JoDENS: Journal of Digital Ecosystem for Natural Sustainability
Vol.6, No.1, Juli 2026, pp. 41~50
e-ISSN: 2798-6179
DOI: https://doi.org/10.63643/jodens.v6i1.375

Monitoring A Nutrient Film Technique (NFT) Hydroponic System For Nutrient Delivery To Bokchoy Plants

Jaswin [1*], Muhammad Khaerul Naim Mursalim [2], Raymond Erz Saragih [3]
[1,2,3]*Department of Informatics Engineering, Faculty of Computer, Universitas Universal, Batam, Indonesia*
**Corresponding author E-mail: jaswinftf1@gmail.com*

Article Info

Article history:

Received 10-07-2026
Revised 22-07-2026
Accepted 25-07-2026

Keyword:

NFT Hydroponics, Internet of Things, Notification System, Nutrient Dosing System, PID Control.

ABSTRACT

A small-scale Nutrient Film Technique (NFT) hydroponic system requires continuous monitoring because it strongly depends on nutrient solution flow, water availability, and the stability of operational parameters. Manual monitoring is often less effective because system disturbances may be detected too late by users. This study aims to design, implement, and test an Internet of Things (IoT)-based NFT hydroponic monitoring and automatic nutrient dosing system prototype capable of displaying data, storing monitoring history, providing warnings during abnormal conditions, and automatically dosing nutrient solution based on sensor readings. The method used is prototyping. The prototype integrates an NFT hydroponic system, IoT devices, Firebase, a web dashboard, Telegram notifications, an automatic nutrient dosing system, and supporting actuators. Test results show that the system is able to read and transmit monitoring data, display information on the dashboard, store historical data, and classify system conditions into normal, warning, and critical statuses based on predetermined thresholds. The system also successfully provides warnings through the dashboard, Telegram, and a local alarm when abnormal conditions are detected. The automatic nutrient dosing system, implemented using two G328 peristaltic pumps controlled via PID-based logic in response to TDS sensor readings, was successfully integrated and functioned as intended.

I. INTRODUCTION

Hydroponics is a soil-less cultivation method in which plants receive nutrients through water, making it suitable for urban areas where land is limited [1]. Urban and indoor farming commonly adopt hydroponics as a land-efficient approach, often implemented in controlled environments to achieve optimal growing conditions [2]. Among hydroponic systems, the Nutrient Film Technique (NFT) is one of the most popular and widely used types [3]. NFT works by circulating a thin film of nutrient solution over the plant roots [1]. For small-scale or household use, hydroponic systems, including NFT, can be designed to accommodate home-garden needs [4].

Although NFT is known for its recirculation approach, maintaining plant performance depends heavily on nutrient and microclimate control [5], [6]. Even under normal NFT operation, deviations in several environmental parameters can cause visible stress such as wilting, indicating that plant condition can change and be measured during the cultivation process [7]. The closed circulation system of NFT requires continuous monitoring of key variables, so manual inspection alone is insufficient to keep conditions stable [8].

Small-scale hydroponic systems are generally operated by users without agronomic or technical expertise, particularly in non-commercial settings [4]. Under such conditions, monitoring of system parameters and plant status is often performed manually and periodically, depending on the user's time and attention [1]. This monitoring practice increases the likelihood that deviations in system conditions or plant responses go undetected in real time; consequently, observable changes in plant condition may persist for some time before corrective action is taken [9].

The development of Internet of Things (IoT) technology enables real-time monitoring of cultivation conditions through internet-connected sensors [10]. In small-scale hydroponic systems, IoT architectures typically integrate environmental sensors such as pH, TDS, temperature, and humidity sensors to observe system conditions and assist users through data visualization [11]. Such systems commonly provide warnings when deviations from established conditions occur, allowing users to respond more quickly than through manual observation [10].

Several studies have developed IoT-based hydroponic monitoring systems using ESP32 as the main microcontroller. Some studies focus on monitoring several parameters with cloud-based data visualization, such as Megantoro et al. [12], Fakhri and Irawati [13], and Aureldo et al. [14], each integrating pH, TDS, temperature, and humidity sensors with Firebase as a real-time database and presenting results through Android applications or web dashboards. Other studies, such as Taqiyuddin et al. [15] and Ratna [16], complement this monitoring with notification mechanisms when parameters such as pH, nutrients, temperature, or water level fall outside the normal range, although neither includes actuators for automatic condition adjustment. Meanwhile, Abu Sneineh and Shabaneh [17] and Hersydano et al. [18] implement full automation features, in which the nutrient or irrigation pump is controlled automatically based on pH and TDS readings that exceed predetermined thresholds.

Although these systems have demonstrated effectiveness in monitoring nutrient and environmental parameters, several gaps remain, particularly in the application of small-scale NFT hydroponic systems. Studies emphasizing visualization and data storage, such as Megantoro et al. [12] and Aureldo et al. [14], are not yet equipped with notifications or automatic control for abnormal conditions. Conversely, studies that include automation, such as Hersydano et al. [18], generally do not monitor environmental variables such as air temperature and humidity, nor do they provide historical data or an integrated dashboard. A critical aspect of NFT systems—continuity of nutrient-solution flow—is also rarely an explicit monitoring focus in these studies. In addition, most studies do not integrate actuators that directly respond to nutrient sensor values, so correction of solution conditions, such as additional nutrient dosing, still depends on manual user action. Based on these gaps, there is an opportunity to develop a system that integrates monitoring of NFT operational conditions, warning notifications, historical data logging, an integrated dashboard, and an automatic nutrient dosing system as an actuator that directly responds to the monitored nutrient sensor values.

This study is directed toward designing, implementing, and testing an IoT-based monitoring and automatic nutrient dosing system for small-scale NFT hydroponics, using Bokchoy as the cultivation object. The system integrates sensors, an ESP32 microcontroller, Firebase, a web dashboard, notifications, an automatic nutrient dosing system, and supporting actuators to monitor system conditions, provide warnings when abnormal conditions occur, and automatically dose nutrients based on sensor readings. Firebase is used as the data-communication medium between the ESP32 and the dashboard, so sensor readings can be displayed on the monitoring interface. The system mechanism uses threshold-based rules to determine the status of the monitored parameters. System effectiveness is assessed based on the system's ability to read sensor data, transmit data from the ESP32, display information and recommendations on the dashboard, log monitoring history, detect and respond to operational disturbances in the NFT hydroponic system, and activate the automatic nutrient dosing system based on sensor readings. The main contribution of this research lies in the integration of two G328 peristaltic pumps for dosing nutrient solutions A and B based on TDS values under PID control, the monitoring of circulation-pump status using YF-S201 and XKC-Y25-V sensors, and the provision of action recommendations on the dashboard when sensor parameters deviate from the optimal range.

II. METHOD

A. NFT Hydroponics and Bokchoy Cultivation

Hydroponics offers substantial advantages over conventional soil-based cultivation, reducing water consumption by up to 90% because water not absorbed by the roots returns to the reservoir through recirculation [19], [20]. Nutrient solutions can be adjusted with high precision, improving fertilization efficiency and yield consistency [21], while an inert medium such as rockwool or cocopeat provides mechanical root support while nutrients are supplied entirely through a controlled solution [22]. Because the whole growing environment can be controlled, hydroponic systems achieve substantially higher nutrient-uptake efficiency than soil-based agriculture [21], [23]; proper pH management governs the availability of macro- and micronutrients, while TDS provides an estimate of dissolved-solute concentration that correlates with electrical conductivity (EC), and an imbalance between the two can cause nutrient deficiency or toxicity that affects growth performance [24], [25]. Hydroponics also reduces the risk of weeds, soil-borne pests, and disease [26], making it an attractive option for urban agriculture, particularly in space-constrained environments [20].

Several hydroponic variants exist, including Deep Water Culture, Wick System, Ebb and Flow, Drip System, Aeroponics, and NFT [27], with NFT being one of the most widely used methods for leafy vegetables such as basil [28]. In NFT, the nutrient solution flows as a thin film along the growing channel, enabling roots to absorb nutrients while obtaining adequate oxygen, resulting in a nutrient-efficient, low-maintenance system with consistent performance as long as the nutrient flow remains stable [29]. NFT systems can be arranged horizontally or vertically [30]; horizontal channels provide a stable, uniform flow with easier maintenance and a lower risk of clogging but require more floor space [30], [6], while vertical configurations maximize planting density per unit area but tend to show uneven nutrient distribution across levels and greater dependence on pump reliability [31]. However, because NFT roots are exposed to only a very thin nutrient film, system performance is highly sensitive to pump failure, channel blockage, or a drop in solution level, which can quickly cause root stress or system failure [32], [33]. On the household scale, such failures are often not immediately detected because manual inspection is periodic rather than continuous, making NFT particularly suitable for combination with sensor- and IoT-based monitoring for early detection of operational disturbances.

Bokchoy (Bok Choy, Brassica rapa L.) is a leafy vegetable of the Brassicaceae family originating from China and now widely cultivated in Indonesia because of its short growth cycle and high economic value [34], [35]. It grows to a compact height of 15–30 cm with oval, dark-green leaves and thick, whitish or light-green petioles [36], reaching harvest in about 30–40 days [37], [38]. Bokchoy grows well at 100–1,000 m above sea level with an air temperature of 15–30 °C and relative humidity of 80–90% [36], [39]; nutrient concentration is typically increased gradually up to around 1,000 ppm near harvest [40], and solution pH is generally maintained between 6.0 and 7.0 to keep nutrients available for growth [41], [39]. Beyond ease of cultivation, Bokchoy is nutritionally valuable, containing approximately 1,555 IU of vitamin A, 66 mg of vitamin C, and 225 mg of potassium per 100 g [42]. In this study, Bokchoy was used to represent realistic NFT operating conditions; plant selection was not intended to evaluate growth performance, productivity, or harvest quality, since the research focus is directed at the performance of the IoT-based monitoring and early-disturbance-detection system, with Bokchoy serving as a functional validation medium rather than an object of agronomic analysis.

B. Internet of Things Architecture

The Internet of Things (IoT) is a technological paradigm that integrates physical devices into the Internet, enabling them to acquire data, communicate with one another, and perform automatic control functions [43]. IoT devices are equipped with sensors, actuators, and communication modules that enable distributed monitoring and control without direct human intervention [44], making IoT a key enabling technology for real-time, data-driven decision-making and improved operational efficiency [45], [44]. IoT architecture generally consists of three layers: the perception layer, which acquires physical data from the environment through sensors; the network layer, which forwards this data through communication protocols such as Wi-Fi, Bluetooth, or MQTT to a local server, cloud platform, or gateway; and the application layer, which processes, stores, and interprets the data before presenting it as visualization, notifications, or automatic actions [43]. In this research, IoT supports continuous monitoring and rule-based closed-loop control of the NFT hydroponic system: sensor acquisition provides feedback to activate the blower and buzzer based on predefined thresholds, while the nutrient dosing pumps are controlled through a PID algorithm that responds to TDS sensor readings.

C. Research Object Overview

The object of this research is a small-scale NFT hydroponic system integrated with an IoT-based monitoring system. The main components consist of a nutrient-solution reservoir, a circulation pump, PVC-pipe NFT channels, and Bokchoy plants as the cultivation object. The developed IoT system reads operational parameters through sensors, transmits data from the ESP32 to Firebase, displays data on a web dashboard, stores monitoring history, and provides notifications when abnormal conditions occur. The monitored parameters include pH, TDS, water temperature, air temperature, air humidity, water flow rate, and water level. Using the YF-S201 flow sensor and the XKC-Y25-V water-level sensor, the system also monitors the operational status of the circulation pump and the success of nutrient flow reaching the NFT channel. The dashboard not only displays data and pump status but also provides recommended actions when the pH or water temperature is too high. In addition, the system is equipped with a buzzer, a blower, and nutrient dosing pumps as actuators used to respond to certain conditions in the NFT hydroponic system.

D. Research Stages

This study uses the prototyping method because the research focuses on developing a prototype of an IoT-based NFT hydroponic system that involves the gradual integration of hardware and software. The developed system not only displays sensor data but also transmits data to Firebase, displays information and recommended actions on the dashboard, provides notifications, monitors pump operational status, and activates actuators in the form of a blower, a buzzer, and a nutrient dosing pump. Each of these components requires repeated testing and refinement, such as sensor-reading verification, adjustment of pH sensor placement, use of the ADS1015 to improve analog-reading stability, calibration of peristaltic-pump flow rate, and testing of PID control based on nutrient-solution concentration. The prototyping method is therefore appropriate because it allows the system to be built, tested, evaluated, and refined incrementally until the prototype functions according to the research objectives [46]. Fig. *1* shows the stages of the prototyping method adopted in this research.

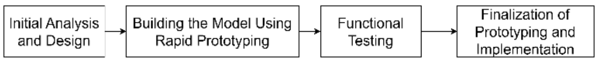

Fig. 1. Prototyping Method [46]

1) Initial Analysis and Design

This stage identifies the system requirements based on the characteristics of small-scale NFT hydroponics and the research objectives. The analysis considers that the NFT system requires a continuous flow of nutrient solution, water availability in the channel, and monitoring of operational parameters such as pH, TDS, water temperature, air temperature, and air humidity. Based on the problem formulation, the system also needs the ability to respond to nutrient-solution concentration through an automatic nutrient dosing system. This stage produces an initial design of the hydroponic physical structure, the IoT hardware, the dashboard, data communication, notifications, and actuators.

2) Building the Model Using Rapid Prototyping

The initial design is developed into a functionally testable prototype using a rapid-prototyping approach, in which parts of the system are built gradually, tested, and revised whenever obstacles are found in the hardware, programming, data-communication flow, or actuator logic. The prototype consists of three main parts: the NFT hydroponic system, the IoT monitoring and warning system, and the automatic nutrient dosing system.

3) Functional Testing

The initial design is developed into a functionally testable prototype using a rapid-prototyping approach, in which parts of the system are built gradually, tested, and revised whenever obstacles are found in the hardware, programming, data-communication flow, or actuator logic. The prototype consists of three main parts: the NFT hydroponic system, the IoT monitoring and warning system, and the automatic nutrient dosing system.

4) Finalization of Prototyping and Implementation

The initial design is developed into a functionally testable prototype using a rapid-prototyping approach, in which parts of the system are built gradually, tested, and revised whenever obstacles are found in the hardware, programming, data-communication flow, or actuator logic. The prototype consists of three main parts: the NFT hydroponic system, the IoT monitoring and warning system, and the automatic nutrient dosing system.

E. System Hardware and Software Components

The prototype integrates an ESP32 microcontroller as the main data-processing and communication hub. ESP32 was selected because of its integrated Wi-Fi connectivity, which enables real-time data transmission without an additional communication module [47], and its support for UART, I2C, and SPI protocols, which simplifies integration with the various sensors and actuators used [48]. The prototype uses a DHT22 sensor for air temperature and humidity [49]; a DS18B20 probe for water temperature [50]; a pH E-201 probe with a PH4502C signal-conditioning module for pH; a DFRobot SEN0244 sensor for Total Dissolved Solids (TDS) [51]; a YF-S201 flow sensor for detecting the presence and rate of water flow from the circulation pump; and a non-contact XKC-Y25-V capacitive level sensor for detecting the presence of liquid at the end of the NFT channel [52]. Because the ESP32's internal analog-to-digital converter produced unstable readings [53], an external ADS1015 ADC module [54] was added to condition the pH and TDS analog signals before converting them to digital values, which were transmitted over I2C.

Actuators consist of a 12 VDC blower [55], a 5 VDC buzzer, and two G328 peristaltic pumps [56] used to add nutrient solutions A and B to the reservoir. All actuators are switched through an 8-channel 5 VDC relay module [57], since the ESP32 cannot directly drive higher-voltage or higher-current loads. A 12 VDC/16.6 A power supply provides power to the actuators, while an LM2596 step-down converter [58] regulates the voltage supplied to the ESP32 expansion board.

On the software side, Firebase Realtime Database is used as the real-time communication medium between the ESP32 and the web dashboard, supporting HTTP REST-API communication with JSON as the data-exchange format [59] and providing an API that is easy to integrate with mobile and web applications without requiring a separate back-end server [60]. The dashboard back end uses PHP, a server-side scripting language embedded in HTML that enables dynamic web development [61], [62], together with a MySQL relational database managed through phpMyAdmin for permanent storage of user data, plant data, and monitoring history [61], [63], [64], [65]. JavaScript is used to dynamically update the dashboard display and visualize sensor data as charts and tables based on data received from Firebase [66], [67], while CSS is used to improve the readability and responsiveness of the interface [68], [69], [70]. Telegram's Bot API [71], [72] is used to deliver notifications whenever a monitored parameter exceeds its threshold.

F. PID-Based Nutrient Dosing Control

The automatic nutrient dosing system uses Proportional–Integral–Derivative (PID) control to determine the active duration of the dosing pumps based on the difference between the actual and target nutrient-solution concentration (TDS). The proportional component produces a response proportional to the current error; the integral component accumulates error over time to eliminate steady-state offset [73]; and the derivative component predicts the rate of change of error to reduce overshoot and improve stability [74]. The three components are combined as shown in Equation 1.

Equation 1. PID Equation

$$u = K_p \cdot e + K_i \cdot \int e \ dt + K_d \cdot \frac{de}{dt} \qquad (1)$$

where Kp, Ki, and Kd are the tuning gains for each component, and e is the error between the target and actual TDS value [74]. In this study, the proportional gain was set to Kp = 0.035, meaning that every 1 ppm of error contributes approximately 0.035 mL to the dosing output, while Ki and Kd were set to 0 to reduce the risk of overdosing, so that the response is dominated by the proportional term. The PID output, expressed as an estimated nutrient volume in milliliters, is converted into an active duration for each pump based on its calibrated flow rate, since Pump A and Pump B were found to deliver different average flow rates, as discussed in Section III.

III. Result and Discussion

A. Initial Design

The initial hydroponic design consists of four horizontally arranged NFT channels made of 2.5-inch PVC pipe, each containing seven planting holes spaced 3 inches apart. All channels are connected to a common reservoir positioned beneath the final channel outlet, with a submersible pump maintaining closed-loop circulation of the nutrient solution. The initial IoT system design is represented by a system flowchart (Fig. *2*) describing the interaction between the sensors, the ESP32 microcontroller, the actuators, and the user interface. The ESP32 captures continuous sensor readings are processes the data to determine the operational status of the NFT system. Normal conditions are logged in the cloud database and displayed on the dashboard, while abnormal conditions trigger an immediate actuator response, such as the blower and buzzer, and send a notification via Telegram.

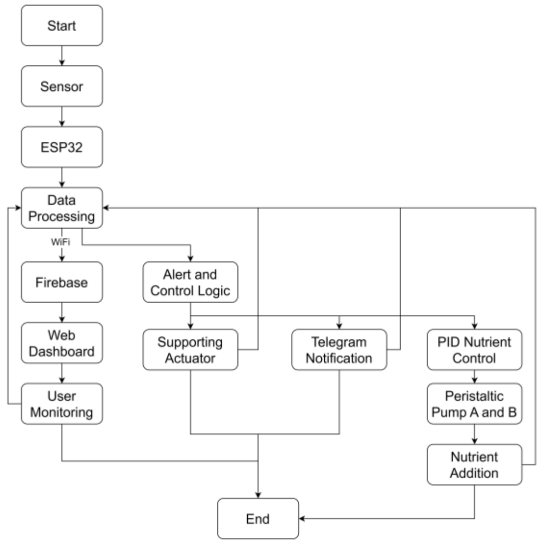

Fig. 2. System Flowchart.

The dashboard was designed through a series of wireframes covering the login page, the admin login and panel, the main dashboard for plant-data management, the plant-registration form, the bulk-logging feature, the plant detail view, the growth-log editing form, the real-time sensor dashboard, and the historical data view with graph and table visualization. These wireframes served as the reference for the subsequent web-dashboard implementation.

B. Prototype Development and Hardware Integration

The hydroponic prototype (Figure 3) was assembled using four stacked NFT channels made of 2.5-inch PVC pipe, with the reservoir placed directly beneath the final channel outlet so that the returning solution could be immediately reused; the submersible pump was placed inside the reservoir to drive the solution back into the NFT channels in a continuous closed loop

Figure 3. Assembled NFT hydroponic prototype

All sensors and actuators were connected to the ESP32 through an expansion board. The DHT22 and DS18B20 sensors were positioned to capture representative air and water conditions around the NFT channel, while the pH probe was placed apart from the TDS and DS18B20 sensors to avoid electromagnetic interference. During initial testing, the DS18B20 sensor was not detected by the microcontroller despite a correct physical connection; this was resolved by adding a 4.7 kΩ pull-up resistor on the One-Wire communication line. Likewise, the raw analog pH and TDS readings exhibited instability and drift when read directly through the ESP32's internal ADC; both sensors were therefore routed through the external ADS1015 module, which substantially improved reading stability. The blower, buzzer, and two G328 peristaltic pumps were each switched through a dedicated channel of the 8-channel relay module, remaining off by default and activating only when the relay received a control signal from the corresponding ESP32 GPIO pin.

On the software side, the ESP32 was programmed in the Arduino IDE to read sensor values, connect to Wi-Fi, transmit data to Firebase, and execute the PID-based dosing logic and the threshold-based actuator rules. Calibration of the two peristaltic pumps, performed over ten trials of 4-second activations each, found that Pump A delivered approximately 4.8 mL in 4 s (an average flow rate of 1.2 mL/s), while Pump B delivered approximately 5.0 mL in 5.2 s (an average flow rate of 0.96 mL/s). Because of this difference, the estimated dosing volume produced by the PID controller was converted into a different active duration for each pump according to its own calibrated flow rate.

C. Sensor Verification and Testing

Table 1 summarizes the verification and functional-testing results of the environmental and operational sensors. Readings were logged via the Arduino IDE Serial Monitor at 1-minute intervals over a 10-minute period for each test condition.

Table 1 Sensor Verification and Testing Summary

Sensor	*Parameter*	*Test Condition*	*Result*	*Status*
DHT22	Air temperature (°C)	Normal environment	32.9 – 33.0	Stable
DHT22	Relative humidity (%)	Normal environment	65.3 – 66.3	Stable

Sensor	*Parameter*	*Test Condition*	*Result*	*Status*
DS18B20	Water temperature (°C)	Normal environment	29.2 – 29.3	Stable
YF-S201	Flow rate (L/min)	Pump off / Pump on	0 / 10.5 – 10.7	As expected
XKC-Y25-V	Liquid presence (binary)	No flow / Flow	OFF / ON	As expected
pH (E-201 + PH4502C)	pH reading	Buffer 4.01 / 6.86 / 9.18	4.06 / 6.82 / 9.23 (avg. dev. ≈ 0.05)	High accuracy
TDS (SEN0244)	TDS (ppm)	Tap water / Salt water	~28 / ~1,078	Responsive
Blower	Trigger response	Air temp. > 33 °C	Activated (10/10 trials)	Success
Buzzer	Trigger response	Status = Critical	Activated (10/10 trials)	Success

The DHT22 sensor produced stable air-temperature readings between 32.9 °C and 33 °C and relative-humidity readings between 65.3% and 66.3%, with no invalid readings or communication errors observed. The DS18B20 water-temperature sensor likewise produced stable readings between 29.2 °C and 29.3 °C. For the operational sensors, the YF-S201 flow sensor correctly distinguished the pump-off condition (0 L/min) from the pump-on condition, reading between 10.5 and 10.7 L/min, while the XKC-Y25-V level sensor correctly switched between the “no water detected” and “water detected” states, confirming that the nutrient solution reached the end of the NFT channel.

The pH sensor was calibrated using standard buffer solutions of pH 4.01, 6.86, and 9.18. After calibration with the ADS1015, the sensor produced average readings of 4.06, 6.82, and 9.23, corresponding to an average deviation of about 0.05 pH units from the reference values, indicating high measurement accuracy. The TDS sensor was verified using tap water and salt water, producing readings of approximately 28 ppm and 1,078 ppm, respectively, confirming the sensor's ability to respond to changes in dissolved solids concentration. The blower and buzzer actuators were each tested over ten trigger cycles and responded correctly to their respective threshold conditions—air temperature above 33 °C for the blower, and a critical status for the buzzer—in all trials

D. PID-Based Nutrient Dosing Test

Table 2 presents the results of testing the peristaltic-pump dosing system under PID control, using a 5-liter reservoir.

Table 2 PID-Based Nutrient Dosing Test Results

Cycle	*Initial TDS (ppm)*	*Target (ppm)*	*Error (ppm)*	*PID Output (mL)*	*Pump A Duration (s)*	*Pump B Duration (s)*	*TDS After Mixing (ppm)*
1	371	950	579	20.26	16.88	21.1	379
2	379	950	571	19.99	16.66	20.83	388

When the nutrient-solution concentration was below the 950 ppm target, the ESP32 activated dosing Pumps A and B for a duration proportional to the PID output. In the first cycle, an initial TDS of 371 ppm produced an error of 579 ppm and a PID output of 20.26 mL, activating Pump A for 16.88 s and Pump B for 21.1 s, after which the TDS increased to 379 ppm. In the second cycle, an initial TDS of 379 ppm produced a comparable PID output and pump activation, raising the TDS to 388 ppm after mixing. These results confirm that the PID control logic and the dosing actuators function correctly in response to TDS errors, although the resulting increase in concentration remains modest and is influenced by factors such as reservoir volume, mixing time, and the stability of the TDS sensor reading.

E. Dashboard, Notification, and System-Level Testing

The completed web dashboard (Figure 4) allows registered users to log in, register new plants, record growth data individually or in bulk, view detailed plant history, and export monitoring history as a CSV file. A separate administrator panel allows management of hydroponic setups and account credentials. Login testing using an incorrect password or incorrect administrator credentials correctly denied access, confirming that the authentication mechanism functions as intended.

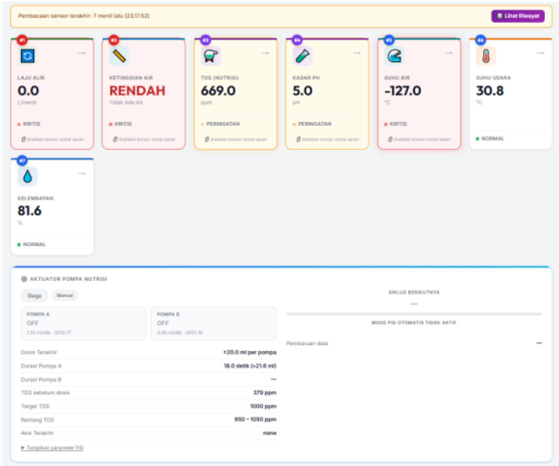

Figure 4. Main web dashboard for sensor monitoring

The sensor dashboard updates from Firebase and displays each parameter together with a recommended action whenever a reading crosses its threshold. Historical data can be viewed as a table or a chart over a selectable time range. End-to-end integration testing confirmed that sensor values read by the ESP32 via the Serial Monitor matched those received by Firebase, with identical timestamps and readings, verifying reliable ESP32-to-Firebase communication.

Telegram notifications were verified by checking sensor values every minute against the configured thresholds. For high-priority operational sensors, flow rate and water level, an alert is repeated every 5 minutes while the abnormal condition persists; for other sensors, such as TDS, pH, water temperature, air temperature, and humidity, alerts are repeated at a lower frequency of every 30 minutes. The buzzer sounds for 30 seconds every 10 minutes while a critical condition persists, and the blower remains active as long as the air temperature stays above 33 °C.

F. Final Prototype and Success Indicators

The prototype was finalized by permanently assembling the four PVC channels, each with seven planting holes spaced 7.5 cm apart, and by completing the integration of all sensors and actuators around the reservoir and sensor enclosure (Fig. *5*, Fig. *6*, and Fig. *7*).

Fig. 5 Hardware Placement on Hydroponic NFT System

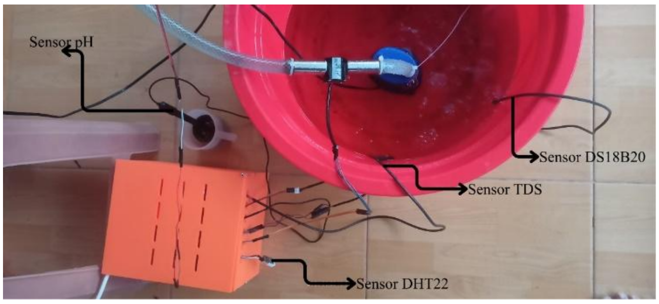

Fig. 6 Hardware Placement on Sensor Enclosure

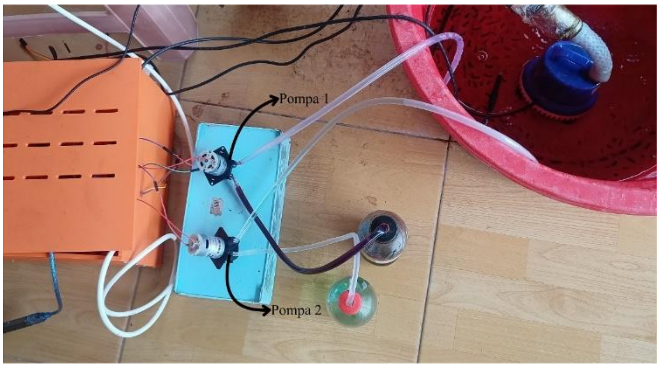

Fig. 7 Nutrient Pump Placement

Table 3 summarizes the success indicators used to evaluate the final prototype, divided into the NFT hydroponic structure and the IoT monitoring system.

Table 3 Success Indicators of The Final Prototype

Aspect	Success Indicator	Result	Status
NFT structure	The system can be assembled and used as a growing medium	Successfully assembled using PVC pipe, reservoir, and pump	Achieved
Nutrient circulation	Solution flows from the reservoir to all channels and back	Closed-loop circulation is maintained during operation	Achieved
Sensor reading	Sensors read air temp., humidity, water temp., TDS, pH, flow, water presence	Data successfully read via ESP32	Achieved
Data transmission	ESP32 sends sensor data to Firebase	Data successfully relayed to Firebase	Achieved
Dashboard	Dashboard performs CRUD, displays info/recommendations, history, and charts	Dashboard used as the monitoring interface	Achieved
Warning mechanism	The system distinguishes normal / warning / critical states	Abnormal conditions shown on the dashboard and Telegram	Achieved
Actuator response	Actuators respond to trigger conditions	Blower and buzzer activate correctly	Achieved
Nutrient dosing pump	Pump responds to TDS via PID and adds nutrients A/B	Pump activated correctly per PID logic	Achieved

Overall, the final prototype met all of the defined success indicators within the scope of this research: the NFT structure was successfully assembled and maintained closed-loop nutrient circulation, Bokchoy plants grew within the system (with limitations, since agronomic optimization was outside the scope of this study), and the IoT system successfully read sensor parameters, transmitted data to Firebase, displayed information and recommendations on the dashboard, distinguished normal, warning, and critical conditions, delivered notifications, and activated actuators—including the PID-controlled dosing pumps—according to the defined rules.

G. Discussion

The results show that the developed system fulfilled its primary monitoring functions: reading operational parameters, transmitting data, displaying information, storing history, and providing warnings and actuator responses to specific conditions. Compared with earlier IoT-based hydroponic monitoring systems that emphasize data visualization and storage but lack notification or automatic control, such as Megantoro et al. [12] and Aureldo et al. [14], or systems that provide automation but do not monitor environmental variables or provide an integrated dashboard, such as Hersydano et al. [18], the system developed in this study combines pH, TDS, water-temperature, air-temperature, humidity, flow-rate, and water-level monitoring with Firebase, a web dashboard, Telegram notifications, a local alarm, and an automatic PID-based nutrient-dosing actuator within a single integrated system.

Nevertheless, the system has several limitations. It remains dependent on a stable Wi-Fi connection and Firebase availability, without local data storage as a backup during connectivity loss. The pH and TDS sensors used are general-purpose modules rather than industrial-grade sensors, which constrains long-term measurement precision. In the nutrient-dosing subsystem, the peristaltic pumps operated correctly according to the PID output, but the resulting increase in nutrient concentration did not yet reach the intended target, indicating that further tuning of the PID parameters, together with consideration of reservoir volume, mixing time, and TDS sensor stability, is required to improve dosing effectiveness. The prototype also does not yet include a power backup, and full automatic control of parameters such as pH remains outside the current scope. Finally, this study did not perform a formal evaluation with external users or an agronomic assessment of plant productivity, harvest weight, or growth quality, since the Bokchoy crop served only as a functional reference for validating system operation rather than as an object of agronomic analysis.

IV. CONCLUSION

Based on the implementation and testing results, an IoT-based monitoring and automatic nutrient dosing system for small-scale NFT hydroponics was successfully designed and implemented by integrating the NFT hydroponic system, an ESP32 microcontroller, environmental and operational sensors, Firebase as the data-communication medium, a web dashboard, Telegram notifications, an automatic nutrient dosing system, and supporting actuators. Functional testing confirmed that the system can read pH, TDS, water temperature, air temperature, air humidity, water flow, and water level; transmit this data from the ESP32 to Firebase and display it on the dashboard; distinguish normal, warning, and critical conditions based on predefined thresholds; and deliver corresponding notifications through the dashboard, Telegram, and a local buzzer alarm. The automatic nutrient dosing system, built around two G328 peristaltic pumps controlled through a PID algorithm based on TDS error, was successfully integrated and activated according to the PID output, increasing the nutrient-solution concentration after mixing, although the increase had not yet reached the defined target concentration. These findings indicate that the developed system is functionally capable of supporting continuous, automated monitoring and basic corrective response for small-scale NFT hydroponic operations, while further refinement of PID tuning, sensor quality, and local data redundancy would be needed to extend its reliability and dosing precision for broader deployment.

REFERENCE

[1] Rocky Alfanz, A. H. A. Aqbal, and Wahyuni Martiningsih, "Smart Farm Agriculture Design by Applying a Solar Power Plant," *JURNAL NASIONAL TEKNIK ELEKTRO*, Jul. 2023, doi: 10.25077/jnte.v12n2.1085.2023.

[2] K. Tan and Y. Zhang, "The configuration optimization of the plants in vertical farming by 3D modeling," in *Journal of Physics: Conference Series*, Institute of Physics, 2023. doi: 10.1088/1742-6596/2580/1/012018.

[3] E. Khater, S. Ali, and A. Amin, "Utilization of Effluent Fish Farms in Lettuce Production," *Misr Journal of Agricultural Engineering*, vol. 0, no. 0, pp. 0–0, Jan. 2022, doi: 10.21608/mjae.2022.112354.1062.

[4] P. A. Y. Ampim, E. Obeng, and E. Olvera-Gonzalez, "Indoor Vegetable Production: An Alternative Approach to Increasing Cultivation," Nov. 01, 2022, *MDPI*. doi: 10.3390/plants11212843.

[5] A. Afonso *et al.*, "Reuse of Pretreated Agro-Industrial Wastewaters for Hydroponic Production of Lettuce," *Water (Switzerland)*, vol. 15, no. 10, May 2023, doi: 10.3390/w15101856.

[6] A. Fussy and J. Papenbrock, "An Overview of Soil and Soilless Cultivation Techniques—Chances, Challenges and the Neglected Question of Sustainability," May 01, 2022, *MDPI*. doi: 10.3390/plants11091153.

[7] G. Rusmayadi, H. Tannady Tan, E. Puspitoningrum, S. A. Pramono, D. M. Ratna, and T. Dewa, "Nutrient film in hydroponic system providing organic fertilizer of the Tithonia diversifolia and AB Mix for lettuce," no. 11, pp. 470–475, 2023, doi: 10.31413/nativa.v11i4.16465.

[8] D. Camen, M. Moatar, A. Ciulca, S. Popescu, and S. Ciulca, "Assessment of some morphological and physiological parameters in lettuce (Lactuca sativa L.) cultivated in hydroponic system," *Columella : Journal of Agricultural and Environmental Sciences*, vol. 9, no. 2, pp. 83–89, Dec. 2022, doi: 10.18380/szie.colum.2022.9.2.83.

[9] P. Atmaja and N. Surantha, "Smart hydroponic based on nutrient film technique and multistep fuzzy logic," *International Journal of Electrical and Computer Engineering*, vol. 12, no. 3, pp. 3146–3157, 2022, doi: 10.11591/ijece.v12i3.pp3146-3157.

[10] W. Booneua, S. Chai-Arayalert, and N. Boonnam, "Automated Hydroponics Notification System Using IOT," *International Journal of Interactive Mobile Technologies*, vol. 16, no. 6, pp. 206–220, 2022, doi: 10.3991/ijim.v16i06.27959.

[11] B. Sriman, H. A. Basha, N. Sampath, S. H. A. Silviya, R. V. Mani, and V. Varadarajan, "Smart hydroponic greenhouse enhanced with the application of the internet of things," *HKIE Transactions Hong Kong Institution of Engineers*, vol. 31, no. 3, 2024, doi: 10.33430/V31N3THIE-2024-0029.

[12] P. Megantoro *et al.*, "Instrumentation system for data acquisition and monitoring of hydroponic farming using ESP32 via Google Firebase," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 27, no. 1, pp. 52–61, Jul. 2022, doi: 10.11591/ijeecs.v27.i1.pp52-61.

[13] H. I. Fakhri and I. D. Irawati, "SIMPONI: Web-Integrated IoT Monitoring System for Indoor Hydroponics," in *BIO Web of Conferences*, EDP Sciences, Dec. 2025. doi: 10.1051/bioconf/202519901004.

[14] M. Aureldo, J. Renaldi, R. Afriansyah, and Y. Agita Rindri, "Rancang Bangun Alat Sistem Monitoring Hidroponik Berbasis Android," Jun. 2025. doi: https://doi.org/10.46764/teknimedia.v6i1.245.

[15] Y. Taqiyuddin, I. Ruslianto, and U. Ristian, "Sistem Monitoring Hidroponik Indoor berbasis Wick menggunakan HOPONIC (Home Pot Hidroponic)," *ELKOMIKA: Jurnal Teknik Energi Elektrik, Teknik Telekomunikasi, & Teknik Elektronika*, vol. 12, no. 1, p. 201, Jan. 2024, doi: 10.26760/elkomika.v12i1.201.

[16] S. Ratna, "Monitoring Kualitas Air Dan Kadar Nutrisi Tanaman Hidroponik Berbasis Internet Of Things (IoT)," *Technologia*, vol. 14, no. 4, 2023, doi: 10.31602/tji.v14i3.12755.

[17] A. Abu Sneineh and A. A. A. Shabaneh, "Design of a smart hydroponics monitoring system using an ESP32 microcontroller and the Internet of Things," *MethodsX*, vol. 11, Dec. 2023, doi: 10.1016/j.mex.2023.102401.

[18] M. Rayhan Hersydano *et al.*, "Rancangan Sistem Monitoring Greenhouse Hidroponik Berbasis IoT," 2025, doi: https://doi.org/10.35957/mdp-sc.v4i1.11234.

[19] S. J. Mishra, D. Rout, and D. Sahoo, "Analysing the Economic Viability of Hydroponic Farming: A Comparative Cost-Benefit Analysis," *International Journal of Progressive Research in*

Engineering Management and Science, Aug. 2024, doi: 10.58257/ijprems35128.
[20] G. Rajaseger *et al.*, "Hydroponics current trends in sustainable crop production," *Biomedical Informatics*, vol. 19, pp. 925–938, Sep. 2023, doi: 10.6026/97320630019925.
[21] A. Regmi, D. Rueda-Kunz, H. Liu, J. Trevino, S. Kathi, and C. Simpson, "Comparing resource use efficiencies in hydroponic and aeroponic production systems," *Technology in Horticulture*, vol. 4, no. 1, pp. 0–0, 2024, doi: 10.48130/tihort-0024-0002.
[22] H. Lee, M. Cui, B. Lee, H. Hwang, and C. Chun, "Optimization of the Pot Volume and Substrate for Strawberry Cultivation in a Hydroponic System," *Horticultural Science and Technology*, vol. 41, no. 6, pp. 634–644, 2023, doi: 10.7235/HORT.20230054.
[23] R. S. Velazquez-Gonzalez, A. L. Garcia-Garcia, E. Ventura-Zapata, J. D. O. Barceinas-Sanchez, and J. C. Sosa-Savedra, "A Review on Hydroponics and the Technologies Associated for Medium-and Small-Scale Operations," May 01, 2022, *MDPI*. doi: 10.3390/agriculture12050646.
[24] M. R. A. Shawon, M. O. K. Azad, B. R. Ryu, J. K. Na, and K. Y. Choi, "The Electrical Conductivity of Nutrient Solution Influenced the Growth, Centellosides Content and Gene Expression of Centella asiatica in a Hydroponic System," *Agriculture (Switzerland)*, vol. 13, no. 12, Dec. 2023, doi: 10.3390/agriculture13122236.
[25] N. N. Venkatasai, D. N. Shetty, C. M. Vinay, M. Sekar, A. Muthusamy, and P. S. Rai, "A Comprehensive Review Of Factors Affecting Growth And Secondary Metabolites In Hydroponically Grown Medicinal Plants," Mar. 01, 2025, *Springer Science and Business Media Deutschland GmbH*. doi: 10.1007/s00425-025-04619-y.
[26] D. I. Pomoni, M. K. Koukou, M. G. Vrachopoulos, and L. Vasiliadis, "A Review of Hydroponics and Conventional Agriculture Based on Energy and Water Consumption, Environmental Impact, and Land Use," Feb. 01, 2023, *MDPI*. doi: 10.3390/en16041690.
[27] S. Rajendran, T. Domalachenpa, H. Arora, P. Li, A. Sharma, and G. Rajauria, "Hydroponics: Exploring innovative sustainable technologies and applications across crop production, with Emphasis on potato mini-tuber cultivation," Mar. 15, 2024, *Elsevier Ltd*. doi: 10.1016/j.heliyon.2024.e26823.
[28] T. Hendrickson, B. L. Dunn, C. Goad, B. Hu, and H. Singh, "Effects of Elevated Water Temperature on Growth of Basil Using Nutrient Film Technique," *HortScience*, vol. 57, no. 8, pp. 925–932, Aug. 2022, doi: 10.21273/HORTSCI16690-22.
[29] K. Mahmudi, R. Dwirgahayu Nurhidayat, N. Budi Nurrohmah, P. Fisika, and U. Jember, "Analisis Konsep Fisika Pada Hidroponik NFT (Nutrient Film Technique)," 2025.
[30] M. Nelson II, G. Langellotto, and L. Nackley, "Hydro hints: Nutrient film technique," May 2025.
[31] I. Găgeanu *et al.*, "Hydroponic Vertical Systems: Enhancing Climate Resilience, Water Efficiency, and Urban Agriculture," vol. 73, no. 2, 2024, doi: 10.35633/inmateh-73-08.
[32] J. C. Escalante-Mamani *et al.*, "Design and Validation of an IoT-Integrated Fuzzy Logic Controller for High-Altitude NFT Hydroponic Systems: A Case Study in Cusco, Peru," *Electronics (Switzerland)*, vol. 14, no. 18, Sep. 2025, doi: 10.3390/electronics14183740.
[33] Triputra, Iinnaninengseh, and M. Fatman, "Efektivitas Penggunaan Hidroponik Sistem Nft (Nutrient FilmTechnique) Dalam Budidaya Tanaman Pakcoy (Brassica rapa L.)Terhadap Kemiringan Pipa Dan Jarak Antar Tanaman," *Jurnal Agroterpadu*, Aug. 2024, doi: 10.35329/ja.v3i2.5122.
[34] J. Herawati, dan Raffiuddin Helmi, P. Studi Agroteknologi, and F. Pertanian, "Efektivitas Rendaman Bawang Merah (Allium Cepa) dan Nutrisi Terhadap Hasil Hidroponik Pakcoy (Brassica Rapa)," Nov. 2022. doi: https://doi.org/10.30742/japt.v1i1.30.
[35] R. Noorhidayah *et al.*, "Respon Tanaman Pakcoy (Brassica rapa L.) terhadap Pemberian Kompos Limbah Ekstraksi Minyak Atsiri pada Tanah Ultisol," *JURNAL BUDIDAYA PERTANIAN BERKELANJUTAN*, vol. 12, pp. 7–14, 2022.
[36] R. Rosariastuti, A. Harir, S. Hartati, E. Irawan, and S. Nugraha, "The effectiveness of biofertilizer biofilm formulation in promoting the growth of Pak choi (Brassica rapa L.) plant," in *E3S Web of Conferences*, EDP Sciences, Dec. 2023. doi: 10.1051/e3sconf/202346701027.
[37] Y. Prasetia, A. G. Putrada, and A. Rakhmatsyah, "Evaluation of IoT-Based Grow Light Automation on Hydroponic Plant Growth," *Jurnal Ilmiah Teknik Elektro Komputer dan Informatika*, vol. 7, no. 2, p. 314, Sep. 2021, doi: 10.26555/jiteki.v7i2.21424.
[38] D. Trung Thanh and N. Huynh Anh Tuyet, "Using Nutrient Solution Instead of Fertilizer to Grow Bok Choy (Brassica chinensis) in Thu Dau Mot City," *VNU Journal of Science: Earth and Environmental Sciences*, Jun. 2025, doi: 10.25073/2588-1094/vnuees.5214.
[39] U. K. J. Suharjo, W. L. Siburian, and M. Marlin, "Uji Enam Racikan Nutrisi Hidroponik pada Tanaman Pakchoy (Brassica rapa L.) sebagai Pengganti Larutan AB-Mix," *Proceedings Series on Physical & Formal Sciences*, vol. 5, pp. 251–259, Aug. 2023, doi: 10.30595/pspfs.v5i.730.
[40] E. Jipasca *et al.*, "Pengaruh Pertumbuhan Pakcoy (Brassica Rapa L.) Dengan Sistem Tanam Hidroponik Tipe Nutrient Film Technique (NFT) Dan Media Kotoran Hewan (KOHE)," *JURNAL BIOSILAMPARI: JURNAL BIOLOGI*, vol. 7, no. 1, pp. 2024–54, 2024.
[41] F. de A. de Oliveira *et al.*, "Production and quality of pak choi grown in different hydroponic systems and electrical conductivities," *Revista Caatinga*, vol. 37, 2024, doi: 10.1590/1983-21252024v3712436rc.
[42] D. Retna Surjaningsih, P. Studi Agroteknologi, and F. Pertanian, "Pengaruh Pemberian Biochar dan Kompos Terhadap Pertumbuhan Tanaman Pakcoy (Brassica Rapa L.) Pada Tanah Vertisol," 2023.
[43] A. Choudhary, "Internet of Things: a comprehensive overview, architectures, applications, simulation tools, challenges and future directions," Dec. 01, 2024, *Springer Nature*. doi: 10.1007/s43926-024-00084-3.
[44] S. Pandey, M. Chaudhary, and Z. Tóth, "An investigation on real-time insights: enhancing process control with IoT-enabled sensor networks," Dec. 01, 2025, *Springer Nature*. doi: 10.1007/s43926-025-00124-6.
[45] K. D. Kang, "A Review of Efficient Real-Time Decision Making in the Internet of Things," Feb. 01, 2022, *MDPI*. doi: 10.3390/technologies10010012.
[46] H. Hasanah, R. Susanto, and W. Lestari, "Internet of Things-Based Hidroponic Plant Monitoring System," *Jurnal Sisfokom (Sistem Informasi dan Komputer)*, vol. 14, no. 4, pp. 484–488, Oct. 2025, doi: 10.32736/sisfokom.v14i4.2443.
[47] M. Pincheira, M. Antonini, and M. Vecchio, "Integrating the IoT and Blockchain Technology for the Next Generation of Mining Inspection Systems," *Sensors 2022, Vol. 22, Page 899*, vol. 22, no. 3, p. 899, Jan. 2022, doi: 10.3390/S22030899.
[48] G. Fabregat, J. A. Belloch, J. M. Badia, and M. Cobos, "Design and Implementation of Acoustic Source Localization on a Low-Cost IoT Edge Platform," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 67, no. 12, pp. 3547–3551, Dec. 2020, doi: 10.1109/TCSII.2020.2986296.
[49] L. Aosong Electronics Co., "Digital-output relative humidity & temperature sensor/module DHT22 (DHT22 also named as AM2302) Capacitive-type humidity and temperature module/sensor."
[50] D. Semiconductor Corp, "Programmable Resolution 1-Wire Digital Thermometer." [Online]. Available: www.dalsemi.com
[51] DFRobot, "Gravity: Analog TDS Sensor / Meter For Arduino SKU: SEN0244." [Online]. Available: https://www.arduino.cc/en/Main/Software%7C
[52] Shenzhen XingKeChuang Technology, "Non-contact liquid level sensor instruction manual (Intelligent externally attached liquid level detection products)."

[53] M. J. Espinosa-Gavira, A. Agüera-Pérez, J. C. Palomares-Salas, J. M. Sierra-Fernandez, P. Remigio-Carmona, and J. J. González de-La-Rosa, “Characterization and Performance Evaluation of ESP32 for Real-time Synchronized Sensor Networks,” in *Procedia Computer Science*, Elsevier B.V., 2024, pp. 261–268. doi: 10.1016/j.procs.2024.05.104.

[54] Texas Instruments, “ADS101x Ultra-Small, Low-Power, I 2 C-Compatible, 3.3kSPS, 12-Bit ADCs With Internal Reference, Oscillator, and Programmable Comparator,” Jan. 2025. [Online]. Available: www.ti.com

[55] “Mini Blower Fan DC Brushless 12V,” Shopee. Accessed: Dec. 04, 2025. [Online]. Available: https://shopee.co.id/Mini-Blower-Fan-DC-Brushless-5V-12V-24V-%E2%80%93-Kipas-Keong-Pendingin-Turbo-Cooler-2PIN-Elektronik-i.62956347.16182078584

[56] Grothen Technology Company LTD, “G328 Datasheet.” Accessed: Jun. 25, 2026. [Online]. Available: https://ae01.alicdn.com/kf/S260c506ae4e04e9ba5d7d25fb5fd49a4Z.pdf

[57] Handson Technology, “Handson Technology User Guide 8 Channel 5V Optical Isolated Relay Module.” [Online]. Available: www.handsontec.com

[58] ON Semiconductor, “LM2596 ONSEMI Datasheet.” [Online]. Available: http://onsemi.com

[59] M. S. Tayeb, M. A. Benallal, M. S. Benabadji, and A. Houari, “IoT monitoring system for air quality assessment and collecting data,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 28, no. 3, pp. 1592–1600, Dec. 2022, doi: 10.11591/ijeecs.v28.i3.pp1592-1600.

[60] A. R. F. Nadhifa, Y. Eliskar, and S. B. P. Fatoni, “Implementation of Firebase as a Cloud Backend for Internet of Things Based Compost Monitoring System on Mobile Application,” in *Journal of Physics: Conference Series*, Institute of Physics, 2026. doi: 10.1088/1742-6596/3188/1/012018.

[61] I. P. Sari, A. Jannah, A. M. Meuraxa, A. Syahfitri, and R. Omar, “Perancangan Sistem Informasi Penginputan Database Mahasiswa Berbasis Web,” *Hello World Jurnal Ilmu Komputer*, vol. 1, no. 2, pp. 106–110, Jul. 2022, doi: 10.56211/helloworld.v1i2.57.

[62] D. Tsania Fatimatuzahra and Somantri, “Perancangan Web Geographic Information System (WebGIS) Kehutanan Pada Wilayah Sukabumi,” 2023.

[63] A. Amugulang, “Design and Application of MOOC Teaching Platform for College English Based on MOODLE System,” 2023, pp. 283–289. doi: 10.2991/978-94-6463-040-4_43.

[64] M. Mokayef *et al.*, “Table Tennis Tracker Web Application for Tournament Statistics Analysis,” 2022.

[65] S. Patel, J. Choudhary, and G. Patil, “Revolution of Database Management System: A literature Survey,” *International Journal of Engineering Trends and Technology*, vol. 71, no. 7, pp. 189–200, Jul. 2023, doi: 10.14445/22315381/IJETT-V71I7P218.

[66] B. M. Mohammad El-Basioni and S. M. Abd El-Kader, “Designing and modeling an IoT-based software system for land suitability assessment use case,” *Environ. Monit. Assess.*, vol. 196, no. 4, Apr. 2024, doi: 10.1007/s10661-024-12483-8.

[67] M. Geshkov, “The Application of Dynamic Web Pages in E-Commerce,” *TRAKIA JOURNAL OF SCIENCES*, vol. 23, no. Supplement 2, p. 6, Oct. 2025, doi: 10.15547/tjs.2025.s.02.050.

[68] L. Trampert, D. Weber, L. Gerlach, C. Rossow, and M. Schwarz, “Cascading Spy Sheets: Exploiting the Complexity of Modern CSS for Email and Browser Fingerprinting,” Internet Society, Mar. 2025. doi: 10.14722/ndss.2025.230238.

[69] Noorkaran Bhanarkar, Aditi Paul, and Dr. Ashima Mehta, “Responsive Web Design and Its Impact on User Experience,” *International Journal of Advanced Research in Science, Communication and Technology*, pp. 50–55, Apr. 2023, doi: 10.48175/ijarsct-9259.

[70] U. R. Sree and P. Mohan, “Comparison of Utility-First CSS Framework,” 2024.

[71] D. N. Bestari and A. Wibowo, “An IoT-Based Real-Time Weather Monitoring System Using Telegram Bot and Thingsboard Platform,” *International Journal of Interactive Mobile Technologies*, vol. 17, no. 6, pp. 4–19, 2023, doi: 10.3991/ijim.v17i06.34129.

[72] Y. Athallah and R. Agung, “Rancang Bangun Prototype Monitoring Lampu Jalan Secara Otomatis Menggunakan Mikrokontroller ESP32 Dan Api Bot Telegram,” 2022, [Online]. Available: http://awesomerockguy.blogspot.com/2015/10/tutorial-

[73] R. Chen, “A Comprehensive Analysis of PID Control Applications in Automation Systems: Current Trends and Future Directions,” 2024.

[74] N. A. Halim, N. Abd. Rahman, and J. M. Ali, “Prediction for Hydrolysisof Ethylene Oxide via Fuzzy Logic and PID Control,” *Jurnal Kejuruteraan*, vol. 35, no. 4, pp. 937–943, Jul. 2023, doi: 10.17576/jkukm-2023-35(4)-16.