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Development of an automated monitoring system for soil moisture and temperature in smart agriculture to enhance lettuce farming productivity based on IoT

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Abstract In the era of advanced agriculture, implementing Internet of Things (IoT) technology has brought significant innovations to monitoring plant growth. This article discusses the development of an automation system to monitor soil moisture and temperature in lettuce farming based on smart agriculture. The system integrates soil moisture and temperature sensors connected in real-time through IoT, enabling accurate and continuous monitoring of the environmental conditions for lettuce cultivation. The soil moisture sensor used is YL-69 with the calibration equation y=-0.0612x+64.38 and an R-square value of 0.8953. The average standard deviation value is 0.36, and the average accuracy value is 98.71%. The temperature sensor used is DHT11 with the calibration equation y=0.9619x+2.8107 and an R-square value of 0.9928. The average standard deviation value is 0.023, and the average accuracy is 99.67%. The microcontroller used is ESP8266, known for its reliable connectivity. The IoT platform employed is the Blynk application. Monitoring results over five days yielded average soil moisture values ranging from 76% to 98%, and average temperature values ranged from 22°C to 27°C. Through continuous data collection, farmers can optimize irrigation, apply corrective measures for temperature fluctuations, and design more innovative farming strategies. The results of implementing this system demonstrate a significant improvement in resource efficiency, operational cost savings, and increased productivity in lettuce farming management.

Keywords: accuracy, calibration, sensor, smart farming, validation

1. Introduction

Modern agriculture increasingly incorporates technological innovations to enhance efficiency and productivity (Karar et al., 2021; Saad et al., 2020). IoT-based automation systems are pivotal in optimizing farm management (Katiyar & Farhana, 2021). IoT technology integrates various devices and sensors for real-time communication (Saikat et al., 2021), allowing farmers to monitor and control environmental parameters such as temperature, humidity, and soil conditions with greater accuracy and efficiency. These systems improve understanding of agricultural dynamics and facilitate the implementation of intelligent solutions like automatic irrigation, optimal planting schedules, and efficient resource management (Fernández-Ahumada et al., 2019). By leveraging this technology, agriculture becomes more adaptive, responsive, and sustainable, effectively addressing contemporary agricultural challenges with innovative and practical approaches. IoT technology also enables real-time data collection from distributed sensors across farmland, providing valuable information for more precise decision-making.

Integrating this technology enhances agricultural environmental monitoring and reduces reliance on intensive human supervision (Saad et al., 2020). With IoT-based automation, farmers can adapt to changes in farming conditions without being physically present. This saves time and reduces the human effort needed for conventional monitoring. Sensors and automation devices manage daily tasks, provide real-time updates, and even initiate corrective actions automatically. Consequently, farmers can allocate their time and resources more effectively, focus on tasks requiring human intervention, and enhance overall farming productivity (Wakchaure et al., 2020). The integration of agricultural technology optimizes management and offers farmers greater freedom and flexibility in their operations (Montoya et al., 2020).

The growing interest in lettuce is driven by increased public awareness of the importance of a healthy lifestyle (Giménez et al., 2020; Michelon et al., 2020). As a nutrient-rich green vegetable, lettuce is a top choice for individuals prioritizing a balanced diet. Its high fiber, vitamin, and mineral content provide a refreshing taste and appealing texture, significantly

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contributing to health (Smoleń et al., 2020). Nutrients such as vitamins A, C, and K and minerals like iron and calcium make lettuce a potent source of antioxidants that support bone health (Di Mola et al., 2020). The benefits of lettuce extend beyond physical health; they also improve mental fitness and aid in weight management. With ease of cultivation and year-round availability, lettuce is a delicious culinary choice and a key component in adopting a healthy and sustainable lifestyle (Shin et al., 2020).

Lettuce is highly responsive to environmental conditions, requiring proper soil moisture for root growth and efficient nutrient absorption (Baz et al., 2020). Controlled soil moisture also protects against plant stress that can affect the quality and quantity of the harvest (Michelon et al., 2020). Moreover, optimal environmental temperatures are crucial for photosynthesis, plant metabolism, and the healthy development of lettuce leaves (Alves et al., 2022). Accurate temperature control can also reduce disease risk and promote conditions that support the agricultural ecosystem balance. By understanding and closely monitoring these parameters, farmers can optimize lettuce growth conditions, increase productivity, and achieve high-quality harvests (Thorp et al., 2020).

While numerous studies have focused on monitoring soil moisture and temperature in lettuce cultivation (Ardiansah et al., 2020; Bella et al., 2021; Montoya et al., 2020; Schröder et al., 2021; Wayangkau et al., 2020), cultivation success depends on highly variable local factors. Some studies emphasize the need to customize farming techniques based on each region's geographical and climatic conditions. Weather, temperature, and soil moisture levels can fluctuate significantly, influencing the success of lettuce crops in specific locations (Kumar et al., 2019; Le Page et al., 2020; Ruslan et al., n.d.). Thus, in-depth knowledge of local conditions, weather forecasts, and soil resources is essential for designing successful farming strategies. Despite general guidelines, a regional and condition-specific approach is crucial for achieving optimal harvest results and enhancing plant resilience to unique environmental challenges.

The calibration process is critical to ensuring that sensors provide accurate and measurable data, especially when faced with complex environmental variations (Muthmainnah et al., 2023). Proper calibration guarantees the accuracy of soil moisture and temperature measurements, which are essential for monitoring lettuce growth. Sensor validation ensures data reliability and checks whether sensors provide consistent results with actual field conditions (Chaganti et al., 2022; Ferrag et al., 2021). This research generates accurate and reliable datasets through careful calibration and validation processes, paving the way for a better understanding of agricultural and environmental conditions and optimizing soil moisture and temperature sensor technology in smart agriculture.

The main objective of this research is to develop an automation system that can effectively monitor soil moisture and temperature in lettuce farming based on smart agriculture. By integrating connected sensors with an IoT platform to provide more detailed data, farmers can design more adaptive and efficient farming strategies. This research also discusses the calibration and validation of the sensors used: soil moisture and temperature. The success of this research is expected to significantly contribute to the development of modern agricultural technology, particularly in improving the efficiency of lettuce farming production. By profoundly understanding plant needs through automated monitoring, it is hoped to create an optimal growth environment, reduce resource waste, and ultimately advance the agenda of sustainable agriculture.

2. Materials and Methods

2.1. Electronic components

The soil moisture sensor employed is the YL-69, chosen for its durability and resistance to the harsh environmental conditions of farming, ensuring consistent long-term performance (Bodunde et al., 2019). Its user-friendly installation and compatibility with various electronic systems simplify the integration process. The temperature sensor used is the DHT11, selected for its ability to operate over a wide temperature range, which offers flexibility for different climatic conditions (Irawan et al., 2021). Additionally, its capability to detect humidity and temperature makes it an efficient solution, eliminating the need for multiple sensors (Gaikwad et al., 2021). The microcontroller used is the ESP8266, which provides reliable WiFi connectivity for real-time data transmission to monitoring platforms or servers, enhancing flexibility in remote access and control of the agricultural monitoring system (Ramirez et al., 2020). The IoT platform employed is Blynk, known for its intuitive user interface that accommodates users of varying skill levels and ensures data security through authentication and encryption (Priyanka & Reji, 2019; Serikul et al., 2018).

2.2. Research design

The YL-69 and DHT11 sensors are connected to the input pins of the ESP8266 microcontroller and are powered by a 3.3V supply from the same device. The 12x6 I2C LCD, which connects to the ESP8266 via the SDA and SCL pins (GPIO21 and GPIO22), and the water pump attached to a relay and an IC regulator require a 5V power supply. All monitoring results are displayed on the LCD and transmitted to a smartphone via WiFi. The layout of this configuration is detailed in Figure 1.

The YL-69 and DHT11 sensors will measure the moisture and temperature conditions of the lettuce planting area. These signals will be sent to the ESP8266, which will then compare the data with the specified setpoint. When the soil moisture is low, the ESP8266 will signal to activate the water pump. Once the soil moisture reaches the specified conditions, the ESP8266 will signal to turn off the water pump. Additionally, the ESP8266 will send the monitoring results to the LCD for display.

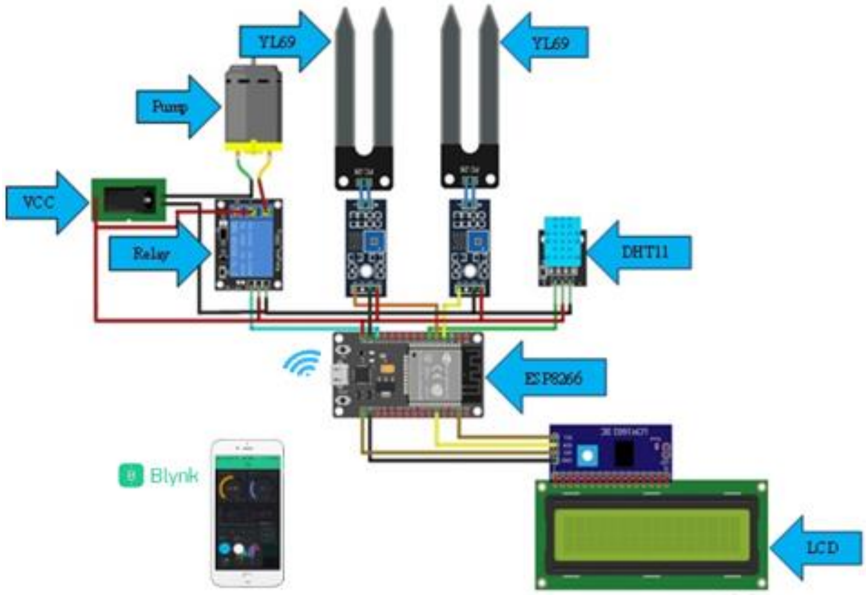

Figure 1 Circuit diagram scheme.

2.3. Procedures

Calibrating and validating the soil moisture and temperature sensors are essential for accurately monitoring the environmental conditions affecting lettuce growth. Calibration establishes a relationship between the sensor output and the actual measured quantity, which is crucial for the well-being and health of the lettuce (Feng et al., 2020). Validation involves comparing the sensor output with reference tools—a Mediatech brand soil meter for soil moisture and a digital thermometer for temperature—to assess the sensors' precision and accuracy. Precision is typically evaluated using the standard deviation formula (Equation 2), and accuracy is determined by Equation 3 (Liu et al., 2022). These processes are critical to guaranteeing the reliability of data obtained from the sensors.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} \text{Xi} \qquad (1)$$

$$sd = \sqrt{\frac{\sum_{i=1}^{n}(Xi-\bar{x})^2}{n-1}} \qquad (2)$$

$$\%\text{Accuracy} = 100\% - \left|\frac{\text{reference}-\text{sensor}}{\text{reference}}\right| \text{x } 100\% \qquad (3)$$

3. Results and Discussion

This device uses soil moisture and temperature sensors to monitor conditions essential for lettuce growth continuously. When soil moisture reaches 76%, the ESP8266 microcontroller activates the water pump to start irrigation. This process continues until soil moisture levels hit 98% when the pump is deactivated. Parameters such as soil moisture and environmental temperature are displayed on the device's LCD screen and can be accessed through a smartphone using the Blynk platform (Figure 2). This system transmits data in real time and stores it for future reference, providing a structured, automated solution for managing optimal soil moisture and reducing human intervention.

Figure 3 displays the regression graph between the sensor output and its reference. The x-axis shows the results from the sensor, while the y-axis shows measurements from the reference device. It is observed that the output of the soil moisture sensor follows the equation y = -0.0612x + 64.38, with an R-squared value of 0.8953. The calibration results for the temperature sensor yield the equation y = 0.9619x + 2.8107, with an R-squared value of 0.9928. These equations demonstrate the linear relationship between the sensor outputs and the valid values, indicating high precision in the measurements and recording data. Calibration processes enable the correction or re-measurement of sensor outputs to align with valid values, enhancing the precision and accuracy of the sensor measurements (Qiu & Ostfeld, 2021; Perkasa et al., 2021; Hasan et al., 2021).

Figure 4 shows the validation results for the soil moisture sensor (a) and the temperature sensor (b). The orange represents the measurements from the reference device, while the blue represents those conducted by the sensor. The overlap of these measurements indicates their similarity, demonstrating the reliability and accuracy of the sensors in reproducing data akin to that of the reference device. This validation enables farmers to accurately measure temperatures and take corrective measures, such as adjusting shading or cooling systems, to ensure optimal growth conditions for lettuce (Al-Agele et al., 2022; Ferrag et al., 2021).

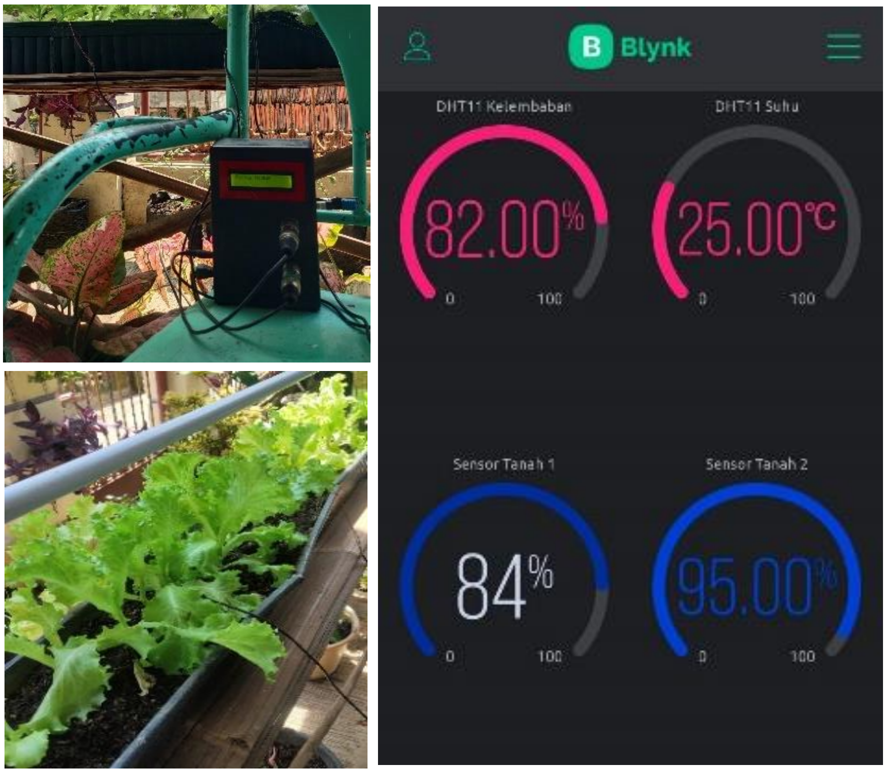

Figure 2 Measurement display on LCD and Blynk.

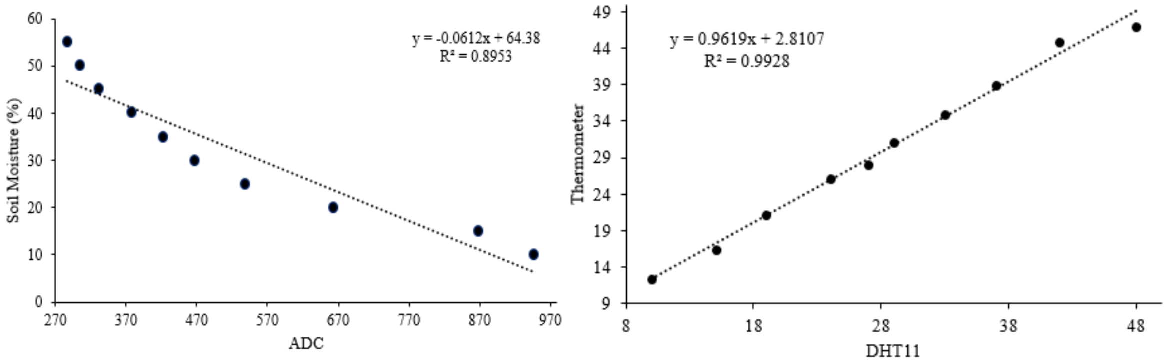

Figure 3 Calibrate soil moisture (a) and temperature (b).

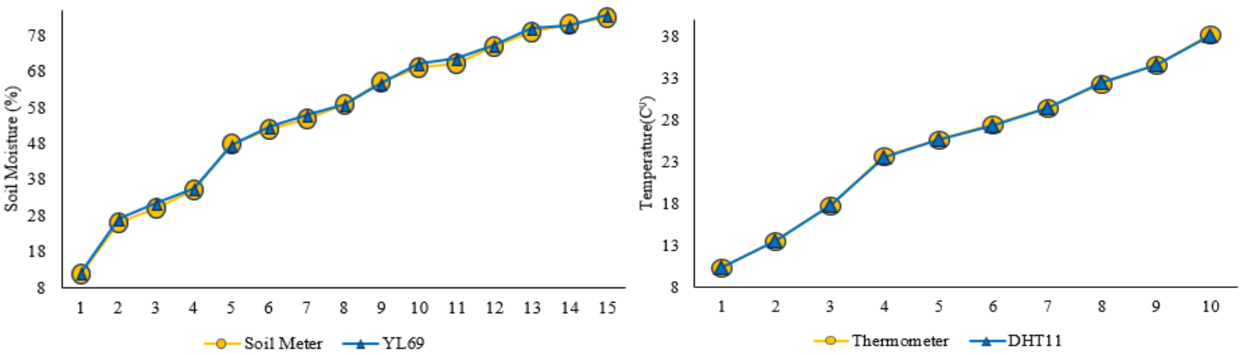

Figure 4 Validation of soil moisture (a) and temperature (b).

Figure 5(a) illustrates the distribution of standard deviation values in each measurement, with the blue color representing the soil moisture sensor's standard deviation, averaging 0.36, and the orange representing the temperature sensor's, averaging 0.023. These values suggest a high level of consistency in the data distribution, indicating that most data points are closely clustered around their mean values (Lakshmeesha et al., 2020; Jeon et al., 2002). Figure 5(b) depicts the distribution of accuracy values for the sensor measurements. The blue color indicates the accuracy of the soil moisture sensor at 98.71%, and the orange represents the temperature sensor's accuracy at 99.67%. These high accuracy percentages reflect the sensors' precision in generating accurate data.

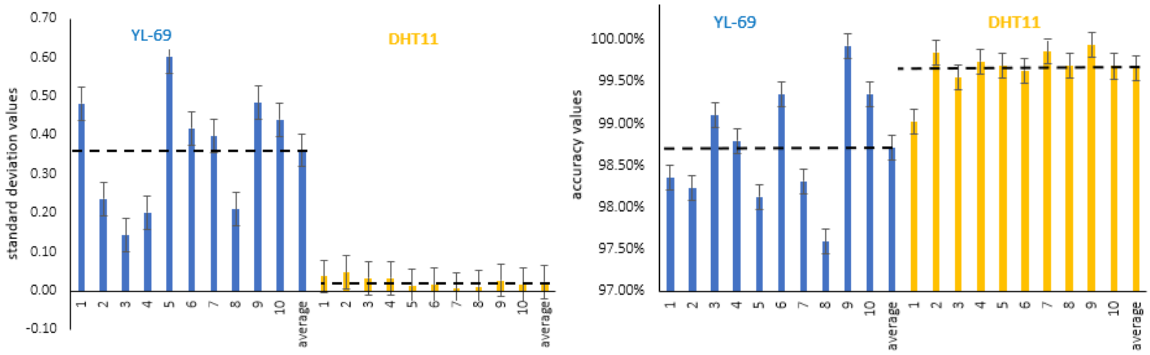

Figure 5 (a) distribution of standard deviation values (b) distribution of accuracy values.

Figure 6 monitors soil moisture over five days, showing levels between 76% and 98% that align with the optimal conditions for lettuce growth. This range supports an environment conducive to healthy growth. The variations in soil moisture, although fluctuating from 98% to 76%, are not significantly large and are explained by the rainy weather contributing to high humidity levels. Additionally, the moderately cool temperatures provide ideal conditions for plant growth without the risk of drought (Bekier et al., 2022).

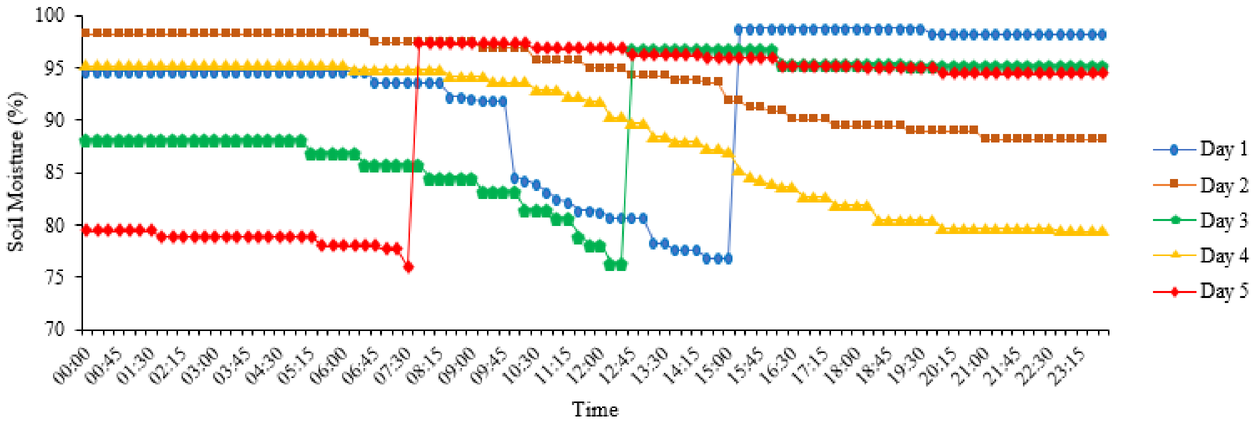

Figure 6 Soil moisture monitoring over five days.

Figure 7 displays temperature monitoring results over five days, with readings ranging from 22°C to 27°C, suitable for lettuce growth. Despite variations, the temperature increase is not pronounced, likely mitigated by the rainy season's cooler weather. These conditions create a comfortable environment for lettuce plants, reducing the risk of heat stress and supporting optimal growth. The stable temperature range is crucial as it fosters an ideal climate for photosynthesis and cellular activities, ensuring the plants remain vigorous and healthy. This steady climate helps maintain the internal processes of the lettuce, which is sensitive to extreme temperature shifts, thereby promoting better yield and quality of the crops (Meng et al., 2020).

With real-time information provided by soil moisture sensors, farmers can accurately optimize irrigation, avoiding over- or under-irrigation that often leads to issues in plant growth. Well-calibrated temperature sensors allow continuous monitoring of environmental temperatures, aiding in identifying temperature fluctuations that could impact lettuce growth. Accurate measurements from these sensors help reduce plant stress caused by suboptimal environmental conditions, enabling early detection and necessary care to prevent harvest loss. Furthermore, using these sensors supports resource conservation by optimizing water and energy use, improving agricultural planning, and adapting farming methods based on sensor data. This integration makes lettuce farming more innovative, efficient, and sustainable (Tomaz et al., 2020).

The application of soil moisture and temperature sensors significantly enhances productivity and supports better planning and decision-making in managing agricultural land. The collected data forms the basis for farmers to effectively plan crop rotations, determine optimal planting times, and adapt farming methods to environmental conditions, thus improving operational efficiency and crop yields. By leveraging this data, farmers can design innovative and responsive farming strategies, creating a robust foundation for sustainability and long-term success in agriculture (Pinto et al., 2020; Yu et al., 2020).

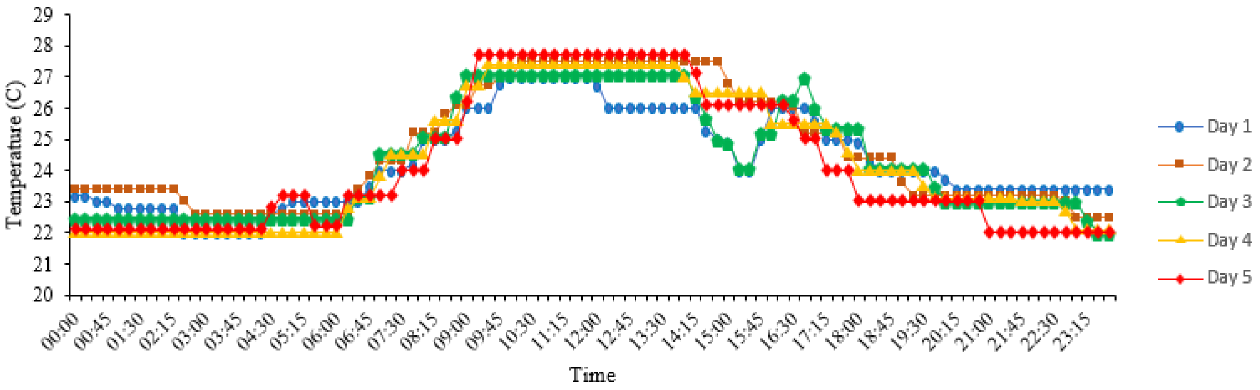

Figure 7 Temperature monitoring over five days.

Based on the data presented from five days of temperature and soil moisture measurements, the conditions that were significantly obtained support the growth of lettuce plants. Soil moisture maintained within the range of 76% to 98% and stable environmental temperatures between 22°C and 27°C indicate that the critical parameters for the growth of lettuce plants have been well achieved. From this data, we can compare with previous studies where optimal soil moisture and stable temperatures are crucial factors for maximizing the growth and quality of lettuce plants (Felipe & Bareng, 2022; Lee et al., 2015). These findings are consistent with previous research that shows that good humidity and temperature control can enhance photosynthesis activity and reduce plant stress, ultimately contributing to improved quality and quantity of the harvest (Choi et al., 2000; Liu et al., 2022).

The success in maintaining soil moisture and temperature within the ideal range highlights the importance of using sensor technology in agriculture. Controlling moisture and temperature sensors integrated into an irrigation automation system, controlled by the ESP8266 microcontroller, shows great potential in more precise agricultural environment management. This helps optimize water and energy resources and provides real-time and accurate data for decision-making in agriculture (Tomaz et al., 2020).

The implications of these findings are highly relevant in modern agriculture, which is increasingly moving towards smart farming practices. The integration of sensor technology and automation in agricultural management allows farmers to enhance efficiency and adapt to unexpected changes in climate conditions, which in turn can increase the sustainability of farming practices. Additionally, using an appropriate and efficient irrigation system can help reduce resource waste and minimize negative environmental impacts (Pinto et al., 2020; Yu et al., 2020).

This research contributes significantly to the development of technology in lettuce farming. It opens up opportunities for further studies to explore the effects of other environmental parameters, such as light intensity and soil nutrition, on plant growth. Furthermore, the research underscores the importance of accurate sensor validation and calibration to ensure the reliability of the data obtained, which is essential in precision agriculture management.

Despite the positive outcomes, this study's limitations include variability in natural environmental conditions that could impact the generalizability of the findings. Future research should focus on developing more precise predictive models for different environmental conditions and lettuce varieties and evaluating the effectiveness of environmental control technologies that dynamically adjust to changing weather and climate conditions.

4. Conclusions

The average standard deviation values for the soil moisture sensor are 0.36, with an average accuracy rate of 98.71%. Meanwhile, the average standard deviation values for the temperature sensor are 0.023, with an average accuracy rate of 99.67%. The five-day monitoring results revealed average soil moisture ranging from 76% to 98% and an average temperature ranging from 22 °C to 27 °C. Developing an automated soil moisture and temperature monitoring system in IoT-based smart agriculture positively impacts lettuce farming management productivity. Integrating IoT technology in monitoring creates intelligent solutions that can enhance efficiency and responsiveness in agricultural management. The data collected by the sensors can provide a better understanding of farming conditions, enabling more precise decision-making. Moreover, the successful implementation of this system affirms that modern agriculture increasingly involves innovative technology to achieve optimal productivity. Using automation technology in the context of lettuce farming opens opportunities to improve crop quality and resource utilization efficiency. Therefore, developing IoT-based automation systems in agriculture significantly contributes to overall improvements in farming management and productivity.

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Ethical considerations

Not applicable.

Conflict of Interest

The authors declare no conflicts of interest.

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