



## Development of an IoT-Based Smart Hydroponic Monitoring System as a Modern Agricultural Solution in Remote Areas

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### ABSTRACT

This research was motivated by the low agricultural productivity on Nias Island caused by limited land availability, inadequate infrastructure, restricted access to modern technology, and highly variable climatic conditions. This study aims to develop an Internet of Things (IoT)-based smart hydroponic monitoring system capable of automatically monitoring key parameters such as temperature, pH, water quality, and nutrient levels in real time, integrated with mobile applications and cloud platforms for remote accessibility. The research methodology consists of needs analysis, system design, prototype implementation, testing, and performance evaluation. The test results demonstrate that the developed prototype operates effectively, with sensor accuracy showing an average error of 3.74% for TDS, 1.28% for pH, and 0.91% for temperature measurements, while actuator testing confirmed 100% correct system response to nutrient and pH control scenarios. The system also maintained stable data transmission to mobile and cloud platforms without significant latency. These findings indicate that the proposed IoT-based monitoring system can significantly improve the efficiency and productivity of hydroponic agriculture, particularly in resource-limited regions such as Nias Island. The study provides empirical evidence of the system's performance, reinforcing its potential as a practical solution for modernizing agriculture in remote areas.

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### Introduction

Agriculture is one of the strategic sectors in the Indonesian economy, especially in supporting national food security (Government Regulation (PP) Number 17 of 2015 concerning Food Security and Nutrition, 2015). However, the Indonesian agricultural sector faces various major challenges that hinder the achievement of optimal food security, especially in remote areas such as Nias Island. This region has limited fertile land, with most of its territory facing geographical and climatic conditions that are not conducive to conventional agriculture (Altieri & Nicholls, 2017; El-Beltagy & Madkour, 2012; Singh & Singh, 2017). In addition, inadequate infrastructure and limited access to modern agricultural technology are major obstacles to increasing agricultural productivity (Abiri et al., 2023; Ahmed et al.,

2022; Dhillon & Moncur, 2023). As the population grows rapidly, food demand continues to increase, while the agricultural sector is unable to keep pace due to these limitations (Suprehatin, 2021; Sutardi et al., 2022; Utami et al., 2019). Increasingly unpredictable climate change has also worsened agricultural conditions, leading to more frequent crop failures (Anderson et al., 2020; Kumar et al., 2018). This further increases dependence on food supplies from outside the region, which increases costs and reduces local food security.

To date, the agricultural system on Nias Island still uses conventional farming methods that depend on weather and the availability of fertile land. On the other hand, hydroponic farming offers a promising solution, especially in areas with limited land and water resources (Sambo et al., 2019). Hydroponics allows farming to be carried out on limited land with water savings of up to 90% compared to conventional farming methods (Naresh et al., 2024; Pomoni et al., 2023). However, despite its great potential, this technology has not been fully utilized, especially in areas with limited infrastructure to support the application of modern technology (Jia et al., 2019; Serrano, 2018).

The Faculty of Science and Technology, Nias Raya University has currently implemented a hydroponic system, although its management is still manual and highly dependent on intensive monitoring by the hydroponic management team. This manual monitoring process is not only time-consuming, but also increases the risk of inaccuracy in management, which ultimately has the potential to reduce agricultural yields. With limited trained labor and high management challenges, the efficiency of hydroponic management at Nias Raya University still needs to be improved.

Therefore, an automated system is needed that can monitor and control important parameters in hydroponic farming in real time, such as temperature, pH, macro and micro nutrients, water volume, and water quality (Kour et al., 2022; Safira et al., 2022; Sangeetha & Periyathambi, 2024). Internet of Things (IoT) technology is the right solution to address these challenges (Patrono et al., 2020; Zikria et al., 2021). By using IoT sensors, various plant parameters can be monitored automatically and efficiently, thereby reducing dependence on manual intervention and providing more accurate and timely data for optimal management (Ali et al., 2023; Lakhier et al., 2018; Nsoh et al., 2024).

Based on this background, this study focuses on three main issues. First, how to design and develop an IoT-based hydroponic monitoring system that is capable of monitoring and controlling important parameters in real time. Second, how to ensure that the system remains easy to use, energy efficient, and affordable, so that it is suitable for the limitations of infrastructure and human resources in remote areas such as South Nias Regency. Third, how to integrate this monitoring system with mobile applications and cloud platforms, enabling remote monitoring and control of plant conditions by local users.

Although previous studies have developed IoT systems for hydroponic monitoring, most of these studies were conducted in areas with adequate infrastructure and did not consider remote geographical conditions such as Nias Island. Previous studies have generally focused on sensor accuracy, energy efficiency, or general cloud integration, but have not addressed the limitations of IoT implementation in areas with limited electricity access, unstable network connectivity, and low human resource capacity to operate modern technology. In addition, the systems that have been developed rarely integrate real-time multi-parametric monitoring that simultaneously covers temperature, pH, nutrients, water volume, and water quality. On the other hand, agricultural conditions in Nias show a more pressing urgency: the productivity of local horticultural crops is still below the provincial average, with agriculture contributing only about 28–30% of the South Nias Regency's GRDP, and more than 60% of agricultural land is not optimally utilized due to limited fertility and unstable rainfall (South Nias BPS, 2023). Based on these research gaps, this study clearly aims to: (1) design and build an IoT-based hydroponic monitoring system that is capable of operating in real time and stably under minimal infrastructure conditions; (2) develop a system that is easy to use, energy efficient, and affordable; and (3) integrate the system with mobile and cloud applications to enable remote monitoring by local users. Thus, this study offers new contributions in the context of IoT-hydroponics application in remote areas, with a focus on technological adaptability, operational efficiency, and improved local food security.

## Method

This study uses a Research and Development (R&D) approach to develop an Internet of Things (IoT)-based hydroponic monitoring system. The research procedure was carried out systematically, starting from problem identification, literature study, data collection, needs analysis, design and planning, prototype creation, to system testing and evaluation.

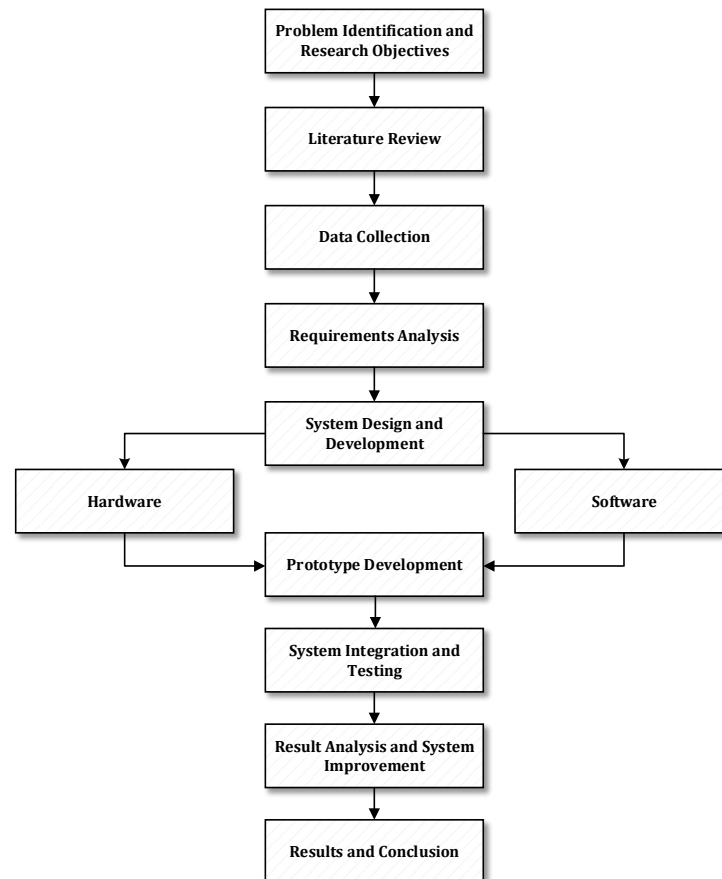


Figure 1. Research Process Flowchart

Research data was obtained through field observations and measurements of hydroponic parameters, including temperature, pH, nutrients, and water volume. The instruments used included an ESP32 microcontroller, a DMS TDS sensor, a pH-4502C sensor, and an SR94 water level sensor. The data obtained was sent wirelessly to a cloud platform (Firebase/ThingSpeak) for analysis. The system was evaluated by testing the accuracy of sensor readings, the reliability of real-time data transmission, and the functionality of actuators (water pump and solenoid valve).

## Results and Discussions

The results of this research are in the form of the development of an Internet of Things (IoT)-based hydroponic monitoring system that is capable of automatically monitoring important parameters such as temperature, pH, nutrient concentration, and water volume in real time. The system was built using an ESP32 microcontroller, integrated with a TDS DMS sensor, a pH-4502C sensor, and an SR94 water level sensor. Data obtained from the sensors can be displayed through a mobile application with a cloud connection, enabling remote monitoring by users. The prototype of the device developed is shown in figure 2. This system is capable of operating automatically by activating actuators (water pumps and solenoid valves) according to the detected parameter conditions. The system integration proved to work well, where each hardware and software component functioned according to the design.



Figure 2. Prototype of an IoT-based Hydroponic Monitoring System



Figure 3. Hydroponics Application Display

### Sensor Test Results

Reading tests were conducted to determine the accuracy of sensor readings by measuring water using a TDS meter and pH meter, then comparing the results with the readings from the device that had been created. The TDS meter was used to measure the conductivity of the solution and water temperature, while the pH meter was used to measure the pH of the water.



a. Solution Conductivity

b. Water Temperature  
Figure 4. Sensor Testing

c. Water pH

Readings on the TDS meter and pH meter are compared with sensor readings, as shown in the image below.



Figure 5. Sensor Reading Display

Table 1. Comparison Test of Sensor Readings

Test No.	TDS device	TDS meter	pH device	pH meter	Device temp.	temp. meter	Difference	Error (%)	Average error
1	101	101	-	-	-	-	0	0	
2	104	101	-	-	-	-	3	2.97	
3	102	100	-	-	-	-	2	2	
4	108	100	-	-	-	-	8	8	
5	106	101	-	-	-	-	5	4.95	3.74
6	105	103	-	-	-	-	2	1.94	
7	108	103	-	-	-	-	5	4.8	
8	105	102	-	-	-	-	3	2.94	
9	110	101	-	-	-	-	9	8.9	
10	106	105	-	-	-	-	1	0.95	
1	-	-	7.8	7.5	-	-	-0.3	-4	
2	-	-	6.9	7.7	-	-	0.8	10.38	
3	-	-	6.5	7.6	-	-	1.1	14.47	
4	-	-	8.1	7.6	-	-	-0.5	-6.57	
5	-	-	7.5	7.7	-	-	0.2	2.59	1.28
6	-	-	7.9	7.7	-	-	-0.2	-2.59	
7	-	-	7.5	7.8	-	-	0.3	3.84	
8	-	-	7.4	7.5	-	-	0.1	1.33	
9	-	-	7.4	7.4	-	-	0	0	
10	-	-	8	7.5	-	-	-0.5	-6.6	
1	-	-	-	-	28.4	28.2	-0.2	-0.70	
2	-	-	-	-	27.9	28.3	0.4	1.41	
3	-	-	-	-	28	28.1	0.1	0.35	
4	-	-	-	-	28	28.4	0.4	1.40	
5	-	-	-	-	28.1	28.4	0.3	1.05	
6	-	-	-	-	27.8	28.1	0.3	1.06	0.91
7	-	-	-	-	27.5	28.2	0.7	2.48	
8	-	-	-	-	28.4	28.5	0.1	0.35	
9	-	-	-	-	27.2	28.1	0.9	3.20	
10	-	-	-	-	26.5	28.2	1.7	6.02	

Based on the results of the sensor comparison test shown in Table 1, the performance of the TDS, pH, and temperature devices showed varying levels of accuracy when compared to standard measuring instruments. In the TDS test, the difference in readings between the device and the TDS meter ranged from 0 to 9 with an error percentage of 0–8.9%, resulting in an average error of 3.74%, which

indicates that the TDS sensor has fairly good accuracy but there were still deviations in some experiments. The pH sensor test showed a difference in values between -0.5 and 1.1 from the standard pH meter with an error ranging from -6.6% to 14.47% and an average error of 1.28%, indicating that the pH device tends to be more sensitive to small fluctuations and has greater error variation. Meanwhile, temperature testing showed relatively small differences, ranging from -0.2 to 1.7 degrees Celsius, with an error percentage of -0.70% to 6.02% and an average error of 0.91%, indicating that the temperature sensor has the best stability and accuracy among the three types of sensors. Overall, these results confirm that all three sensors have performed at an acceptable level of accuracy, although there is still room for improvement in accuracy, particularly for the TDS and pH sensors.

The error calculation is the difference between the sensor reading and the reading (TDS/pH meter) multiplied by 100%.

$$Error \% = \frac{\text{Difference} - \text{TDS or pH meter reading}}{\text{TDS or pH meter reading}} \tag{1}$$

The calculation of the average error is as follows:

$$Average Error = \frac{\text{Total error}}{\text{Many tests}} \tag{2}$$

**TDS Test on the Device System**

This test aims to determine the performance of the automatic system device in reading the TDS sensor and the age of plants stored in the Firebase database, then activating the mix A and mix B peristaltic pumps in providing plant nutrients.

Table 2. TDS Testing on the Equipment System

Test No.	Plant Age (weeks)	TDS Sensor Reading (ppm)	Peristaltik Pump		Compliance Notes
			Mix A	Mix B	
1	1	0 - 200	ON	ON	Correct
2		201 - 400	OFF	OFF	Correct
3		401 - 600	OFF	OFF	Correct
4		601 - 800	OFF	OFF	Correct
1	2	0 - 200	ON	ON	Correct
2		201 - 400	ON	ON	Correct
3		401 - 600	OFF	OFF	Correct
4		601 - 800	OFF	OFF	Correct
1	3	0 - 200	ON	ON	Correct
2		201 - 400	ON	ON	Correct
3		401 - 600	ON	ON	Correct
4		601 - 800	OFF	OFF	Correct
1	4	0 - 200	ON	ON	Correct
2		201 - 400	ON	ON	Correct
3		401 - 600	ON	ON	Correct
4		601 - 800	ON	ON	Correct

Based on the TDS test results on the equipment system shown in table 2, the overall response of the system to variations in TDS concentration and plant age shows a consistent control pattern and complies with the requirements. At 1 week of plant age, the peristaltic pump was only active in the TDS range of 0–200 ppm, while for the range of 201–800 ppm, both pumps were deactivated, indicating an appropriate nutrient control mechanism. Entering plant ages of 2 weeks and 3 weeks, the system showed an increase in nutritional requirements, reflected in the activation of the pump at higher TDS ranges, namely up to 400 ppm in the second week and up to 600 ppm in the third week, before finally being deactivated at the highest range. At 4 weeks of age, both pumps remained active across the entire TDS range up to 800 ppm, indicating greater plant nutrient requirements during the advanced growth phase. Overall, all tests showed a “Correct” status, indicating that the TDS sensor-based nutrient control

system worked according to the designed logic and was able to accurately adjust the supply of Mix A and Mix B nutrient mixtures based on plant age and solution concentration levels.

#### pH Test on the Device System

This test aims to determine the performance of the automatic system device in reading the pH sensor in activating the peristaltic pump for pH up and pH down.

Table 3. pH Testing on the Device System

Test No.	pH sensor reading	Peristaltic Pump		Statement of compliance
		pH up	pH down	
1	1	ON	OFF	Correct
2	2	ON	OFF	Correct
3	3	ON	OFF	Correct
4	4	ON	OFF	Correct
5	5	ON	OFF	Correct
6	6	OFF	OFF	Correct
7	7	OFF	OFF	Correct
8	8	OFF	OFF	Correct
9	9	OFF	ON	Correct
10	10	OFF	ON	Correct
11	11	OFF	ON	Correct
12	12	OFF	ON	Correct
13	13	OFF	ON	Correct
14	14	OFF	ON	Correct

The conclusions in the following test table are:

1. If the pH reading is between 1 and 5, the peristaltic pump for pH up will be activated.
2. If the pH reading is between 6 and 8, the peristaltic pump will not be activated.
3. If the pH reading is between 9 and 14, the peristaltic pump for pH down will be activated.

The results of this study indicate that an IoT-based hydroponic monitoring system can improve the efficiency of modern agricultural management, especially in remote monitoring. This is in line with emphasizing the importance of applying IoT in the agricultural sector to minimize manual intervention and improve monitoring accuracy. The advantages of this system lie in the integration of sensors with ESP32 and cloud platform support that allows data to be accessed in real-time through a mobile application. However, there are several limitations, including dependence on internet network stability and power limitations on devices. The implementation of this system has the potential to be applied in remote areas to support hydroponic agricultural productivity. With automatic monitoring, farmers can monitor crop conditions without having to be on site, thereby saving time, energy, and operational costs.

#### Discussion

The results of testing the accuracy of the TDS, pH, and temperature sensors show that although all three are in the acceptable accuracy category, the variation in error has direct implications for the stability of the nutrition automation system and water quality control. The greater deviation in the TDS and pH sensors compared to the temperature sensor has the potential to affect the accuracy of nutrient pump and pH pump activation, so the system needs to adopt a threshold margin to prevent overdosing or under-adjustment. These findings are in line with reports by Lakhier et al. (2018) and Kour et al. (2022), which also note that TDS and pH sensors in IoT devices are more sensitive to environmental changes and therefore require periodic calibration to maintain system stability. However, unlike previous studies that only emphasized passive monitoring, this study contributes a new aspect in the form of full integration between sensors, actuators, and plant age-based control logic so that the system not only monitors but also performs adaptive nutrient regulation. Testing of the device showed that the nutrient-mixing and pH adjustment control logic ran consistently at various stages of plant growth, indicating the successful integration of sensors and actuators in a real-world scenario. Thus, this study confirms that the level of sensor accuracy obtained is sufficient to support automated hydroponic

operations, and despite some variation in error, the system is still able to maintain nutrient stability and solution quality. This contribution strengthens previous literature by offering a more applicable, adaptive, and relevant IoT-hydroponics implementation model for areas with limited infrastructure such as Nias.

### Conclusions

This study successfully developed an Internet of Things (IoT)-based hydroponic monitoring and control system capable of measuring temperature, pH, nutrient concentration (TDS), and water volume in real time, supported by ESP32 microcontroller integration with TDS, pH, and water level sensors. The system's performance was validated through sensor accuracy testing, which showed that the TDS sensor achieved an average error of 3.74%, the pH sensor 1.28%, and the temperature sensor 0.91%, indicating that the developed device is sufficiently reliable for automated nutrient and pH regulation. The automated control logic also operated consistently across all test scenarios, ensuring correct activation of nutrient pumps and pH regulators according to plant age and solution conditions. Scientifically, this study contributes to the IoT-based agriculture literature by demonstrating a fully integrated sensor-actuator architecture that not only monitors but also adaptively controls hydroponic parameters—an advancement compared to prior studies that focused primarily on passive monitoring. The findings confirm that IoT can significantly enhance operational efficiency and precision in hydroponic management, particularly in remote agricultural settings. Nevertheless, system limitations remain, including reliance on stable internet connectivity and power constraints that may affect real-time data transmission. Future research should quantitatively optimize the system through improved calibration models, integrate predictive algorithms or AI-based decision-making for anticipatory nutrient management, and explore renewable energy solutions such as solar-powered modules to enhance system autonomy and scalability.

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