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DESIGN AND DEVELOPMENT OF AN AUTOMATION AND PUMP TIMER SYSTEM FOR AEROPONICS

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Abstract

This study aims to design an automation and timer system for aeroponic pumps in the cultivation of currant tomatoes (Solanum pimpinellifolium) to improve energy efficiency and optimize nutrient delivery. The system was designed using an Arduino Nano microcontroller integrated with the RTC DS3231 module as a pump operational time controller, TDS Meter sensor to monitor dissolved nutrient concentration, and pH Meter sensor to measure nutrient solution acidity level. Testing was conducted for 14 days to evaluate sensor performance in responding to predetermined setpoints. The results showed that the implementation of the timer system resulted in energy savings of 83% compared to the system without a timer, where energy consumption decreased from 11.62 kWh to 1.93 kWh per day. TDS Meter and pH Meter sensors were able to consistently monitor nutrient parameters with values approaching optimal setpoints. The RTC DS3231 module functioned optimally in controlling the pump operational cycle without experiencing time reading errors. The designed system proved effective in improving energy efficiency and maintaining stable plant growth environment conditions, making it suitable for implementation as an automation-based aeroponic system.

Keywords: Aeroponics, Automation, Energy Efficiency.

INTRODUCTION

As one of the countries with the largest agricultural sectors in the world, Indonesia faces significant challenges in agriculture. The Food and Agriculture Organization (FAO) predicts that global food demand will continue to surge and is expected to increase by 70% by 2050. This projection highlights pressing issues related to the declining availability of water and energy resources. Despite Indonesia's abundant natural resources, managing the agricultural sector remains a complex challenge. Technological advancement is therefore essential to foster innovation and progress in agriculture, as it can enhance production yields, facilitate farm management, and ultimately improve farmers' incomes.

Tomatoes are among the most widely cultivated and well-known horticultural crops in Indonesia. In addition to being consumed as a vegetable, tomatoes provide various other benefits, including use as raw materials for pharmaceuticals, cosmetic products, and processed foods such as sauces and juices. In terms of agricultural development, horticulture represents a highly promising commodity sector due to strong domestic market demand for agricultural products. Tomatoes are rich in nutrients, including vitamins C and A, protein, calcium, sodium, potassium, phosphorus, thiamine, riboflavin, niacin, and ascorbic acid. Consequently, tomatoes are valued as a vegetable with substantial health benefits and high economic value (Annisaturaida et al., 2023).

To support tomato cultivation in Indonesia, the implementation of technologies capable of increasing yields, even in limited land areas, is essential. One viable solution is aeroponic technology. This method enables plants to grow without soil, where the roots are suspended in air and sprayed with nutrient-rich water in the form of mist. The development of aeroponic technology has been previously explored, as described in a study entitled "Implementation of Automation and Monitoring Systems in Aeroponic Farming Methods." This research developed an automatic control system for water irrigation based on sensors connected to a portable control box, ensuring that plants receive sufficient water at the appropriate time. Furthermore, the automation system was equipped with a nutrient sensor connected to the irrigation reservoir. This sensor measured nutrient concentration in parts per million (ppm) and automatically mixed nutrient solutions A and B in a small container using pumps connected to the control unit. Another study entitled "Comparative Analysis of Power Consumption in Aeroponic Irrigation Based on Time Scheduling and Sensor-Based Irrigation" compared energy consumption between time-based and sensor-based irrigation systems. The results indicated that over a 4-hour operation period in two different locations, power consumption in a residential setting using time-based control was 32.70 W, while the sensor-based system consumed 32.98 W. The overall average difference in power usage between the time-based system and the DHT22 sensor-based system was 0.28 W. However, energy wastage remains a challenge. Excessive electricity consumption often occurs in hydroponic systems due to the continuous operation of water circulation pumps and automated control systems for 24 hours per day. This condition not only increases operational costs but also raises overall energy demand.

According to (Ade Sugito1, Joko Sumarsono2 & 1Mahasiswa, 2023), the implementation of an aeroponic system involves spraying cycles operating from morning to afternoon with intervals of 30 minutes active and 30 minutes inactive, while at night the system is set to 15 minutes active and 45 minutes inactive. The study demonstrated that with such scheduling, the aeroponic system operated effectively, achieving a pump discharge rate of approximately 3.58–3.676 ml/s and utilizing a 0.1 mm nozzle that provided spray uniformity of up to 97.17%. Additional measured parameters included nutrient solution temperature (26–37°C), pH (5.7–7.5), and plant water consumption reaching a maximum of 11.32 liters to support irrigation effectiveness. An aeroponic system with 15-minute spraying intervals was found to enhance oxygen absorption (Halimawan et al., 2020). Furthermore, (Deperiky et al., 2023) designed an automatic cycle that sprayed for 2 minutes every 10 minutes, emphasizing that such a spraying schedule effectively maintained root moisture and nutrient supply in aeroponic potato cultivation.

This aeroponic system employs a microcontroller designed to execute commands according to a predefined format, enabling automated operation. This approach simplifies management and maintenance while improving system efficiency. Moreover, the microcontroller-based system automatically regulates irrigation timing and monitors water pH and nutrient solution levels throughout the planting and growth process. The development of this aeroponic system has the potential to enhance production quality, thereby meeting domestic vegetable demand in Indonesia as well as supporting export commodities. Therefore, the author prepared a scientific paper entitled: “Design and Development of an Automated Pump Timer System for Aeroponic Cultivation of Cherry Tomato (*Solanum pimpinellifolium*).”

METHOD

This study employed an experimental approach consisting of several stages, including a literature review, system planning, procurement of tools and materials, installation and configuration of the microcontroller, followed by system testing and analysis of the results to evaluate the performance of the designed system. The research was conducted over approximately sixteen weeks through a structured sequence of stages. The first to the third weeks were devoted to the literature review. During the third and fourth weeks, system requirements were identified. Concurrently, system design was carried out from the fourth to the fifth week, while the procurement of tools and materials took place in the sixth week. System assembly and implementation were conducted from the seventh to the ninth week, followed by system testing from the tenth to the fourteenth week. The final stage, consisting of result analysis and report preparation, was completed during the fifteenth and sixteenth weeks.

To achieve optimal results in the preparation of this scientific paper, the author employed the following research methods:

1. Literature Review Method
   This method was used to collect data from various references, including books, academic journals, online sources, and other relevant scientific materials that support data collection and theoretical foundations.
2. Observation Method
   This method was applied to test the developed object through experimental procedures, conducted either directly or indirectly, to evaluate system performance.
3. Consultation Method
   This method involved communication and discussion with the academic supervisor as a means of exchanging ideas and obtaining guidance to facilitate the writing and completion of the scientific report.

RESULTS AND DISCUSSION

Testing Phase

Working Voltage Measurement Test

The working voltage measurement test on the hardware components was conducted to ensure that the voltage supplied to each component complied with its respective operational voltage specifications.

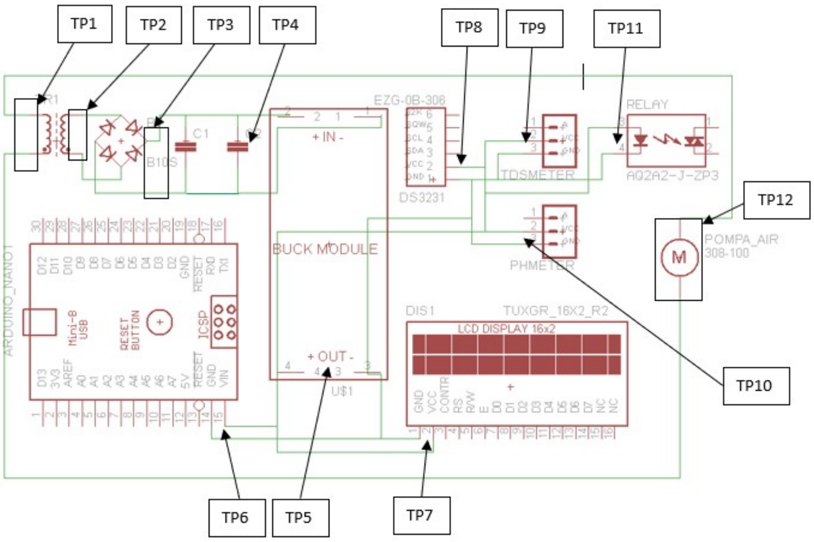

Figure 1. Component Measurement Points
(Source: Personal Data, 2026)

The measured working voltage points included the power supply source, the operating voltage of the microcontroller and sensors, as well as supporting components.

Measurement Point Description:
TP1: Measurement point at the transformer input
TP2: Measurement point at the transformer output
TP3: Diode measurement point
TP4: 1000 µF capacitor measurement point
TP5: LM2596 step-down output measurement point
TP6: Arduino Nano power input measurement point
TP7: LCD I2C 16×2 power input measurement point
TP8: RTC DS3231 module voltage input measurement point
TP9: TDS meter sensor voltage input measurement point
TP10: pH meter sensor voltage input measurement point
TP11: Relay input measurement point
TP12: Pump motor voltage measurement point

Measurement Results

Each component was measured five times to obtain a higher level of accuracy. The collected data were subsequently processed by calculating the average value using the following equation:

$$x = \frac{x_1+x_2+x_3+x_4+x_5}{n} = \frac{S_{xi}}{n} \qquad (4.1)$$

Where:
$\frac{S_{xi}}{n}$ = Sum of all measurement samples
X_1 = Measurement
n = Number of Measurements
x = Average Price

The percentage difference or error occurring in the test and measurement results can be determined using the following equation:

$$\% \, Error = \frac{Measurament-Calculation}{Measurament} \, x \, 100\% \qquad (4.2)$$

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Differences between measured and calculated values may lead to potential errors. Therefore, further verification or validation is required to determine the magnitude of the percentage error and to minimize possible inaccuracies in the measurement results.

Table 1. Component Measurement Test Results

No	Device Name	Test Point (TP)	Measurement Results (V)					Average (V)	Description
1	Power Supply	Transformer Input (TP1)	221.6	222.4	222.1	221.9	221.8	221.96 Vac	**Trafo Output**
		Transformer Output (TP2)	13.04	13.08	13.06	13.04	13.06	13.05 Vac	**Diode Voltage**
		Diode Voltage (TP3)	17.5	17.5	17.6	17.5	17.5	17.52 vdc	**Capacitor Voltage**
		Capacitor Voltage (TP4)	17.6	17.6	17.5	17.6	17.6	17.63 Vdc	**LM 2596 Input**
2	LM2596	Output LM 2596 (TP5)	5.05	5.07	5.06	5.06	5.06	5.06 Vdc	**Arduino Nano input**
3	Arduino Nano	Input Arduino (TP6)	5.06	5.03	5.05	5.07	5.07	5.06 Vdc	**Arduino Input**
4	LCD I2C 16x2	Input LCD (TP7)	5.03	5.04	5.05	5.04	5.05	5.04 Vdc	**LCD I2C 16x2 Input**
5	RTC Module DS3231	Input RTC (TP8)	3.99	4.01	3.98	4.00	3.98	3.99 Vdc	**RTC Input**
6	TDS Sensor	Input TDS Meter (TP9)	3.29	3.30	3.28	3.31	3.30	3.30 Vdc	**TDS Meter Input**
7	pH Sensor	Input pH Meter (TP10)	3.31	3.30	3.28	3.31	3.29	3.30 Vdc	**pH Meter Input**
8	Relay	Input Relay (TP11)	5.04	5.05	5.04	5.06	5.06	5.05 Vdc	**Relay Input**
9	**Pump Motor**	**Motor Voltage (TP12)**	**221.8**	**222.2**	**221.9**	**222.3**	**221.9**	**222.02 Vac**	**Pump Motor Voltage**

(Source: Personal Data, 2026)

Based on the test results presented in Table 1, measurements of each system component were conducted five times to obtain accurate and consistent data. The average value was then calculated to represent the actual condition of each measured parameter. In the power supply section, the measurement results of the transformer input voltage (TP1) showed an average value of 221.96 Vac, indicating that the AC voltage source was stable. The transformer output voltage (TP2) had an average value of 13.05 Vac, demonstrating that the voltage step-down process performed by the transformer operated properly. Furthermore, the measured voltages at the diode (TP3) and capacitor (TP4), which were 17.52 Vdc and 17.63 Vdc respectively, indicate that the rectification and DC voltage filtering processes functioned optimally.

Testing of the LM2596 module (TP5) produced an average output voltage of 5.06 Vdc. This value indicates that the DC step-down module operated effectively in reducing and stabilizing the voltage. This voltage was subsequently supplied to the Arduino Nano (TP6), which also showed an average value of 5.06 Vdc, indicating that the microcontroller received a stable power supply in accordance with its operational specifications. In testing the LCD I2C 16×2 module (TP7), an average input voltage of 5.04 Vdc was obtained, which remains within the permissible tolerance range for display module operation. Meanwhile, measurements of the RTC DS3231 module (TP8) resulted in an average voltage of 3.99 Vdc, indicating that the real-time clock module received sufficient power to operate normally. The test results for the TDS meter sensor (TP9) and the pH meter sensor (TP10) each showed an average voltage of 3.30 Vdc. These values indicate stable input voltage conditions for both sensors, thereby supporting accurate and consistent data readings. In addition, measurement of the relay (TP11) yielded an average value of 5.05 Vdc, indicating that the relay received sufficient voltage for proper switching operation.

Finally, voltage testing of the pump motor (TP12) showed an average value of 222.02 Vac. This indicates that the voltage supply to the pump motor was within normal operating conditions, enabling the motor to function properly. Overall, the test results demonstrate that each component in the system received a relatively stable voltage in accordance with the design specifications. It can therefore be concluded that the power supply and voltage distribution system functioned properly and supported the overall performance of the system optimally. The obtained measurement results will subsequently be compared with the values specified in the respective data sheets as a reference to evaluate conformity with the operational voltage ranges. This comparison ensures that each component operates optimally and in accordance with the specified technical requirements. The comparison between the measured values and the data sheet specifications is presented in the table below.

Table 2. Comparison of Component Measurements with Datasheet Specifications

No	Measurement	TP	Datasheet Range (VAC/VDC)	Average Measurement (VAC/VDC)	Description
1	Transformer Input	TP1	110 – 220	220.26	*Out of range (*)*
2	Transformer Output	TP2	6, 9, 12, dan 15	13.05	*In range*
3	Diode	TP3	– 1000	17.52	*In range*
4	Capacitor	TP4	~25	17.63	*In range*
5	Output LM2596	TP5	1.25 – 35	5.06	*In range*
6	Arduino Nano Input	TP6	5 - 12	5.07	*In range*
7	LCD I2C 16x2	TP7	3 - 5	5.04	*Out of range (*)*
8	RTC Module DS3231	TP8	2.3 – 5.5	3.99	*In range*
9	TDS Sensor	TP9	3.3 - 5.5	3.3	*In range*
10	pH Sensor	TP10	3.3 - 5.5	3.3	*In range*
11	Relay Input	TP11	±5	5.03	*In range*
12	Pump Motor	TP12	220	222.02	*Out of range (*)*

(Source: Personal Data, 2026)

Based on the measurement results presented in Table 2, it can be observed that most measurement points exhibit voltage values within the specification ranges stated in their respective datasheets. This indicates that the components and the overall circuit generally operate in accordance with the intended design characteristics. On the input side, the transformer measurement (TP1) produced an average voltage value of 220.26 VAC, which is slightly above the upper limit of the datasheet range (110–220 VAC). This condition is categorized as *out of range* and may be influenced by fluctuations in the main utility power supply (PLN). In the regulator and power supply output section, most measurement points, such as TP2 through TP6, showed voltage values within the specified range (*in range*). However, several measurement points were identified as *out of range*, including TP7 (IC D1C 2C) and TP12 (pump motor). At TP7, the measured voltage slightly exceeded the upper limit specified in the datasheet, while at TP12, the measured voltage of 220 VAC exceeded the defined nominal limit.

Equipment Testing Results

Testing of the RTC DS3231 Module

The testing of the RTC DS3231 module was conducted to determine the accuracy of the module's timekeeping in comparison with real-time conditions. The test was performed ten times, in which the RTC DS3231 module functioned as both a time indicator and a timer controlling the activation and deactivation of the pump. The RTC module was programmed to activate the system (logic 1) after 15 minutes had elapsed and to deactivate the system (logic 0) after 3 minutes of operation. Observations were carried out by recording the time at which the device was initially powered on. The timer then counted 15 minutes before the system activated the pump (logic 1). After operating for 3 minutes, the timer subsequently deactivated the pump (logic 0). The results of the RTC DS3231 module testing are presented in Table 3.

Table 3. Test results of the DS3231 RTC module

No	Recorded Time	Description
1	19:12:23	Water pump OFF (Logic 0)
2	19:27:26	Water pump ON (Logic 1)
3	19:30:26	Water pump OFF (Logic 0)
4	19:45:27	Water pump ON (Logic 1)
5	19:48:27	Water pump OFF (Logic 0)
6	20:03:28	Water pump ON (Logic 1)
7	20:06:28	Water pump OFF (Logic 0)
8	20:21:29	Water pump ON (Logic 1)
9	20:24:29	Water pump OFF (Logic 0)
10	20:39:30	Water pump ON (Logic 1)

(Source: Personal Data, 2026)

Table 3 presents the results of the RTC DS3231 module testing, which was conducted to evaluate the system's logical response to time changes.

Testing of Water Pump Power Consumption With and Without Timer

This test was conducted to compare the power consumption (kWh) of the aeroponic system over a 24-hour period during irrigation operations using a timer and without a timer. The measurements were performed five times using a multimeter and a clamp meter to determine the pump voltage and current when operating (ON condition).

Table 4. Results of Water Pump Measurements

Measurement of the-	Voltage (VAC)	Curent (I)
1	219	0.08
2	220	0.1
3	219	0.09
Measurement of the--	Voltage (VAC)	Curent (I)
4	221	0.1
5	222	0.1
Average	220.2	0.09

(Source: Personal Data, 2026)

Table 4 presents the results of the water pump measurements, from which the average values were calculated to determine the power consumption (kWh) of the aeroponic system operating with a timer and without a timer over a 24-hour period. The final percentage comparison between the aeroponic pump system using a timer and the system operating without a timer indicates an 83% difference in performance.

Testing of the TDS Meter Sensor

The TDS meter sensor is used to measure the PPM value of the water contained in the reservoir. The sensor operates based on the principle of light scattering or light absorption reflected by suspended particles in the water. A light source (LED/laser) is directed at the sample, and a detector measures the intensity of the scattered or absorbed light to determine the level of water turbidity. The greater the number of suspended particles, the higher the scattering or absorption of light, resulting in a higher turbidity value (generally expressed in NTU). This experiment was conducted over a period of 14 days with the objective of analyzing the sensor's performance in responding to the setpoint values predetermined in the aeroponic system. Data collection was carried out periodically and recorded systematically as part of the observation process. The measurement results were used as the basis for system evaluation and as a reference for decision-making and the implementation of corrective measures to maintain the aeroponic environment within the optimal range. The results obtained include the nutrient concentration values expressed in parts per million (PPM), as detected by the sensor and displayed on the LCD screen.

Table 5. Results of TDS Meter Sensor Testing

Testing Time	Sensor Reading (PPM)
Day 1	873
Day 2	912
Day 3	897
Day 4	933
Day 5	910
Day 6	891
Day 7	865
Day 8	987
Day 9	1004
Day 10	1018
Day 11	1024
Day 12	968
Day 13	1037
Day 14	1218

(Source: Personal Data, 2026)

Table 5 presents the results of the TDS meter sensor testing in monitoring the PPM value of the water in the reservoir. Based on the data shown in Table 4.5 and the reference nutrient concentration values applied in this study, the PPM setpoints were determined as follows: 900 for days 1–7, 1000 for days 8–13, and 1200 for day 14. The results of the TDS meter sensor testing indicate that the PPM readings during the observation period were generally close to the predetermined setpoints, although several fluctuations were observed. To complement the TDS meter sensor evaluation, a comparison was conducted between the sensor measurements and manual measurements using a conventional measuring instrument. The purpose of this test was to determine the accuracy of the sensor readings relative to the actual values obtained through direct physical measurement. Measurements were carried out five times across five different containers filled with water. The comparison results are presented in the following table:

Table 6. Comparison of TDS Sensor Measurements and Manual Measurements

No	TDS Meter Sensor Measurement (PPM)	Manual Measurement (PPM)
1	54	52
2	53	50
3	55	51
4	55	50
5	54	50

(Source: Personal Data, 2026)

The error testing of the TDS meter sensor readings was performed by comparing the sensor measurements with a reference accuracy standard of 95%. The error value was calculated using the percentage error formula as follows:

$$\%Error = \frac{|Sensor\ reading - References\ reading|}{References\ reading}\ x\ 100\%$$

The following table presents the results of the error measurement calculations:

Table 7. Error Calculation of the TDS Meter Sensor

No	Sensor Reading (PPM)	Reference Reading (PPM)	Error (%)
1	54	52	3.8
2	53	52	1,9
3	55	53	3.8
4	55	51	7
5	54	52	3.8

(Source: Personal Data, 2026)

The results indicate that the majority of error values are below 4%, with the highest error recorded at 7% in the fourth trial. The distribution of the TDS sensor error presented in the table above is illustrated in the graph below.

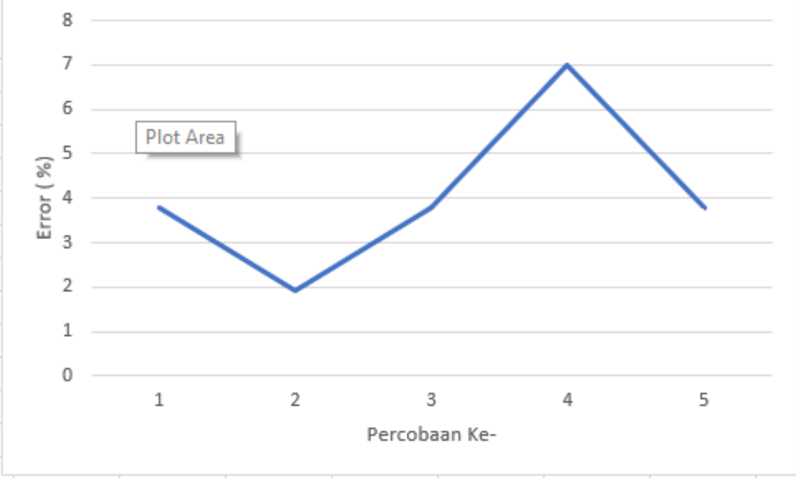

Figure 2. TDS Meter Sensor Error Graph
(Source: Personal Data, 2026)

Testing of the pH Meter Sensor

The pH meter sensor is used to measure the pH level of the water contained in the reservoir. The sensor operates based on electrochemical principles by measuring the electrical potential difference between a glass electrode sensitive to hydrogen ions (H^+) and a stable reference electrode. This voltage difference is then converted into a readable pH value. The primary process involves the exchange of H^+ ions across the glass membrane, which generates a voltage proportional to the hydrogen ion concentration in the solution. This experiment was conducted over a period of 14 days with the objective of analyzing the sensor's performance in responding to the predetermined setpoint values within the aeroponic system. Data collection was carried out periodically and recorded systematically as part of the observation process. The measurement data were used as the basis for system evaluation and as a reference for decision-making and the implementation of corrective actions to ensure that the aeroponic environment remained within the optimal range. The measurement results obtained include the pH values detected by the sensor and displayed on the LCD screen.

Table 8. Results of pH Sensor Testing

Testing Time	Sensor Reading (pH)
Day 1	6.8
Day 2	6.6
Day 3	6.5
Day 4	6.4
Day 5	6.9
Day 6	6.8
Day 7	6.6
Day 8	6.3
Day 9	6.4
Day 10	6.6
Day 11	6.0
Day 12	6.3
Day 13	6.5
Day 14	6.4

(Source: Personal Data, 2026)

Table 8 presents the results of the pH meter sensor testing in monitoring the pH level of the water in the reservoir. Based on the data shown in Table 4.8, the results of the 14-day pH sensor testing indicate that the pH value of the nutrient solution in the aeroponic system ranged between 6.6 and 7.2. This range is relatively close to the predetermined pH setpoint of 7. To complement the pH meter sensor evaluation, a comparison was conducted between the sensor measurements and manual measurements using a conventional measuring instrument. The purpose of this test was to determine the accuracy of the sensor readings relative to the actual values obtained through direct physical measurement. Measurements were carried out five times across five different containers filled with water. The comparison results are presented in the following table:

Table 9. Comparison of pH Sensor Measurements and Manual Measurement

No	pH Sensor Measurement (pH)	Manual Measurement (pH)
1	6.2	6.1
2	6.2	6.2
3	6.3	6.1
4	6.2	6.0
5	6.2	6.1

(Source: Personal Data, 2026)

Error testing of the pH sensor readings was conducted by comparing the sensor measurements with the reference measurements. The error value was calculated using the percentage error formula as follows:

$$\%Error = \frac{|Sensor\ reading - References\ reading|}{References\ reading}\ x\ 100\%$$

The results of the error calculation are presented in the following table:

Table 10. Error Calculation of the pH Meter Sensor

No	Sensor Reading (pH)	Reference Reading (pH)	Error (%)
1	6.2	6.1	1,6
2	6.2	6.2	0
3	6.3	6.1	3,2
4	6.2	6.0	3,3
5	6.2	6.1	1,6

(Source: Personal Data, 2026)

The results indicate that the majority of errors were below 1.8%, with the highest error value of 3.3% observed in the fourth trial. The error distribution of the pH sensor shown in the table above is illustrated in the graph below.

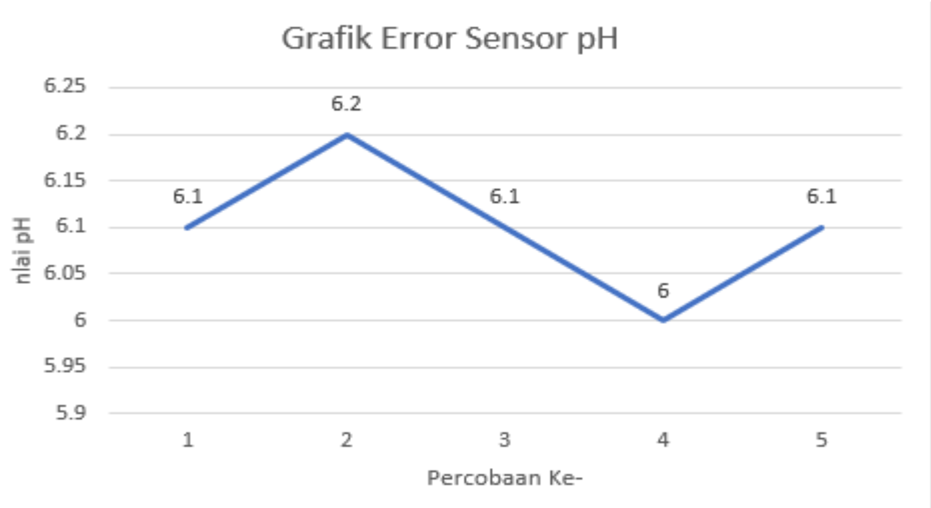

Figure 3. pH Sensor Error Graph
(Source: Personal Data, 2026)

Analysis

RTC DS3231 Module

Based on the data presented in Table 3, the RTC DS3231 module demonstrated reliable performance in accurately regulating and reading time to control the operational status of the water pump within the system. The test results indicate that the water pump operated under two conditions, namely ON (logic 1) and OFF (logic 0), in accordance with the pre-programmed schedule. During the testing period from 19:12:23 to 20:39:30, changes in the pump status occurred consistently and sequentially. The pump was activated (ON) at designated times and subsequently deactivated (OFF) at the next scheduled intervals, indicating that the RTC module was capable of delivering precise timing signals to the microcontroller to execute the appropriate logical commands. The repeated ON and OFF switching pattern confirms that the system operated stably without delays or time-reading errors. Furthermore, the intervals between status changes were relatively consistent, demonstrating the high accuracy and reliability of the RTC DS3231 as a timing controller in the automation system. Therefore, it can be concluded that the RTC DS3231 module functioned effectively in controlling pump operations based on the predetermined schedule, thereby supporting the overall system performance.

Water Pump Power Consumption With and Without Timer

Based on the calculation results, the aeroponic system without a timer exhibited relatively high power consumption. The water pump operated continuously for 24 hours with a power rating of 19.81 W, resulting in an energy consumption of 0.475 kWh per day. This condition indicates low energy efficiency, as the pump operated continuously without consideration of the actual requirements of the aeroponic system. In contrast, the implementation of a timer significantly reduced energy consumption. With a work cycle of 18 minutes, during which the pump operated for only 3 minutes per cycle, the total pump operating time within 24 hours was reduced to 4 hours. Under these conditions, daily energy consumption decreased to 0.079 kWh. This finding demonstrates that the use of a timer effectively optimizes pump operation according to system requirements, thereby improving electrical energy efficiency. The comparison between the non-timer and timer-based systems shows a difference in energy consumption of 0.396 kWh per day. The resulting energy savings reached 83%, indicating that the application of a timing control system is highly effective in reducing electrical power consumption in the aeroponic system. Therefore, implementing a time-control system not only enhances energy efficiency but also has the potential to reduce operational costs and support the development of more energy-efficient and sustainable agricultural systems.

TDS Meter Sensor

From Day 1 to Day 7, the PPM values recorded by the sensor ranged between 865 and 933 PPM. These values were relatively close to the setpoint of 900 PPM, with deviations still within acceptable limits. The observed fluctuations were likely influenced by nutrient absorption by plants and changes in solution volume due to evaporation. From Day 8 to Day 13, the PPM setpoint was increased to 1000 in accordance with the plant growth phase. The measurement results showed PPM values ranging from 968 to 1037 PPM. These values remained close to the established setpoint, indicating that the system was capable of adjusting and maintaining nutrient concentration according to plant requirements during subsequent growth stages. On Day 14, the PPM setpoint was set at 1200, and the sensor reading indicated a value of 1218 PPM, which was very close to the designated setpoint. Overall, the test results demonstrate that the TDS meter sensor consistently monitored nutrient solution PPM values in accordance with the predetermined setpoints based on plant requirements. Therefore, this sensor is suitable for use as a primary component in the nutrient monitoring and control system of the aeroponic setup.

pH Meter Sensor

From Day 1 to Day 7, the measured pH values ranged between 6.4 and 6.9. These results indicate minor fluctuations around the setpoint, likely influenced by nutrient uptake by plants and chemical processes occurring within the nutrient solution. From Day 8 to Day 14, the pH values tended to stabilize within a range of 6.0 to 6.6. The highest recorded value was pH 6.9 on Day 5, while the lowest value, pH 6.0, occurred on Day 10. The observed fluctuations were relatively small and remained close to the pH setpoint of 6.5.

CONCLUSION

Based on the results of testing and analysis of the developed device, several conclusions can be drawn as follows:

1. The RTC DS3231 module performed effectively in reading and regulating time with high accuracy, enabling the water pump to operate according to the programmed schedule without delays or timing errors.

2. The implementation of a timer in the aeroponic system proved effective in improving energy efficiency. The system without a timer consumed 11.62 kWh per day, whereas the system equipped with a timer consumed only 1.93 kWh per day.
3. The comparison of energy consumption between the timer-based and non-timer systems demonstrated an energy saving of 83%, indicating that the application of a time-control system is highly effective in reducing electrical power consumption and operational costs.
4. The TDS meter sensor was able to consistently monitor the nutrient solution concentration (PPM) at levels close to the predetermined setpoint according to the plant growth phase, thereby supporting nutrient stability within the aeroponic system.
5. The pH meter sensor showed satisfactory performance in monitoring the acidity level of the nutrient solution, with measured pH values remaining around the setpoint of pH 7 and exhibiting relatively minor fluctuations throughout the testing period.
6. Overall, the integration of the RTC DS3231 module, TDS meter sensor, and pH meter sensor within the aeroponic system enhanced energy efficiency while maintaining the stability of the plant growth environment. Therefore, the designed system is considered feasible for implementation as an automation-based aeroponic system.

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