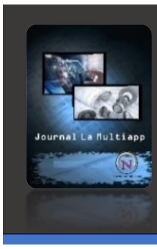

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Automatic Fuzzy Logic–Based Nutrient Film Technique Hydroponic System with IoT Integration

Muhammad Akmal[1], Ida Laila[1], Arifin Arifin[1]

[1]*Department of Physics, Faculty of Mathematics and Natural Sciences, Hasanuddin University, Makassar 90245, Indonesia*

**Corresponding Author: Arifin Arifin*
Email: arifinpide@gmail.com

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Abstract

This study addresses the need for efficient crop cultivation solutions, particularly in urban areas, by developing an automatic Nutrient Film Technique (NFT) hydroponic system integrated with the Internet of Things (IoT). Traditional hydroponic systems often require intensive monitoring and can be rigid in adapting to changing conditions, especially when using binary logic for control. The proposed system utilizes fuzzy logic as its core calculation method to manage uncertainty in decision-making, allowing for more flexible control than classical binary logic. It incorporates pH, Total Dissolved Solids (TDS), temperature, and water level sensors, connected to an Arduino Nano and ESP32 microcontroller. Data is stored and communicated in real-time via Firebase, and the system is controlled through an Android application developed with MIT App Inventor. This design aims to enhance automation, improve system control, and enable more efficient management of hydroponic operations.

Introduction

Indonesia is a country with a climate and soil conditions that are very conducive to agriculture and plantations. However, massive and sustainable infrastructure development has led to the conversion of agricultural land into industrial areas (Juniyanti et al., 2021). This condition has prompted farmers to seek alternative solutions for efficient crop cultivation without the need for large areas of land, including soilless cultivation. Modernization is one of the answers to this problem. One of the methods that has developed is hydroponic farming, which is a technique of cultivating plants without using soil, but instead utilizing nutrient-rich water as a growing medium (Fussy & Papenbrock, 2022). This system allows farming to be carried out in urban areas with increased yield in space (Serey et al., 2024; Xi et al., 2022; Payen et al., 2022; Yuan et al., 2022; Oh & Lu, 2023).

One type of hydroponic system that is commonly used is the NFT model, which is a cultivation method that utilizes a continuous flow of nutrient-rich water on the surface of plant roots at a certain angle. The NFT system has the advantage of allowing plant roots to continuously obtain nutrients and oxygen (Jones, 2014; Nituet al., 2024; Kaushal, 2024). However, this system requires intensive monitoring of nutrient levels, pH (acidity), temperature, and water volume (Sportelli et al., 2025; Sulaiman et al., 2025).

To improve the efficiency and effectiveness of monitoring, a system is needed that can monitor and control parameters automatically and remotely. One technology that supports this is the IoT, has transformed hydroponic practices by enabling automation, improved system control, and more efficient management (Aurasopon et al., 2024; Hostalrich et al., 2022). IoT is increasingly essential in the digitalization process, particularly for automating hydroponic operations (Aurasopon et al., 2024; Komala et al., 2025; Hostalrich et al., 2022). Such automation becomes possible through the direct connection established between IoT platforms and the hydroponic system (Olasehinde, 2025; Taha et al, 2022; Hanafi et al., 2025; Rosca et al., 2025; Ramsari & Hidayat, 2022; Hanafi et al., 2025).

In automatic control systems, uncertainty often arises in decision-making. Therefore, an intelligent control approach such as fuzzy logic is needed (Tang & Ahmad, 2024; D'Aniello, 2023; Sathya et al., 2024). Fuzzy logic is a computational method that can handle uncertainty and inexact data, unlike classical binary logic, which only recognizes two values (0 or 1). Fuzzy logic allows values between the two, such as 0.1, 0.2, 0.3, and so on, which reflect the degree of truth of a statement more flexibly (Hakim et al., 2021).

Several previous studies have developed IoT-based smart hydroponic systems. For example, Shin et al. (2024) designed an automated hydroponic system capable of measuring electrical conductivity (EC), pH, temperature, and water level using EC DFR0300, PH4502C, DS18B20 temperature sensors, and JSN-SR04T ultrasonic sensors with an ESP32 microcontroller, connected to an Android application via a Firebase connection. However, the control method used is not explained in detail.

Another study was conducted by Shrivastava et al. (2023), who designed a robotics and IoT-based vertical hydroponic system with similar parameters. Meanwhile, previous research was also conducted by Abu Sneineh & Shabaneh (2023), who developed a hydroponic system with TDS, water temperature, and pH control based on IoT through the Blynk platform. However, the system still uses binary logic (0 or 1), which is rigid and inflexible to changing conditions.

Based on these issues, this study aims to design and implement an automatic NFT hydroponic system equipped with nutrient and water pH control based on fuzzy logic. This system utilizes pH, TDS, temperature, and water level sensors integrated with the Firebase platform and controlled through an Android application based on MIT App Inventor.

Methods

In conducting this research, several systematic stages were carried out. This research focuses on developing an IoT-based device for controlling and monitoring a hydroponic NFT system using fuzzy logic as the core calculation method. The workflow begins with an extensive literature review to gather references related to hydroponic automation, IoT- based monitoring, and fuzzy logic control. The next step involves identifying the key issues in nutrient water control within NFT systems, followed by designing and building the device, which includes both hardware and software components. Each sensor is then calibrated using accurate reference instruments to ensure reliable measurements. The software development phase includes integrating the system with Firebase for data storage and real-time communication, as well as creating a mobile application using MIT App Inventor. Finally, the complete system is tested to evaluate its performance and effectiveness in maintaining optimal hydroponic conditions.

The system design consists of two main parts: hardware and software. The hardware design has been carefully planned so that the device can run optimally as desired. Figure 1 shows the hardware circuit diagram of the system.

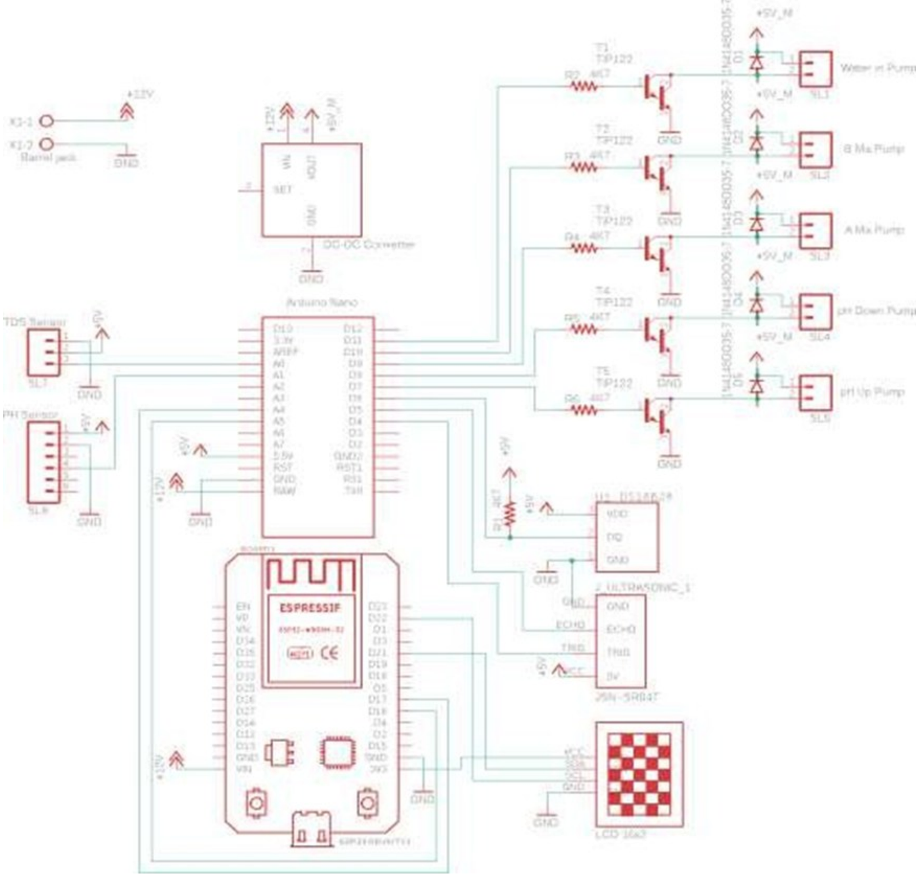


Figure 1. Hardware circuit diagram of the system

The system hardware consists of two microcontrollers, sensors, actuators, a display screen, and a power supply. The Arduino Nano functions as the main microcontroller that connects the sensors as inputs and the actuators as outputs. The sensors consist of PH4502C pH sensor, a Gravity TDS sensor, a DS18B20 temperature sensor, and an HC-SR04 ultrasonic sensor to measure water level. The actuators consist of five water pumps to control the quality of the hydroponic nutrient water and increase the water level. The main controller is also connected to ESP32 as a second microcontroller that is tasked with calculating fuzzy logic, connecting the system to IoT, and displaying the status on the LCD 16x2 display screen. The block diagram of the system shows in Figure 2.

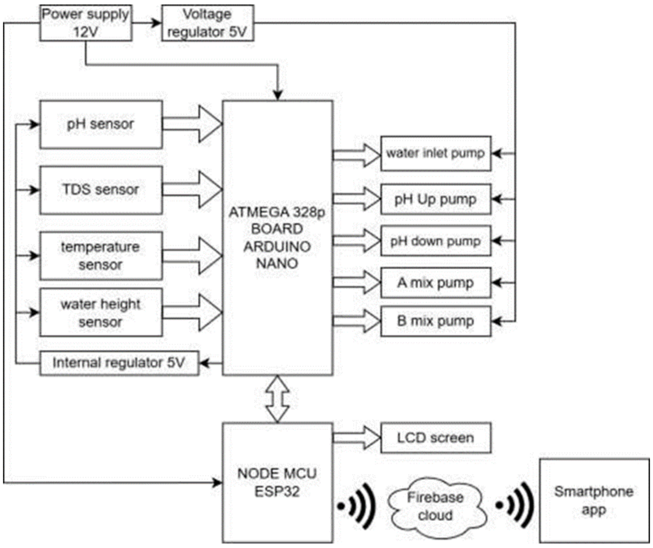


Figure 2. Block diagram of the system

In addition to the hardware, the software design also plays as a critical role in processing and integrating the system as a whole unit. In this research, four applications are used in software design, which is MATLAB, Arduino IDE, Firebase, and MIT App Inventor. Figure 3 shows the chart of the software system design.

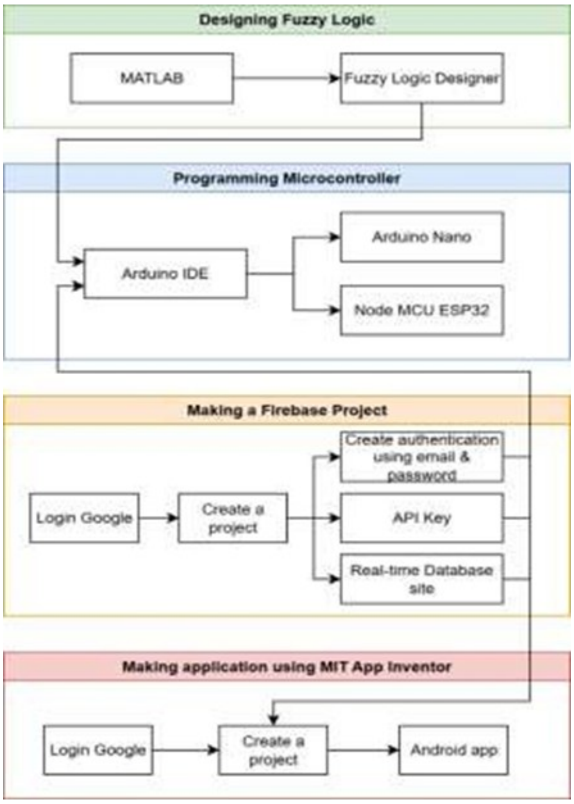


Figure 3. Software design chart

The fuzzy logic controller is designed in MATLAB, consisting of fuzzification, inference, and defuzzification processes to determine the appropriate control actions for each parameter. Arduino IDE is used to program Arduino Nano to read sensors data, while ESP32 is programmed to calculate fuzzy logic process, transmit sensor data to Firebase in real time, and shows status on the display screen. The data from Firebase is then read by an application created by MIT App Inventor as a live reading and a history of data readings over a period of time.

The system is operated according to the process shown in Figure 4 as a flowchart. The system starts with reading data from pH, TDS, temperature and water level sensor by main microcontroller and then send captured data to second microcontroller to then send again to Firebase to be shown in smartphone app as user reading in long distances over internet. The ESP32 also take the pH and TDS reading to be calculated by fuzzy logic before sending back to main microcontroller as calculated result. The calculated pH result controls the pH controller pumps. If pH is high or low, the system activates either the pH down or pH up pump according to certain amount of time calculated by fuzzy logic. The system then waits for 5 minutes until the solution is dissolved properly to nutrient water and the reading is stable enough to be processed by system again. Same processes happen for controlling nutrients too. For controlling water level, the process read data directly from the sensor then adjust the water level according to sensor data. There is no further process for water temperature after reading its data

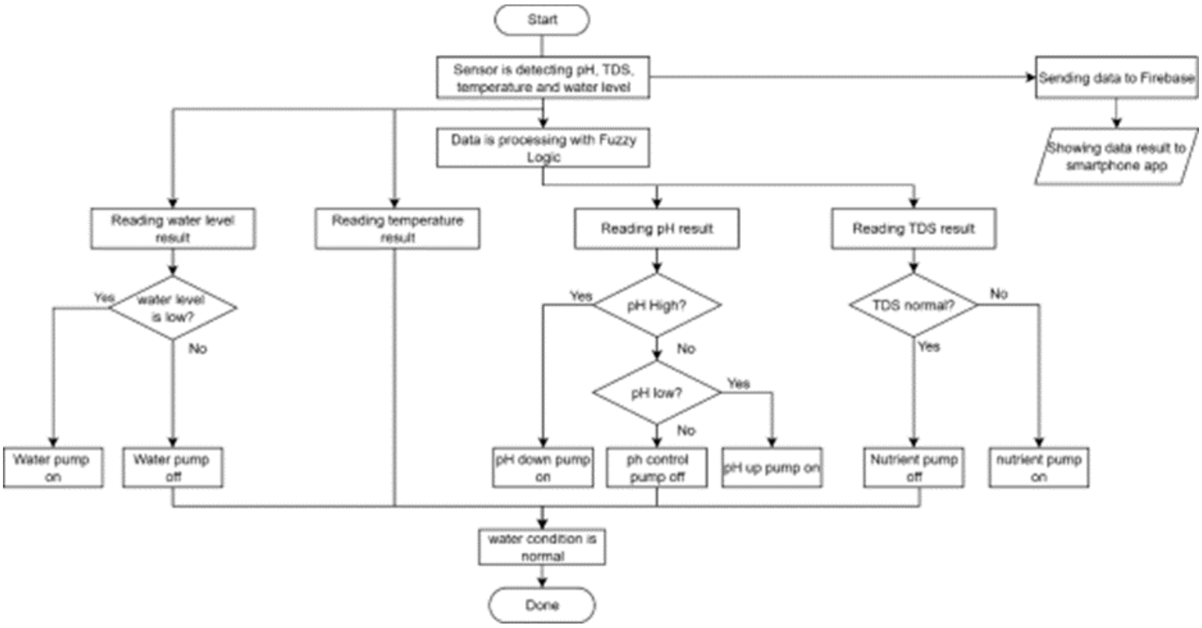
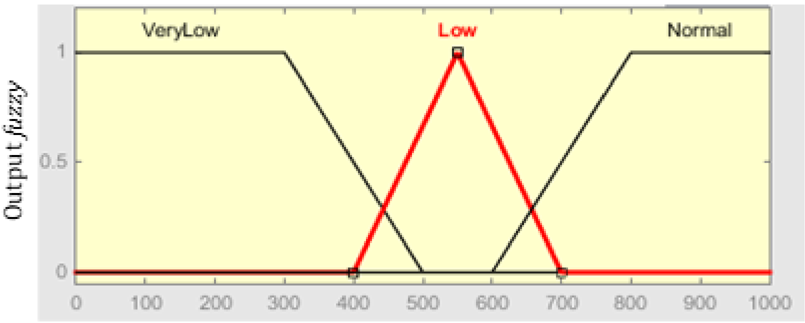


Figure 4. Flowchart of the system

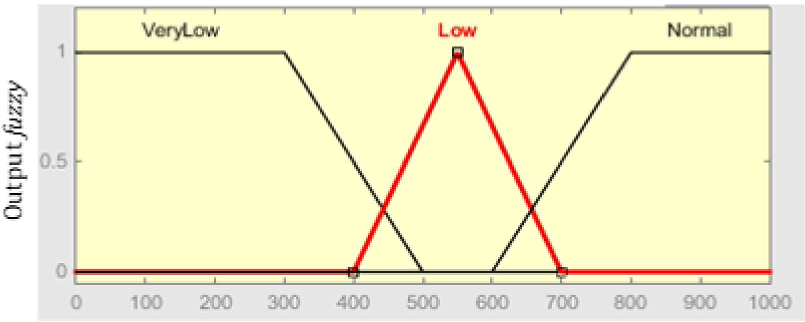
Results and Discussion

System Design Results

Fuzzy logic is implemented in the pH and nutrient control system for NFT hydroponic plants. The first step is fuzzification, which is mapping the crisp data into fuzzy sets presented in form of membership function. The system inputs for this fuzzy logic are pH and TDS values. There are five variables for pH linguistic function, very low, low, normal, high and very high. For TDS linguistic function, there are three variables, very low, low, and normal. The membership function diagrams for the pH and TDS inputs are shown in Figure 5.



pH (a)



TDS (PPM) (b)

Figure 5. Membership function diagram of fuzzy input: (a) pH, (b) TDS

The amount of solution given from each pump is determined through a defuzzification process based on fuzzy logic inference results. The membership function of these consists of three linguistic functions, off, medium and high. The membership function of the output for solution pumps is shown in Figure 6.

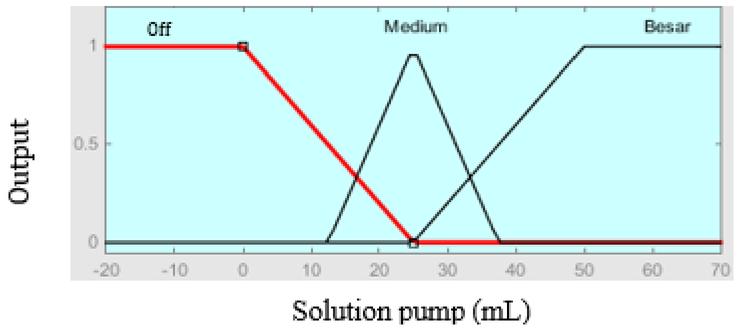


Figure 6. Membership function diagram of solution pump output

The next stage is inference. The fuzzy inference process for pH control uses pH input, with the output being pH control via pH up and pH down pumps. The pH fuzzy rules are presented as follows:

IF pH is very low THEN pH up pump is on at high setting.

IF pH is low THEN pH up pump is on at medium setting.

IF pH is normal THEN pH up pump AND pH down pump is off.

IF pH is high THEN pH down pump is on at medium setting.

IF pH is very high THEN pH down is on at high setting.

For TDS control, the input is TDS, while the output is nutrient pumps which is two solution A and B mix pumps working simultaneously, with the fuzzy rules show as follows:

IF TDS is very low THEN solution A pump AND solution B pump are on at high setting.

IF TDS is low THEN A pump AND solution B pump on at medium setting.

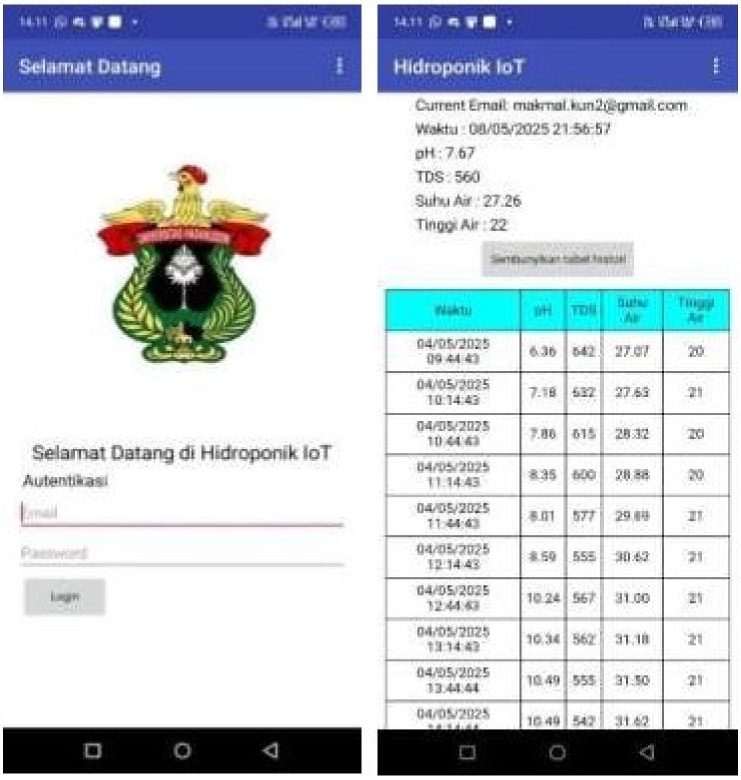
IF TDS is normal THEN A pump AND solution B pump off.

The last step is defuzzification. Defuzzification converts fuzzy inference result back into crisp number. Defuzzification process was performed using the centroid method. The fuzzy output parameter range is shown in Table 1.

Table 1. Fuzzy output parameter

Parameter	**Amount (ml)**
Off	0 - 25
Medium	12.5 - 37.5
High	25 - 50

Figure 7 shows the results of user application design using MIT App Inventor. On the front is a login screen which user should authenticate their email and password based on their authentication in Firebase. After that, the user is presented with the main screen that shows current status of the hydroponic system and its history every 30 minutes.



Selamat Datang di Hidroponik IoT

Autentikasi

Current Email: makmal.kun2@gmail.com

Waktu : 08/05/2025 21:56:57

pH : 7.67

TDS : 560

Suhu Air : 27.26

Tinggi Air : 22

Waktu	pH	TDS	Suhu Air	Tinggi Air
04/05/2025 09:44:43	6.36	642	27.07	20
04/05/2025 10:14:43	7.18	632	27.63	21
04/05/2025 10:44:43	7.86	615	28.32	20
04/05/2025 11:14:43	8.35	600	28.88	20
04/05/2025 11:44:43	8.01	577	29.69	21
04/05/2025 12:14:43	8.59	555	30.62	21
04/05/2025 12:44:43	10.24	567	31.00	21
04/05/2025 13:14:43	10.34	562	31.18	21
04/05/2025 13:44:44	10.49	555	31.50	21
04/05/2025	10.49	542	31.62	21

Figure 7. The interface of the IoT Hydroponics application on a smartphone

Sensors and Actuators Calibration result

pH sensor calibration is performed by comparing the pH sensor readings with a pH meter as a reference tool. Testing is conducted within a pH range of 3.75 to 10.49. The calibration process is performed by immersing the sensor and pH meter in test water, which is then gradually added with pH up and pH down solutions. The sensor output results in the form of voltage are shown in Figure 8.

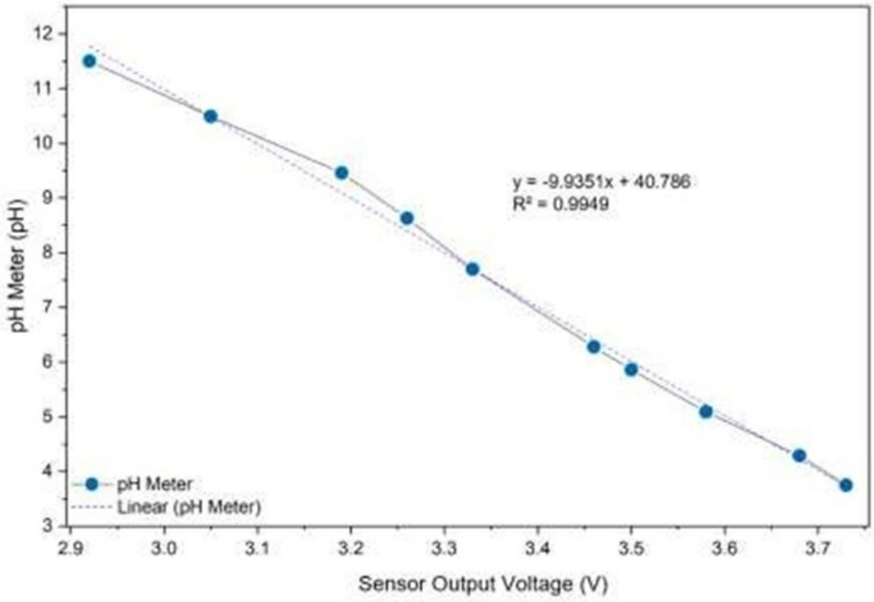


Figure 8. Calibration graph of the pH sensor in voltage units with a comparison tool

Figure 8 shows the graph of the initial calibration results of the pH sensor against the pH meter. A linear equation of y = -9.9351x + 40.786 was obtained with a coefficient of determination (R^2) of 0.9949. This equation is used to convert the sensor voltage value into a pH value. The calibration results graph after conversion is shown in Figure 9.

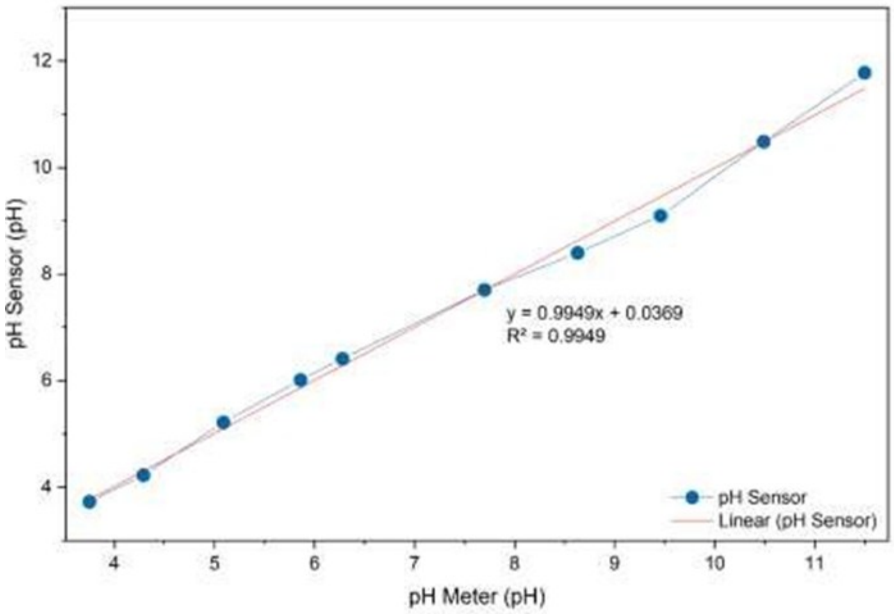


Figure 9. Calibration graph of the pH sensor with a reference device

Figure 9 shows the relationship between the pH value converted from the sensor and the pH value on the pH meter as reference device. The calibration result shows a linear equation y = 0.9949x + 0.0369 with an R^2 value of 0.9949. The average relative error percentage is 1.84% with an accuracy level of 98.16%. As a comparison, the results of the study by Pratama et al. (2025) show an accuracy level of 96.39%.

Calibration of the DS18B20 temperature sensor is performed by comparing the sensor readings with a standard thermometer. The sensor and thermometer are immersed in water, the temperature of which is adjusted gradually. The calibration results graph is shown in Figure 10.

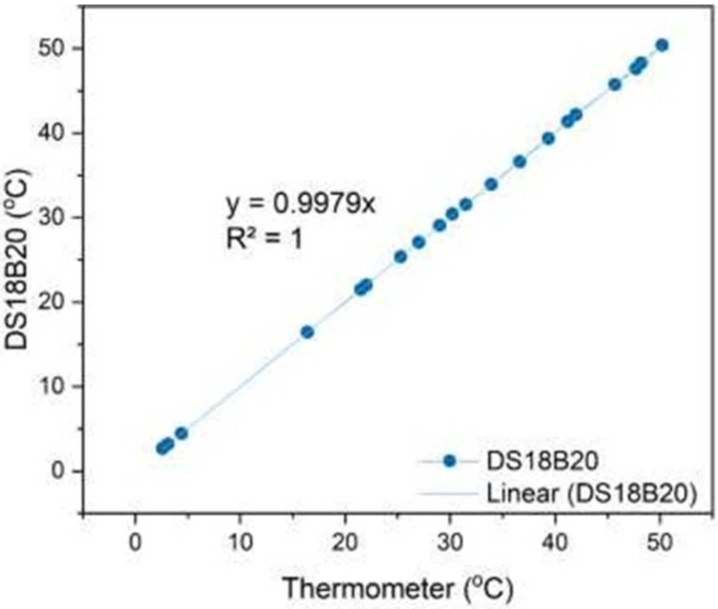


Figure 10. Calibration graph of the DS18B20 temperature sensor with a reference device

Figure 10 shows the relationship between the DS18B20 sensor value and value of the thermometer as reference device. The calibration result shows the equation y = 0.9979x and

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an R^2 value of 1. The average relative error is 0.55%, with an accuracy of 99.45%. These results are better than those by Pratama et al. (2025), which had an accuracy of 99.13%.

Gravity TDS sensor calibration was performed by comparing the sensor readings with those of a TDS meter. Since TDS measurements are affected by temperature, a DS18B20 temperature sensor was used for compensation (Toruan et al., 2023). Measurements were taken in the range of 10–1100 ppm. The sensor and TDS meter were immersed in a test solution containing AB mix nutrients in stages. The calibration results are shown in Figure 11.

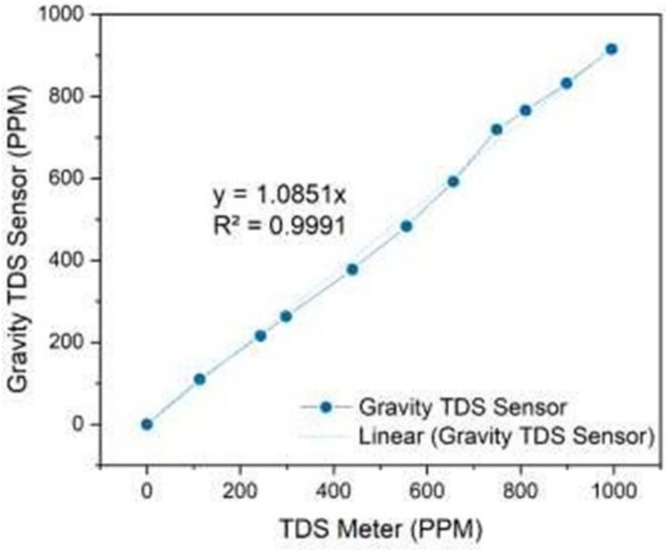

Figure 11. Calibration graph of the TDS sensor with a reference device

Figure 11 shows a relationship between the TDS sensor value and value of the TDS meter as reference device. The calibration result shows the linear equation y = 1.0851x with an R^2 value of 0.9991. The average relative error is 3.16%, with an accuracy level of 96.84%. In comparison, Sanjaya et al. (2024) reported an accuracy of 96.16%.

The HC-SR04 water level sensor was calibrated by comparing the sensor's measurements against a ruler. Testing was conducted within a range of 1–30 cm. The sensor was set parallel to the 0 cm mark on the ruler, and measurements were taken by adding 1 cm to the water level. The calibration results are shown in Figure 12.

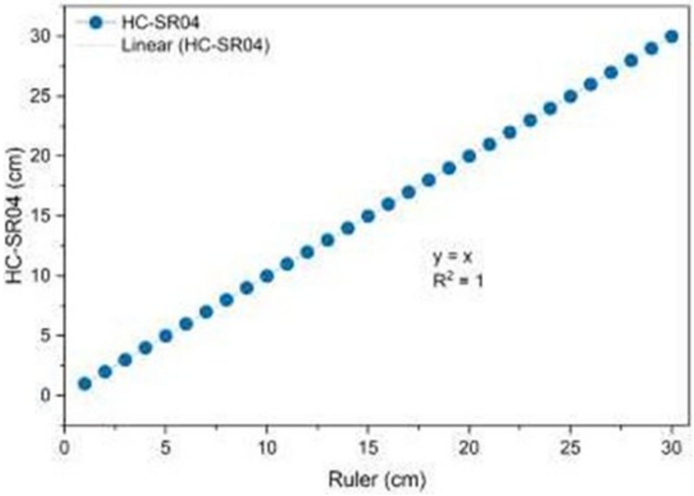

Figure 12. Calibration graph of the HC-SR04 water level sensor with a comparison tool

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Figure 12 shows relationship between the HC-SR04 sensor value and value of the ruler as reference device. The calibration result shows the linear equation y = x with an R^2 value of The average relative error is 0%, with an accuracy level of 100%. In comparison, Fiqar et al., (2023) reported an accuracy of 100%.

Actuator pump calibration aims to ensure that the volume of fluid discharged corresponds to the pump's operating time. The volume discharged is measured in milliliters (ml) based on the duration of pump operation. After calibration, the pumps show different duration in millisecond when pouring some amount of liquid in milliliter. The calibration results for the four pumps are shown in Figure 13.

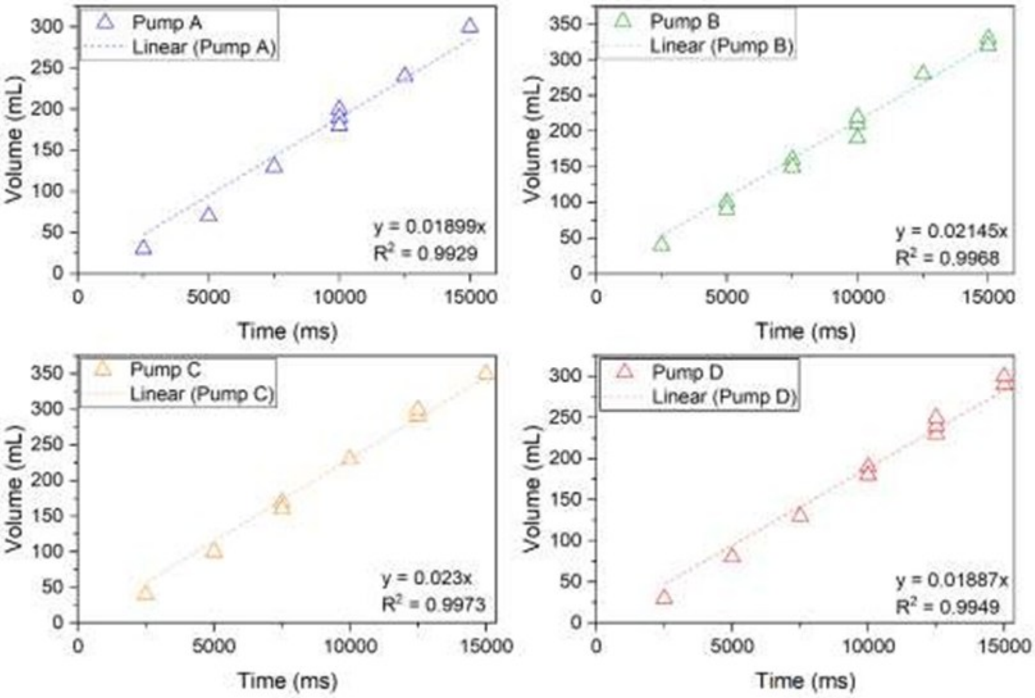

Figure 13. Calibration Results for Pump A, B, C, and D

Implementation Results

Data collection was conducted over three consecutive days with recording intervals of every 30 minutes. Implementation starts at 14.32 GMT+8. Parameter monitoring was carried out using an automated hydroponics user application developed using MIT App Inventor. The pH setpoint was set in the range of 5.5-7.5, while the TDS setpoint was set in the range of 600-800 ppm.

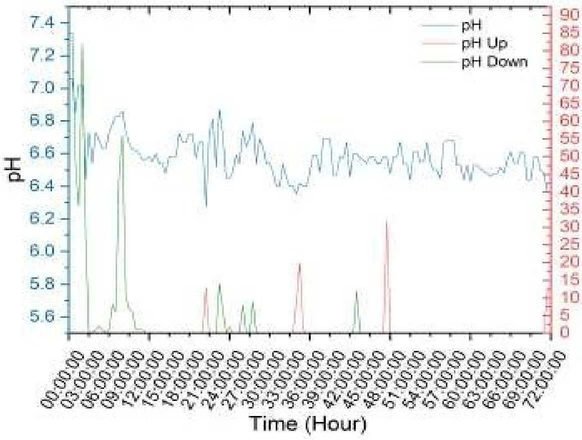

Figure 14. Data graphic of water pH level

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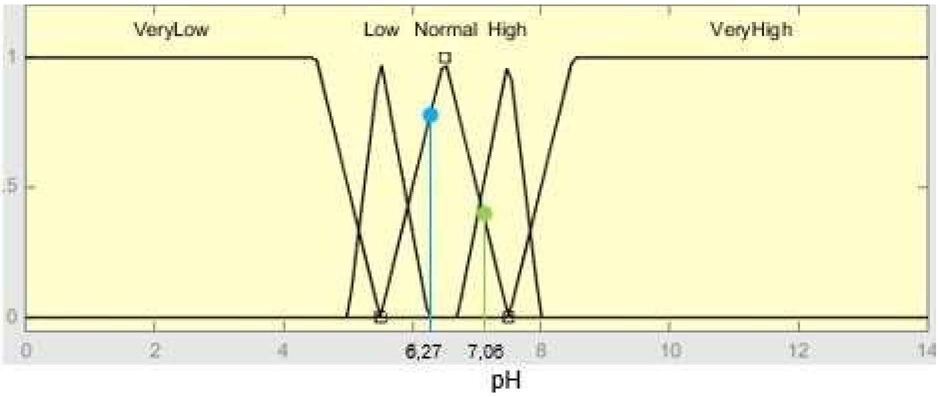

Figure 15. Fuzzy curve of pH levels over three days

Figure 14 shows a graph of hydroponic nutrient water pH measurements over three- day period. The measurement results show that the pH value ranged from 6.27 to

7.06. The total volume of pH Up liquid dispensed per 30 minutes was recorded between 0 and 32 ml, while the volume of pH Down liquid ranged from 0 to 85 ml. The fuzzy level pH curve recorded during this period is shown in Figure 16. This result shows that fuzzy logic method for pH control with 5 inference rules can control output value of pumps activation duration suitable with given input. The fuzzy control system instructs pH up pump when pH in solution tank is lower than defined pH value. The system also instructs pH down pump when pH in solution is higher than defined pH value.

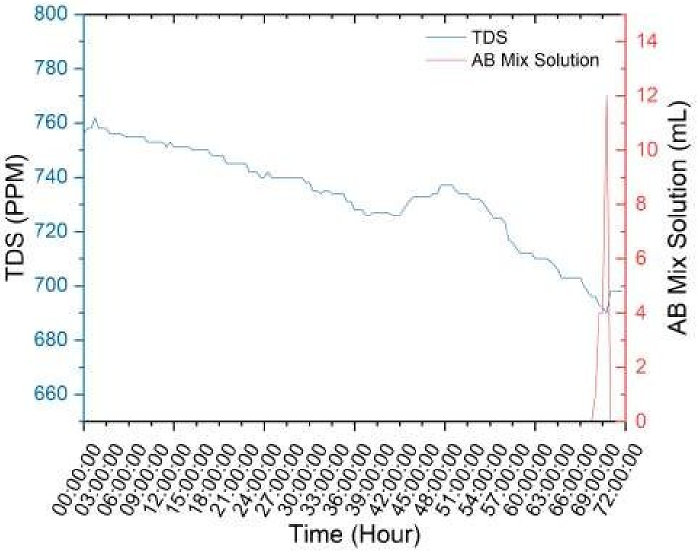

Figure 17. Data graphic of water TDS level

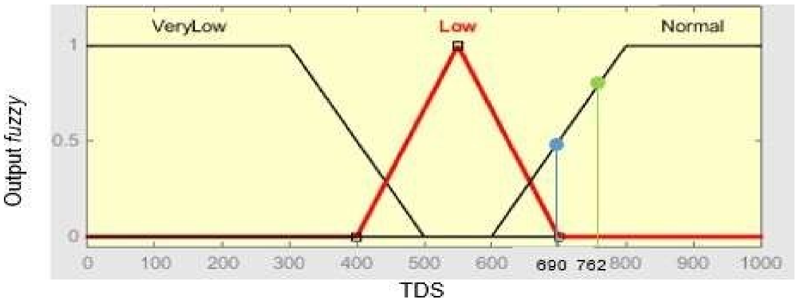

Figure 18. Fuzzy curve of TDS levels over three days

Figure 19 shows a graph of TDS measurements in nutrient water over three days. The recorded TDS values ranged from 690 to 762 ppm. The total amount of liquid added to increase the

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nutrient concentration was recorded at between 0 and 12 ml every 30 minutes. The fuzzy curve of the TDS level during the observation period can be seen in Figure 20. This result shows that fuzzy logic method for TDS control with 3 inference rules can control output value of pumps activation duration suitable with given input. The fuzzy control system instructs A and B mix pumps when TDS in solution tank is lower than defined TDS value.

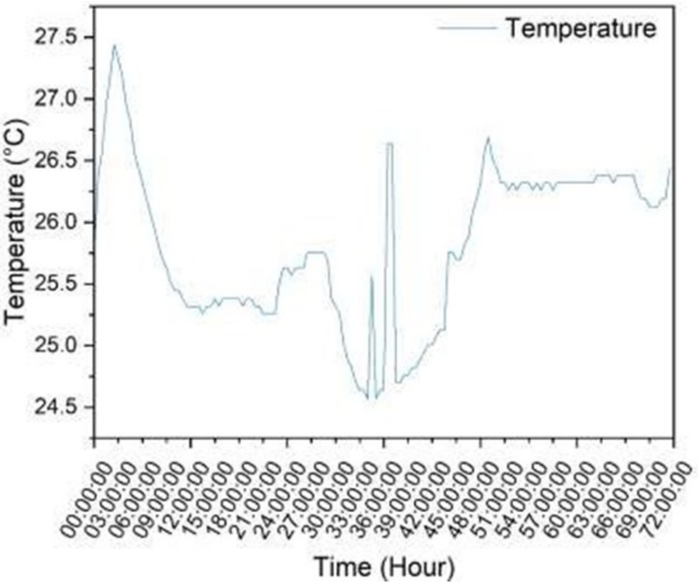

Figure 21. Data graphic of water temperature

Figure 22 shows a graph of hydroponic nutrient water temperature measurements over three days. The recorded temperature range was between 24.57°C and 27.44°C. During the measurement, two abnormal temperature spikes were recorded in the early hours of the morning, between 01:02 GMT+8 and 03:32 GMT+8. This was due to a temporary sensor error that caused measurement errors.

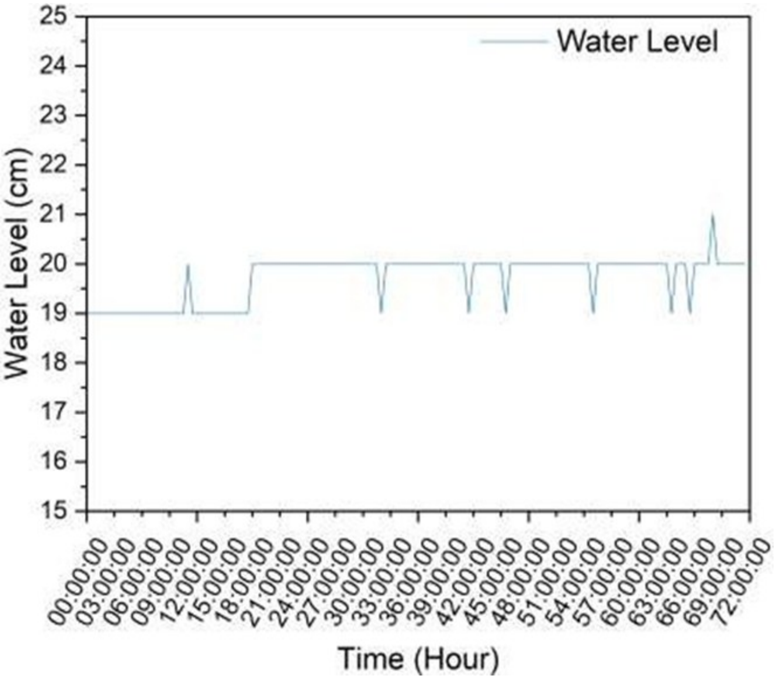

Figure 23. Data graphic of water level

Figure 24 shows a graph of water level measurements in the hydroponic system over three days. The recorded water level ranged from 19 to 21 cm. During implementation, the water

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of the nutrient tank raised slightly due to added pH control and AB Mix solutions to the tank. There is no noticed reduction of the water during implementation.

Conclusion

This research was conducted to design an automatic nutrient control for NFT hydroponic system that uses fuzzy logic controller and IoT integration. The system effectively monitored and controlled key parameters including pH, TDS, temperature, and water level. Fuzzy logic enabled adaptive regulation, while IoT technology provided real-time monitoring and control via a mobile application. The results confirmed that the system can maintain stable hydroponic conditions, making it suitable for modern precision agriculture applications

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