Design and Development of an ESP32-Based IoT System for Hydroponic Nutrient Monitoring and Control

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Abstract

Nutrient solution monitoring and control are essential aspects of hydroponic cultivation because they directly influence plant growth. Conventional monitoring methods require continuous manual observation, making the cultivation process less efficient. This study aims to design and implement an Internet of Things (IoT)-based hydroponic nutrient monitoring and control system using an ESP32 microcontroller integrated with a Total Dissolved Solids (TDS) sensor, a pH sensor, and a DS18B20 temperature sensor. Measurement data are transmitted in real time to the ThingsBoard platform via the MQTT protocol, enabling remote monitoring and control through a web-based dashboard. The proposed system is also equipped with an automatic nutrient dosing mechanism using a peristaltic pump based on predefined nutrient concentration setpoints. Sensor performance was evaluated by comparing the measurement results with reference instruments and analyzed using statistical parameters, including the mean, standard deviation, Root Mean Square Error (RMSE), and mean error. The experimental results show that the DS18B20, TDS, and pH sensors achieved mean errors of 0.58%, 0.20%, and 1.75%, respectively, with RMSE values of 0.16 °C, 1.95 ppm, and 0.12 pH, indicating good agreement with the reference instruments. Furthermore, the system successfully performed real-time monitoring of nutrient solution parameters, executed automatic nutrient control according to the programmed control logic, and stored and exported monitoring data to Microsoft Excel. These results demonstrate that the proposed system operates as intended and is suitable for real-time hydroponic nutrient monitoring and control applications based on the Internet of Things (IoT).

Keywords: *ESP32; Hydroponics; Internet of Things (IoT); Monitoring, Nutrient control; ThingsBoard.*

1. Introduction

Modern agriculture faces various challenges, including limited land availability, the need for efficient resource utilization, and increasing demands for higher crop productivity. One cultivation method that has been widely developed to address these challenges is hydroponics, a soilless cultivation technique that uses nutrient solutions as the primary growing medium for plants. Hydroponic cultivation can be implemented in limited spaces, both indoors and outdoors, and has the potential to produce high-quality crops when environmental conditions and nutrient availability are properly managed [1]. The success of hydroponic cultivation largely depends on the quality of the nutrient solution. Key parameters that must be maintained include nutrient concentration (Total Dissolved Solids, TDS), pH, and solution temperature. Imbalances in these parameters may interfere with nutrient uptake by plant roots, thereby reducing plant growth and productivity [2]. In practice, particularly in household-scale and small-scale hydroponic cultivation, monitoring of nutrient solution parameters is still commonly performed manually. This approach requires considerable time, labor, and continuous supervision, making it less efficient, especially for long-term operation.

The development of the Internet of Things (IoT) has created opportunities to improve the efficiency of hydroponic system management through real-time monitoring and control. IoT technology enables the integration of sensors, microcontrollers, and internet connectivity, allowing nutrient solution data to be transmitted, monitored, and managed remotely. Furthermore, IoT platforms provide centralized data storage and visualization, enabling users to monitor system conditions and make data-driven decisions efficiently [3]. Several studies have applied the Internet of Things (IoT) technology to hydroponic systems to improve the efficiency of nutrient solution monitoring and control. Purwanto et al. [4] developed an Arduino NodeMCU-based nutrient supply control system using TDS and ultrasonic sensors with monitoring through an Android application. Putra and Pambudi [5] proposed an automatic pH control system for an NFT hydroponic system using a DFRobot pH sensor, an Arduino Nano, and a Fuzzy Logic Controller. More recently, Faisal et al. [6] developed an ESP32-based hydroponic solution quality monitoring system employing pH and TDS sensors with MQTT communication and a Node-RED dashboard for real-time monitoring. Meanwhile, Muhammad et al. [7] developed an ESP32-based hydroponic nutrient monitoring and control system integrating TDS and DS18B20 temperature sensors, pumps, and a solenoid valve through MQTT communication. Despite these advancements, several limitations remain. Purwanto et al. [4] monitored only nutrient concentration (TDS) and water level without integrating pH and nutrient solution temperature measurements. Putra and Pambudi [5] focused exclusively on pH control and did not incorporate nutrient concentration or temperature monitoring. Faisal et al. [6] developed only a monitoring system without implementing automatic actuator control. Although Muhammad et al. [7] integrated both monitoring and nutrient control functions, their study did not report sensor accuracy validation against reference instruments, nor did it provide a monitoring data export feature for further analysis.

Based on these challenges, this study aims to design and develop an Internet of Things (IoT)-based hydroponic nutrient monitoring and control system using an ESP32 microcontroller integrated with TDS, pH, and DS18B20 temperature sensors. Measurement data are transmitted to the ThingsBoard platform in real time through the MQTT protocol, enabling users to monitor nutrient solution conditions via a web-based dashboard. In addition, the system incorporates an automatic nutrient control mechanism using a peristaltic pump based on predefined setpoints. The proposed system is expected to provide an alternative solution for real-time hydroponic nutrient monitoring and control while supporting the implementation of IoT technology in indoor hydroponic cultivation based on the Nutrient Film Technique (NFT).

2. Materials and Methods

2.1 Study Site and Research Period

This study was conducted at the TS1 employee residence area of PT Riau Andalan Pulp and Paper, located in Pangkalan Kerinci, Indonesia. The research activities included the design, development, integration, testing, and evaluation of an Internet of Things (IoT)-based hydroponic nutrient monitoring and control system. The system was developed from April 2026, while data collection was carried out over a five-day period from 8 to 13 May 2026. The experiments were performed using an indoor hydroponic system based on the Nutrient Film Technique (NFT), which was designed to support controlled plant cultivation through real-time monitoring of nutrient solution parameters.

2.2 Materials and Equipment

The study employed both hardware and software components to support the design, implementation, and evaluation of the proposed IoT-based hydroponic nutrient monitoring and control system. The primary hardware components included an ESP32 microcontroller as the central processing unit, a DFRobot TDS Sensor V1.0 for measuring nutrient concentration, a DFRobot pH Sensor V1.1 for measuring solution acidity, a DS18B20 temperature sensor for monitoring nutrient solution temperature, peristaltic pumps for automatic nutrient dosing, a circulation pump for nutrient recirculation, an L298N motor driver module, and a step-down converter for voltage regulation. The technical specifications of the microcontroller and sensors used in this study were based on the official documentation provided by the respective manufacturers [8], [9], [10], [11].

The hydroponic setup consisted of an indoor Nutrient Film Technique (NFT) system comprising PVC pipes, a nutrient solution reservoir, and LED grow lights as an artificial lighting source. Lettuce (*Lactuca sativa*) was used as the plant material in this study. The plants served solely as the operational medium to simulate hydroponic cultivation conditions during system testing, while the primary focus of this research was the evaluation of the performance of the Internet of Things (IoT)-based nutrient monitoring and control system rather than plant growth analysis. The software used in this study included Arduino IDE for ESP32 programming, the ThingsBoard platform for IoT-based monitoring and control, and Microsoft Excel for data processing and analysis. For calibration and accuracy evaluation, a thermometer, a TDS meter, and a pH meter were used as reference instruments. In addition, pH buffer solutions of 4.01, 6.86, and 9.18 were used for pH sensor calibration.

2.3 System Architecture

The proposed system was implemented using an indoor hydroponic setup based on the Nutrient Film Technique (NFT). The hydroponic system consisted of a vertical PVC pipe with 18 planting holes, a nutrient solution reservoir, a circulation pump, and LED grow lights as an artificial light source. The nutrient solution was continuously circulated to form a thin film flowing over the plant roots. The developed system was designed to monitor nutrient solution parameters in real time while providing both automatic and manual nutrient control.

The integration of sensors, the ESP32 microcontroller, Wi-Fi communication, the MQTT protocol, and dashboard platforms has been widely implemented in Internet of Things (IoT)-based hydroponic systems to support real-time data acquisition, remote monitoring, and data-driven decision-making [12], [13], [14]. The system consisted of three main units: a data acquisition unit, a data processing and communication unit, and an actuation unit. The data acquisition unit included a DFRobot TDS Sensor V1.0 for measuring nutrient concentration, a DFRobot pH Sensor V1.1 for measuring solution pH, and a DS18B20 sensor for monitoring nutrient solution temperature. Measurement data collected from these sensors were processed by the ESP32 microcontroller, which served as the central controller of the system. The processed data were transmitted to the ThingsBoard platform via the MQTT protocol over a Wi-Fi network, allowing users to monitor nutrient solution parameters in real time. Besides serving as a monitoring platform, ThingsBoard was also used to configure the minimum and maximum nutrient concentration thresholds and to select the operating mode (manual or automatic). These configuration parameters were then transmitted back to the ESP32 through bidirectional MQTT communication. The actuation unit consisted of an L298N motor driver module controlling two peristaltic pumps for nutrient A and nutrient B solutions. In automatic mode, the ESP32 continuously compared the measured TDS value with the predefined threshold values. When the measured TDS value fell below the minimum threshold, both peristaltic pumps were activated to inject AB Mix nutrient solution until the nutrient concentration reached the target range. Once the target concentration was achieved, the pumps were automatically turned off. The overall system architecture is illustrated in Figure 1.

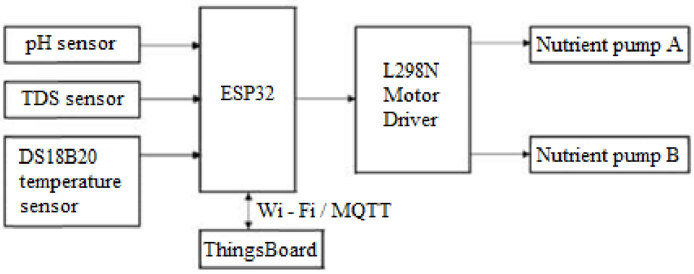


Figure 1. Architecture of the ESP32-Based IoT Hydroponic Nutrient Monitoring and Control System.

2.4 Sensor Calibration

2.4.1 TDS Sensor Calibration

The DFRobot TDS Sensor V1.0 was calibrated to improve the accuracy of nutrient concentration measurements in the hydroponic system. The calibration procedure followed the method recommended by DFRobot by comparing the sensor readings with those obtained from a commercial TDS meter used as the reference instrument. Initially, the nutrient solution was measured using the reference TDS meter to obtain the reference value. The TDS probe was then rinsed with clean water, dried, and immersed in the same solution until the reading became stable. The reference TDS value was subsequently entered into the system through the Arduino IDE Serial Monitor. The ESP32 automatically calculated the calibration coefficient (kValue) based on the difference between the sensor reading and the reference measurement. The calculated kValue was stored in the ESP32 EEPROM, allowing the calibration parameters to be retained after power cycling. The calibrated sensor was subsequently used for nutrient concentration monitoring throughout the experiments. The calibration procedure followed the technical documentation of the Gravity Analog TDS Sensor/Meter V1.0 provided by DFRobot [10].

2.4.2 pH Sensor Calibration

The DFRobot pH Sensor V1.1 was calibrated to improve the accuracy of nutrient solution pH measurements. The calibration followed the three-point calibration procedure recommended by DFRobot using standard buffer solutions with pH values of 4.01, 6.86, and 9.18 [9]. Before calibration, the pH probe was rinsed with clean water to prevent contamination. The probe was first immersed in the pH 4.01 buffer solution and allowed to stabilize before the first calibration point was recorded through the Arduino IDE Serial Monitor. The same procedure was repeated using the pH 6.86 and pH 9.18 buffer solutions to obtain the second and third calibration points. Between calibration steps, the probe was rinsed with clean water to avoid cross-contamination between buffer solutions. After completing the calibration procedure, the ESP32 automatically stored the calibration parameters in its EEPROM memory, eliminating the need for recalibration whenever the system was restarted. The calibrated sensor was subsequently used to monitor pH variations in the nutrient solution.

2.5 System Testing Procedure

System testing was conducted to evaluate the performance of individual components and to verify the integration of the proposed IoT-based hydroponic nutrient monitoring and control system. Sensor accuracy was evaluated by comparing the sensor measurements with those obtained from reference instruments. This approach is widely adopted for validating sensor performance in Internet of Things (IoT)-based monitoring systems [6], [7]. The evaluation included sensor accuracy testing, peristaltic pump performance testing, and overall system functionality testing. The DS18B20 temperature sensor was evaluated by comparing its measurements with those obtained from a reference thermometer. Ten measurements were recorded at 10-minute intervals. The DFRobot TDS Sensor V1.0 was evaluated by comparing its readings with those obtained from a commercial TDS meter. Similarly, the DFRobot pH Sensor V1.1 was evaluated against a reference pH meter. For both sensors, ten measurements were collected at 10-minute intervals using the same nutrient solution. The performance of the peristaltic pump was evaluated by measuring its flow rate. The pump was operated for one minute under ESP32 timer control, after which the discharged nutrient solution was measured using a graduated cylinder.

Overall system functionality was evaluated by verifying the monitoring of nutrient solution parameters, manual and automatic nutrient control, bidirectional communication with the ThingsBoard platform, and data export to Microsoft Excel. In addition, long-term system performance was evaluated through continuous monitoring over a five-day period using the indoor NFT hydroponic system. During this period, variations in Total Dissolved Solids (TDS), pH, and nutrient solution temperature were monitored together with the response of the automatic control system to changes in nutrient concentration.

2.6 Data Collection and Analysis

Data were collected over a five-day period using the indoor hydroponic system based on the Nutrient Film Technique (NFT). The monitored parameters included nutrient concentration (Total Dissolved Solids, TDS), pH, and nutrient solution temperature. These parameters were measured automatically using the DFRobot TDS Sensor V1.0, the DFRobot pH Sensor V1.1, and the DS18B20 temperature sensor connected to the ESP32 microcontroller. All sensor data were transmitted to the ThingsBoard platform via the MQTT protocol for real-time monitoring and storage. The MQTT protocol enables lightweight and efficient data communication in Internet of Things (IoT)-based systems [14]. The recorded data were subsequently exported to Microsoft Excel for processing and analysis.

The nutrient control system employed a target nutrient concentration range of 800 – 1000 ppm. Whenever the measured TDS value fell below the minimum threshold of 800 ppm, the ESP32 activated the peristaltic pumps to inject AB Mix nutrient solution. The pumps operated for 10 s, followed by a 1 min mixing period before the TDS value was measured again. This cycle was repeated until the nutrient concentration reached the target range. Data analysis was performed on the sensor accuracy tests, the performance of the nutrient control system, and the monitoring results of the nutrient solution parameters. Sensor performance was evaluated by comparing the sensor measurements with those obtained from the corresponding reference instruments, namely a thermometer for the DS18B20 sensor, a TDS meter for the TDS sensor, and a pH meter for the pH sensor. To provide a more comprehensive evaluation of sensor performance, the experimental data were analyzed using several statistical parameters, including the arithmetic mean, standard deviation (SD), Root Mean Square Error (RMSE), and mean error. These statistical metrics were used to assess the accuracy, measurement stability, and agreement between the proposed sensors and the corresponding reference instruments [15].

The arithmetic mean was used to determine the central tendency of the measurement data and was calculated using Equation (1).

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{1}$$

where:

$\bar{x}$ = arithmetic mean

x_i = ith measurement value

n = number of observations

The standard deviation (SD) was used to evaluate the dispersion of the measurement data around the mean value and was calculated using Equation (2).

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \tag{2}$$

Furthermore, the agreement between the sensor measurements and the corresponding reference instruments was evaluated using the Root Mean Square Error (RMSE), as expressed in Equation (3).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - R_i)^2} \tag{3}$$

where:

S_i = sensor measurement

R_i = reference instrument measurement

In addition, the mean error was calculated using Equation (4).

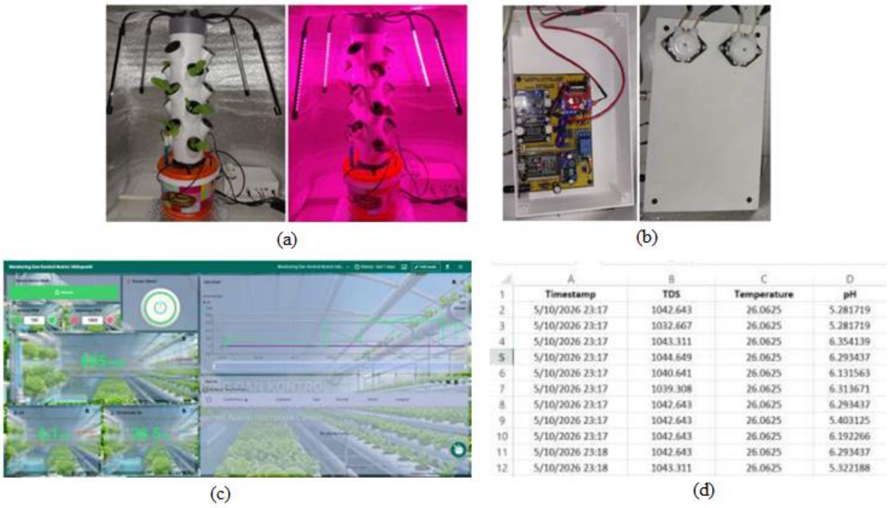
$$Mean\ Error = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{S_i - R_i}{R_i}\right| x\,100\% \tag{4}$$

These statistical parameters were used to evaluate the performance of the DS18B20 temperature sensor, the DFRobot V1.0 TDS sensor, and the DFRobot V1.1 pH sensor employed in this study.

3. Results and Discussion

3.1. System Implementation

The proposed Internet of Things (IoT)-based hydroponic nutrient monitoring and control system was successfully implemented and integrated with the ThingsBoard platform for real-time monitoring and control of nutrient solution parameters. The developed system consisted of an indoor hydroponic unit based on the Nutrient Film Technique (NFT), an ESP32-based data acquisition unit, pH and TDS sensors, a DS18B20 temperature sensor, peristaltic pumps, and a web-based monitoring dashboard. The implementation of the Internet of Things (IoT)-based hydroponic nutrient monitoring and control system in this study is consistent with previous studies, which demonstrated that the integration of sensors, the ESP32 microcontroller, the MQTT protocol, and a web-based dashboard can support real-time monitoring of nutrient solution conditions while enabling remote system control [6], [7]. The overall implementation of the developed system is presented in Figure 2.



	A	B	C	D
1	Timestamp	TDS	Temperature	pH
2	5/10/2026 23:17	1042.643	26.0625	5.281719
3	5/10/2026 23:17	1032.667	26.0625	5.281719
4	5/10/2026 23:17	1043.311	26.0625	6.354139
5	5/10/2026 23:17	1044.649	26.0625	6.293437
6	5/10/2026 23:17	1040.641	26.0625	6.131563
7	5/10/2026 23:17	1039.308	26.0625	6.313671
8	5/10/2026 23:17	1042.643	26.0625	6.293437
9	5/10/2026 23:17	1042.643	26.0625	5.403125
10	5/10/2026 23:17	1042.643	26.0625	6.192266
11	5/10/2026 23:18	1042.643	26.0625	6.293437
12	5/10/2026 23:18	1043.311	26.0625	5.322188

Figure 2. Implementation of the proposed IoT-based hydroponic nutrient monitoring and control system. (a) Indoor NFT (Nutrient Film Technique) hydroponic tower, (b) nutrient monitoring and control device, (c) ThingsBoard dashboard, and (d) exported monitoring data in Microsoft Excel.

Figure 2(a) shows the indoor hydroponic tower based on the Nutrient Film Technique (NFT), which was constructed using a vertical PVC pipe with 18 planting holes. The nutrient solution was continuously circulated as a thin film flowing over the plant roots before returning to the reservoir for recirculation. The system was also equipped with red blue LED grow lights as an artificial lighting source, allowing the hydroponic system to operate indoors. The nutrient monitoring and control device shown in Figure 2(b) was housed inside a project box to protect the electronic components from environmental disturbances. The device consisted of an ESP32 microcontroller, pH and TDS sensor modules, a DS18B20 temperature sensor, an L298N motor driver, a step-down converter, peristaltic pumps, and supporting electronic components. The ESP32 served as the central controller by acquiring sensor data, executing the nutrient control algorithm, and transmitting measurement data to the ThingsBoard platform via Wi-Fi using the MQTT protocol.

The monitoring interface is presented in the ThingsBoard dashboard shown in Figure 2(c). The dashboard displays the TDS value, pH, nutrient solution temperature, pump status, and the predefined minimum and maximum nutrient concentration thresholds. In addition, it provides both manual and automatic control functions together with real-time trend graphs, enabling users to remotely monitor the condition of the nutrient solution. As shown in Figure 2(d), the monitoring data stored in the ThingsBoard platform can be exported to Microsoft Excel for further analysis. The exported data include timestamps together with the corresponding TDS, temperature, and pH measurements. This feature facilitates data documentation, processing, and analysis throughout the experimental period. Overall, the implementation results demonstrated that all system components including the hydroponic unit, sensors, actuators, ESP32 microcontroller, communication network, monitoring dashboard, and data export functionality were successfully integrated and operated according to the proposed design. The performance of each sensor, actuator, and the overall system is evaluated in the following sections.

3.2. Performance Evaluation of the DS18B20 Temperature Sensor

The performance of the DS18B20 temperature sensor was evaluated to determine its measurement accuracy for the hydroponic nutrient solution. The sensor readings were compared with those obtained from a reference thermometer. A total of ten measurements were recorded at 10-minute intervals. The comparison between the temperature measurements obtained from the DS18B20 sensor and the reference thermometer is presented in Figure 3.

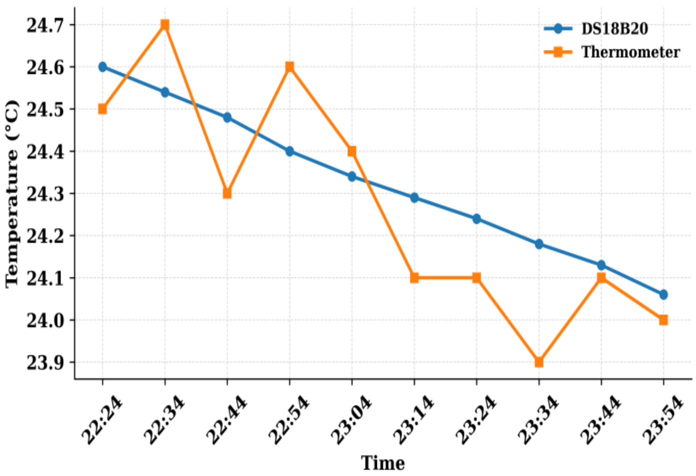


Figure 3. Comparison of temperature measurements obtained from the DS18B20 sensor and the reference thermometer.

As shown in Figure 3, the temperature measurements obtained from the reference thermometer exhibited slightly greater fluctuations than those recorded by the DS18B20 sensor, whose readings decreased gradually throughout the observation period. Nevertheless, both instruments produced temperature values within a similar range, indicating good agreement between the two measurement methods. The detailed measurement results are presented in Table 1.

Table 1. Performance evaluation of the DS18B20 sensor using a reference thermometer (May 8, 2026).

No	Time	DS18B20 (ºC)	Thermometer (ºC)	Difference (ºC)	Error (%)
1	22:24	24.60	24.50	0.10	0.41
2	22:34	24.54	24.70	-0.16	0.65
3	22:44	24.48	24.30	0.18	0.74
4	22:54	24.40	24.60	-0.20	0.81
5	23:04	24.34	24.40	-0.06	0.25
6	23:14	24.29	24.10	0.19	0.79
7	23:24	24.24	24.10	0.14	0.58
8	23:34	24.18	23.90	0.28	1.17
9	23:44	24.13	24.10	0.03	0.12
10	23:54	24.06	24.00	0.06	0.25
Average					0.58

Based on Table 1, the temperature measured by the DS18B20 sensor ranged from 24.06 to 24.60 °C, while the reference thermometer recorded temperatures between 24.00 and 24.70 °C. The measurement difference varied from −0.20 °C to 0.28 °C. The measurement error ranged from 0.12% to 1.17%, indicating that the DS18B20 sensor exhibited good agreement with the reference thermometer. The remaining measurement discrepancies may be attributed to sensor tolerance, response time, and environmental conditions during the data acquisition process. In addition to the error analysis, the sensor performance was further evaluated using statistical parameters, including the mean, standard deviation (SD), Root Mean Square Error (RMSE), and mean error, as presented in Table 2

Table 2. Statistical analysis results of the DS18B20 sensor performance

Mean Sensor (°C)	**Mean Thermometer (°C)**	**Mean Difference (°C)**	**Sensor SD (°C)**	**Thermometer SD (°C)**	**RMSE (°C)**	**Mean Error (%)**
24.33	24.27	0.06	0.18	0.27	0.16	0.58

As shown in Table 2, the DS18B20 sensor produced a mean temperature of 24.33 °C, while the reference thermometer recorded a mean value of 24.27 °C, resulting in a mean difference of only 0.06 °C. The standard deviation of the sensor (0.18 °C) was lower than that of the reference thermometer (0.27 °C), indicating that the sensor provided relatively stable measurements throughout the testing period. Furthermore, the RMSE value of

0.16 °C demonstrates that the deviation between the sensor measurements and the reference instrument was minimal. The mean error of 0.58% further confirms that the DS18B20 sensor achieved satisfactory measurement accuracy, making it suitable for temperature monitoring in the proposed Internet of Things (IoT)-based hydroponic system.

3.3. TDS Sensor Evaluation

Following the calibration process, the accuracy of the DFRobot V1.0 TDS sensor was evaluated by comparing its measurements with those obtained from a TDS meter used as the reference instrument. Data were collected 10 times at 10-minute intervals. This evaluation aimed to assess the accuracy and consistency of the sensor in measuring nutrient concentration in the developed hydroponic system. The comparison between the measurements obtained from the DFRobot V1.0 TDS sensor and the reference TDS meter is presented in Figure 4.

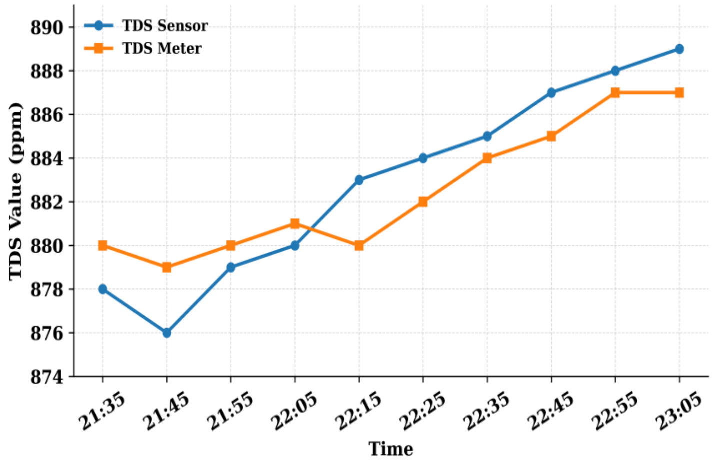


Figure 4. Comparison of TDS measurements obtained from the DFRobot V1.0 TDS sensor and the reference TDS meter.

As shown in Figure 4, the TDS values measured by the DFRobot V1.0 sensor closely followed the trend observed with the reference TDS meter. Both measurement curves exhibited a similar increasing pattern throughout the observation period, with only minor differences between the two instruments, indicating good agreement between the sensor and the reference device. The detailed measurement results are presented in Table 3.

Table 3. Performance evaluation of the DFRobot V1.0 TDS sensor against the reference TDS meter (May 11, 2026).

No	Time	TDS Sensor	TDS Meter	Difference (ppm)	Error (%)
1	21:35	878	880	-2	0.23
2	21:45	876	879	-3	0.34
3	21:55	879	880	-1	0.11
4	22:05	880	881	-1	0.11
5	22:15	883	880	3	0.34
6	22:25	884	882	2	0.23
7	22:35	885	884	1	0.11
8	22:45	887	885	2	0.23
9	22:55	888	887	1	0.11
10	23:05	889	887	2	0.23
Average					0.20

Based on Table 3, the TDS values measured by the sensor ranged from 876 to 889 ppm, whereas the reference TDS meter recorded values ranging from 879 to 887 ppm. The measurement difference ranged from −3 ppm to 3 ppm, with a percentage error between 0.11% and 0.34%. Throughout the testing period, the sensor exhibited a stable response without significant measurement fluctuations. The remaining discrepancies between the sensor and the reference instrument may be attributed to the characteristics of the analog sensor, variations in the nutrient solution, and environmental conditions during the measurement process. To provide a more comprehensive evaluation of the sensor's accuracy and measurement stability, a statistical analysis was performed. The results are presented in Table 4.

Table 4. Statistical analysis results of the TDS sensor performance

Mean Sensor (ppm)	Mean TDS Meter (ppm)	Mean Difference (ppm)	Sensor SD (ppm)	TDS SD Meter (ppm)	RMSE (ppm)	Mean Error (%)
882.90	882.50	0.40	4.48	3.03	1.95	0.20

As presented in Table 4, the DFRobot V1.0 TDS sensor produced a mean value of 882.90 ppm, whereas the reference TDS meter recorded a mean value of 882.50 ppm, resulting in a mean difference of only 0.40 ppm. The sensor exhibited a standard deviation of 4.48 ppm, indicating relatively stable measurements throughout the testing period. Furthermore, the RMSE value of 1.95 ppm demonstrates that the deviation between the sensor measurements and the reference instrument was minimal. The mean error of 0.20% further confirms the excellent measurement accuracy of the DFRobot V1.0 TDS sensor, indicating that it is suitable for monitoring nutrient concentration in the proposed Internet of Things (IoT)-based hydroponic system.

3.4. pH Sensor Evaluation

The performance of the DFRobot V1.1 pH sensor was evaluated to assess its accuracy in measuring the acidity of the hydroponic nutrient solution. The sensor readings were compared with those obtained from a pH meter used as the reference instrument. A total of 10 measurements were collected at 10 minute intervals. The comparison between the measurements obtained from the DFRobot V1.1 pH sensor and the reference pH meter is presented in Figure 5.

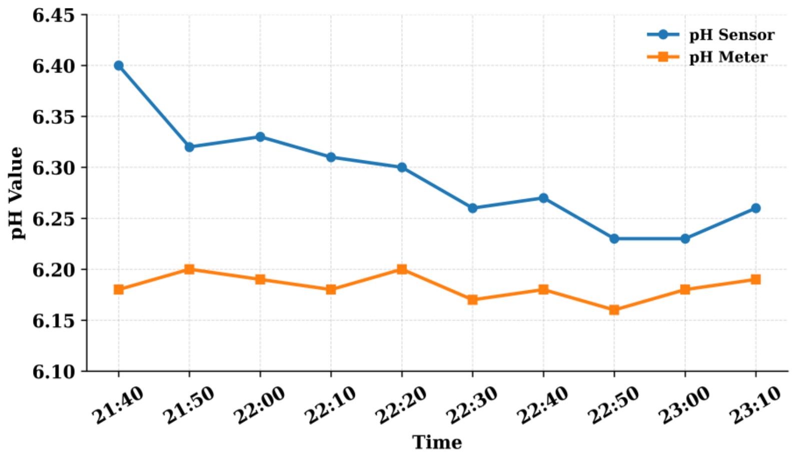


Figure 5. Comparison of pH measurements obtained from the DFRobot V1.1 pH sensor and the reference pH meter.

As shown in Figure 5, the pH values measured by the DFRobot V1.1 sensor were consistently slightly higher than those obtained from the reference pH meter throughout the observation period. The sensor readings decreased from approximately 6.40 to 6.23, whereas the reference pH meter remained relatively stable within the range of 6.16–6.20. Although a difference between the two instruments was observed, the measurement discrepancy remained relatively small, indicating that the sensor was able to provide pH estimates that were close to the reference measurements. The detailed results are presented in Table 5.

Table 5. Performance evaluation of the DFRobot V1.1 pH sensor against the reference pH meter (May 11, 2026).

No	Time	pH Sensor	pH Meter	Difference (pH)	Error (%)
1	21:40	6.40	6.18	0.22	3.56
2	21:50	6.32	6.20	0.12	1.94
3	22:00	6.33	6.19	0.14	2.26

4	22:10	6.31	6.18	0.13	2.10
5	22:20	6.30	6.20	0.10	1.61
6	22:30	6.26	6.17	0.09	1.46
7	22:40	6.27	6.18	0.09	1.46
8	22:50	6.23	6.16	0.07	1.14
9	23:00	6.23	6.18	0.05	0.81
10	23:10	6.26	6.19	0.07	1.13
Average					1.75

Based on Table 5, the pH values measured by the sensor ranged from 6.23 to 6.40, while the reference pH meter recorded values between 6.16 and 6.20. The measurement difference ranged from 0.05 to 0.22 pH units, indicating that the sensor measurements were in good agreement with those obtained from the reference pH meter. Although the pH values measured by the sensor were consistently slightly higher than those recorded by the reference instrument, both measurements exhibited a similar trend throughout the testing period. This finding is consistent with the study conducted by Purwanto et al. [4], which demonstrated that pH sensors can be effectively utilized for monitoring hydroponic nutrient solutions in Internet of Things (IoT)-based systems with satisfactory measurement accuracy. The remaining discrepancies between the sensor and the reference instrument may be attributed to the characteristics of the analog sensor, variations in the nutrient solution, and environmental conditions during the measurement process. To provide a more comprehensive evaluation of the sensor's accuracy and measurement stability, a statistical analysis was performed. The results are presented in Table 6.

Table 6. Statistical analysis results of the pH sensor performance

Mean Sensor	Mean pH Meter	Mean Difference	Sensor SD	pH Meter SD	RMSE	Mean Error (%)
6.29	6.18	0.11	0.05	0.01	0.12	1.75

As presented in Table 6, the DFRobot V1.1 pH sensor produced a mean value of 6.29, whereas the reference pH meter recorded a mean value of 6.18, resulting in a mean difference of only 0.11 pH units. The sensor exhibited a standard deviation of 0.05, indicating relatively stable measurements throughout the testing period. Furthermore, the RMSE value of 0.12 pH units demonstrates that the deviation between the sensor measurements and the reference instrument was minimal. The mean error of 1.75% further confirms the satisfactory measurement accuracy of the DFRobot V1.1 pH sensor, indicating that it is suitable for monitoring the pH of nutrient solutions in the proposed Internet of Things (IoT)-based hydroponic system.

3.5. Peristaltic Pump Output Evaluation

The peristaltic pump was evaluated to determine its output flow rate for the automatic nutrient dosing system. The evaluation was conducted by operating the pump continuously for 1 minute and measuring the volume of liquid delivered during the operation. The measurement result is presented in Figure 6.

Figure 6. Volume of nutrient solution delivered by the peristaltic pump after 1 minute of operation.

Based on the evaluation results, the peristaltic pump delivered 3 mL of nutrient solution after 1 minute of operation, corresponding to a flow rate of 3 mL/min (0.05 mL/s). This result indicates that the peristaltic pump is capable of delivering the nutrient solution at a measurable and consistent flow rate, making it suitable for use in the ESP32-based automatic nutrient control system.

3.6. System Functional Evaluation

A functional evaluation was conducted to verify that all components integrated into the IoT-based hydroponic nutrient monitoring and control system operated according to the intended design. The evaluation covered the monitoring function, control function, network communication with the ThingsBoard platform, and data export to Microsoft Excel. The evaluation results are summarized in Table 7.

Table 7. Results of the system functional evaluation.

Tested Component	Evaluation Result
Monitoring system	Successful
Control system	Successful
Network communication with ThingsBoard	Successful
Data export to Microsoft Excel	Successful

Based on Table 7, all system components operated as intended. The monitoring system successfully displayed real-time sensor data on the ThingsBoard dashboard. The control system successfully performed both manual and automatic nutrient dosing based on the predefined TDS threshold values. The ESP32 reliably transmitted and received data through the WiFi network, enabling stable communication with the ThingsBoard platform without any data transmission failures during the evaluation. Furthermore, the monitoring data were successfully exported to Microsoft Excel for data storage and further analysis. Overall, the evaluation results demonstrate that the integration of the sensors, ESP32 microcontroller, peristaltic pump, internet connectivity, and the ThingsBoard platform was successfully achieved, and all subsystems operated reliably as an integrated IoT-based hydroponic nutrient monitoring and control system.

3.7. Nutrient Control System Performance

The performance of the nutrient control system was evaluated by monitoring changes in the Total Dissolved Solids (TDS) concentration during the automatic addition of AB Mix nutrient solution. Nutrient concentration control based on TDS values is a widely adopted approach in automated hydroponic systems to maintain nutrient availability according to plant requirements [4]. During the evaluation, the minimum and maximum nutrient concentration thresholds were set to 800 ppm and 1000 ppm, respectively. The variation in TDS concentration during the nutrient dosing process is presented in Figure 7.

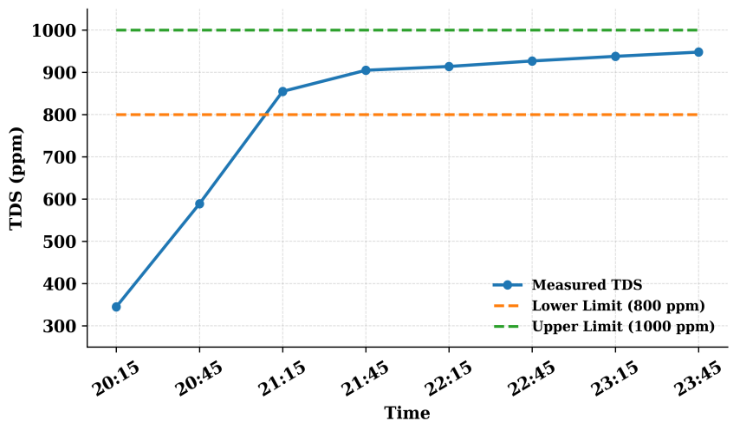


Figure 7. Changes in TDS concentration during the automatic addition of AB Mix nutrient solution.

As shown in Figure 7, the TDS concentration increased gradually from 345 ppm at 20:15 to 948 ppm at 23:45. The minimum threshold of 800 ppm was reached at 21:15, when the measured TDS concentration was 855 ppm. After exceeding the minimum threshold, the increase in TDS concentration became more gradual until it stabilized within the target range of approximately 900 – 950 ppm. The detailed TDS measurements during the nutrient dosing process are presented in Table 8.

Table 8. TDS concentration during the AB Mix nutrient dosing process (May 8, 2026).

No	Time	Measured TDS (ppm)	Lower TDS Limit (ppm)	Upper TDS Limit (ppm)
1	20:15	345	800	1000
2	20:45	589	800	1000
3	21:15	855	800	1000
4	21:45	905	800	1000
5	22:15	914	800	1000
6	22:45	927	800	1000
7	23:15	938	800	1000
8	23:45	948	800	1000

Based on the experimental data, the addition of the nutrient solution gradually increased the TDS concentration until it reached the predefined target range. Throughout the evaluation period, the TDS concentration remained below the maximum threshold of 1000 ppm. These results indicate that the peristaltic pump, controlled by the ESP32 microcontroller, successfully increased the nutrient concentration in a gradual and controlled manner until the target range of 800 – 1000 ppm was achieved.

3.8. Monitoring of Nutrient Concentration (TDS)

Nutrient concentration was continuously monitored to evaluate the stability of the Total Dissolved Solids (TDS) in the hydroponic nutrient solution. Measurements were acquired using a DFRobot V1.0 TDS sensor integrated with an ESP32-based Internet of Things (IoT) system. The monitoring process was conducted from May 8 to May 13, 2026. To facilitate the analysis of the effect of probe repositioning, the monitoring results were divided into two stages: May 8–11, 2026, before probe repositioning, and May 11–13, 2026, after probe repositioning. The date and time of each measurement are presented on the graph to provide a clearer interpretation of TDS variations throughout the monitoring period. The nutrient concentration monitoring results before and after probe repositioning are presented in Figure. 8.

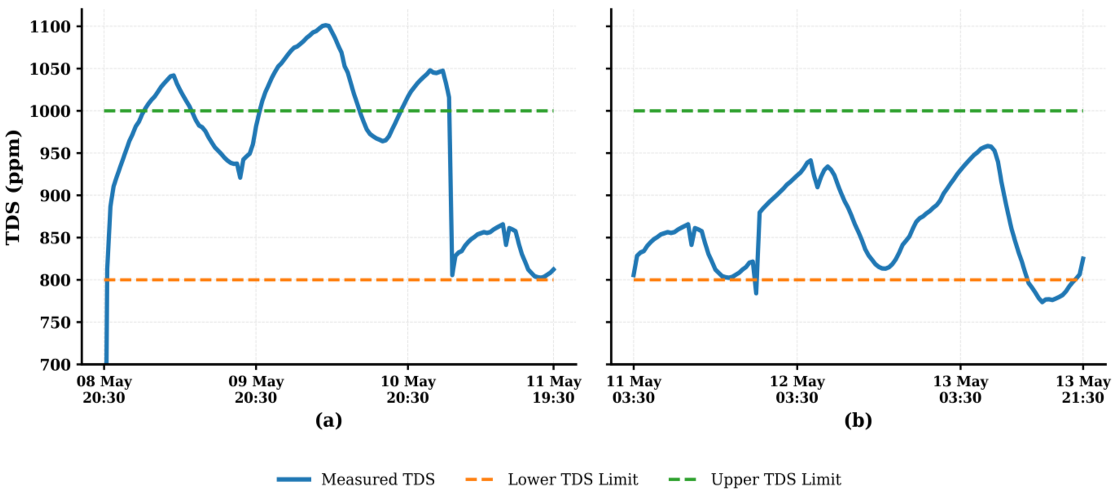


Figure. 8. Nutrient concentration (TDS) monitoring results: (a) May 8–11, 2026, before probe repositioning; (b) May 11–13, 2026, after probe repositioning.

As shown in Figure 8(a), the monitoring results indicate that the measured TDS values exceeded the predefined upper limit of 1000 ppm at several observation times. This suggests that the sensor readings did not fully represent the actual nutrient concentration in the reservoir. Following a system evaluation, it was found that the TDS probe was not optimally submerged in the nutrient solution. In the NFT tower hydroponic system, the returning nutrient solution generated ripples on the liquid surface, making the probe more susceptible to flow disturbances near the surface and resulting in unstable TDS measurements. Therefore, the probe was repositioned deeper into the nutrient solution to minimize the influence of surface ripples on the measurement process. This observation is consistent with the DFRobot technical documentation, which states that both the probe installation position and the surrounding flow conditions affect measurement stability. Accordingly, the probe should be installed in a well-submerged location and positioned away from strong flow disturbances or the container walls [16].

After the probe position was adjusted by submerging it deeper into the nutrient solution, the monitoring results presented in Figure 8(b) show that the measured TDS values remained within the predefined control range of 800–1000 ppm. Although the TDS values occasionally fell slightly below the lower limit of 800 ppm at several observation times, the overall fluctuations remained close to the target range and no measurements exceeded the upper limit after the probe repositioning. The deeper probe installation reduced the influence of surface ripples on the sensor, resulting in more stable measurements that more accurately represented the actual nutrient concentration in the reservoir. These results demonstrate that the placement of the TDS sensor probe has a significant influence on the measurement results. Therefore, proper sensor placement is essential for obtaining monitoring data that more accurately represent the actual condition of the hydroponic nutrient solution.

In addition to providing more stable measurements, the monitoring results also demonstrate that the system automatically activated the peristaltic pump whenever the TDS value approached the predefined lower threshold, allowing additional nutrient solution to be supplied to the reservoir. Following nutrient supplementation, the TDS value increased and returned to the target range. This behavior indicates that the proposed automatic control mechanism was able to maintain the nutrient concentration within the desired operating range. Consequently, the developed system functions not only as a real-time monitoring platform but also as an automatic nutrient control system based on predefined setpoint values. Therefore, the DFRobot V1.0 TDS sensor can be reliably employed as the feedback input for an Internet of Things (IoT)-based hydroponic nutrient monitoring and control system.

3.9. Monitoring of Nutrient Solution Temperature and pH

The nutrient solution temperature and pH were continuously monitored to evaluate changes in the solution conditions during system operation. Temperature and pH measurements were acquired using the DS18B20 temperature sensor and the DFRobot V1.1 pH sensor, both of which were integrated into the ESP32-based Internet of Things (IoT) system. Monitoring was conducted over the period of 11–13 May 2026, during which the measured temperature and pH data were transmitted to the ThingsBoard platform in real time. The monitoring graphs include complete date and time information to facilitate the interpretation of parameter variations throughout the monitoring period. The monitoring results of the nutrient solution temperature and pH are presented in Figure 9.

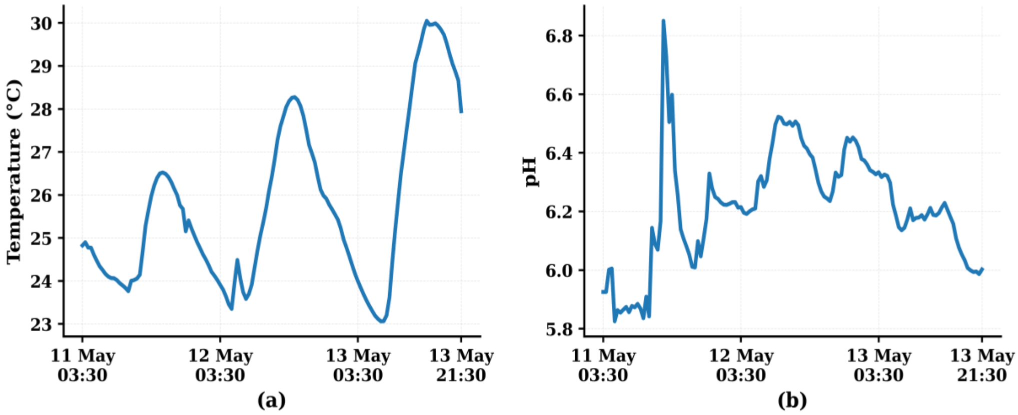


Figure 9. Monitoring results of nutrient solution temperature and pH during 11–13 May 2026. (a) Nutrient solution temperature monitoring. (b) Nutrient solution pH monitoring.

As shown in Figure 9(a), the nutrient solution temperature ranged from 23°C to 30°C throughout the monitoring period. The lowest recorded temperature was approximately 23°C, while the highest reached approximately 30°C. The temperature changed gradually, exhibiting alternating increasing and decreasing trends during system operation. This temperature range indicates that the nutrient solution temperature varied in response to the surrounding environmental conditions during system operation. In general, the recommended nutrient solution temperature for hydroponic lettuce cultivation is between 20 and 26 °C, whereas higher temperatures may affect the plant metabolic rate and reduce the dissolved oxygen concentration in the nutrient solution [17]. Although the nutrient solution temperature reached approximately 30 °C at certain observation times, the proposed monitoring system successfully recorded these temperature variations continuously, thereby providing valuable information for environmental management and operational decision-making in hydroponic cultivation.

The pH monitoring results presented in Figure 9(b) show that the nutrient solution pH ranged from 5.8 to 6.8 throughout the monitoring period. At the beginning of the observation, the pH increased to approximately 6.8, followed by a gradual decrease and fluctuations within the range of 6.0 – 6.5. Overall, the observed pH values remained close to the optimum range for hydroponic lettuce cultivation, which is approximately 5.5–6.5 [18]. Although the pH occasionally increased to approximately 6.8, indicating variations in the nutrient solution conditions during system operation, the monitoring system was able to record these changes in real time. This capability enables users to take timely corrective actions whenever the pH value deviates from the desired operating range.

4. Conclusion

This study successfully designed and implemented an Internet of Things (IoT)-based hydroponic nutrient monitoring and control system using an ESP32 microcontroller, TDS sensor, pH sensor, DS18B20 temperature sensor, peristaltic pumps, and the ThingsBoard platform for real-time monitoring. The developed system was capable of measuring TDS, pH, and temperature, transmitting sensor data in real time via the MQTT protocol, and storing and exporting the monitoring data to Microsoft Excel. The experimental results showed that the DS18B20 temperature sensor, TDS sensor, and pH sensor achieved average measurement errors of 0.58%, 0.20%, and 1.75%, respectively, compared with the reference instruments. In addition, the automatic control system successfully activated the peristaltic pumps according to the programmed control logic based on the predefined nutrient concentration setpoints. Overall, the developed system operated as intended and can be used for real-time IoT-based monitoring and control of hydroponic nutrient solutions. This study has several limitations. First, the proposed system was evaluated using only a single plant species (*Lactuca sativa*) and a single NFT hydroponic configuration; therefore, its performance under different environmental conditions or with other crop species has not yet been investigated. In addition, the developed system focuses primarily on nutrient concentration (TDS) control, while pH measurement is limited to real-time monitoring without automatic control. Future research should consider integrating automatic pH regulation, cloud-based data storage, remote notification features, and artificial intelligence (AI)-based methods to enhance the decision-making capability of hydroponic nutrient monitoring and control systems.

Authors' Contributions

M.F.D. conceived the study, conducted the experiments, analyzed the data, and drafted the manuscript. Y. and A.D. supervised the research, contributed to the methodology, and reviewed the manuscript. D.S.K. contributed to data analysis, validation, and manuscript revision. A.U.B. supervised the project and reviewed the manuscript. All authors read and approved the final manuscript.

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