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# Hydroponic Nutrition and PH Parameter Monitoring System Based on Esp32 Using Rule-Based Control Algorithm and Prototyping Method

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***Abstract :*** *Monitoring pH and nutrient concentration is an important aspect in maintaining the condition of hydroponic solutions. This study aims to develop a pH and Total Dissolved Solids (TDS) monitoring system based on ESP32 with a Rule-Based Control algorithm and prototyping method. This research is a development research with an object in the form of a Nutrient Film Technique (NFT) hydroponic system prototype, without involving human respondents. The research instruments include a PH-4502C pH sensor, a TDS sensor, an ESP32, a relay, a nutrient pump, and a web interface. Data were obtained through observation and device testing, then analyzed descriptively based on the results of sensor readings, pump responses, and the suitability of the web display. The test results showed a difference in pH sensor readings of 0.11 to 0.16 units, while TDS readings ranged from 42 to 1,250 ppm. The system successfully activated the pump when the TDS was less than 800 ppm and deactivated it at a value of 800 ppm or more. The latency of web data updates was recorded at 0.3 to 0.4 seconds. Thus, the prototype can perform nutrient monitoring and control functions automatically based on defined rules, although long-term testing and automatic pH control are still required.*

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## Introduction

Hydroponics is a plant cultivation method that uses nutrient-rich water instead of soil as the primary growing medium. This method offers an alternative for cultivation in areas with limited land and allows nutrient solution conditions to be managed more systematically. Maintaining appropriate nutrient solution conditions is essential for supporting plant growth, particularly through monitoring acidity (pH) and Total Dissolved Solids (TDS). The pH value indicates the acidity or alkalinity of the solution, while

TDS provides an estimate of the concentration of dissolved substances. Changes in these parameters need to be monitored to help maintain the suitability of the nutrient solution for hydroponic cultivation.

Several previous studies have developed sensor-based monitoring systems to obtain information about hydroponic conditions. Linelson and Saputri (2025) developed an IoT-based monitoring device for a vertical hydroponic system by integrating pH, TDS, nutrient temperature, air temperature, and humidity sensors with ESP32 and Arduino IoT Cloud. Similarly, Abu Sneineh and Shabaneh (2023) designed an ESP32-based hydroponic monitoring system that integrates pH and TDS sensors to collect nutrient solution data and support pump operation. These studies demonstrate the potential of ESP32 and IoT technology for monitoring hydroponic parameters. However, the main contribution of these systems is the collection and presentation of environmental or nutrient solution data, while the implementation of a clearly defined nutrient pump control mechanism integrated with a local web monitoring interface requires further examination.

Another issue in hydroponic management is the reliance on manual measurement and nutrient administration. Faisal et al. (2025) identified the limitations of manual pH and TDS measurement and developed an ESP32-based monitoring system using Node-RED to present sensor data through a web interface. Although this approach facilitates digital monitoring, the monitoring function needs to be distinguished from automatic control based on sensor readings. Meanwhile, Setiawan and Santoso (2025) developed an IoT-based hydroponic system integrating pH and TDS sensors with actuators to support automatic parameter adjustment. Prasetyoaji and Anifah (2025) also implemented a rule-based system to classify hydroponic solution conditions and control actuators based on pH and nutrient parameters. These studies provide relevant foundations for automated hydroponic management. Nevertheless, differences in system design, control mechanisms, and monitoring platforms indicate the need to examine an integrated prototype that connects sensor measurement, rule-based decision-making, physical pump operation, and web-based data presentation within a single system.

Based on this comparison, the research problem addressed in this study concerns how to integrate pH and TDS monitoring with rule-based nutrient pump control and a local web interface using an ESP32 microcontroller. The proposed system is designed to process sensor readings and determine pump operation according to a predefined TDS threshold. In this arrangement, the pH and TDS sensors provide information about the nutrient solution, while the Rule-Based Control algorithm determines whether the nutrient pump should be activated or deactivated based on the TDS reading. The web interface presents the measured parameters and pump status, enabling users to monitor system conditions through a device connected to the local network.

The technical contribution of this research is the development and functional testing of an ESP32-based hydroponic prototype that combines a PH-4502C pH sensor, a TDS sensor, a nutrient pump controlled through a relay, a Rule-Based Control algorithm, and a local web monitoring interface. The integration is intended to connect three functions within one prototype: measurement of hydroponic solution parameters, automatic pump control based on a predefined TDS threshold, and digital presentation of sensor readings and actuator status. The system is developed using the prototyping method, which supports gradual design, implementation, testing, evaluation, and improvement. Bjarnason et al. (2023) explain that prototyping can be used to explore requirements, identify problems, and examine alternative solutions during system development. In this study, the method provides a basis for evaluating the functional suitability of the integrated hardware and software components.

Therefore, this study aims to design, develop, and test an ESP32-based hydroponic pH and TDS monitoring system using a Rule-Based Control algorithm and the prototyping method. Specifically, the system is developed to read pH and TDS values, activate or deactivate the nutrient pump according to a predetermined TDS threshold of 800 ppm, and display sensor readings and pump status through a local web interface. The evaluation focuses on sensor readings, pump responses to the established control rules, and the consistency and latency of data displayed on the website.

## Method

This research is a development research that aims to build a hydroponic parameter monitoring system in the form of pH and TDS based on ESP32 using the Rule-Based Control algorithm. The development method used is prototyping, with the stages of needs analysis, system design, prototype


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creation, testing, and evaluation and improvement. This method allows the initial design to be developed and evaluated gradually to identify functional inconsistencies before the system is implemented as a whole. Bjarnason et al. (2023) discuss the practice of prototyping in software development as an approach to explore needs, problems, and alternative solutions during the development process.

The research instruments included an ESP32, pH sensor, TDS sensor, relay, 5 V DC pump, adapter, cable, and software for programming and monitoring via the website. Data were obtained through literature review, observation, and system testing. Data analysis was conducted descriptively by examining the sensor readings, pump response based on the TDS threshold rule of 800 ppm, and the conformity of the data displayed on the website with the data processed by the ESP32. Abu Sneineh and Shabaneh (2023) discussed the development of a hydroponic monitoring system using an ESP32 and sensors to obtain information on solution conditions. Meanwhile, the application of IoT-based monitoring in this study serves as a foundation for integrating sensor readings, data processing, and digital information presentation.

The object of this research is a prototype hydroponic system using the Nutrient Film Technique (NFT) method, which is used to test pH and TDS monitoring and nutrient pump control. This research does not involve human respondents. Testing focuses on the accuracy of sensor readings, hardware function, pump response to established rules, and the suitability of data display on the website. Linelson and Saputri (2025) developed an IoT-based monitoring device for a vertical hydroponic system by integrating sensors and a microcontroller to obtain information on cultivation conditions. This approach is relevant as a reference for developing a hydroponic monitoring system that combines digital measurement and data presentation devices.

The research procedure includes needs analysis, hardware and software design, Rule-Based Control algorithm design, web interface design, prototype creation, testing, and evaluation and improvement. The system is designed so that the ESP32 reads pH and TDS values, sends and displays data via a website, and controls the pump based on the TDS value. The pump is active when the TDS value is below 800 ppm and inactive when the TDS value is equal to or exceeds 800 ppm. The use of these rules aims to provide a consistent control response based on the read solution conditions. Prasetyoaji and Anifah (2025) discuss the application of rule-based systems in hydroponics to support solution condition classification and actuator control. Testing in this study was conducted to check sensor function, the accuracy of the pump response to the set threshold, and the conformity of the data displayed on the website with the data processed by the ESP32.

## Results and Discussion

### System Design Results

The system design results represent the realization stage of the previously developed hardware and software design. At this stage, all components are integrated into a prototype ESP32-based hydroponic parameter monitoring system. The realized system has the main functions of reading pH and Total Dissolved Solids (TDS) parameters, processing sensor readings, determining control conditions based on the Rule-Based Control algorithm, controlling the nutrient pump via a relay, and displaying monitoring results via a local website.

The prototype uses the ESP32 Dev Module as the control center. The PH-4502C pH sensor is used to obtain the acidity level of the solution, while the TDS V1.0 sensor is used to measure the concentration of dissolved substances in ppm. The readings of both sensors are sent to the ESP32 via analog input for further processing by the program. In the hardware design, the pH sensor is connected to GPIO 34, the TDS sensor is connected to GPIO 35, while the relay module used to control the pump is connected to GPIO 26.

The system uses a nutrient pump as an actuator. The pump is not controlled directly through the ESP32's GPIO, but through a relay module. The ESP32 sends control signals to the relay based on the TDS value evaluation. The use of a relay allows the pump's power supply to be electronically controlled without directly burdening the ESP32's GPIO.

The prototype's power source uses a 5V USB adapter or charger. All components are placed in a prototype designed to be installed in hydroponic media. The prototype's physical form uses a cube design with the pH and TDS sensor probes directed outward so they can be placed in the hydroponic


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solution. The prototype also features an additional part that functions as a container for the AB Mix nutrient solution and a hook for attaching the device to the side of the hydroponic media.

Overall, the working relationship between parts of the system can be explained as follows:

pH Sensor and TDS Sensor → ESP32 → Data Processing → Rule-Based Control → Relay → Nutrient Pump

When the system is powered on, the ESP32 initializes the device and then periodically reads sensor values. The pH value is used to determine the solution's acidity, while the TDS value serves as an indicator of nutrient concentration and a key input for decision-making. The readings are then sent to a local webpage, allowing users to monitor the solution's condition and pump status via a smartphone or laptop.

**Hardware Design Results**

This research successfully realized a prototype of an Internet of Things (IoT) device to monitor pH values and nutrient concentrations in hydroponic plants. The prototype was developed using an ESP32 Dev Module microcontroller as a system control center integrated with a PH-4502C pH sensor to measure the acidity level of the solution and a Total Dissolved Solids (TDS) sensor to measure the concentration of dissolved substances in water. The system was designed to read sensor data periodically and send the measurement results to a local monitoring website accessed via the ESP32. The obtained data is then displayed in real-time on a web-based dashboard so that users can monitor the condition of the hydroponic solution more easily. Software implementation was carried out using a program developed via the Arduino IDE and uploaded to the ESP32. The program functions to initialize the device, read pH and TDS sensor data, process measurement results, run the Rule-Based Control algorithm, and control relays and nutrient pumps based on predetermined conditions. With the integration of hardware and software, the prototype is expected to help monitor solution conditions and support automatic control of nutrient provision in hydroponic systems.

**1. Appearance of Hardware/Tools**

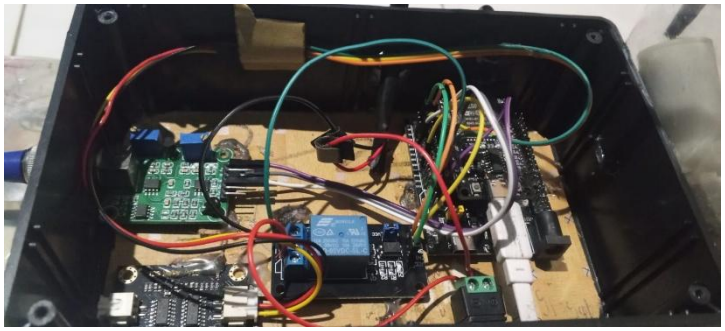


**Figure 1. Wiring in the Tool**



**Figure 2. Overall Tool**

**2. Software Design Results**

The software for this system was developed using the Arduino IDE integrated development environment, utilizing a C/C++-based programming language. The choice of language and software was


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based on the extensive library support for ESP32-based microcontrollers, particularly those related to TCP/IP protocol management, Wi-Fi connection handling, and analog-to-digital converter (ADC) signal reading.

The program code structure embedded in the ESP32 flash memory is designed with a modular approach that is divided into several essential functions:

A. System Initialization and Pin Mapping:
   At the beginning of the program (void setup()), the microcontroller configures the input/output (I/O) pins. GPIO pins 34 and 35 are declared as analog input pins to read voltage signals from the pH and TDS sensors.
B. Network Module Configuration (Wi-Fi Server):
   The program initializes the ESP32 to operate in Soft-Access Point (Soft-AP) mode with a specified SSID and password, or connects to an existing local router network. The module then runs the WebServer.h library to open an HTTP port on the local IP address so it can respond to requests from a web browser.
C. Data Sampling and Filtering Function: Since analog sensor readings are susceptible to electrical noise from the surrounding environment, the program applies a moving average filter algorithm by taking multiple data samples in a certain millisecond time interval,
D. Control Execution and Loop Logic (void loop()):
   The program runs continuously (infinite loop), where each cycle includes reading sensor values, evaluating Rule-Based Control logic, updating relay/pump status.

3. Table of programming coding usage in software

**Table 1. Table of Programming Coding Usage in Software**

| Code Section | Main Function | Compliance with the Thesis |
|---|---|---|
| #include <WiFi.h> / #include <WebServer.h> | Enable local Wi-Fi and Web Server features on ESP32. | Supports the implementation of local network-based IoT systems without relying on an internet connection. |
| pinSensorPH and pinSensorTDS | Determines the ESP32 ADC pin used to read the pH and TDS sensors. | Ensuring compatibility between hardware design and program implementation. |
| thresholdTDS = 800 | Determine the nutrient concentration threshold value of 800 ppm. | It is one of the main parameters in the implementation of the Rule-Based Control algorithm. |
| WiFi.softAP(...) | Create a Wi-Fi network independently using ESP32 as an Access Point. | Allows a smartphone or laptop to connect directly to the ESP32 for monitoring. |
| server.on("/data", ...) | Provides an endpoint for sending sensor data in JSON format. | Supports sending sensor data to the website interface periodically without the need to reload the page. |
| server.handleClient() | Handles HTTP requests received by the ESP32 Web Server. | Maintain communication between the ESP32 and the user device so that the monitoring system can run responsively. |
| if (TDS value < 800) | Compare the TDS reading results with the predetermined threshold value and determine the system action on the relay/pump. | Implementing a decision mechanism in the Rule-Based Control algorithm to automatically regulate the system. |

**Implementation of Rule-Based Control**

The implementation of the Rule-Based Control algorithm in this NFT hydroponic system aims to mimic the decision-making process of conventional farmers, but with significantly greater precision and response speed. The primary focus of this automated control is to maintain nutrient concentrations in the water reservoir within the optimal range for leafy vegetable growth.

Based on the system requirements analysis, the nutrient concentration threshold was set at 800 ppm. This value serves as the critical reference point (setpoint) for the microcontroller to determine the


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status of the nutrient pump actuator. The implementation of the IF-THEN logic rule is detailed as follows:

1. **Rule 1 (Nutritional Deficit Conditions):**

IF TDS < 800 THEN Nutrient Pump = ON

If the TDS sensor reading is below 800 ppm, the microcontroller concludes that the nutrient solution has been diluted (due to absorption by plants or evaporation of pure water). The microcontroller then sends a LOW/HIGH logic signal (depending on the type of active-low/high relay module) to GPIO pin 26 to transmit electric current to the nutrient pump, so that the pump turns on and injects the concentrated AB Mix solution into the reservoir.

2. **Rule 2 (Sufficient/Optimal Nutritional Conditions):**

IF TDS ≥ 800 THEN Nutrient Pump = OFF

If the sensor reading results show that the TDS value is equal to or has exceeded the threshold of 800 ppm, the microcontroller immediately cuts off the electric current to the relay module, so that the nutrient pump stops working to prevent poisoning due to excessive nutrient concentration (nutrient burn).

The following is a table of the implementation of the Rule-Based Monitoring decision matrix.

**Table 2. Implementation of Rule-Based Control Decision Matrix in the System**

| NO | TDS Reading Range | Environmental Condition Evaluation | Algorithmic Decision | GPIO 26 Output Signal |
|---|---|---|---|---|
| 1 | TDS < 600 ppm | Severe Nutritional Deficit | Activate the Pump | LOW / Active |
| 2 | 600 ≤ TDS < 800ppm | Mild Nutritional Deficit | Activate the Pump | LOW / Active |
| 3 | TDS = 800ppm | Threshold Reached | Turn off the pump | HIGH / Disabled |
| 4 | TDS > 800ppm | Optimal Nutrition / Concentrated | Turn off the pump | HIGH / Disabled |

**Web Monitoring Interface Implementation**

The web-based user interface (UI) is designed directly within the ESP32 microcontroller's memory using an HTML5 document framework, responsive CSS3 styling, and lightweight JavaScript scripts to support asynchronous data update mechanisms (AJAX/Fetch API). This method eliminates the need for users to install a dedicated mobile app (native app) on their smartphones; instead, they can simply open a standard web browser (such as Google Chrome, Mozilla Firefox, or Safari) and enter the ESP32's local IP address.

The web page design is divided into several blocks of visual information (card layout) for easy and quick analysis by users:

1. Water pH Information Box (pH Level Card):Displays the water acidity value in real-time with a two-digit decimal format, equipped with a dynamic color indicator (e.g. green if it is in the neutral range of 6.0–7.0, and red if it is too acidic or alkaline).
2. Nutrient Concentration Information Box (TDS Level Card):Displays the value of dissolved substance concentration in ppm units accompanied by a nutrient load indicator graph.
3. Pump Actuator Status Card:Displays the operational visual status of the nutrient pump as a text marker "ON" (with a green background) or "OFF" (with a gray/red background) to ensure that instructions from the control algorithm are correctly conveyed to the physical world.
4. JavaScript Based Auto-Refresh Function:The web page is programmed to make background data requests to the ESP32 every 2 seconds (setInterval), so that changes in sensor values and pump status can be observed directly without the user having to manually press the refresh button on the browser.


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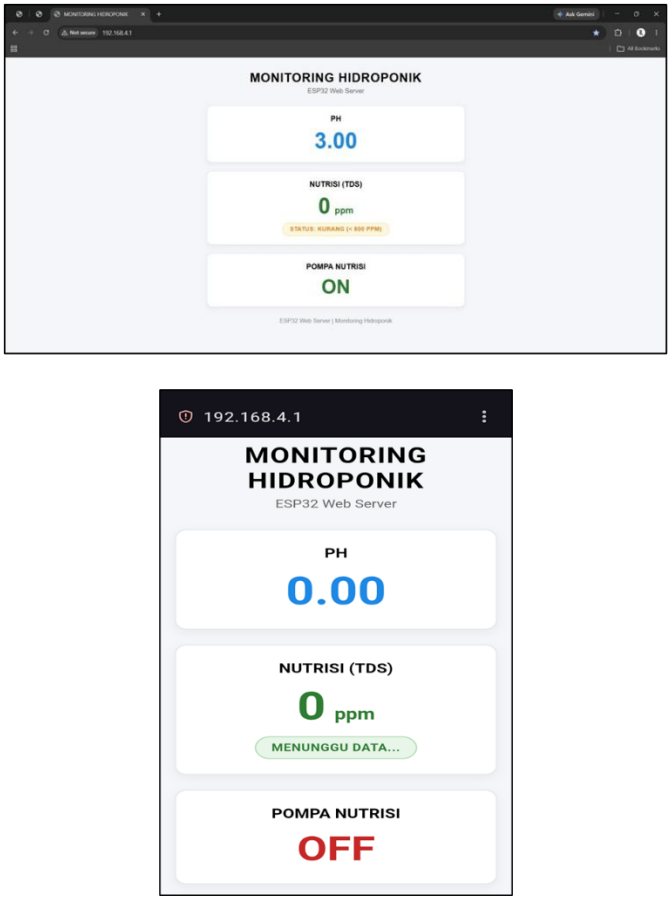



**Figure 3. Monitoring Website UI Image**

**Device Physical Test Results**

Physical testing aims to ensure that the wiring paths, pin connections, and power supply of each electronic module do not experience short circuits and can respond well to electrical power.

**Table 3. Table of Device Physical Test Results**

| No. | Component Name | Technical Specifications | Testing Scenario | Testing Results and Analysis |
|---|---|---|---|---|
| 1 | ESP32 DevKit V1 | Tensilica Dual-Core 32-bit, 240 MHz | Connecting a 5V Micro-USB power supply | Microcontroller booting normally, power LED indicator is on steady |
| 2 | pH Sensor PH-4502C | Liquid probe module with dual output op-amp | Dip the probe tip into a pH 7.0 buffer solution. | The module provides a proportional analog voltage output to GPIO pin 34. |
| 3 | TDS Sensor V1.0 | Input Voltage 3.3V–5.5V, Waterproof probe | Dip the electrode probe into the test solution | Water conductivity is detected and passed to the ESP32 ADC without excess noise. |
| 4 | 1 Channel Relay Module | 5V Relay Module with optocoupler isolation | Provides digital logic trigger from GPIO pin 26 | The relay responds instantly, indicated by a mechanical click sound and an active LED indicator. |

Based on the test results, the condition of each component can be determined based on the responses generated during the testing process. These results are then used as a basis for ensuring that the hardware can be used in testing the overall system.


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**pH Sensor Activation Test Results**

pH sensor activation testing is performed to determine the sensor's ability to detect the acidity level of a solution. The test is performed using a solution with a specific pH value as the measurement object. The sensor readings are then recorded and compared to the reference value used.

**Table 4. Results of PH Sensor Activation Test**

| No. | Solution Test Sample | Reference Value (pH Meter Standard) | pH Sensor Reading Results (Prototype) | Absolute Difference (Error) |
|---|---|---|---|---|
| 1 | Acid Standard Buffer Solution | 4.00 | 4.12 | 0.12 |
| 2 | Neutral Mineral Water | 7.00 | 6.85 | 0.15 |
| 3 | Basic Standard Buffer Solution | 9.18 | 9.02 | 0.16 |
| 4 | Ready-to-Use AB Mix Nutrient Solution | 6.20 | 6.31 | 0.11 |

Based on the data in the table, the accuracy of the pH sensor readings on the prototype has a very small absolute difference (error) (maximum 0.16 pH units). This value proves that the linear equation resulting from the ADC conversion in the microcontroller program has worked with a level of precision that is very adequate for hydroponic farming applications.

**TDS Sensor Activation Test Results**

TDS sensor activation testing was conducted to determine the sensor's ability to read Total Dissolved Solids (TDS) values in hydroponic solutions. Testing was conducted using several solution conditions with varying solute concentrations. Each reading was recorded to determine changes in the sensor's TDS values.

**Table 5. TDS Sensor Activation Test Results**

| No. | Stages of Adding Nutrients | Estimated AB Mix Dosage | TDS Sensor Reading Results | Unit |
|---|---|---|---|---|
| 1 | Raw Water (Without Added Nutrients) | 0 mL / Liter | 42 | ppm |
| 2 | Phase I Addition (Low Concentration) | 2 mL / Liter | 380 | ppm |
| 3 | Phase II Addition (Optimal Concentration) | 5 mL / Liter | 815 | ppm |
| 4 | Stage III Addition (Heavy Concentration) | 8 mL / Liter | 1250 | ppm |

**Rule-Based Control Test Results**

Rule-Based Control testing was conducted to determine the system's ability to determine pump conditions based on the TDS values obtained from the sensor. The test was conducted by providing several TDS values representing conditions below, near, and above a predetermined limit.

**Table 6. Rule-Based Control Test Results**

| No. | Actual TDS Value at Sensor | Logical Conditions against Threshold (800 ppm) | Rule Execution | ESP32 Output Commands |
|---|---|---|---|---|
| 1 | 450 ppm | Below threshold (< 800) | IF TDS < 800 | Activate Pump (LOW) |
| 2 | 720 ppm | Below threshold (< 800) | IF TDS < 800 | Activate Pump (LOW) |
| 3 | 800 ppm | Right on the threshold (800) | IF TDS >= 800 | Turn Off Pump (HIGH) |
| 4 | 950 ppm | Above threshold (800) | IF TDS >= 800 | Turn Off Pump (HIGH) |


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From the test results in the table, it is proven that the rule-based control system runs with the best success rate. No logical glitch or delay in microcontroller response was found when the TDS value crossed the critical point of 800 ppm.

**Web Monitoring Test Results**

Web monitoring testing was conducted to determine the system's ability to display sensor readings and pump condition data on a web page. Testing was performed by comparing the data processed by the ESP32 with the data displayed on the monitoring page.
The following is a table of web monitoring test results:

**Table 7. Web Monitoring Test Results**

| No. | Observation Test Parameters | Actual Values of ESP32 Variables | Values Displayed on the Website | Transmission Latency Time (Delay) | Status Description |
|---|---|---|---|---|---|
| 1 | Acidity Parameter (pH) | 6.25 | 6.25 | 0.4 seconds | Synchronous & Real-time |
| 2 | Nutritional Parameters (TDS) | 785 ppm | 785 ppm | 0.4 seconds | Synchronous & Real-time |
| 3 | Nutrition Pump Working Status | ON (On) | ON(Green Indicator) | 0.3 seconds | Synchronous & Real-time |

**Discussion**

Based on the description of all the implementation data and the series of experimental tests above, several in-depth discussion points can be drawn regarding the overall system performance:

1. The use of the ESP32 microcontroller has proven to be highly reliable because it has sufficient memory capacity and processor speed to handle parallel sensor data processing while also running a standalone web server function. Although analog-based sensors such as the PH-4502C and TDS V1.0 are susceptible to electromagnetic interference, the application of a moving average sampling technique within the program line successfully dampens wild signal fluctuations, so that the displayed data has a stable and consistent level of readability.
2. The applied rule-based control algorithm has proven to be a simple yet highly effective automation solution for maintaining nutrient stability in hydroponic NFT (Nutrient Film Technique) systems. The system is able to respond instantly to decreasing nutrient concentrations by activating the nutrient pump and precisely stopping it when the 800 ppm threshold is reached. This significantly reduces the risk of human error—where farmers often delay manual checks, resulting in stunted vegetative plant growth.
3. The web-based interface, hosted directly within the ESP32, offers significant flexibility. Users or farmers can monitor the nutrient solution's health in real time directly from their personal devices without the need for constant visits to the installation site. Automatic data updates via asynchronous scripts ensure that the information read always reflects the actual conditions in the water reservoir.

**System Limitations**

Although the prototype of this hydroponic automatic monitoring and control system has been successfully realized and meets all planned functional targets, the authors identified several technical and operational limitations that could provide room for further research:

1. The web server architecture embedded directly within the ESP32 uses a local Wi-Fi connection (Soft-AP or local router network without a global cloud connection). As a result, remote monitoring is not possible if the user is outside the local signal range (for example, when the user is out of town). The system does not yet integrate the cloud-based IoT protocols MQTT or Firebase for remote monitoring via the global internet.
2. The prototype's automated control focus is currently limited to regulating nutrient concentration (TDS) using a single pump. The system lacks an automatic mechanism to raise or lower the water's acidity (pH) level if it falls outside the optimal range, so pH correction still requires manual intervention by the manager.


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3. This device relies heavily on a constant power supply from a 5V DC adapter. If the main power supply at the planting site fails without an emergency backup supply (such as a Mini UPS or external dry cell battery), the entire sensor monitoring system and pump actuators will immediately stop operating completely, potentially stopping the nutrient flow circulation in the NFT channel if not addressed immediately.

## Conclusion

This research successfully developed a prototype of an ESP32-based hydroponic parameter monitoring system that integrates a PH-4502C pH sensor, a Total Dissolved Solids (TDS) sensor, a Rule-Based Control algorithm, a relay, a nutrient pump, and a local web interface. Test results showed that the pH sensor produced an absolute difference to the reference value of 0.11 to 0.16 pH units. The TDS sensor was able to indicate changes in solute concentration as nutrients were added, with readings increasing from 42 ppm in water without added nutrients to 1,250 ppm at the highest concentration tested. The Rule-Based Control algorithm also successfully executed a pump control rule based on an 800 ppm threshold, activating the pump when the TDS was less than 800 ppm and deactivating it when the TDS reached or exceeded that value. In addition, the web interface test results showed a match between the data processed by the ESP32 and the data displayed, with a transmission latency of 0.3 to 0.4 seconds. These findings indicate that the integration of hardware and software can support automatic monitoring and control of hydroponic nutrients according to established rules.

However, this study still has limitations, namely that monitoring can only be done through a local network, automatic control is limited to nutrient concentrations based on TDS parameters, and the system is not equipped with a backup power source in the event of a power outage. Testing also does not include long-term evaluation of sensor stability, the influence of environmental changes, and the impact of automatic control on plant growth and yield. Future research is recommended to develop cloud-based monitoring, add an automatic pH regulation mechanism, provide a backup power source, and conduct regular sensor calibration and testing using reference instruments. Testing on various plant types and cultivation conditions is also needed to evaluate the suitability of the TDS threshold. Practically, this system has the potential to help hydroponic managers monitor solution conditions from digital devices, reduce reliance on manual inspections, and improve the consistency of nutrient delivery. However, its implementation still requires sensor calibration and adjustment of control rules to suit plant needs.

## Bibliography

Abu Sneineh, A., & Shabaneh, A. A. (2023). Design of a smart hydroponics monitoring system using an ESP32 microcontroller and the Internet of Things. MethodsX, 11, Article 102401. https://doi.org/10.1016/j.mex.2023.102401

Bjarnason, E., Lang, F., & Mjöberg, A. (2023). An empirically based model of software prototyping: A mapping study and a multi-case study. Empirical Software Engineering, 28, Article 115. https://doi.org/10.1007/s10664-023-10331-w

Faisal, M., Bachtiar, A. N., & Darwis, M. (2025). IoT implementation for hydroponic water monitoring using web-based pH and TDS sensors with Node-RED. JISA (Jurnal Informatika dan Sains), 8(1). https://doi.org/10.31326/jisa.v8i1.2209

Linelson, R., & Saputri, F. R. (2025). Design of a nutrient and environment monitoring IoT device in vertical hydroponic system. Ultima Computing: Jurnal Sistem Komputer, 17(1). https://doi.org/10.31937/sk.v17i1.4145

Prasetyoaji, M. R. E., & Anifah, L. (2025). Design of smart hydroponics based on Internet of Things (IoT) using rule-based system on hydroponic wick system. Journal FORTEI-JEERI, 6(1), 51–62. https://doi.org/10.46962/forteijeeri.v6i1.34

Setiawan, F., & Santoso, B. (2025). IoT implementation for adjustment automatic pH and TDS/EC parameters on the system hydroponics lettuce. Applied Science and Technology Research Journal, 4(1), 43–53. https://doi.org/10.31316/astro.v4i1.7878


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