monitoring system were installed in close proximity to the potted garlic plant. The remote camera module was positioned to capture clear images of the plant, while the sensor module was placed near the pot to measure the ambient temperature, humidity, and soil moisture levels.

The system was configured to capture plant images every 1 h and collect sensor readings every 10 min. The captured sensor data was securely transmitted to the AWS cloud platform. The Android application was utilized for securely monitoring real-time data and viewing historical trends. Fig. 8 illustrates the GIC Project application in operation on an Android mobile device, displaying sensor data readings.

To assess the performance of the proposal, we focus on three key aspects: sensor accuracy, battery life, and the system's ability to accurately authenticate users.

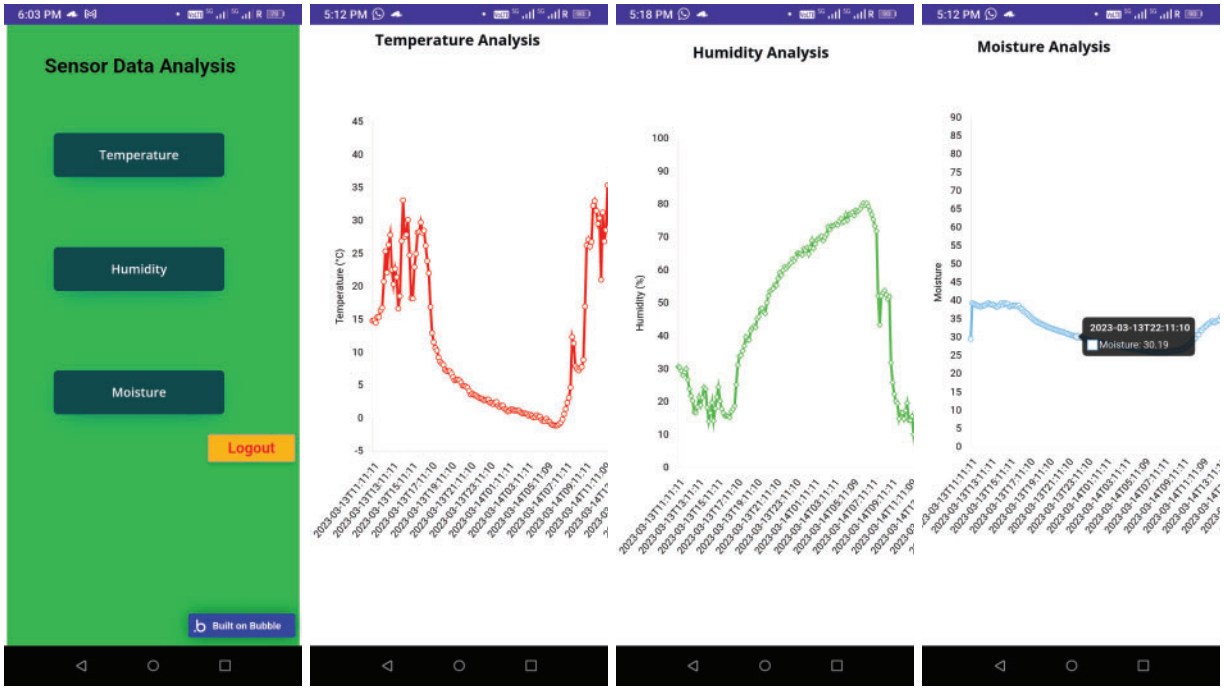


Figure 8: "GIC project app" sensor data display

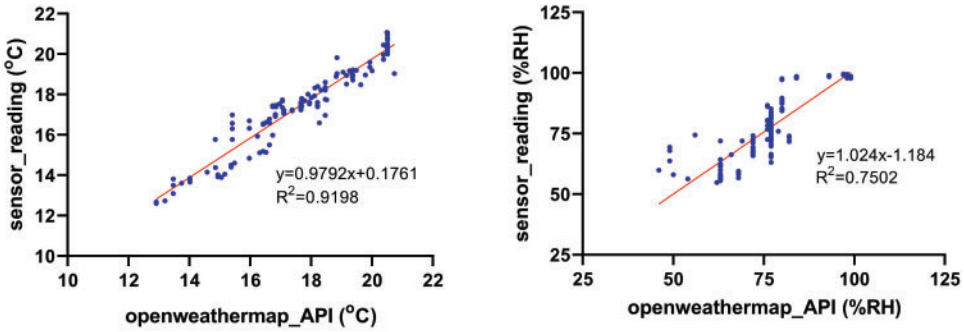
4.1 *Evaluation on Sensor Accuracy*

In farming, it's really important that the sensors we use are right. When sensors are accurate, it means the information they give us is reliable and shows exactly what's happening in the real world. This helps farmers make good choices about how to take care of their crops and use things like water and fertilizer in the best way.

We assessed the accuracy of the sensor readings by comparing data collected from the proposed monitoring system with reference data obtained from the *openweathermap API* [39] over a 24-h period. For this evaluation, we utilized standard weather data from the current conditions in Okayama city.

Fig. 9 compares data readings from local sensors and the *openweathermap API* for temperature and humidity. The determination coefficients are 0.979 for temperature and 0.750 for humidity, indicating a strong correlation between the sensor readings and the reference data. These results demonstrate that the measured sensor data aligns closely with the reference, indicating accurate readings.

For humidity, the vertical stagnation of points with the same X value in Fig. 9c highlights a phenomenon where multiple 'sensor_reading (%RH)' values correspond to a single 'openweathermap_API (%RH)' value. This suggests that the sensor readings are not consistent for those specific API humidity levels. Such variability could be due to environmental factors, such as changes in temperature or pressure, affecting the sensor's performance. Overall, these accuracy levels are sufficient for most agricultural applications, allowing for reliable monitoring of environmental conditions.



(a) (b)

Figure 9: Comparison of data readings from local sensor data and *openweathermap API*. (a) Temperature comparison. (b) Humidity comparison

4.2 Evaluation on Power Battery Life

In farming, it's essential for the system to continuously monitor crops and weather conditions. Having a long-lasting battery is essential for this, ensuring the system can keep running without needing to be charged or replaced often.

The experiment extended over a 48-h period, during which sensor data was continuously collected. One day operated without power management, while the subsequent day incorporated configured power management settings. The expected battery runtime was then calculated using the following formula:

$$\text{expected\_battery\_runtime} = \frac{\text{battery\_capacity} \times \text{voltage}}{\text{power\_consumption}} \tag{1}$$

where the battery_capacity is expressed in ampere-hours (Ah) and the power_consumption is denoted in watts (W), respectively.

Table 3 presents a summary of the battery life comparison results. Under normal operating conditions, with the sensors collecting data every 10 min, system with the power management achieved an average battery life of 10 days on a single charge. This demonstrates the effectiveness of the power management techniques in ensuring long-term operation in agricultural settings with limited power accessibility.

Table 3: Battery life comparison with and without power management

Power management status	Battery capacity (Ah)	Voltage (V)	Power consumption (W)	Expected battery duration (h)
Without power management	10	5.13	2.397	21.4
With power management	10	5.13	0.21375	240

In upcoming studies, exploring the incorporation of solar panels for energy harvesting may further extend the battery life, enabling the system to operate autonomously for prolonged periods without the need for frequent battery replacements. The solar panel would harness energy from sunlight and charge the mobile battery during daylight hours. This renewable energy source could help extend the operational duration of the system, reducing the need for frequent battery replacements or recharges. Moreover, the solar panel's energy output could be factored into the dynamic power allocation algorithm, optimizing power usage based on the available solar energy [40].

4.3 Evaluation on Secure Authentication

In this section, we ensure the function of our implementation through system testing. First, tested TOTP based 2FA under time-set and overtime-set scenarios. Then, tested the JWT under normal use case, access duration, token renewal cases. In the end, we analyzed them.

In the TOTP-based 2FA scheme, users were able to access the app by inputting the correct TOTP code within the specified time limit in the time-set situation. However, in the overtime-set scenario, despite having the correct username and password, users were unable to access the app due to the expired TOTP code. This highlights the importance of timely code entry for successful access.

In the JWT testing, under normal use case scenarios, authentication using the access token within the designated time frame consistently resulted in successful access, confirmed by HTTP response code 200. However, once it expired, authentication failed, leading to denied access with 401 error response. Similarly, attempting to access the system without the access token altogether triggered a detection of a bad request, indicated by error response code 400. To fix expired tokens, a refresh-token mechanism was implemented, allowing users to renew the access token after its expiration. These results highlighting the importance of token management and renewal mechanisms in maintaining seamless user experiences and system security.

4.3.1 Reduced Attack Surface

2FA effectively mitigates the risk of password-related vulnerabilities, as even if an attacker obtains a user's credentials, they will still need to bypass the second authentication factor. This extra layer of security can prevent attackers from attempting to gain unauthorized access to the plant agriculture monitoring system, thereby protecting valuable sensor data and ensuring the integrity of the application.

The short-lived nature of JWT limits the exposure of sensitive authentication data. This makes it considerably more challenging for attackers to exploit weaknesses in the authentication process and gain unauthorized access to the IoT application.

By incorporating 2FA and JWT, the application reduces its attack surface and potential entry points for attackers such as password guessing and brute-force attacks.

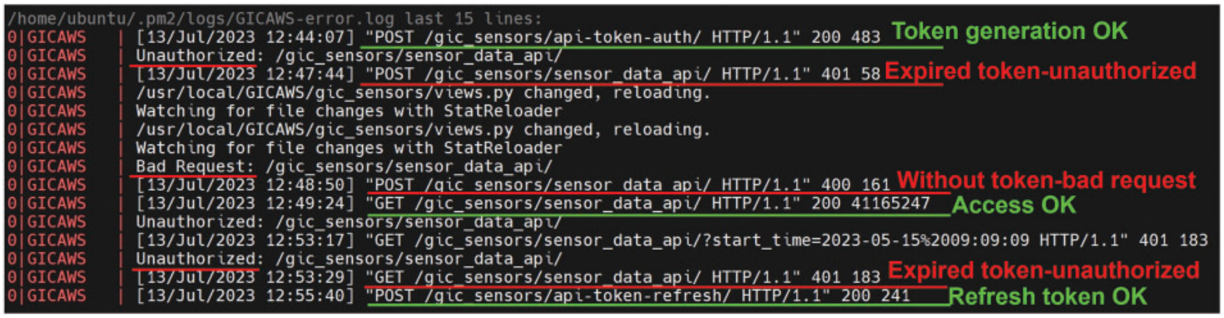
4.3.2 User Awareness and Security Behaviors

Implementing 2FA and JWT in this work promotes user awareness and encourages secure behaviors. As users receive notifications of successful and unsuccessful login attempts, they are more likely to promptly detect and respond to potential security breaches. This feedback loop contributes to a more secure environment and empowers users to safeguard their accounts actively.

Furthermore, Users become more aware of the importance of protecting their accounts as they actively participate in the authentication process through 2FA. This heightened awareness may lead to better security practices.

Next, we assessed the JWT token-based authentication functionality using the *Postman* tool. This involved sending HTTP requests to Django API endpoints. We tested authentication by making API requests to access protected resources under four conditions: using a correct and valid token, using an expired token, without any token, and refreshing token to obtain a new access token.

Fig. 10 illustrates the log of authentication tests. The tests confirm that the authentication system is working as intended. When a valid access token is provided, the API returns a "200" response and the requested data. Requests with an expired are rejected with a "401" error, while requests without a token receive "400" error. Finally, the token refresh process successfully issues a new valid access token when the correct refresh token is submitted.



```
/home/ubuntu/.pm2/logs/GICAWS-error.log last 15 lines:
0|GICAWS    | [13/Jul/2023 12:44:07] "POST /gic_sensors/api-token-auth/ HTTP/1.1" 200 483
0|GICAWS    | Unauthorized: /gic_sensors/sensor_data_api/
0|GICAWS    | [13/Jul/2023 12:47:44] "POST /gic_sensors/sensor_data_api/ HTTP/1.1" 401 58
0|GICAWS    | /usr/local/GICAWS/gic_sensors/views.py changed, reloading.
0|GICAWS    | Watching for file changes with StatReloader
0|GICAWS    | /usr/local/GICAWS/gic_sensors/views.py changed, reloading.
0|GICAWS    | Watching for file changes with StatReloader
0|GICAWS    | Bad Request: /gic_sensors/sensor_data_api/
0|GICAWS    | [13/Jul/2023 12:48:50] "POST /gic_sensors/sensor_data_api/ HTTP/1.1" 400 161
0|GICAWS    | [13/Jul/2023 12:49:24] "GET /gic_sensors/sensor_data_api/ HTTP/1.1" 200 41165247
0|GICAWS    | Unauthorized: /gic_sensors/sensor_data_api/
0|GICAWS    | [13/Jul/2023 12:53:17] "GET /gic_sensors/sensor_data_api/?start_time=2023-05-15%2009:09:09 HTTP/1.1" 401 183
0|GICAWS    | Unauthorized: /gic_sensors/sensor_data_api/
0|GICAWS    | [13/Jul/2023 12:53:29] "GET /gic_sensors/sensor_data_api/ HTTP/1.1" 401 183
0|GICAWS    | [13/Jul/2023 12:55:40] "POST /gic_sensors/api-token-refresh/ HTTP/1.1" 200 241
```

Figure 10: JWT testing log

5 Conclusion

In this paper, we introduced an IoT-based plant agriculture monitoring system that effectively addresses key challenges in outdoor agricultural environments. Our system successfully integrates precise sensor technology, energy-efficient design, and strong security measures, demonstrating its potential to transform modern agricultural practices. The system uses high-precision sensors to accurately monitor critical plant growth conditions in outdoor settings, compared with references from the *openweathermap API*. This enables farmers to make data-driven decisions that optimize resource use and improve crop yields. We achieved remarkable energy efficiency, resulting in extended battery life of up to 10 days under power management constraints. This makes our system particularly suitable for remote or resource-limited agricultural areas, enhancing its portability and practical applicability. Furthermore, our implementation of strong security measures, including JWT and 2FA, addresses the growing concern of data protection in smart agriculture, ensuring the integrity and confidentiality of sensitive agricultural data. We validated the system's real-world applicability through a field test monitoring two potted garlic plants at Okayama University. This practical demonstration underscores the system's potential to provide valuable, actionable insights for various agricultural scenarios. In the future, our focus will be on advancing data analysis capabilities to derive actionable insights that benefit farmers directly. Additionally, we plan to implement an intrusion detection system to further secure the network from potential cyber threats.

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Biplob Hossain, Muhammad Bisri Musthafa, Yang Jie; analysis and interpretation of results: Samsul Huda, Maya Rahayu, Takuma Akada, Md. Biplob Hossain, Muhammad Bisri Musthafa, Yang Jie, Le Hoang Anh; draft manuscript preparation: Samsul Huda. All authors reviewed the results and approved the final version of the manuscript.

Availability of Data and Materials: Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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