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Design of an IoT-based microclimate monitoring system for shallots in a greenhouse

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ABSTRACT

Shallots (Allium ascalonicum L.) are a high-value vegetable commodity that is strategically important for the Indonesian economy. However, shallot cultivation, particularly watering and fertilization, is still largely done manually, requiring human labor and simple equipment, making it less efficient and prone to errors in environmental monitoring. This study aims to design an Internet of Things (IoT)-based shallot microclimate monitoring system in greenhouses to improve the efficiency of automatic environmental monitoring. The method used includes the development of an ESP32 microcontroller-based system integrated with soil moisture sensors, temperature sensors, and air humidity sensors, as well as a GSM/GPRS wireless communication module for real-time data transmission. The system is also equipped with an alarm module to provide early warnings of unsuitable environmental conditions. Test results show that the system is able to operate stably and effectively in automatically monitoring microclimate changes in greenhouses. In conclusion, this IoT-based monitoring system can support more efficient shallot greenhouse management and reduce reliance on manual monitoring.

Keywords : Microclimate, Monitoring system, Shallot, GPRS, GSM

INTRODUCTION

Shallots (Allium ascalonium) are categorized as a spice vegetable in horticultural agricultural commodities (Girsang et al., 2021). They function as a component of kitchen spices or flavorings (Dini & Laneri, 2021). Shallots are typically cultivated annually during the dry season, leading to uncertain supply constraints to meet domestic demand. This substantially impacts shallot price volatility.

Shallots can grow throughout the rainy season; however, this makes them highly susceptible to pests and diseases, and the risk of crop failure. Infestations of caterpillars and diseases such as anthracnose, fusarium wilt, and purple blotch caused by the fungus Alternaria porrii are widespread (Korlina et al., 2021). Increased incidence of fusarium wilt is influenced by inadequate soil moisture. Furthermore, soil moisture influences the pests that attack them. In addition to soil moisture, the spread of pests and diseases is also caused by residual precipitation that adheres to shallot plants.

One approach to reducing pest and disease attacks in shallot cultivation is to cultivate shallots in a greenhouse equipped with a microclimate monitoring system. Growing shallots in a greenhouse helps protect the plants from direct rain and prevents soil splashes from adhering to the shallots. One benefit of growing shallots in a greenhouse is the ability to control the moisture content of the growing medium and the microclimate, thus creating an optimal environment for shallot production (Askari-Khorasgani & Pessarakli, 2020).

The microclimate monitoring system is designed to determine the moisture level of the growing medium, as well as the temperature and humidity inside the greenhouse (Bhujel et al., 2020). The monitoring system is automated and scheduled. Observation data on microclimate parameters is measured and recorded periodically, and the data is then transmitted online. In future studies, microclimate measurement data can be used to establish fixed points for automated shallot irrigation systems and algorithms within the greenhouse.

Several previous studies have examined various aspects related to shallot cultivation and environmental monitoring. For example, research by Askari-Khorasgani & Pessarakli (2020) highlighted the benefits of greenhouses in controlling the moisture content of the growing medium and the microclimate to increase shallot yields. Bhujel et al. (2020) developed a sensor-based microclimate monitoring system to automatically measure temperature and humidity in greenhouses. Meanwhile, research by Pramudita et al., (2024) integrated IoT technology to monitor soil moisture in horticultural crops, but it has not been specifically applied to shallots in greenhouses. Furthermore, research by Gatkal et al., (2024) developed a microcontroller-based alarm system to detect critical environmental conditions in vegetable crops, but did not incorporate GSM/GPRS wireless communication for long-distance data transmission. Finally, research by Prasojo et al., (2024) examined the effect of soil moisture on pest attacks in shallots, but did not develop an integrated automated monitoring system. The review reveals a research gap related to the development of a shallot microclimate monitoring system in greenhouses that integrates soil moisture, temperature, and air humidity sensors with GSM/GPRS wireless communication technology for real-time monitoring and automatic alarming. The novelty of this research lies in the design of an ESP32 microcontroller-based system capable of automatic environmental monitoring, online data transmission, and early warnings via an alarm module. This can improve the efficiency of shallot greenhouse management and reduce reliance on manual monitoring.

Based on this background, this study aims to design and develop an Internet of Things (IoT)-based shallot microclimate monitoring system in greenhouses that can monitor soil moisture, temperature, and air humidity in real time and provide early warnings via an alarm module to support more efficient and optimal shallot cultivation management.

RESEARCH METHOD

This study was carried out in a thorough stage, including research design, mechanical and electronic design, instrumentation, and field testing in the greenhouse of the Sindang Sari experimental garden, Serang. Figure 1 depicts the study approach used in this research design.

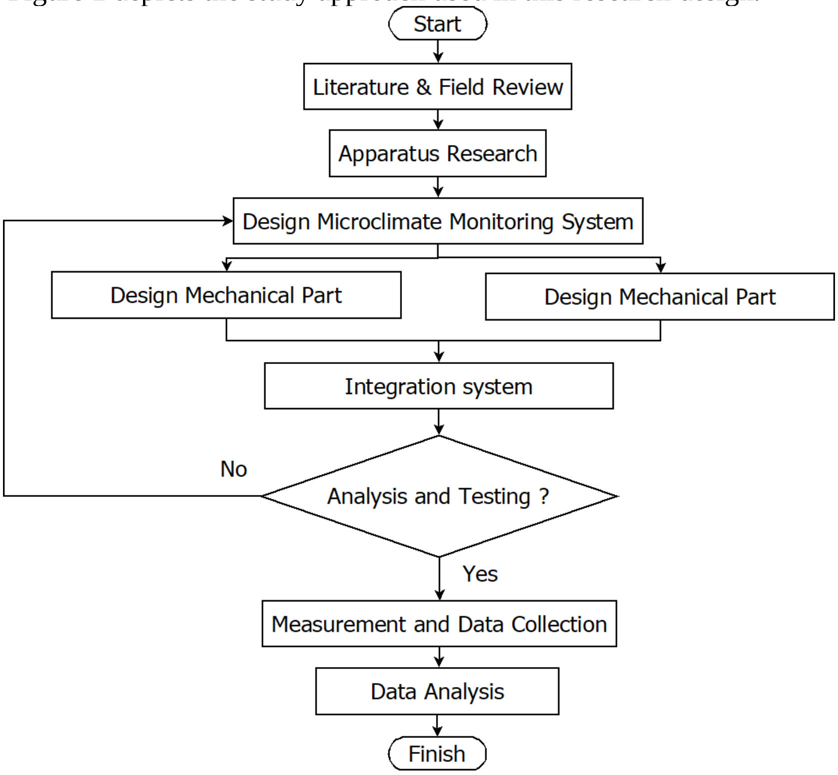

Figure 1. Research flow of design and testing of a microclimate monitoring system in shallot cultivation

Design Microclimate Monitoring System

Microclimate environmental monitoring is carried out utilizing a variety of integrated electronic devices and sensors that operate automatically (Bhujel et al., 2020). The microclimate monitoring system has been built around an ESP32 microcontroller, which serves as the core control system. The control system regulates the system's operation, communicates with electronic modules and sensors, processes data digitally, and manages data transmission.

In this study, microclimate characteristics were determined using various sensors, as needed. The AM2305 sensor with the characteristics shown in Table 1 was used to monitor air temperature (T) and relative humidity (RH), while soil moisture (SM) was measured using a resistive sensor with a value of 0-100%.

Table 1. AM2305 sensor specifications

Parameter	Resolution	Accuracy	Range	Unit
Temperature	0.1	±0.3	-40 – 125	°C
Relative humidity	0.1	±2	0 – 99.9	% RH

The control system has the capacity to send commands to the sensor for data reading and to execute commands to save data on internal media in the form of a micro-SD. Additionally, the control system is integrated with a Global System for Mobile Communication/ General Packet Radio Service (GSM/GPRS) SIM7000E modem that is capable of transmitting data in real time (Purbakawaca et al., 2022). The monitoring system is designed to operate for an extended period of time by incorporating a 12V/5A VRLA dry battery as its DC power source. The ABS plastic boxes are then used to install all electronic components. To prevent direct exposure to sunlight and moisture, the box is wrapped in plastic. In general, the microclimate monitoring system is built and assembled in accordance with the scheme depicted in Figure 2.

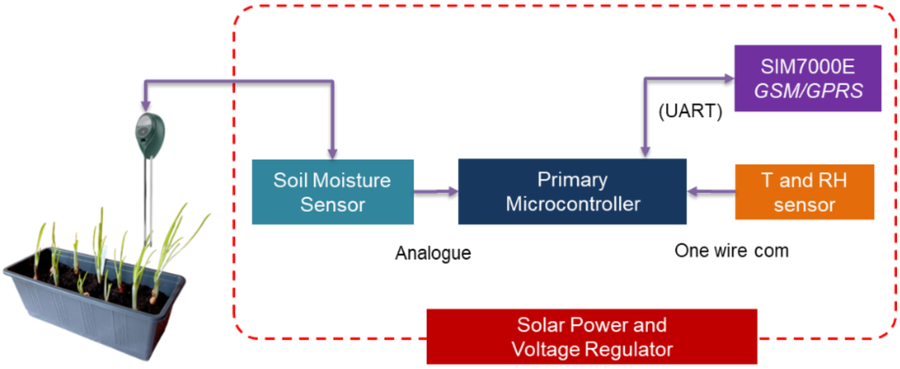

Figure 2. Block functionality diagram of a microclimate monitoring system

System Workflow and Testing

After the mechanical and electronic components are designed according to the scheme above, the control program development process is carried out. Algorithms and program codes are built using a software editor in the form of Arduino IDE. This platform was chosen because of its ease in developing programming codes and is an open-source platform that provides many libraries and is a public domain. The Arduino IDE gives complete programming and control over the ESP32 control chip, allowing for control system optimization (Manzanero-Vazquez et al., 2021).

Figure 3 illustrates the microclimate monitoring system's essential workflow. In general, the system serves three primary roles, the first of which is to collect sensor data for microclimate parameters. (2) Storing sensor data on internal storage media in txt file format, which was chosen for its ease of degradation on microSD card and because it is a generic file that can be read and opened by a variety of digital devices. Finally, (3) delivering data in real time via the internet network to enable fast and accurate measurements.

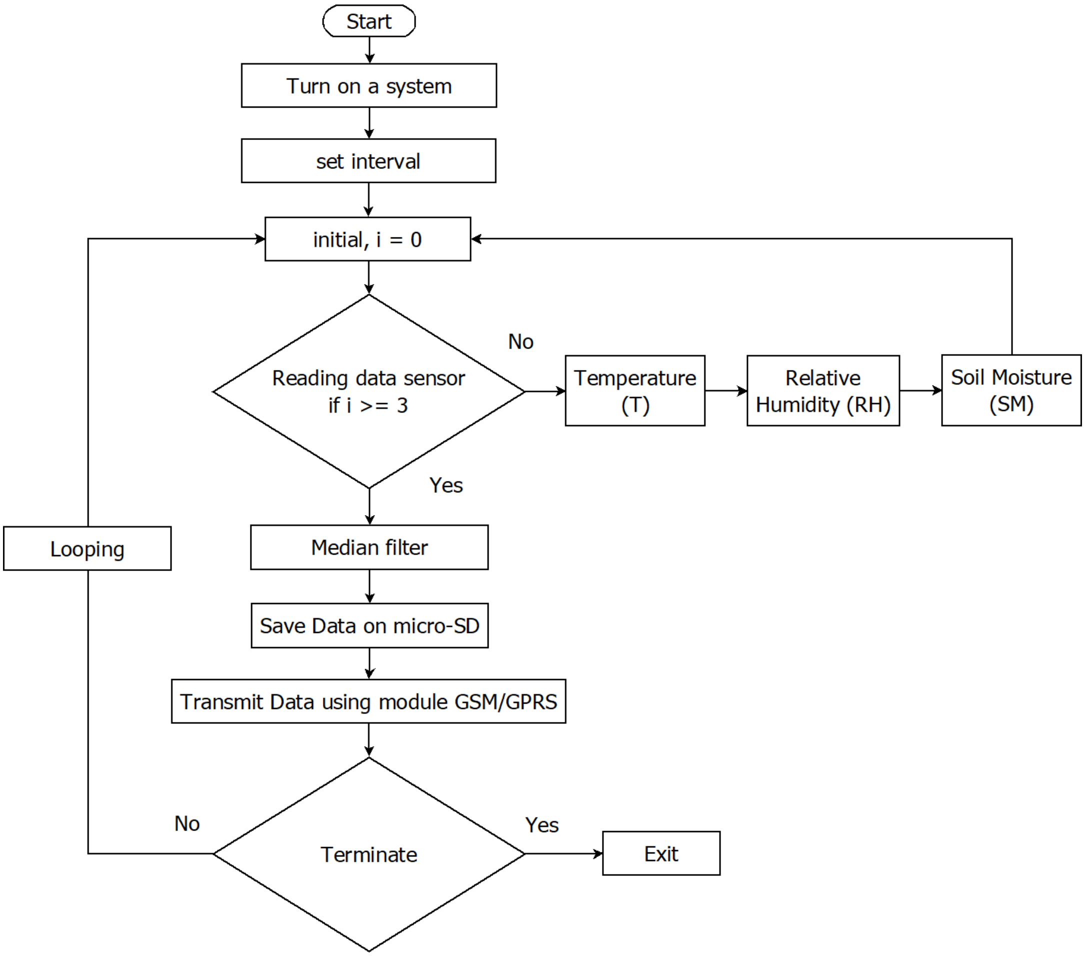

Figure 3 Microclimate monitoring system workflow scheme for shallot cultivation in the Sindang Sari Greenhouse, Serang.

This study employs a filter model utilizing a fixed point of a one-dimensional median filter with a window length of $(2k + 1)$ the input-output relationship is $\{y_n\} = MF_{(2k+1)}\{X_n\}$, where the one-dimensional median filter equation is as in equation 1 (Mai et al., 2025).

$$y_n = median(x_{n-k}, \ldots, x_n, \ldots, x_{n+k}) \quad (1)$$

To implement the aforementioned equation, sensor readings are collected periodically at specified intervals, completing three data sampling instances within a single process cycle.

RESULT AND DISCUSSION

Design of Microclimate Monitoring System

The ESP32 microcontroller uses the AM2305 one-wire sensor communication protocol to read temperature and relative air humidity sensors, meanwhile soil moisture sensors are obtained by digital processing of analog signals. Figure 4 shows the software segment for sensor reading. To improve accuracy, the total value of the sensor measurements is expressed as two decimal digits. Afterwards, the *rawDataSens* command is used to save the data from each sensor reading to an array. The purpose of storing data in an array is to enable it to be further processed.

```
  tempVal = readTemperature();
  RHVal = readRH();
  soilVal = readMoisture();
  Serial.printf("Sensor Mace : %.2f, %.2f, %.2f, %.2f \n", tempVal, soilVal, RHVal);


 for (uint8_t i = 0; i < buSize; i++) {
   tempVal = readTemperature();
   RHVal = readRH();
   soilVal = readMoisture();
   Serial.printf("Sensor Mace : %.2f, %.2f, %.2f, %.2f \n", tempVal, soilVal, RHVal);

   rawDataSens(i, tempVal, soilVal, RHVal);
   Serial.println("Raw data : ");
   printarraay(arrayTemp, arrayRH, arraySoil);
```

Figure 4 Sample code for reading temperature, relative humidity, and soil moisture sensors

The stored reading data in the array will initially be sorted in ascending order using the *insertionSort* command code. Furthermore, the sorted data is ascertained by identifying the median value, which is obtained from the sensor reading at the first array index using the *medianFilter* command code, as illustrated in Figure 5. The identification of this array index is contingent upon the quantity of data samples, namely three, obtained from the prior microclimate parameter measurement phase.

```
  insertionSort(arrayTemp);
  insertionSort(arraySoil);
  insertionSort(arraySoil);
  Serial.print("Data Sorted : \n");
  printarraay(arrayTemp, arrayRH, arraySoil);

  // Perhitungan nilai Median Filter
  medTemp = medianFilter(arrayTemp);
  medRH = medianFilter(arrayRH);
  medRH = medianFilter(arraySoil);

 Serial.printf("Median filter \n Temperature : %.2f   RH : %.2f   Soil Moisture : %.2f \n", medTemp, medSoil, medRH);
```

Figure 5. Sample code for sorting and running median filter

The program code for sending data to the server may be found in the main routine program section and includes the GSM/GPS modem command for connecting to the GSM network, GPRS connection settings, and data transmission to the server. Wireless data transmission uses GSM connectivity. GPRS was chosen for its network dependability, more uniform deployment of cellular networks, particularly in urban and rural areas, and more signal coverage than other wireless technologies. However, sending data over a cellular network costs more than alternative wireless techniques.

In addition to transferring data via the SIM7000E modem, the device stores data on internal microSD memory. Local storage ensures that no data is lost, particularly owing to data transmission errors in online acquisition data. Figure 6 shows a program fragment that uses the SIM7000E modem to transmit data from a microclimate monitoring device to a receiver both online and locally.

```
  savetoSD();
  cellularParam();
  showTimeLocal();
  runGPS();
  sendingData(medTemp, medRH, medSoil, "-6.52242", "106.84105", "150.0", "0.0");
```

Figure 6. Example code for connecting a monitoring system to the internet network, sending data in real time, and storing data locally and online

The assembled electronic components are placed in a box and powered by a VRLA battery. The monitoring system is subsequently installed in the greenhouse, as illustrated in Figure 7. The controller and sensor are put near the shallot cultivation pot; however, due to the restricted number of sensors, the number of pots or planting medium monitored using the soil moisture sensor is just one pot.

(a) (b) (c)

Figure 7 Microclimate monitoring system devices are placed in (a) plastic boxes, (b) controller boxes side shallot planting pots, and (c) controller boxes in greenhouses.

Testing The Performance of The Microclimate Monitoring System

The ESP32, serving as the central controller of the system circuit, will manage all input and output components depicted in Figures 2 and 3. Following the successful completion of the system function test and the absence of issues with the components, the installation of the microclimate monitoring system in the greenhouse commenced as seen in Figure 7. The sensor data acquired over multiple days in the field was assessed, as illustrated in Figure 8.

The graph in Figure 8 indicates that the data was accurately documented from August 26 to August 29, 2024. Temperature, air humidity, and soil moisture exhibit fluctuations that adhere to analogous patterns on each day. The graph demonstrates that the temperature increases in the morning, peaking at noon. Simultaneously, the temperature progressively declines in the afternoon, attaining its nadir in the early morning. The relative humidity in the greenhouse was found to decrease markedly in the morning, reaching its nadir at midday, followed by a substantial increase in the afternoon, culminating in a peak at night.

Temperature and relative humidity levels exhibit noticeable variations, displaying divergent patterns. The results of the descriptive analysis of temperature and humidity readings in the greenhouse are presented in Table 2. Temperature and humidity readings may provide confirmation of precipitation conditions at the greenhouse site on August 26, 2024. This is evidenced by a significant decrease in temperature and an increase in humidity during the day (see Figure 8 labeled "a"). Conversely, the air's relative humidity may reach 100% virtually all night, as the area surrounding the greenhouse is marked by significant vegetation cover (see Figure 8 labeled "b").

Figure 8 illustrates that soil moisture values increase in the morning, stabilize until the afternoon, and subsequently decline at night, only to rise again in the morning. The variation in soil moisture is attributable to scheduled manual watering conducted every morning and evening with a specific volume. According to the graphs in Figure 8 and Table 2, soil moisture fluctuations are quite consistent, exhibiting an average of 58.69% and a mean of 65%, with a range of 14.7%.

Utilizing microclimate measurement data, the attributes of the greenhouse microenvironment can serve as a reference for developing an automated, continuous, and scheduled irrigation system tailored to the water requirements of plants, contingent upon environmental conditions and planting media in shallot cultivation (Rafrin et al., 2024).

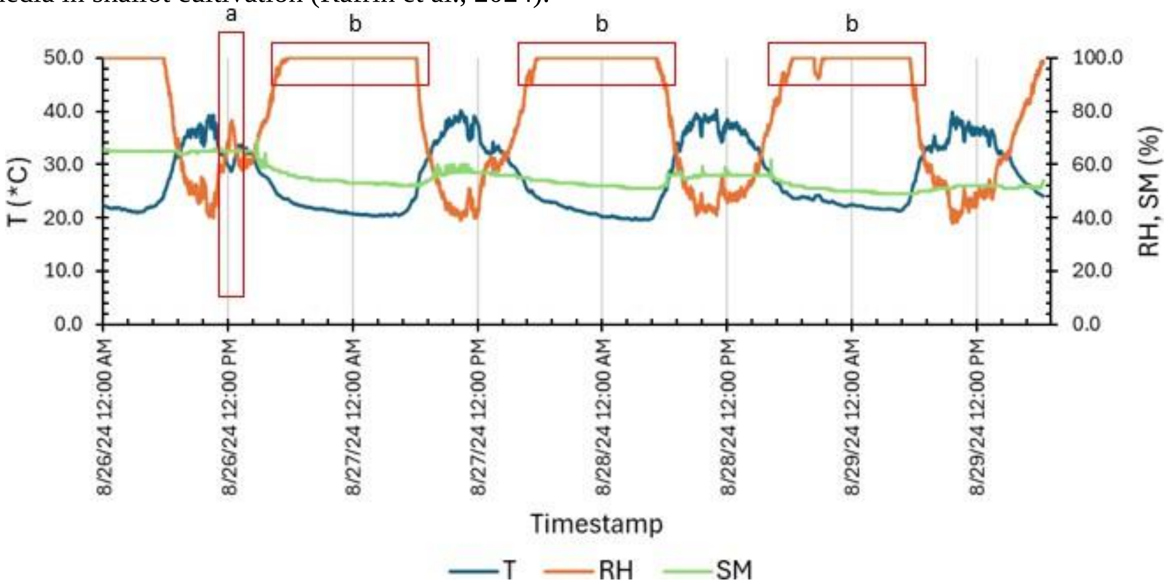

Figure 8. Sample code for sorting and running median filter

Table 2. Descriptive analysis of sensor readings for micro-climatic parameters in the greenhouse from August 26, 2024, to August 29, 2024.

Statistical Parameter	Temperature °C	Relative Humidity %	Soil Moisture %
Mean	27.21	81.70	58.69
Standard Error	0.07	0.25	0.09
Median	24.52	96.57	56.00
Mode	21.60	100.00	65.00
Standard Deviation	6.00	21.49	7.95
Range	20.68	62.15	14.70
Minimum	19.60	37.85	51.30
Maximum	40.28	100.00	66.00

The average temperature value was recorded at 24.52°C with a maximum value reaching 40.28°C and a minimum of 19.60°C, indicating a significant temperature fluctuation with a range of 20.68°C and a standard deviation of 6.00°C. This indicates a fairly wide daily temperature variation, which is in accordance with the pattern of temperature increases during the day and decreases at night. The relative humidity of the air showed a high average of 96.57%, with a maximum value reaching 100% and a minimum of 37.85%, and a range of 62.15%. The relatively large standard deviation of relative humidity, namely 21.49%, reflects significant humidity variations throughout the day, which are influenced by changes in temperature and environmental conditions in the greenhouse. For soil moisture, the average value was recorded at 56.00% with a maximum value of 66.00% and a minimum of 51.30%, and a relatively small range of 14.70%. The soil moisture standard deviation of 7.95% indicates that soil moisture is relatively more stable compared to air temperature and humidity, likely due to the influence of scheduled manual watering. Overall, these data illustrate dynamic and variable microclimate conditions in the greenhouse, yet soil moisture is maintained sufficiently to support shallot growth.

Discussion

This research successfully designed and implemented an ESP32 microcontroller-based microclimate monitoring system capable of reading real-time temperature, relative humidity, and soil moisture data in a shallot greenhouse. The use of AM2305 sensors for air temperature and humidity, along with a digitally processed soil moisture sensor, enabled data collection with two-decimal digit accuracy. The obtained data was then processed using insertion sort and median filtering to ensure data stability and reliability before being sent to a server via a GSM/GPRS network. The system also features local data storage on a microSD card to anticipate disruptions in online data transmission.

Key findings indicate that the system can record fluctuations in temperature and humidity that follow a consistent daily pattern, with temperatures peaking during the day and relative humidity dropping sharply at the same time. Soil moisture also exhibited a stable pattern, with variations influenced by manual watering schedules. These data confirm the system's ability to accurately monitor microclimate conditions and can serve as a basis for developing an automatic irrigation system that responds to environmental conditions.

This research aligns with the study by Dany'el Irawan et al., (2022) developed a sensor-based microclimate monitoring system for greenhouses, which automatically measures temperature and humidity. Furthermore, these results support the findings of Ofure et al., (2017), who emphasized the importance of controlling the moisture content of the growing medium and the microclimate in increasing shallot yields in greenhouses. Research by Laha et al., (2023) also demonstrated the effectiveness of using IoT technology in monitoring soil moisture in horticultural crops, which aligns with the application of soil moisture sensors in this system.

The implications of this research are significant for managing shallot cultivation in greenhouses. With an automated, real-time microclimate monitoring system, farmers can optimize irrigation settings and environmental conditions without the need for time-consuming and labor-intensive manual monitoring. This has the potential to increase water use efficiency and reduce the risk of pest and disease attacks influenced by inappropriate humidity conditions. Furthermore, locally and online data storage ensures data security and monitoring continuity.

The developed system also opens up opportunities for further integration with other automation technologies, such as sensor-based automatic irrigation systems that can dynamically adjust water volume according to plant needs. Thus, this research can serve as a foundation for the development of more sophisticated and integrated smart greenhouses. The use of GSM/GPRS networks as a data transmission medium also demonstrated advantages in terms of range and reliability, although operational costs must be considered.

However, this research has limitations, particularly in the number of soil moisture sensors monitoring only one plant pot. This may affect the representativeness of soil moisture data across the greenhouse. Therefore, future research is recommended to increase the number of soil moisture sensors to allow monitoring to cover a wider area and provide a more comprehensive picture of the growing medium's condition.

Furthermore, the development of more sophisticated data processing algorithms, such as the use of machine learning to predict irrigation needs and early detection of pest attacks based on microclimate patterns, could be a focus of future research. System integration with a mobile application could also improve data access for farmers and greenhouse managers.

Overall, this research makes a significant contribution to the application of IoT technology for precision agriculture, particularly in shallot cultivation in greenhouses. With accurate and automated microclimate monitoring, it is hoped that shallot productivity and quality can be increased, while reducing reliance on less efficient manual monitoring methods.

CONCLUSION

Extensive testing of the greenhouse microclimate monitoring system demonstrated its ability to continuously and in real time measure temperature, relative humidity, and soil moisture. This technique allows for accurate identification of microclimate conditions and provides data with high temporal precision, facilitating accurate documentation of microclimate variations over the measurement period. Therefore, further testing over a longer period is needed to characterize microclimate differences within the greenhouse, replicating the dry and rainy seasons. This longitudinal data can be used to accurately determine irrigation setpoints for shallot cultivation as the greenhouse climate fluctuates.

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