

# Design and Construction of Hydroponic Plant Cultivation Based on the Internet of Things on Lettuce

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## Abstract

This research discusses the design of an Internet of Things (IoT)-based hydroponic cultivation system applied to lettuce plants. This system is designed to automatically monitor and control plant environmental conditions, such as solution pH, nutrient content (TDS), and water temperature, using an ESP32 microcontroller connected to related sensors. Data obtained from the sensors are then sent to a Firebase-based platform for real-time monitoring via a monitoring website. This system is also equipped with automatic water pump control to increase or decrease the nutrient solution according to the conditions detected by the sensors. With this system, users can monitor and manage hydroponic plants without having to be physically present at the location, simply by accessing the website to see the condition of the plants directly. The results of this study indicate that the system is able to increase lettuce plant productivity through more optimal growth and better quality. In addition, this system also provides efficiency in cultivation management, both in terms of time, energy, and nutrient use, because the monitoring and control processes are carried out automatically and in real-time.

**Keywords:** ESP32; Firebase; Hydroponics; Internet of Things; Pump Automation

## 1. Introduction

Technology-based agriculture has developed rapidly as a solution to the reduction of productive agricultural land due to land conversion and a growing population. Therefore, innovation in more efficient and sustainable farming methods is required [1].

Hydroponics has become a modern farming method that offers high efficiency by growing plants soil-lessly using a nutrient solution. However, a major challenge is maintaining optimal water and nutrient quality against fluctuations in temperature, humidity, and pH levels [2].

The implementation of IoT based on the ESP32 microcontroller and various sensors serves as an innovative solution to automatically transmit environmental condition data to a server in real-time. This research aims to develop such a monitoring system to enhance productivity and optimize resource efficiency [3].

Manual management requires considerable time and labor, leading to the utilization of IoT technology with sensors and applications for remote, real-time monitoring. This system is developed to improve efficiency, increase productivity, and practically reduce the risk of crop failure [4].

## 2. Basic Theory

### 2.1. Jonction RZ lettuce

Jonction RZ lettuce is a Batavia (crisphead) variety developed by Rijk Zwaan that is highly adaptable to hydroponic systems in tropical climates due to its high heat tolerance and low risk of bolting. Successful cultivation of this variety requires precise control of environmental parameters, including an optimal temperature range of 25°C–28°C and a relative humidity of 65%–78%. Furthermore, nutrient solution management must be strictly maintained at a concentration of 800–1200 ppm (equivalent to an EC of 1.5–2.0 mS/cm) with a stable water pH between 6.0 and 6.5 to ensure efficient nutrient absorption. By fulfilling these parameters, this variety can reach its optimal harvest period in a relatively short time, approximately 45 days after sowing [5].

## 2.2. Internet Of Things

The Internet of Things (IoT) utilizes internet networks and smart sensors to integrate various devices, enabling remote monitoring and automated control across multiple sectors. In agriculture, this technology is applied to hydroponic systems to facilitate continuous and efficient crop cultivation management, such as for lettuce [6]. Through sensor integration, crucial parameters including temperature, humidity, water pH, and nutrient levels can be monitored automatically and in real-time, ensuring optimal plant growth even within limited environmental conditions.

## 2.3. ESP-32

The ESP32 is a Wi-Fi-enabled microcontroller featuring a dual-core processor and integrated GPIOs, capable of operating independently for various IoT applications [6]. In lettuce hydroponic cultivation systems, this device serves as the central control unit that connects environmental sensors—such as temperature, humidity, pH, and nutrient levels—to a cloud platform in real-time. Furthermore, the integration of the ESP32 enables precise automation in pH adjustment and nutrient solution distribution, ultimately contributing to enhanced crop yields, resource efficiency, and the operational sustainability of smart agriculture.

## 2.4. Total Dissolved Solids (TDS)

Total Dissolved Solids (TDS) is an indicator of the total mass of dissolved organic and inorganic substances within a solution, typically measured in parts per million (ppm) or milligrams per liter (mg/L) [7]. In hydroponic systems, TDS functions to measure the concentration of the nutrient solution; a TDS level that is too low leads to plant nutrient deficiencies, whereas an excessively high level induces elevated salinity that can damage root structures and cause leaf burn. Consequently, the integration of a TDS sensor is crucial for real-time monitoring of solution conditions, enabling precise adjustments to the nutrient formulation to ensure optimal plant growth [8].

## 2.5. pH Meter Sensor

The pH meter sensor measures the acidity or alkalinity of a solution by detecting the concentration of  $H_3O^+$  ions via a low-impedance glass electrode probe containing an HCl solution. This structural composition enables the sensor to provide rapid readings, maintain stability across various liquid temperature fluctuations, and remain reliable for long-term monitoring [9]. Physically, the sensor module features an LED power indicator, a BNC connector, and a PH 2.0 interface, which facilitates seamless connection and analog data transmission to the microcontroller.

## 2.6. DS18B20

The DS18B20 digital temperature sensor features an accuracy of  $\pm 0.5^\circ C$  and utilizes 1-wire communication for data line efficiency [10]. In hydroponics, this sensor is crucial for maintaining the solution within the ideal temperature range of  $20^\circ C$ – $30^\circ C$ , as temperatures above  $30^\circ C$  can reduce dissolved oxygen levels and trigger root rot. The integration of the DS18B20 ensures that automated monitoring remains precise and sustainable [11].

## 2.7. Water Pump

The 12V DC pump functions as an automated actuator to distribute the nutrient solution in IoT-based hydroponic systems via microcontroller control (such as the ESP32) and a relay module. Featuring low power consumption and flexible flow capacity, selecting the appropriate pump specifications is crucial to ensure efficient circulation and precise crop nutrient distribution.

## 2.8. Firebase

Firebase is a cloud-based backend-as-a-service (BaaS) that operates without manual server management. Through the Firebase Realtime Database, JSON-formatted data is automatically synchronized in real-time across all connected platforms, facilitating instant and efficient data exchange.

## 3. Research Methods

To build a prototype of an Internet of Things-based hydroponic plant cultivation system for lettuce, the author utilized the Waterfall development method. This method allows system development to be conducted linearly and sequentially, focusing on structured stages to ensure that environmental monitoring and automation features run precisely. The stages carried out in this method are: (1) Requirements Analysis, which is the stage of identifying functional and non-functional system requirements, such as sensors and automatic pump control. (2) Data Collection, aiming to gather theoretical and empirical data through literature studies and direct field observations. (3) System Analysis and Design, encompassing the creation of block diagrams, schematic diagrams, flowcharts, physical hardware designs, and the web monitoring interface layout. (4) Implementation, which involves the physical assembly of hardware components such as the ESP32 microcontroller, sensors, and relays, alongside software coding and Firebase database integration. (5) Testing, establishing an evaluation process through black-box testing and sensor calibration to ensure the accuracy and reliability of the overall system.

### 3.1. Tools and Materials

The hardware utilized includes an ESP32 microcontroller, various sensors (such as pH, TDS, and water temperature sensors), a relay module, a water pump, and a power supply module. The software employed consists of the Arduino IDE for microcontroller programming, Firebase for real-time database management, and a web browser for displaying the web-based monitoring interface.

## 4. Result and Discussion

### 4.1. Requirements Analysis

The requirements analysis for the IoT-based hydroponic system for lettuce cultivation encompasses both functional and non-functional aspects. The primary functional requirements include real-time monitoring of water parameters (TDS, temperature, and pH) using an ESP32 microcontroller and a Firebase database, as well as automated water pump control. However, testing results revealed integration issues with the pH sensor, making sensor compatibility and stability a critical focus. Meanwhile, non-functional requirements emphasize operational continuity, system stability, power efficiency, and a responsive web monitoring interface. The overall system is implemented through a combination of hardware (ESP32, TDS/DS18B20/pH sensors, relay, and water pump) and software (Arduino IDE, VS Code, and Firebase), serving as the foundation for the subsequent design and testing phases.

### 4.2. Data Collection Method

#### 4.2.1. Literature Study

The literature study was conducted by reviewing scientific publications regarding hydroponic cultivation and IoT technology. The review focused on the optimal growth parameters for lettuce, establishing system thresholds of pH 5.5–6.5 and TDS levels of 800–1200 ppm. This method also provided the foundation for sensor selection, automatic pump control mechanisms, and the architecture of the web-based IoT platform for real-time monitoring. Ultimately, the literature study serves as the conceptual framework and technical specification benchmark for the system design phase.

#### 4.2.2. Observation

Field observations were conducted at a Nutrient Film Technique (NFT) hydroponic farm to gather empirical data on system layouts, nutrient flow patterns, and real-world constraints such as pH fluctuations and water supply disruptions. The insights gained directly guided optimal sensor placement, automated control strategies, and hardware specifications. Synthesizing the literature review and field observations establishes a robust scientific and practical foundation, ensuring the proposed IoT system effectively and sustainably addresses operational challenges in the field.

### 4.3. Analysis and Design

#### 4.3.1. Block Diagram

The system workflow begins with data acquisition from pH, TDS, and DS18B20 temperature sensors connected to the ESP32 microcontroller. The ESP32 processes these environmental inputs; if the pH or TDS levels deviate from the predefined thresholds, the microcontroller automatically triggers the relay pump to adjust the nutrient solution. For data management, all parameters are uploaded to Firebase for real-time cloud storage. On the user interface side, the real-time parameters and pump status are visualized locally via an LCD screen and integrated into a web monitoring platform, enabling remote monitoring and dual-mode (manual/automated) pump control.

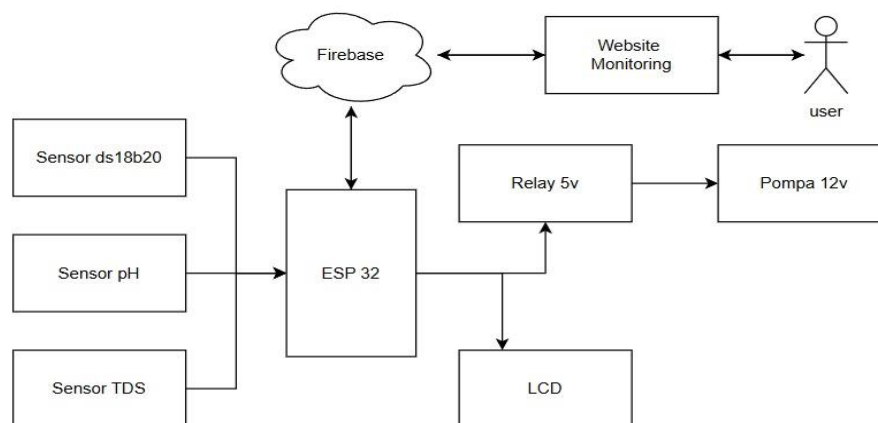


Fig. 1: Block Diagram

#### 4.3.2. Schematic

The schematic illustrates the wiring between components, ranging from the pH sensor, TDS meter sensor, and DS18B20 temperature sensor on the input side, the ESP32 as the controller, to the 12V water pump, relay module, and LCD on the output side, as illustrated in Figure 2.

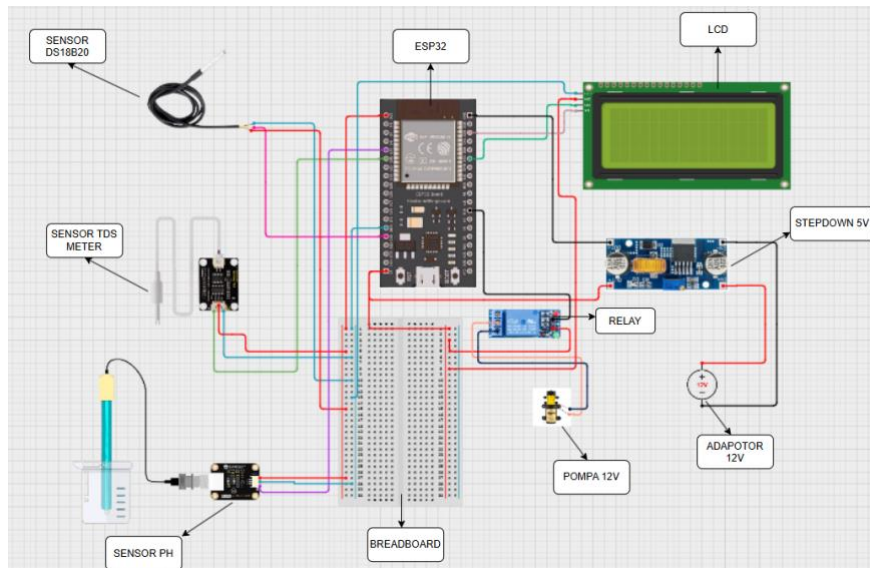


Fig. 2: Schematic

4.3.3. System Workflow

The system workflow is illustrated through a flowchart. The process begins with system initialization and an internet connectivity check; once connected, the system reads the temperature, pH, and nutrient sensors, monitors their values and status, and transmits the data to Firebase. Concurrently, the data and system status are displayed on the web interface, leading to a decision rule where the water pump is automatically activated to supply nutrients until the threshold is fulfilled before shutting off, or the process concludes directly if no nutrient adjustment is required, as illustrated in Figure 3.

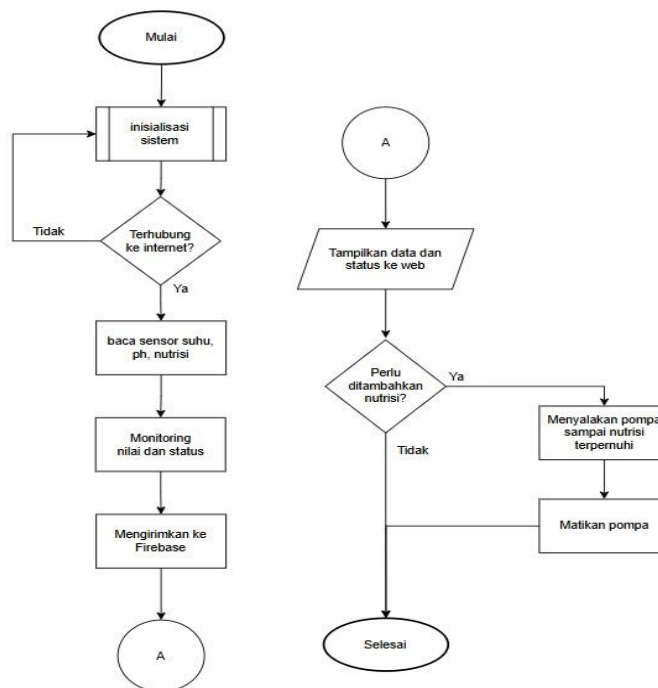


Fig. 3: System Workflow

4.3.4. System Workflow

The physical design of the device consists of a multi-tiered framework supporting parallel PVC cultivation pipes equipped with net pots as the main plant growth mechanism, a localized control box on the bottom left side housing the electronics and LCD screen as the user interface, and two black nutrient reservoirs at the bottom of the device that function as temporary storage and drainage for the water solution. The flexible connection tubes link the reservoirs to the upper pipes to ensure a continuous fluid loop. The entire design is

constructed to support space-efficient vertical hydroponic farming and automated environmental monitoring, and the device design is illustrated in Figure 4.

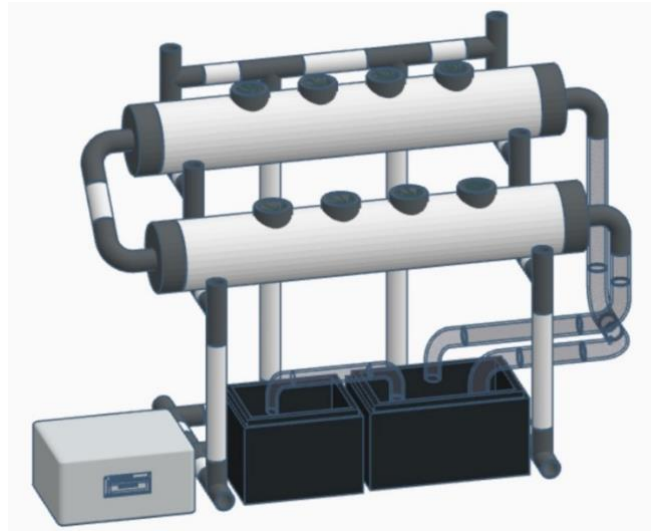


Fig. 4: Hydroponic Device Physical Design

#### 4.3.5. Web Interface Design

The web monitoring interface design is developed to facilitate remote, real-time visualization of critical hydroponic environmental parameters. The user interface displays continuous readouts of water temperature, pH levels, and Total Dissolved Solids (TDS), all of which directly influence lettuce plant development. The layout features data visualization cards for instantaneous sensor feedback alongside real-time pump status indicators, enabling streamlined system oversight and dual-mode operational control from a single responsive dashboard, as illustrated in Figure 5.

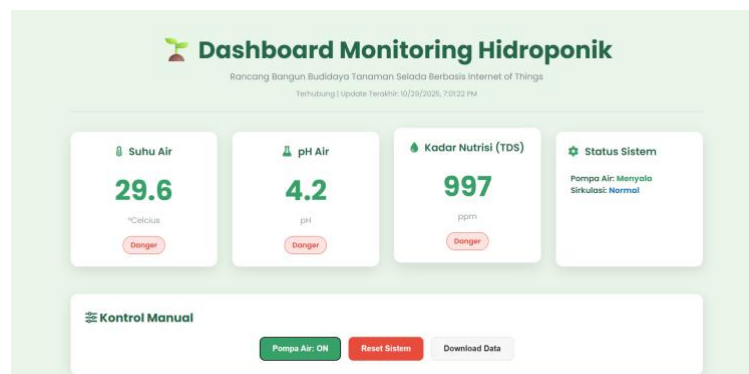


Fig. 5: Web Interface Design

## 4.4. Implementation

### 4.4.1. Hardware Implementation

The hardware implementation involves integrating all electronic components inside a protective junction box to ensure system stability against external disturbances. The assembled architecture centers on the ESP32 microcontroller as the primary processing unit, automation controller, and Wi-Fi gateway for Firebase data transmission. For data acquisition, the system utilizes three core sensors: a DS18B20 temperature sensor, a pH sensor, and a TDS meter. On the output side, a relay module acts as an electronic switch to automatically regulate a 12V DC water pump based on sensor thresholds, while an LCD screen provides localized data visualization. The entire system is powered by a 12V DC adapter configured with jumper wires and routed through a step-down module to deliver a stable 5V supply to the ESP32.

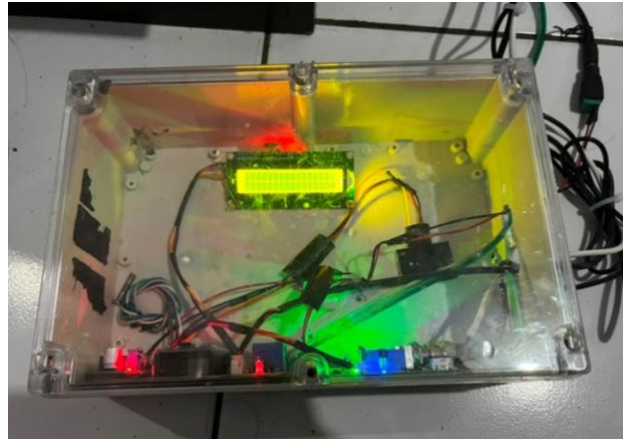


Fig. 6: Hardware Implementation

#### 4.4.2. Software Implementation

The software implementation is structured into three primary architectural components: microcontroller programming, cloud database configuration, and web interface development.

**Microcontroller Programming:** Executed using the Arduino IDE to develop the firmware for the ESP32. This software layer manages network initialization, data acquisition protocols for the three sensors (pH, TDS, and DS18B20), and the conditional logic governing automated relay pump activation.

**Cloud Database Integration:** Utilizes Firebase Realtime Database as the centralized data repository. The database is configured to facilitate low-latency, bi-directional data synchronization between the telemetry sent by the ESP32 and the control states accessed by the web platform.

**Web Interface Development:** Developed using a code editor (such as VS Code) to build a responsive monitoring dashboard. The client-side software implements data-fetching scripts from Firebase to visualize hydroponic environmental parameters in real-time and provides interactive toggles for dual-mode (manual/automated) pump override control.

### 4.5. Testing

#### 4.5.1. Black Box Testing

Functional testing of the automated water pump mechanism was conducted using the black box testing method to evaluate the output response (pump state) against variations in the input parameter (TDS/ppm values). The test results indicate that the system successfully executed the control logic with high precision; the water pump automatically activated when the nutrient level dropped below the 800 ppm threshold to replenish the solution. Conversely, once the nutrient concentration increased to meet or exceed 800 ppm, the system responsively deactivated the pump. This evaluation demonstrates that the sensor-driven automation algorithm operates in strict compliance with the design specifications, effectively maintaining stable nutrient concentrations and enhancing operational efficiency in lettuce cultivation.

Table 1: Black Box Testing

Time	(Automatic)		(Manual)		Pump Status
	Temperature (°C)	Nutrients (PPM)	Temperature (°C)	Nutrients (PPM)	
20.41.15	26.87	335	26.83	316	ON
20.41.16	26.87	351	26.83	338	ON
20.41.17	26.81	363	26.78	346	ON
20.41.18	26.81	378	26.78	358	ON
20.41.19	26.75	421	26.71	406	ON
20.41.20	26.75	455	26.70	439	ON
20.41.21	26.68	497	26.64	484	ON
20.41.22	26.67	512	26.63	499	ON
20.41.23	26.66	545	26.62	526	ON
20.41.24	26.67	583	26.64	563	ON
20.41.25	26.68	612	26.63	597	ON
20.41.26	26.70	642	26.68	627	ON
20.41.27	26.71	687	26.67	669	ON
20.41.28	26.66	726	26.62	709	ON
20.41.29	26.67	761	26.60	750	ON
20.41.30	26.65	803	26.60	789	OFF
20.41.31	26.65	837	26.61	819	OFF
20.41.32	26.65	856	26.61	838	OFF
20.41.33	26.66	842	26.61	824	OFF
20.41.34	26.67	840	26.62	822	OFF

#### 4.5.2. Calibration TDS Sensor

Calibration testing for the TDS sensor was carried out to evaluate the measurement accuracy of nutrient concentrations (ppm) by comparing the developed automated system with a standard manual reference tool. The empirical results showed that the manual instrument maintained highly stable readings within the range of 834–836 ppm, whereas the automated sensor exhibited minor fluctuations across measurements. Nonetheless, the resulting variance (error margin) remained minimal, ranging between 13 and 17 ppm. This negligible deviation demonstrates that the automated TDS sensor achieves sufficient operational accuracy and is highly viable for real-time plant nutrient monitoring and control.

Table 2: Calibration TDS Sensor

Time	Nutrients (PPM)		Difference
	(Automatic)	(Manual)	
14.33	853	836	17
14.36	853	836	17
14.39	853	836	17
14.42	852	836	16
14.45	852	836	16
14.48	850	835	15
14.51	850	835	15
14.54	850	835	15
14.57	851	835	16
15.00	850	835	15
15.03	850	835	15
15.06	850	835	15
15.09	850	835	15
15.12	848	834	14
15.15	848	834	14
15.18	848	834	14
15.21	847	834	13
15.24	848	834	14
15.27	849	834	15
15.30	849	834	15

#### 4.5.3. Temperature Sensor Calibration

Based on the calibration testing results presented in Table 4.3, the comparison between the DS18B20 temperature sensor and the standard reference instrument reveals a highly stable and constant error margin of exactly **0.04 °C** across all trials. This minimal and consistent variance demonstrates exceptional precision and accuracy in the DS18B20 sensor's performance. Consequently, the sensor is verified to operate normally and is highly viable for integration into real-time nutrient solution temperature monitoring within the hydroponic lettuce cultivation system.

Table 3: Temperature Sensor Calibration

Time	Temperature (°C)		Difference
	(Automatic)	(Manual)	
14.33	27.8	27.8	0.04
14.36	27.8	27.7	0.04
14.39	27.8	27.7	0.04
14.42	27.7	27.7	0.04
14.45	27.7	27.7	0.04
14.48	27.7	27.7	0.04
14.51	27.7	27.7	0.04
14.54	27.7	27.7	0.04
14.57	27.7	27.7	0.04
15.00	27.7	27.7	0.04
15.03	27.8	27.7	0.04
15.06	27.8	27.7	0.04
15.09	27.8	27.8	0.04
15.12	27.8	27.8	0.04
15.15	27.7	27.7	0.04
15.18	27.7	27.7	0.04
15.21	27.7	27.7	0.04
15.24	27.7	27.7	0.04
15.27	27.7	27.7	0.04
15.30	27.7	27.7	0.04

#### 4.5.4. pH Sensor Calibration

The calibration testing of the pH sensor revealed an operational anomaly during full system integration. Although the sensor demonstrated normal functionality and responsiveness during isolated testing, its readouts suffered from constant stagnation at approximately **3.53** when all sensors were operated simultaneously, failing to reflect the actual solution states. This systemic error is attributed to several potential technical constraints, including code conflicts within the program architecture, microcontroller processing limitations during concurrent multi-sensor data acquisition, voltage supply instability, or electromagnetic signal interference. Consequently, the pH sensor module requires further optimization and hardware-software reconfiguration to achieve the desired reliability and precision within the integrated system.

Table 4: pH Sensor Calibration

Time	pH		Remarks
	(Automatic)	(Manual)	
14.33	3.53	5.9	Automated Non-functional
14.36	3.53	5.8	Automated Non-functional
14.39	3.53	5.8	Automated Non-functional
14.42	3.53	5.9	Automated Non-functional
14.45	3.53	6	Automated Non-functional
14.48	3.53	5.9	Automated Non-functional
14.51	3.53	5.9	Automated Non-functional
14.54	3.53	6	Automated Non-functional
14.57	3.53	6.1	Automated Non-functional
15.00	3.53	6	Automated Non-functional
15.03	3.53	5.9	Automated Non-functional
15.06	3.53	5.8	Automated Non-functional
15.09	3.53	5.9	Automated Non-functional
15.12	3.53	6	Automated Non-functional
15.15	3.53	6	Automated Non-functional
15.18	3.53	6.1	Automated Non-functional
15.21	3.53	6	Automated Non-functional
15.24	3.53	5.9	Automated Non-functional
15.27	3.53	5.9	Automated Non-functional
15.30	3.53	6	Automated Non-functional

## 5. Conclusion

The research and development of the Internet of Things (IoT)-based hydroponic cultivation system for lettuce successfully demonstrates automated environmental monitoring capabilities. Centered around an ESP32 microcontroller, the system integrates TDS, temperature, and pH sensors to acquire nutrient solution data, which is then transmitted in real-time to the Firebase cloud platform for remote visualization via a dedicated web monitoring dashboard.

Empirical testing indicates that the TDS and temperature sensor modules exhibit satisfactory operational performance. Although minor fluctuations and slight deviances were observed when compared against standard manual measuring instruments, the resulting error margins remain strictly within acceptable operational tolerances, verifying the technical viability of both sensors for continuous nutrient and thermal monitoring.

Furthermore, the system successfully executes automated water pump control driven by sensor telemetry thresholds. This automation layer effectively regulates and maintains stable plant nutrient levels without requiring continuous manual intervention, thereby significantly reducing user workload and optimizing overall operational efficiency within hydroponic cultivation management.

However, full system integration revealed a critical technical constraint involving the pH sensor module, which suffered from readout stagnation (stuck values) due to software or signal interference despite performing normally during isolated initial tests. In conclusion, while the system operates efficiently regarding nutrient and temperature parameters, future development and reconfiguration are highly required to resolve multi-sensor integration conflicts and fully optimize the pH sensor's functionality.

## Acknowledgement

The authors highly appreciate the technical support and facilities provided by the Department of Information Technology, Politeknik Negeri Samarinda, during the development of this device. Furthermore, sincere gratitude is extended to the advisors, family members, peers, and everyone who contributed directly or indirectly to the success of this study.

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