Design of Smart Hydroponics Based on Internet of Things (IoT) Using Rule-Based System on Hydroponic Wick System

Mukhamad Rio Eka Prasetyoaji[1*], Lilik Anifah[2]
Department of Electrical Engineering, Universitas Negeri Surabaya, Surabaya, Jawa Timur, Indonesia[1,2]
*Corresponding Author Email: mukhamad.21030@mhs.unesa.ac.id

Abstract -- This research develops an IoT-based intelligent hydroponic system to monitor and control nutrient and pH levels in wick-type hydroponic cultivation. The system uses an ESP32 microcontroller integrated with an MQTT-based IoT platform for real-time monitoring and automation. The rule-based system classifies plant conditions and controls actuators based on pH and nutrient levels. Experimental testing shows that the TDS and pH sensors work well. Using the two-factor correction method, the TDS sensor achieved high accuracy with a maximum error of 0.08% within the optimal range of 1,050-1,400 ppm. The pH sensor maintains an error below 2% within the ideal range of 5.5-6.5. The system supports automatic and manual pump control. QoS evaluation of MQTT communication showed stable performance with average throughput of 36.38 kbps (QoS 0), 2.54 kbps (QoS 1), and 1.55 kbps (QoS 2); delays of 762.68 ms, 1053.3 ms, and 1433.12 ms; and jitter of 26.91 ms, 28.44 ms, and 35.62 ms. Packet loss was 0% at all QoS levels, indicating reliable data transmission. Overall, the system improves monitoring accuracy and control efficiency, offering a practical solution for real-time automated hydroponic cultivation to support urban food security.

Keywords:
ESP32, Hydroponic, IoT, MQTT, Rule-Based

Article History:
Received: 21 April 2025
Revised: 20 May 2025
Accepted: 30 May 2025
Published: 31 May 2025

DOI: 10.46962/forteijeeri.v6i1.34

I. INTRODUCTION

Increasing population growth has resulted in a higher demand for food. On the other hand, rampant urbanization and the development of the industrial sector have significantly reduced productive agricultural land. Based on data reported by the Central Statistics Agency (BPS) in 2021, it is stated that the conversion of national paddy fields varies between 60,000-80,000 hectares per year [1]. This poses a serious problem in an effort to meet the increasingly high demand for food. Therefore, many innovations in crop cultivation technology have been developed to answer this problem. One of the plant cultivation technology innovations developed is the hydroponic system.

Hydroponics is a plant cultivation technology that uses water as the main growing medium. In the hydroponic system, nutrients will be given to the water to deliver important minerals and nutrients directly to the roots of hydroponic plants [2]. This system allows plants to grow faster because nutrients will be more easily absorbed by the plants. In addition, another advantage of the hydroponic system is that it can be applied to limited land such as rooftops, building walls, terraces, and balconies [3]. This makes hydroponic crop cultivation suitable for application in areas with minimal land availability but a high need for high crop production.

There are several techniques commonly used to grow plants using the hydroponic method. One of them is the wick system. This system utilizes wicks to channel nutrients from the nutrient basin to the plant roots [4]. The advantage of the wick system is that it does not require electricity and also a water pump to work so it can minimize production costs. However, this system also has disadvantages, including requiring intensive maintenance. Especially to maintain the stability of nutrients and water pH [5]. This is considered less effective because it results in farmers having to routinely check the nutrient levels and pH of the water in the hydroponic solution reservoir.

IoT is a technology that allows a device to communicate with other devices with the help of the internet.

Through IoT, various electronic devices can connect and exchange data with the help of the internet. This technology provides convenience in the monitoring and control process, especially in environments that require supervision and rapid response [6]. Therefore, IoT is considered an effective and efficient solution to increase productivity in various sectors, from agriculture to industry.

Several researchers have previously researched IoT-based hydroponic solution pH and nutrient monitoring systems. One of them is a research conducted by Hamidah and friends entitled Prototype Monitoring System for Nutrition and Water pH Level in Hydroponic Cultivation of Pakcoy Vegetables Using Internet of Things (IoT) Technology. In this research, the microcontroller used is NodeMCU ESP8266 as the main controller of the system. The system utilizes IoT to monitor nutrient content and pH value in hydroponic nutrient solutions using Blynk as an IoT platform [7]. In addition, Rouhillah and friends have also conducted similar research with the title Design of Hydroponic Garden Nutrition Monitoring Tool. This research focuses on monitoring the nutrient content and height of the hydroponic solution in the reservoir. NodeMCU ESP8266 was chosen as the main controlling microcontroller of the system. Meanwhile, the IoT platform used is a Firebase-based mobile phone application [8].

From some of these studies, it can be concluded that IoT can be used to facilitate plant cultivation using the hydroponic method, especially to monitor the content of hydroponic solutions. However, there are still shortcomings in these studies, namely that they only utilize IoT to monitor the parameters under study. In addition, there is no follow-up from the system, such as adding nutrient solution or stabilizing pH when the value of nutrient content and pH value of the solution is not equal to the specified limit. Therefore, developing an IoT system capable of performing automation actions based on monitoring data is a challenge that needs to be addressed.

Based on the background that has been described, this research will develop a smart hydroponic system to monitor and control the amount of nutrients and pH of water in plant cultivation with the wick system hydroponic method. The system is built using the ESP32 microcontroller module as the main controller of the system and the MQTT IoT Panel as an IoT Platform. This system is designed to provide convenience for users in accessing real-time data through IoT-based devices. In addition, an automation feature is also added to adjust the solution content directly based on the monitoring results.
Research Problem

II. METHODS

Figure 1 shows the research flow chart relating to the methods used by the authors to obtain the required data. The chart outlines the steps taken during the research, starting from the initial problem identification, followed by the testing procedure and data analysis.

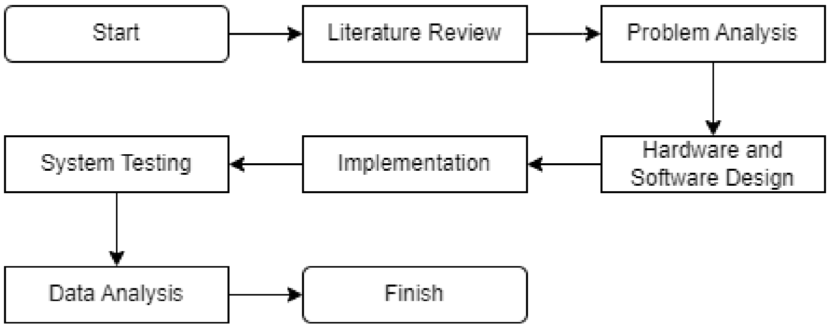

Figure 1 Research Flowchart

A. Literature Review

In this stage, the author conducted a review of several previous relevant studies. This is useful for understanding the basic concepts, current technologies, and methods that have been used in similar studies. In addition, the author also identified aspects of the research that needed further development. The data that has been obtained is the basis for researchers to choose research topics and then formulate problems.

B. Problem Analysis

At this stage, the author analyzes the problems found based on the results of literature review and initial studies. This analysis aims to identify gaps between ideal conditions and real conditions in the field. Through this analysis, the author can understand the root of the problem more deeply, and determine the scope and limits of the problem to be studied.

C. Hardware and Software Design

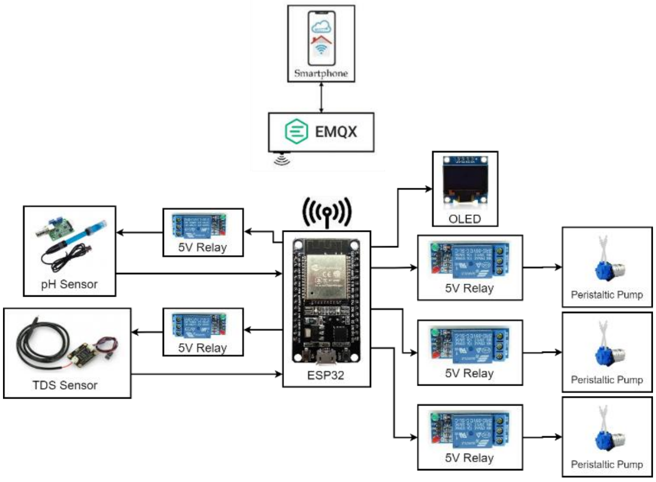

Figure 2 Hardware Design

Figure 2 shows the hardware design. The pH sensor and TDS sensor function as inputs. To prevent interference between sensors, the ESP32 sets up two relays so that the sensors turn on alternately. Data from the active sensors will be processed by the ESP32. If the pH or nutrient values do not match the specified limits, the ESP32 will activate the actuators to adjust. The sensor readings are also displayed on the OLED screen and sent to the smartphone via MQTT. The smartphone is used to monitor the data in real-time and can also be used to manually control the pump, such as adding pH up, pH down, or nutrient solutions.

TABLE I RULE-BASED SYSTEM ALGORITHM TABLE

Condition	Input	Output
1	$1050 \le n \le 1400$ $5,5 \le pH \le 6,5$	C=3, P1=0, P2=0, P3=0
2	$1050 \le n \le 1400$ $pH < 5,5$	C=2, P1=0, P2=1, P3=0
3	$1050 \le n \le 1400$ $pH > 6,5$	C=2, P1=0, P2=0, P3=1
4	$n < 1050$ $5,5 \le pH \le 6,5$	C=2, P1=1, P2=0, P3=0
5	$n < 1050$ $pH < 5,5$	C=1, P1=1, P2=1, P3=0
6	$n < 1050$ $pH > 6,5$	C=1, P1=1, P2=0, P3=1
7	$n > 1400$ $5.5 \le pH \le 6,5$	C=2, P1=0, P2=0, P3=0
8	$n > 1400$ $pH < 5,5$	C=1, P1=0, P2=1, P3=0
9	$n > 1400$ $pH > 6,5$	C=1, P1=0, P2=0, P3=1

Software programming for the smart hydroponics system was carried out using the Arduino IDE, starting with the reading of data from the pH and nutrient sensors displayed on the serial monitor and OLED. After that, a rule-based system program was developed to analyze the health condition of the plants and control the actuators to keep the system optimized. The rule-based algorithm used is shown in table 1. This algorithm is adapted to the needs of kale plants that require nutrients between 1050-1400 ppm and pH 5.5-6.5[9].

Caption for Table 1:

1. n = Nutrient
2. pH = pH Value
3. C = Plant Condition $\begin{Bmatrix} 1 = \text{Not Healthy} \\ 2 = \text{Less Healthy} \\ 3 = \text{Healthy} \end{Bmatrix}$

4. P1 = Nutrient Pump
5. P2 = pH UP Pump
6. P3 = pH DOWN Pump
7. Pump Description $\begin{Bmatrix} 0 = \text{Pump Off} \\ 1 = \text{Pump On} \end{Bmatrix}$

The interface of the IoT MQTT Panel application is designed to be easy to use and displays real-time data on pH, nutrients, and plant health status. The app also supports manual control of the pump for addition of pH up, pH down, or nutrient solution. The program is further developed to send (publish) sensor data and analysis results to the app via MQTT, and receive (subscribe) commands from the app to manually or automatically control the pump.

D. System Design

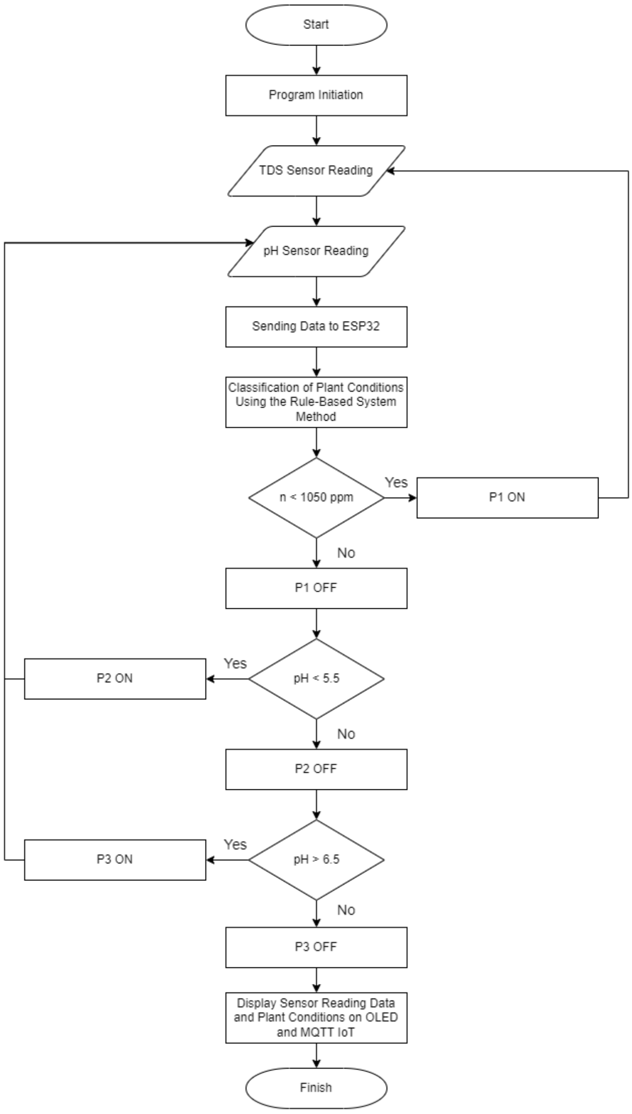

Figure 3 System Design

Figure 3 shows the flowchart describing the workflow of the ESP32-based hydroponic automation system starting from the initialization process, which is connecting the module to the WiFi network, setting up initial parameters such as MQTT connection, sensor and actuator pin configuration, and system variables. After that, the TDS and pH sensors will read the value of nutrients and the acidity of the solution, then this data is processed by ESP32 using a rule-based classification method to determine the condition of the plants and activate the pump as needed, namely the nutrient pump, pH up, or pH down. If nutrients are less than 1050 ppm, the nutrient pump turns on; if pH < 5.5, the pH up pump turns on; and if pH > 6.5, the pH down pump turns on. The system then sends the status of the TDS value, pH, and plant condition in real-time via MQTT for remote monitoring.

E. System Testing

The testing is divided into 2 processes, namely device testing and MQTT IoT testing. Both tests are conducted to ensure the system functions optimally. Device testing includes verifying electrical connections, device communication, and evaluating the accuracy of the pH and TDS sensors by comparing the readings to the reference measuring instrument, then calculating the percentage error using the equation:

$$\%Error = \frac{|x - x1|}{x} \times 100\% \quad (1)$$

Meanwhile, the MQTT IoT test includes two main aspects: monitoring and control. In the monitoring stage, it was tested whether data such as pH, nutrients, and plant conditions could be sent in real-time to the IoT platform. In the control stage, it is tested whether the system can respond to commands from the platform to activate or deactivate the pump quickly and accurately. In addition, Quality of Service testing was also conducted. Quality of Service (QoS) itself is one of the important elements in the Internet of Things (IoT) system that acts as a benchmark to evaluate the performance and quality of the entire system [10]. QoS testing involves measuring several parameters, such as throughput, delay, jitter, and packet loss.

Throughput is the effective data transfer rate, measured in bps. Throughput can be found with the equation:

$$\text{Throughput} = \frac{\text{Number of Data Sent}}{\text{Total Delivery Time}} \quad (2)$$

Delay is the total time that a packet travels from the sender to the receiver through the network. Delay can be found with the equation:

$$\text{Delay} = \text{Packet Time Received} - \text{Packet Time Sent} \quad (3)$$

Jitter is the variation or fluctuation in delay. Jitter shows how consistent the data transmission time is. Jitter can be found with the equation:

$$\text{Jitter} = \frac{1}{N-1} \sum_{i=1}^{N-1} |Delay(i+1) - Delay(i)| \quad (4)$$

Packet loss indicates packet loss in the delivery process, which can be caused by bottlenecks in the network or overloads that cause packet buildup and eventual packet loss. Packet loss can be found with the equation:

$$\text{Packet-loss} = \left(\frac{\text{Data Sent} - \text{Data Packets Received}}{\text{Data Packets Received}}\right) \quad (5)$$

F. Data Analysis

The data obtained from the test will then be analyzed. Calculation of the percentage of failure is also carried out to determine the reliability of the system that has been made. This involves comparing the number of unsuccessful operations or errors against the total number of trials, which provides a quantitative measure of system performance. The results of this analysis will help identify any weaknesses or components that require improvement and serve as a reference for future enhancements to increase system stability and efficiency.

III. Result and Discussion

A. System Implementation

This research has produced a smart hydroponic system device with dimensions of 21.5 × 14.5 × 8.5 cm, as shown in Figure 4. This system uses ESP32 as the main microcontroller that controls the entire process, with the support of pH sensors with a PH-4502C probe and TDS sensors V1.0 to monitor the condition of the hydroponic solution in real-time. In addition, the system is equipped with three relays, each connected to a peristaltic pump, which functions to add nutrient solution, pH up, and pH down automatically to maintain optimal conditions for plant growth. In this system, a rule-based system is successfully implemented to determine plant health conditions and regulate pump activation based on measured pH values and nutrient concentrations. IoT implementation is also successfully implemented through the MQTT protocol, using the MQTT IoT Panel application as a user interface that supports real-time monitoring of pH and nutrient parameters as well as manual and automatic pump control.

Figure 4 Smart Hydroponic Device

B. Device Performance Analysis

Testing and analyzing the performance of the smart hydroponic device includes three main aspects, namely evaluating the error value of the pH and nutrient sensor readings, the accuracy of the plant condition classification results along with the pump actuation logic response generated by the rule-based system, and the process of publishing and subscribing the device to the EMQX broker.

1) Nutrition Value Reading

TABLE II PERCENTAGE ERROR OF NUTRIENT MEASUREMENT

Sample	Measurement Results		Error Percentage
	TDS Meter	TDS Sensor	
1	501	533	6.39%
2	550	580	5.45%
3	575	604	5.04%
4	613	639	4.24%
5	651	675	3.69%
6	689	710	3.05%
7	727	746	2.61%
8	782	797	1.92%
9	803	818	1.87%
10	841	855	1.66%
11	879	893	1.59%
12	917	930	1.42%
13	971	984	1.34%
14	993	1,006	1.31%
15	1,031	1,044	1.26%
16	1,060	1,074	1.32%
17	1,106	1,115	0.81%
18	1,144	1,149	0.44%
19	1,182	1,183	0.08%
20	1,220	1,312	7.54%
21	1,258	1,321	5.01%
22	1,296	1,334	2.93%
23	1,334	1,358	1.80%
24	1,372	1,375	0.22%
25	1,410	1,385	1.77%
26	1,448	1,407	2.83%
27	1,486	1,441	3.03%
28	1,504	1,445	392%
29	1,562	1,445	7.49%
30	1,641	1,445	9.69%

Nutrient measurements were made using a TDS Meter V1.0 sensor that has an effective measurement range of 0 to 1000 ppm. To overcome the limited accuracy in sensor readings, two correction factors are applied to the voltage to ppm value conversion formula, namely a factor of 0.606 for input voltages less than 2.05V, and a factor of 0.715 for voltages greater than or equal to 2.05V. This correction aims to extend the sensor's reading range to about 1445 ppm, allowing the system to detect nutrient concentrations higher than the sensor's built-in effective limit. Thus, the system can still provide accurate and relevant data for decision-making in nutrient control of hydroponic solutions, especially in conditions where the TDS value exceeds 1000 ppm. The measurement data is shown in Table 2.

From table 2, it can be analyzed that samples 1 to 19 show a downward trend in percentage error, from 6.39% to 0.08%, indicating that the use of a factor of 0.606 (the result of 0.5 × 1.212) at voltages below 2.05V results in increasingly accurate sensor readings as the TDS value rises. This is due to the fact that at low TDS, the sensor tends to produce a voltage higher than the actual value. The factor of 0.606 plays a role in correcting this excess so that the results are closer to reality. This is suitable for applications such as hydroponics or drinking water, where accuracy at low TDS is crucial.

However, at the 20th sample, there was a drastic jump in error to 7.54%. This is a strong indication that at this point, the voltage had exceeded the 2.05V threshold and the system moved from a correction factor of 0.606 to a factor of 0.715. This change in factor was intended to extend the measurement range of the sensor, but the side effect was that there was a mismatch in the moment of transition. This causes a spike in error because the non-linear nature of the sensor readings has not been fully compensated for by just changing the factor.

After the factor transition, the accuracy of the sensor increases again for some points. For example, at the 21st to 24th samples, the error decreased from 5.01% to only 0.22%. This shows that the factor of 0.715 is effective enough to compensate for the sensor characteristics at high TDS, especially in the range of 1250-1370 ppm. That is, after the system adapts to the new factor, the measurement results become more stable and return closer to the reference value. However, this only applies to TDS values that are still within the linear range of the sensor after factor correction.

Starting from the 25th sample (TDS 1410 ppm) to the 30th (TDS 1641 ppm), the sensor accuracy again decreased significantly. At this point, even though a factor of 0.715 has been used, the sensor reading value is saturated, as evidenced by the sensor value, which no longer increases significantly, even stagnating at 1445 ppm from the 28th to the 30th sample. This shows that the physical limit of the sensor has been reached, and the correction formula or factor is no longer effective. The percentage error again jumped to 9.69% in the last sample. This reinforces the conclusion that the formula is optimal only up to about 1350-1400 ppm. Above that, neither the correction factor nor the polynomial model can compensate for the limitations of the sensor's linearity and resolution. But overall, the formula is effective for nutrient value readings of 1050-1400 ppm, which is the optimal nutrient value to support the growth of kale plants.

2) pH Value Reading

TABLE III PERCENTAGE ERROR OF pH MEASUREMENT

Sample	Measurement Results		Error Percentage
	pH Meter	pH Sensor	
1	4.86	4.8	1.23%
2	5.12	5.19	1.37%
3	5.37	5.46	1.68%
4	5.63	5.71	1.42%
5	5.89	5.95	1.02%
6	6.14	6.2	0.98%
7	6.4	6.44	0.63%
8	6.66	6.69	0.45%
9	6.92	6.93	0.14%
10	7.11	7.12	0.14%
11	7.43	7.45	0.27%
12	7.69	7.81	1.56%
13	7.82	7.98	2.05%
14	8.2	8.11	1.10%
15	8.46	8.27	2.25%
16	8.72	8.35	4.24%
17	8.89	9.39	5.62%
18	9.08	9.57	5.40%
19	9.28	9.87	6.36%
20	9.74	10.26	5.34%
21	10	10.42	4.20%
22	10.25	10.83	5.66%
23	10.51	10.59	0.76%

Sample	Measurement Results		Error Percentage
	pH Meter	pH Sensor	
24	10.77	11.24	4.36%
25	11.02	11.88	7.80%
26	11.28	11.97	6.12%
27	11.54	12.5	8.32%
28	11.79	12.81	8.65%
29	12.05	12.94	7.39%
30	12.31	13.39	8.77%

The pH measurement was carried out using pH sensors with a PH-4502C probe on 30 solution samples with different ph values. The pH measurement data is shown in Table 3, which shows that the pH value measurement ranges from 4.86 to 12.31. The percentage error is in the range of 0.14% to 8.77%. In general, at low pH values (around 4.86 to 7.11), the resulting error is relatively low, which is below 2%. This shows that the sensor works quite well in the acidic to neutral pH range. In particular, in the pH range of 5.5 to 6.5-which is the optimal pH range for hydroponic growth of kale, the percentage of measurement error is low. Therefore, it can be concluded that the pH sensor used is reliable and safe enough to be used in monitoring the nutrition of hydroponic kale plants.

However, when the pH value starts to enter the alkaline region (above pH 8), there is a significant increase in error. The highest error was recorded at pH 12.31 with a value of 8.77%. This increase began to be evident at pH values above 9, indicating that the pH sensor began to lose accuracy in that range. The average error of all samples was around 3.72%, with 12 out of 30 samples having an error ≤ 2%, indicating good accuracy. Meanwhile, the other 9 samples were in the error range between 2% and 5% (medium accuracy), and the remaining 9 samples had an error of more than 5%, indicating low accuracy. The degraded sensor performance at high pH is likely due to the sensor calibration being more focused on the low to neutral pH range, the decreased sensitivity of the sensor at alkaline pH, or the influence of temperature and other interfering ions.

3) Classification of Plant Condition and Pump Output based on Rule-based system

TABLE IV RULE-BASED OUTPUT TESTING RESULTS

Nutrient Value (ppm)	pH Value	Plant Condition Classification	Relay Logic Output
1,247	5.87	Healthy	R1 = 0, R2 = 0, R3 = 0
1,338	5.22	Less healthy	R1 = 0, R2 = 1, R3 = 0
1,207	6.87	Less healthy	R1 = 0, R2 = 0, R3 = 1
954	5.79	Less healthy	R1 = 1, R2 = 0, R3 = 0
991	5.31	Unhealthy	R1 = 1, R2 = 1, R3 = 0
873	8.36	Unhealthy	R1 = 1, R2 = 0, R3 = 1
1,445	6.11	Less healthy	R1 = 0, R2 = 0, R3 = 0
1,591	5.04	Unhealthy	R1 = 0, R2 = 1, R3 = 0
1,612	6.69	Unhealthy	R1 = 0, R2 = 0, R3 = 1

Caption for Table 4:

1. R1 = Relay 1 for controlling the nutrient pump
2. R2 = Relay 2 for controlling the pH UP pump
3. R3 = Relay 3 for controlling the pH DOWN pump

Based on Table 4, it can be concluded that the system has functioned properly in classifying plant conditions and controlling the logic of relay outputs according to the value of nutrients and pH of the solution. In conditions with a nutrient value of 1,247 ppm and a pH of 5.87, the system classifies the plants as healthy, and all relays (R1, R2, R3) are off (0), indicating that no corrective action is required. In the condition with a nutrient value of 1,338 ppm and a pH of 5.22, the plant is categorized as unhealthy because the pH is too low. The system responded by sending logic (1) to R2 connected to the pH UP pump to raise the acidity level, while R1 and R3 remained off. Furthermore, at a nutrient value of 1,207 ppm and pH 6.87, the pH is close to the upper limit (alkaline) so the system sends logic (1) to R3 to lower the pH, and the other relays remain off. In conditions with low nutrient values, namely 954 ppm and pH 5.79, the system sends logic (1) to R1 to add nutrients, according to plant needs.

In another case, when the nutrient value of 991 ppm and pH 5.31 are classified as unhealthy, the system sends logic (1) to two relays at once, namely R1 and R2, to correct the lack of nutrients and the acidity of the solution simultaneously. The same is also seen in the data with a nutrient value of 873 ppm and a very high pH of 8.36, which is also classified as unhealthy. The system responded by sending logic (1) to R1 and R3 simultaneously to add nutrients and lower the pH of the solution. In addition, in the condition with a nutrient value of 1,445 ppm and a pH of 6.11, which is considered quite ideal but still in the "Less Healthy" category, the system did not activate any relays (R1 = 0, R2 = 0, R3 = 0), indicating that the system did not take corrective action because the values were still within the tolerance threshold. This indicates that the system is able to distinguish conditions that are still tolerable and do not need to be corrected immediately, so that no overreaction occurs.

Furthermore, at a nutrient value of 1,591 ppm and pH of 5.04, the plant condition is classified as "Unhealthy" because the pH is too low, even though the nutrients are high enough. The system responded by activating R2 (pH UP pump) to raise the pH, while R1 and R3 remained off. This shows that the system is able to provide a specific solution based on the parameter at issue without triggering all actuators. A similar response was shown in a condition with a nutrient value of 1,612 ppm and a pH of 6.69, which was categorized as "Unhealthy" because the pH was close to the upper limit (alkaline). The system only activated R3 (pH DOWN pump) to lower the pH to the ideal range. Thus, from the overall data in Table 4.4, the system is proven to be able to accurately classify plant conditions based on nutrient and pH parameters and provide appropriate and selective corrective action through relay output logic. This shows that the rule-based method applied is not only consistent but also efficient in decision-making and reliable for automatic nutrient and pH management in hydroponic systems.

4) Publish and Subscribe Data to and from EMQX Brokers

ESP32 will publish data to the *skripsi/sensor/data* topic. In addition, the ESP32 will subscribe to the *skripsi/control* topic to receive commands to turn the pump on or off. Conversely, the MQTT IoT Panel Platform on the smartphone will publish data to the *skripsi/control* topic to give commands to activate or turn off the pump, and subscribe to the *skripsi/sensor/data* topic which then the data will be displayed on the panel that has been created in the MQTT IoT Panel platform.

C. MQTT Performance Analysis

MQTT IoT performance testing was conducted by analyzing throughput, delay, jitter, and packet loss parameters in response to devices using the MQTT IoT protocol, with the help of MQTTX software. This test was conducted at three different Quality of Service (QoS) levels, namely QoS 0, QoS 1, and QoS 2, to evaluate the overall performance of data communication. This series of tests aims to measure the extent to which the quality of service of each QoS level affects data transmission performance in MQTT-based IoT systems. Each test was performed by sending one sample of 10 data at a time, and sending was performed five times. During the test, the network was in a stable condition with a download speed of 7.85 Mbps and an upload speed of 9.10 Mbps.

TABLE V THROUGHPUT TESTING RESULTS

No.	**Sample**	**Throughput (kbps)**		
		QoS0	**Qos1**	**Qos2**
1	1	34.89	2.73	1.52
2	2	37.97	2.50	0.93
3	3	37.72	2.51	2.51
4	4	33.62	2.46	1.4
5	5	37.72	2.51	1.41
Average		36.38	2.54	1.55

Based on Table 5, which shows the throughput test results at three levels of MQTT QoS (Quality of Service), it can be seen that the higher the QoS level, the lower the throughput. At QoS 0 (At Most Once), the average throughput reaches the highest number of 36.38 kbps. This happens because at this level, there is no confirmation mechanism for receiving or resending messages, so the overhead is minimal and the data transmission speed is optimized. At QoS 1 (At Least Once), the average throughput drops dramatically to 2.54 kbps. This decrease is due to the acknowledgment process from the receiver to ensure the message is received at least once, although this allows for message duplication. Meanwhile, in QoS 2 (Exactly Once), the throughput decreased further to 1.55 kbps. This is due to the complex four-stage handshake process to ensure that each message is received exactly once without any duplication. When compared to QoS 0, the throughput in QoS 1 decreased by about 93.01%, while in QoS 2, the decrease reached about 95.73%. Overall, the data shows that there is a clear trade-off between data transmission speed (throughput) and message delivery reliability.

TABLE VI DELAY TESTING RESULTS

No.	Sample	Delay (ms)		
		QoS0	Qos1	Qos2
1	1	747.6	1,067.6	1,433.7
2	2	752.3	1,045.3	1,461.1
3	3	751.3	1,044	1,452.3
4	4	778	1,037.5	1,387.3
5	5	784.2	1,072.1	1,431.2
Average		762.68	1,053.3	1,433.12

Based on Table 6, which displays the results of delay testing at three levels of MQTT QoS (Quality of Service), it can be seen that the higher the QoS level, the greater the delay. At QoS 0 (At Most Once), the average delay was recorded at 762.68 ms. This value is the lowest among the three QoS levels because there is no confirmation process or message retransmission, so the time required for data transmission is shorter. In QoS 1 (At Least Once), the average delay increased to 1,053.3 ms. This increase is due to the acknowledgment process from the receiver to ensure that the message has been received, which increases the communication time between devices. Although QoS 1 assures that the message is received at least once, this mechanism adds to the communication latency. Meanwhile, in QoS 2 (Exactly Once), the average delay increases further to 1,433.12 ms. This is the highest delay value due to the communication process that involves four handshake stages to ensure the message is only sent and received once without any duplication. This process does provide the highest level of reliability, but it also causes the slowest response time. Comparatively, the delay in QoS 1 increases by about 38% from QoS 0, while the delay in QoS 2 increases by about 88% from QoS 0. This shows a clear trade-off between the speed of response (delay) and the reliability of communication.

TABLE VII JITTER TESTING RESULTS

No.	Sample	Jitter (ms)		
		QoS0	Qos1	Qos2
1	1	7	23	37.44
2	2	38.78	32.67	45.78
3	3	41.33	18.56	46
4	4	24.55	34	27.67
5	5	22.89	34	21.22
Average		26.91	28.44	35.62

Based on Table 7, which presents the results of jitter testing at three levels of QoS (Quality of Service) MQTT, it can be analyzed that the QoS level has an influence on the resulting jitter value. In this test, QoS 0 (At Most Once) produces an average jitter of 26.91 ms. This value is quite low because there is no acknowledgment or retransmission process, which causes the time fluctuation between packets to be smaller. This shows that data transmission in QoS 0 is more consistent in terms of time, although it does not guarantee the reliability of data transmission. QoS 1 (At Least Once) produces an average jitter of 28.44 ms, slightly higher than QoS 0. This increase is due to the acknowledgment process, which increases the possibility of time variations between packet transmissions. Although the increase is not very significant, it still shows that the reliability mechanism in QoS 1 has an impact on the stability of data transmission time. QoS 2 (Exactly Once) recorded the highest average jitter, at 35.62 ms. This is because the data transmission process under QoS 2 involves more communication stages to ensure that the message is only received once, without duplication. This complexity increases the chance of timing irregularities between packets, resulting in greater jitter.

TABLE VIII PACKET LOSS TESTING RESULTS

No.	Sample	Packet Loss (%)		
		QoS0	Qos1	Qos2
1	1	0	0	0
2	2	0	0	0
3	3	0	0	0
4	4	0	0	0
5	5	0	0	0
Average		0	0	0

Based on Table 8, which presents the results of packet loss testing at three levels of MQTT QoS (Quality of Service), it can be concluded that there is no packet loss in all tests, either at QoS 0, QoS 1, or QoS 2. This is indicated by the consistent average packet loss value of 0% for all samples. These results indicate that the data communication system tested has excellent and stable network quality, with high reliability in transmitting data without any loss of information. Even at QoS 0, which has no retransmission or reception confirmation mechanisms, no packet loss occurred. This indicates that the test site network has low latency, sufficient bandwidth, and does not experience significant interference during the data transmission process.

IV. Conclusion

Based on the research and testing that have been carried out, the following conclusions are obtained:

1. The developed TDS sensor-based hydroponic nutrient monitoring and control system shows quite accurate and reliable performance within a certain TDS range. The dynamic correction method with two factors (0.606 and 0.715) successfully improved the reading accuracy, reducing the error to 0.08% in the optimal range (1,050-1,400 ppm). Despite error spikes during correction transitions and saturation symptoms at TDS above 1,400 ppm, the system still showed good adaptability with high accuracy in the range of 1,250-1,370 ppm. In addition to measurement, the system supports nutrient data transmission via MQTT, local display via OLED, and nutrient pump control in flexible automatic and manual modes.
2. The developed smart hydroponic system successfully performs real-time monitoring and control of solution pH with fairly good accuracy. The pH sensor with the Ph-4502C module works optimally in the pH range of 5.5-6.5 with an error below 2%, although the accuracy decreases at alkaline pH above 9. The pH data is displayed locally through the OLED screen and sent wirelessly to the EMQX broker using the MQTT protocol in JSON format, so that it can be monitored through the MQTT IoT Panel application. The pH control system consists of a rule-based automatic mode and a manual mode via MQTT commands, and features an automatic return to automatic mode if there is no manual command within 30 seconds. To ensure data stability, the ADC smoothing method and low-pass filter are used.
3. The MQTT protocol Quality of Service test results show adequate performance with an average throughput for QoS 0 of 36.38 kbps, for QoS 1 of 2.54 kbps, and for QoS 2 of 1.55 kbps. The average delay for QoS 0 is 762.68 ms, for QoS 1 is 1053.3 ms, and for QoS 2 is 1433.12 ms. The average jitter for QoS 0 is 26.91 ms, for QoS 1 is 28.44 ms, and for QoS 2 is 35.62 ms. In addition, the test results on packet loss show that there is no packet loss at all QoS levels, namely QoS 0, QoS 1, and QoS 2, with a packet loss percentage of 0%. This indicates that data transmission was reliable and stable during the test.

V. Acknowledgment

The author would like to thank Prof. Dr. Lilik Anifah, S.T., M.T. as the final project supervisor for all her guidance and motivation so that the author can complete this final project and thank Dr. Raden Roro Hapsari Peni Agustin Tjahyaningtijas, S.Si., M.T. and Endryansyah, S.T., M.T. for all the input that has been given so that this research becomes better.

VI. References

[1] Nugroho, R. A. (2024, 14 Agustus). Pantas Petani Gurem Meledak, Lahan Pertanian RI Hilang 'Ditelan Bumi'. Accessed on December 16, 2024, from https://www.cnbcindonesia.com/news/20240814154359-4-563062/pantas-petani-gurem-meledak-lahan-pertanian-ri-hilang-ditelan-bumi

[2] R. A. Panjaitan and I. Suharjo, "PROTOTYPE SISTEM PEMBERIAN NUTRISI OTOMATIS PADA TANAMAN HIDROPONIK SELADA DENGAN WICK SYSTEM BERBASIS INTERNET OF THING (IoT)," *Jurnal Informatika dan Teknik Elektro Terapan*, vol. 12, no. 2, Apr. 2024, doi: 10.23960/jitet.v12i2.4063.

[3] A. Heryanto, J. Budiarto, and S. Hadi, "Sistem Nutrisi Tanaman Hidroponik Berbasis Internet Of Things Menggunakan NodeMCU ESP8266," *Jurnal BITe*, vol. 2, no. 1, pp. 31–39, Jun. 2020, doi: 10.30812/bite.v2i1.805.

[4] A. Fauzan and R. Fahlefie, "SISTEM MONITORING HIDROPONIK BERBASIS ARDUINO UNO," *Jurnal Ilmiah Mahasiswa Kendali dan Listrik*, vol. 3, no. 1, pp. 84–94, Jun. 2022, doi: 10.33365/jimel.v1i1.

[5] Susilawati, *DASAR-DASAR BERTANAM SECARA HIDROPONIK*. Palembang: Unsri Press, 2019. [Online]. Available: www.unsri.unsripress.ac.id

[6] P. N. Safiroh W.P, G. F. Nama, and M. Komarudin, "Sistem Pengendalian Kadar PH dan Penyiraman Tanaman Hidroponik Model Wick System," *Jurnal Informatika dan Teknik Elektro Terapan*, vol. 10, no. 1, Jan. 2022, doi: 10.23960/jitet.v10i1.2260.

[7] M. N. Hamidah, N. I. Safitri, D. W. Akbar, O. S. I. Uly, and D. Kurnianto, "Prototype Sistem Monitoring Nutrisi dan Tingkat pH Air pada Budidaya Hidroponik Sayur Pakcoy Menggunakan Teknologi Internet of Things (IoT)," *Elektron : Jurnal Ilmiah*, pp. 13–20, Jun. 2023, doi: 10.30630/eji.15.1.336.

[8] Rouhillah, I. Salfikar, and J. Hamar, "Rancang Bangun Alat Monitoring Nutrisi Kebun Hidroponik," *Jurnal J-Innovation*, vol. 10, no. 2, Dec. 2021, doi: 10.55600/jipa.v10i2.114.

[9] E. K. Pramartaningthyas, S. Ma'shumah, and M. I. Fuad, "ANALISIS PERFORMA SISTEM KENDALI pH DAN TDS TERLARUT BERBASIS INTERNET OF THINGS PADA SISTEM HIDROPONIK DFT," *Jurnal Rekayasa Sistem Komputer (RESISTOR)*, vol. 5, p. 1, Apr. 2022, doi: https://doi.org/10.31598.

[10] S. Pawar, D. B. Jadhav, M. Lokhande, P. Raskar, and M. Patil, "Evaluation of quality of service parameters for MQTT communication in IoT application by using deep neural network," *International Journal of Information Technology (Singapore)*, vol. 16, no. 2, pp. 1123–1136, Feb. 2024, doi: 10.1007/s41870-023-01664-2.