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IoT-Integrated Monitoring System for Environmental Parameters in a Rice Seedling Greenhouse Using ESP32

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Abstract – *The application of Internet of Things (IoT) technology in modern agriculture has become increasingly important for improving efficiency, productivity, and environmental monitoring. This study presents the design and implementation of an ESP32-based IoT monitoring system for a rice seedling greenhouse. The proposed system was developed to monitor multiple environmental parameters simultaneously, including temperature, soil moisture, pH, and Total Dissolved Solids (TDS) of the nutrient solution. The research employed a Research and Development (R&D) approach involving system requirement analysis, hardware and software design, implementation, IoT integration, and performance evaluation. The hardware architecture consists of an ESP32 microcontroller, DS18B20 temperature sensor, soil moisture sensor, pH sensor, TDS sensor, and an I2C LCD for local data visualization. Sensor data are transmitted via WiFi using the HTTP protocol and displayed in real time through a web-based monitoring platform. Experimental results demonstrated that the developed system successfully acquired, processed, and transmitted environmental data continuously to the monitoring server. Analysis of the collected data showed soil moisture values ranging from 47.8% to 59.1%, temperature values between 28.13°C and 31.69°C, TDS values from 118.22 ppm to 138.02 ppm, and pH values between 3.27 and 13.78. The results also revealed an inverse relationship between temperature and soil moisture, indicating the influence of environmental temperature on water evaporation within the growing medium. Furthermore, the monitoring platform enabled real-time remote supervision and historical data storage, supporting data-driven decision-making for greenhouse management. Overall, the proposed system demonstrates the effectiveness of integrating electronic sensing devices and IoT technology to support smart agriculture applications in rice seedling cultivation.*

Keywords – *Internet of Things (IoT); ESP32; Smart Agriculture; Rice Seedling Greenhouse; Environmental Monitoring.*

I. Introduction

THE modern agricultural sector has experienced significant advancements through the implementation of automation technologies and the Internet of Things (IoT). These technologies enable real-time, accurate, and internet-connected monitoring and control of agricultural environments [1, 2]. Digital transformation in agriculture has become an essential component of smart agriculture, aiming to improve productivity, resource-use efficiency, and crop quality [3]. One of the applications of these technologies is in rice seedling greenhouses, where stable environmental conditions are required to support optimal seedling growth.

Rice nurseries represent a critical initial stage that significantly influences the subsequent growth and productivity of rice plants [4, 5]. High-quality seedlings contribute directly to improved crop performance after transplantation to the main cultivation field. Environmental parameters such as temperature, growing media moisture, and water nutrient quality play important roles in determining nursery success [6]. Instability in these environmental parameters may result in uneven seedling growth, reduced germination rates, and physiological disorders in plants [7, 8]. Conventional manual monitoring often leads to delayed observations, inconsistent data collection, and inefficient greenhouse management, particularly when multiple monitoring points are involved.

The development of WiFi-enabled microcontrollers such as the ESP32 provides an effective solution for implementing IoT-based monitoring systems with relatively low cost and reliable communication capabilities [9, 10]. The ESP32 is capable of sensor data acquisition, data processing, and real-time transmission to remote servers through internet connectivity [11, 12]. The integration of sensor technologies

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with IoT enables users to remotely monitor greenhouse conditions through web-based platforms. Furthermore, the ESP32 supports flexible system development due to its relatively high processing capability, integrated wireless communication features, and low power consumption [10].

Research on smart greenhouses and IoT-based agriculture has grown considerably in recent years. Several studies have developed greenhouse monitoring systems using temperature and humidity sensors integrated with Arduino and NodeMCU platforms to monitor plant environmental conditions remotely [13,14]. Other studies have implemented wireless sensor network-based monitoring systems supported by cloud computing technologies for agricultural environmental monitoring. In addition, ESP32 has been utilized as a data acquisition platform for hydroponic monitoring systems and automated irrigation applications [15, 16].

Despite these developments, several limitations identified in previous studies provide opportunities for further research. Most existing studies focus on monitoring a single parameter, such as temperature or humidity, and therefore cannot provide a comprehensive representation of greenhouse environmental conditions [11, 14]. Other studies have employed multiple sensors; however, they have not been optimally integrated with web-based monitoring platforms capable of providing real-time visualization and historical data storage [17–19]. Furthermore, some monitoring systems still rely on microcontrollers with limited communication capabilities, requiring additional modules to establish internet connectivity [20]. Research specifically addressing IoT-based monitoring systems for rice seedling greenhouses also remains limited compared to applications in horticultural and hydroponic cultivation systems.

Based on these challenges, this study aims to develop an ESP32-based monitoring system for rice seedling greenhouse applications capable of simultaneously monitoring multiple environmental parameters, including temperature, growing media moisture, and water nutrient quality. The proposed system integrates both electronic and IoT components comprehensively, covering sensor data acquisition, data processing, local display through an I2C LCD, and real-time data transmission to a web-based monitoring platform. Therefore, this research is expected to contribute to the development of a more integrated, efficient, and practical IoT-based smart greenhouse monitoring system suitable for modern rice nursery applications.

II. Research Methods

This study employed a Research and Development (R&D) approach to design and develop an Internet of Things (IoT)-based greenhouse monitoring system. The R&D method was selected because the research focused not only on theoretical analysis but also on the design, implementation, testing, and evaluation of an electronic monitoring system integrated with IoT technology. The research stages consisted of identifying the requirements of a rice seedling greenhouse monitoring system, designing the hardware and software, implementing the system, integrating IoT communication, and evaluating the overall system performance.

Figure 1 illustrates the research flowchart used in this study. At the initial stage, system requirements were identified based on environmental parameters affecting rice seedling growth in the greenhouse. The primary parameters monitored included temperature, growing media moisture, pH, and Total Dissolved Solids (TDS) of the nutrient solution [21,22]. Based on these requirements, a monitoring system was designed using an ESP32 microcontroller as the main processing unit due to its built-in WiFi capability, which supports direct internet communication.

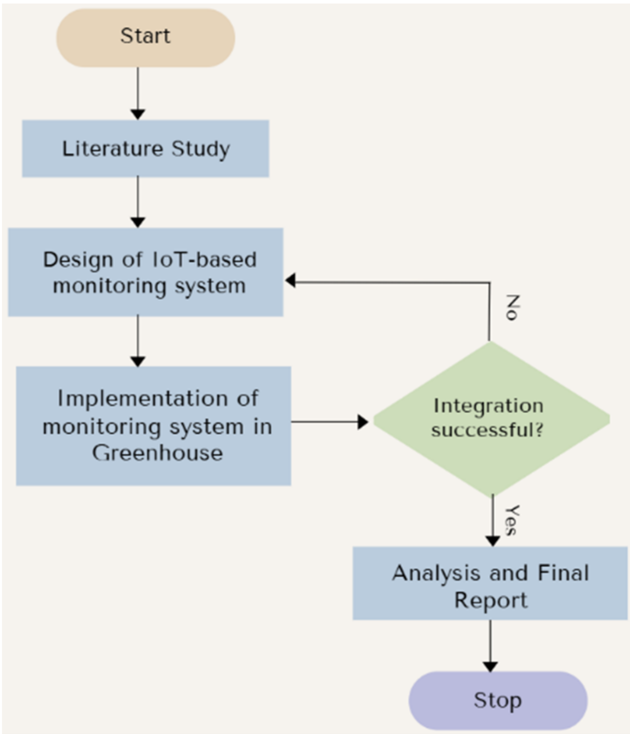

Figure 1: Research flowchart of the study.

The next stage involved the implementation of both hardware and software components of the monitoring system. After the system was successfully developed, IoT integration was performed by connecting the monitoring device to a web-based platform, enabling real-time visualization of sensor data through the internet. Finally, system testing was conducted to evaluate the performance of the electronic devices, communication reliability, and web-based monitoring functionality.

i. Greenhouse Monitoring System Design

The hardware design was developed by integrating several sensors and supporting modules into the monitoring system. A DS18B20 temperature sensor was used to measure greenhouse temperature, while a soil moisture sensor was employed to monitor the moisture content of the growing medium. In addition, pH and TDS sensors were utilized to assess the quality of the nutrient solution. All sensor data were acquired and processed by the ESP32 microcontroller and displayed locally through an I2C LCD module.

Figure 2 presents the overall schematic of the proposed monitoring system. The electronic circuit was designed with consideration for sensor measurement stability and communication reliability. The DS18B20 sensor utilizes a One-Wire communication protocol and requires a pull-up resistor to ensure stable data transmission. Meanwhile, the soil moisture, pH, and TDS sensors provide analog output signals that are read through the analog input channels of the ESP32. Furthermore, a circuit breaker was incorporated into the electrical system to enhance operational safety and protect the electronic components from electrical faults.

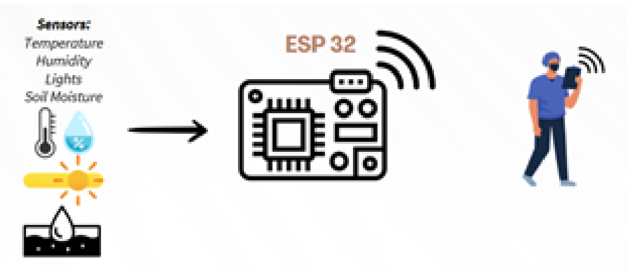

Figure 2: Overall schematic of the proposed monitoring system.

Software development was carried out using the Arduino IDE with C++ programming language. The software running on the ESP32 is responsible for sensor initialization, periodic data acquisition, data processing, local display management, and transmission of monitoring data to the server through an internet connection. Data communication between the ESP32 and the monitoring server was established via a WiFi network using the HTTP protocol.

The monitoring system was designed to provide continuous data communication through the internet. The ESP32 acts as both the data acquisition unit and the communication gateway between the sensors and the monitoring server. Sensor readings are transmitted to the database server and subsequently visualized on a web-based monitoring dashboard in real time.

ii. IoT Integration and System Testing

IoT integration was achieved by connecting the monitoring system to a web-based platform, allowing sensor data to be accessed in real time through a web browser. The monitoring website serves as a visualization platform for greenhouse environmental conditions and as a repository for historical monitoring data. Through this platform, users can remotely monitor greenhouse conditions using computers, tablets, or smartphones connected to the internet.

The testing phase was conducted to evaluate the overall performance of both the electronic hardware and IoT communication system. Performance tests were carried out on the DS18B20 temperature sensor, soil moisture sensor, pH sensor, and TDS sensor to assess the stability and consistency of sensor readings. In addition, communication tests between the ESP32 and the monitoring server were performed to verify successful real-time data transmission.

The web-based monitoring interface was also evaluated to ensure that sensor data could be accurately displayed on the monitoring dashboard. Furthermore, continuous operation tests were conducted to assess the stability and reliability of the system during prolonged greenhouse monitoring activities. The collected test data were subsequently analyzed to determine the effectiveness of integrating electronic monitoring devices with IoT technology for real-time monitoring of rice seedling greenhouse conditions.

III. Results and Discussion

The developed system was implemented and tested in a rice seedling greenhouse environment, as shown in Figure 3. The implementation results demonstrate that the monitoring system was successfully developed and integrated with an IoT network. The ESP32 microcontroller was capable of acquiring data from all sensors and transmitting the collected information to the monitoring server in real time.

The developed monitoring system consists of four main subsystems: a sensor data acquisition system, a WiFi-based data communication system, a local data visualization system using an LCD display, and a web-based monitoring system. The use of ESP32 provided stable communication performance for transmitting greenhouse monitoring data to the server.

Figure 3: Integration of the monitoring system in the greenhouse.

(a) (b) (c)

Figure 4: Operational electronic monitoring system: (a) LCD display integrated with the ESP32-based control panel, (b) installation of pH, temperature, and TDS sensors, and (c) placement of the soil moisture sensor.

i. Electronic System Performance

This subsection discusses the performance of the individual electronic components, including the temperature, soil moisture, pH, and TDS sensors, as well as the local display module. The DS18B20 sensor was able to measure greenhouse temperature consistently and demonstrated better resistance to electrical noise compared to conventional analog sensors. The implementation of a pull-up resistor on the data line ensured stable One-Wire communication between the sensor and the ESP32. Temperature data served as a critical parameter for monitoring rice seedling growth conditions, as excessive temperatures may negatively affect seedling development. Therefore, continuous temperature monitoring is essential for maintaining optimal greenhouse conditions.

Figure 4 shows the operational electronic monitoring system installed in the greenhouse. The soil moisture sensor was utilized to measure the moisture content of the planting medium. The sensor generated an analog signal that was converted through the ESP32's Analog-to-Digital Converter (ADC). Experimental results showed that changes in media moisture produced corresponding variations in output voltage that could be accurately detected by the system. The collected moisture data enabled operators to assess the condition of the planting medium and determine appropriate irrigation requirements.

The TDS and pH sensors were employed to measure nutrient concentration and acidity levels in the nutrient solution, respectively. These parameters are particularly important in hydroponic greenhouse systems and seedling nurseries that rely on nutrient solutions for plant growth. Monitoring TDS and pH helps maintain nutrient quality within the optimal range required for rice seedling development.

The sensors used in this study were factory-calibrated and underwent functional verification before installation in the greenhouse system. To ensure the reliability of the monitoring system, all sensors were calibrated and validated prior to system deployment in the greenhouse environment. The DS18B20 temperature sensor was evaluated by comparing its readings with a commercially available digital thermometer under similar environmental conditions. Likewise, the pH and TDS sensors were calibrated using standard reference solutions according to the manufacturer's recommendations before being integrated into the monitoring system. The soil moisture sensor was also tested under varying moisture conditions to verify its response consistency.

The validation process indicated that all sensors responded consistently to changes in the measured parameters and produced stable readings throughout the monitoring period. The DS18B20 sensor demonstrated stable temperature measurements without significant fluctuations, while the pH and TDS sensors showed responses that were consistent with changes in nutrient solution conditions. Similarly, the soil moisture sensor exhibited a gradual response corresponding to variations in water content within the growing medium.

During the greenhouse operation, the sensor readings remained within reasonable ranges for rice seedling cultivation and showed logical relationships among the monitored variables. For example, increasing temperature tended to be accompanied by decreasing soil moisture levels, indicating that the sensors were capable of capturing actual environmental changes occurring inside the greenhouse. These observations suggest that the developed monitoring system provides sufficiently reliable measurements for real-time greenhouse monitoring applications.

Although the obtained results demonstrate satisfactory sensor performance, periodic calibration is recommended, particularly for the pH and TDS sensors, to maintain measurement accuracy during long-term operation in greenhouse environments.

The I2C LCD successfully displayed monitoring parameters locally while requiring fewer microcontroller pins compared to conventional parallel LCD modules. The use of I2C communication also reduced wiring complexity, resulting in a simpler and more practical installation process.

ii. IoT System Performance

This subsection presents the performance of the IoT communication system and the web-based monitoring platform during real-time greenhouse operation. The ESP32 successfully connected to the WiFi network and transmitted sensor data to the monitoring server. The transmitted parameters included temperature, soil moisture, pH, and TDS values. IoT communication enabled real-time monitoring without geographical limitations, allowing users to access greenhouse data through smartphones, tablets, or computers connected to the Internet.

The web-based monitoring platform successfully displayed greenhouse parameters in real time. The monitoring dashboard provided an intuitive interface for observing greenhouse conditions through graphical visualization and numerical sensor readings. The implementation of a web-based platform improved operational flexibility because greenhouse supervision could be performed remotely. Furthermore, historical data storage enabled trend analysis and supported decision-making processes related to greenhouse management.

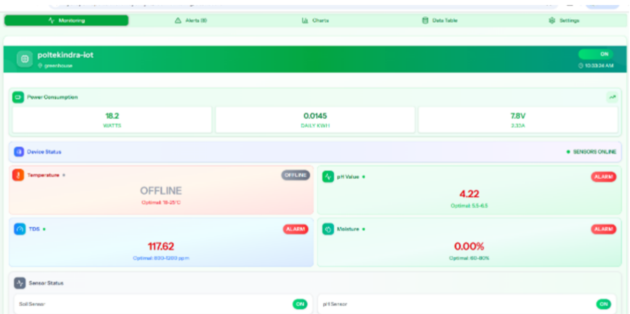

Figure 5: IoT-based monitoring website interface.

Figure 5 presents the IoT-based monitoring website interface. The testing results indicated that the monitoring system could operate continuously as long as an internet connection was available.

To evaluate the monitoring performance, four key parameters—soil moisture, pH, TDS, and temperature—were continuously recorded through the monitoring website. Sampling data were collected from 04:05 WIB to 06:45 WIB at 10-minute intervals. The monitoring results are presented in Table 1.

Based on the collected data, soil moisture values ranged from 47.8% to 59.1%, with an average value of approximately 52.4%. These values remained within the acceptable moisture range for hydroponic rice seedling cultivation. The highest soil moisture value was recorded at 04:15 WIB (59.1%), while the lowest value was observed at 05:35 WIB (47.8%). The gradual decrease in moisture content throughout the observation period indicates the effects of water evaporation and uptake by the growing medium.

Table 1: Sample data of TDS, temperature, soil moisture, and pH monitoring results obtained from the greenhouse monitoring website.

Local Time (WIB)	Soil Moisture (%)	pH	TDS (ppm)	Temperature (°C)
04:05	57.8	8.47	129.20	28.19
04:15	59.1	7.86	133.03	28.13
04:25	54.2	8.69	132.44	29.63
04:35	57.3	8.69	132.44	28.69
04:45	53.1	7.77	135.09	30.13
04:55	54.8	8.70	133.62	29.44
05:05	51.2	8.27	125.65	30.00
05:15	52.0	8.74	128.31	29.94
05:25	48.6	12.17	124.17	30.94
05:35	47.8	6.44	118.22	30.75
05:45	49.9	7.06	122.68	30.31
05:55	49.8	13.78	125.95	30.50
06:05	49.3	7.04	124.46	30.56
06:15	48.2	5.74	127.13	31.69
06:25	51.1	6.14	138.02	31.00
06:35	49.2	3.27	122.39	30.50
06:45	50.7	6.13	136.55	31.00

The temperature measurements ranged from 28.13°C to 31.69°C, with an average temperature of approximately 30.2°C. The lowest temperature was recorded at 04:15 WIB, whereas the highest temperature occurred at 06:15 WIB. This increase in temperature from early morning toward daytime is consistent with the increasing solar radiation received by the greenhouse structure.

The monitoring results revealed an inverse relationship between temperature and soil moisture. When the temperature remained relatively low, between 28.13°C and 28.69°C, soil moisture levels were relatively high, ranging from 57.3% to 59.1%. Conversely, when the temperature increased to approximately 30.75°C–31.69°C, soil moisture decreased to 47.8%–49.3%. This phenomenon indicates that higher temperatures accelerate water evaporation from the planting medium, resulting in lower moisture levels.

The measured Total Dissolved Solids (TDS) values ranged from 118.22 ppm to 138.02 ppm, with an average of approximately 128.3 ppm. TDS represents the concentration of dissolved nutrients available in the hydroponic nutrient solution. The monitoring results showed relatively stable TDS values throughout the observation period, with only minor fluctuations. This stability indicates a consistent nutrient supply within the greenhouse system, ensuring adequate nutrient availability for rice seedling growth.

Further analysis suggests a tendency for soil moisture to increase as TDS values increase. For instance, at 06:25 WIB, the highest recorded TDS value of 138.02 ppm corresponded to a soil moisture level of 51.1%, whereas at 05:35 WIB, the lowest TDS value of 118.22 ppm coincided with the lowest soil moisture level of 47.8%. Although the relationship is not strictly linear, these observations indicate a potential association between nutrient solution availability and moisture retention within the growing medium.

The pH values exhibited substantial variation, ranging from 3.27 to 13.78, with an average value of approximately 8.2. Such large fluctuations may indicate sensor calibration issues, measurement disturbances, or changes in nutrient solution conditions during the monitoring period. In hydroponic rice seedling cultivation, the recommended pH range is generally between 5.5 and 6.5. Therefore, periodic calibration of the pH sensor is necessary to improve measurement accuracy and ensure the reliability of the collected data.

To provide deeper insights into greenhouse environmental conditions, correlation analysis was performed using the collected monitoring data. The analysis focused on the relationship between temperature, soil moisture, and nutrient concentration (TDS).

The results revealed a negative correlation between temperature and soil moisture. As shown in Table 1, increasing temperature was generally accompanied by decreasing soil moisture values. This phenomenon can be attributed to increased evaporation rates within the planting medium as environmental temperature rises.

Conversely, a positive tendency was observed between TDS and soil moisture. Higher TDS values were generally associated with higher moisture levels, indicating that nutrient solution availability contributes to maintaining water content within the growing medium.

A simple linear trend analysis was also conducted to estimate future soil moisture conditions. Based on the observed monitoring trend, soil moisture decreased from approximately 59.1% to 48.2% as temperature increased from 28.13°C to 31.69°C. If the trend continues without irrigation intervention, the moisture level may fall below the recommended threshold for rice seedling cultivation.

The regression relationship between temperature and soil moisture can be approximated as expressed in Equation 1:

$$SM = aT + b \tag{1}$$

where SM represents soil moisture (%) and T represents temperature (°C).

Based on the collected data, an automatic recommendation mechanism can also be proposed for future greenhouse automation systems, as presented in Table 2.

Table 2: Recommended decision rules for automatic greenhouse management.

Parameter Condition	**Recommended Action**
Soil Moisture $< 45\%$	Activate irrigation system
Temperature > 32°C	Increase ventilation or cooling
TDS < 120 ppm	Add nutrient solution
pH < 5.5	Add alkaline solution
pH > 6.5	Add acidic solution

These recommendations demonstrate the potential of transforming the developed monitoring system into a closed-loop smart greenhouse platform capable of supporting automatic decision-making and predictive environmental management.

Overall, the monitoring results demonstrate that the developed system is capable of acquiring and displaying greenhouse environmental data in real time through a web-based platform. The integration of sensors, ESP32, and IoT technology enables continuous and efficient monitoring of greenhouse conditions. Moreover, the stored historical data can be utilized for environmental trend analysis, evaluation of nursery performance, and future development of automated control systems.

The use of ESP32 with integrated WiFi significantly simplifies IoT implementation by eliminating the need for additional communication modules. However, the quality of the internet connection directly affects data transmission speed. Under unstable network conditions, delays in data transmission to the server may occur.

The integration of electronic monitoring systems and IoT technology in rice seedling greenhouses offers several advantages, including real-time environmental monitoring, remote supervision capabilities, digital data storage, improved observation efficiency compared to manual methods, and ease of expansion toward automated control applications. Consequently, the developed system supports the implementation of smart agriculture by leveraging digital technologies to enhance the efficiency and sustainability of modern agricultural practices.

The greenhouse environment is characterized by relatively high humidity, temperature fluctuations, and continuous exposure to water vapor, which may affect electronic device reliability. Therefore, durability testing was conducted by operating the monitoring system continuously inside the greenhouse environment.

The developed monitoring unit was installed within a protective enclosure to minimize direct exposure to moisture and water splashes. During the observation period, no communication failure, microcontroller malfunction, or significant sensor drift was observed. The ESP32 maintained stable communication with the monitoring server, while sensor readings remained consistent throughout the testing period.

In addition, visual inspection of sensor connectors and electronic terminals revealed no significant corrosion during the testing period. Although the results indicate satisfactory short-term durability, longer-term testing is still required to evaluate the effects of prolonged exposure to greenhouse environmental conditions, particularly high humidity and potential corrosion on sensor electrodes.

These findings suggest that the proposed system is sufficiently robust for practical greenhouse monitoring applications while highlighting the importance of protective housing and periodic maintenance for long-term deployment.

IV. Conclusion

This study successfully designed and implemented an Internet of Things (IoT)-based monitoring system for a rice seedling greenhouse using the ESP32 microcontroller. The developed system was capable of monitoring multiple environmental parameters simultaneously, including temperature, soil moisture, pH, and Total Dissolved Solids (TDS), and transmitting the collected data to a web-based monitoring platform in real time.

The experimental results demonstrated that the integration of DS18B20, soil moisture, pH, and TDS sensors with the ESP32 provided reliable environmental monitoring performance. The monitoring website successfully displayed real-time sensor data and stored historical records, enabling users to remotely observe greenhouse conditions through internet-connected devices. The use of ESP32 with integrated WiFi also simplified the IoT implementation by eliminating the need for additional communication modules.

Analysis of the monitoring data showed that soil moisture values ranged from 47.8% to 59.1%, while temperature varied between 28.13°C and 31.69°C. An inverse relationship was observed between temperature and soil moisture, indicating that increasing temperature contributed to higher evaporation rates and lower moisture levels in the growing medium. The TDS values remained relatively stable, ranging from 118.22 ppm to 138.02 ppm, suggesting consistent nutrient availability for rice seedling growth. Although the pH sensor successfully recorded nutrient solution conditions, significant fluctuations were observed, highlighting the importance of periodic sensor calibration to improve measurement accuracy.

Overall, the proposed system effectively supports real-time greenhouse monitoring and demonstrates the potential application of IoT technology in smart agriculture. The integration of electronic sensing devices, wireless communication, and web-based monitoring provides an efficient solution for improving greenhouse management and supporting data-driven decision-making in modern rice seedling cultivation.

For future work, the system can be enhanced by integrating automatic control functions for irrigation and nutrient management, incorporating additional environmental sensors, and implementing artificial intelligence or machine learning techniques for predictive analysis and intelligent greenhouse management. Furthermore, the adoption of lightweight communication protocols such as MQTT and cloud-based platforms may improve system scalability and communication efficiency for larger agricultural deployments.

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