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Design And Implementation Of Fuzzy Logic Based Automatic Hydroponic System With Adaptive Control Based On Plant Type And Age

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ABSTRACT

Hydroponic systems have gained popularity in modern agriculture for their effectiveness. Precise and consistent control of water and nutrients, however, remains a challenge, and it is critical for the growth and yield of the plants. Nutrient control in manual hydroponic systems cannot change based on the different stages of plant growth, and therefore is susceptible to delivery errors. In order to solve these issues, this research aims to design and implement a hydroponic system with two modules: automation and adaptation based on fuzzy logic depending on plant age and type. This system combines time scheduled controller, control based on rules, and fuzzy logic to automate microcontroller based systems for nutrient adjusting of hydroponics systems. TDS, tempertature, and pH sensors provide real-time data which is processed using fuzzy inference system taking into account plant type and age. Experimental results demonstrated the learning capability of the system to sustain the nutrient levels within the set optimal threshold, while realizing a high degree of autonomy as a result of automated control. This proves that the applied adaptive control responds well to dynamic changes in the environment and the developmental stages of the plants, thereby enhancing robust plant growth and efficient maintenance.

1. INTRODUCTION

Background

The advantages of hydroponic system are particularly apparent when evaluated interm of its efficiency in the usage of water and land. This method is known increasingly among the public as a modern cultivation system. However, there several challenges remain in hydroponic system. especially, maintaining nutrient and water management to support optimal plant growth. If the application of nutrient solutions are given in incorrect dosages, it can negatively impacts plant development process. Also, poorly controlled environments, such as stagnant water and unmonitored levels of dissolved oxygen lead to water stress, which lowers productivity [1, 2]. These limitations are associated with automated systems relying on human controllers can worsen nutrient management problems [3].

Automatic control designed through algorithms alongside data structures would serve as the most effective solution to these challenges. Integrated adaptive and time-controlled monitoring and provisioning of nutrients and water utilizes time-based control algorithms, rule-based systems, and fuzzy logic. Algorithms based on time control offer the capability of systematic operation scheduling, and rule-based systems execute control as a reaction to the output provided by the sensors. Fuzzy logic handles the uncertainty and variability of the sensor data, in this case, total dissolved solids (TDS) and pH, and retroactively adjusts nutrient level changes based on the plant's age without overly relying on complex historical data [4]. Rapid responses to environmental changes can be achieved by real-time computation and efficient data structure storage of sensor data.

A microcontroller-based automation system has been developed to combine combine TDS , Temperature, RTC and Ph sensors to monitor and manage nutrient. sensors to monitor and manage nutrient. The results from the fuzzy logic processing are applied to automatically control pumps that instantly adjust the concentration of nutrients within the solution. Aerators commonly used in aquariums are effective at maintaining adequate oxygen levels, which is critical for root development and the absorption of nutrients in plants [5]. By managing nutrients, this system optimally and sustainably drives the growth of hydroponic plants, reduces manual intervention, and greatly enhances yield.

Problem Formulation

1. How to implement fuzzy logic to regulate plant nutrient requirements based on Sensor parameters and plant age?
2. How effective is the fuzzy logic method in maintaining the stability of nutrient concentration in real-time to support optimal growth of hydroponic plant growth?
3. How to develop a hydroponic automation system based on microcontroller that is able to automatically control the delivery of nutrients without manual intervention?

Scope

This research focuses on the development of an automatic hydroponic system capability of adapting to the age and type of plants. The system is designed to autonomously regulate nutrients delivery based on real time TDS measurements since the plants were planted. Adaptation is achieved through a combination of time-based, rule-based, and fuzzy logic which operate in real time without using historical data. the microcontroller is used as the main control unit, supported by sensors TDS, pH, as well as actuators such as nutrient pumps.

The research focuses on hydroponic varieties of leafy vegetables, specifically pakcoy and lettuce. The system is designed to meet the requirements of each type, through adjustable fuzzy parameters. This study does not focus on the algorithms performance in terms of their computational efficiency or processing speed, or does it cover the automatic control of external environmental factors such as light, temperature, and humidity. The assessment of the system was carried out with an emphasis on the stability of nutrients, as well as the system's capacity to adapt to the different plant growth stages, rather than focusing on large-scale overall production.

Objective

Objective of this research is to devise an automated hydroponic cultivation system that is powered by a microcontroller. The system is capable to autonomously regulates the nutrient distribution , without manual intervention. Decision making is implemented through a fuzzy logic control which is applied in the microcontroller. With this approach, the system is expected to ensure stable nutrient conditions, improve effectiveness, and support optimal growth of plants.

Literature Study

Modern hydroponic systems are gaining increasing attention due to their ability in optimizing land use and improving agricultural productivity. In recent years, studies have focused on the automation and monitoring of hydroponic cultivation using microcontroller based, frequently integrated with intelligent control. Sneineh and Shabaneh [1], developed an ESP32 based hydroponic monitoring system capable of collecting environmental and water quality parameters. Despite its effectiveness in data acquisition, the system does not implement adaptive control strategies that consider plant age or different growth phases

Duangpakdee et al. [4] introduced an enhanced deep water culture (DWC) system using IoT technology to optimize the yield of Chinese celery. However, this system still employs a fixed control schedule and lacks dynamic adjustment of nutrients or pH levels based on the changing needs of plants. A comparable limitation is also found in the work of Kushawaha et al. [5], who developed a compact smart hydroponic system for household use. Although equipped with environmental sensors, the system does not utilize adaptive algorithms that consider plant type or age.

Hariono and Fanani [6] developed an automatic nutrient regulation system driven by a microcontroller and TDS sensor. Although the system shows potential in maintaining nutrient concentration levels, it does not address pH regulation and does not adapt to the plants growth cycle. In contrast, Nguyen et al. [3] presented an IoT-based monitoring system integrating multiple sensors to observe environmental conditions. However, the system primarily functions as a monitoring tool and provides limited autonomous control, requiring manual intervention when sensor values fluctuate.

Al Hakam and Puriyanto [7], implemented an automatic nutrient refill mechanism based on water level and TDS measurements. While this approach improves solution consistency, it does not incorporate plant growth awareness or pH control. Likewise, Prathap et al. [2] developed an automated nutrient dosing unit. however, the system does not employ fuzzy logic, pH regulation, or plant growth-stage consideration.

From a biological perspective, Baharrudin et al. [8] highlighted the importance of consistent nutrient in achieving optimal growth of Pakchoy (Brassica rapa L.), although their study did not utilize automation system. Baiyin et al. [9] investigated the effect of aeration intensity on nutrient uptake and demonstrated that adequate oxygenation enhances plant growth. Nevertheless, their experimental setup lacked automation and real time regulation. Morchid et al. [10] implemented a fuzzy logic based irrigation system supported by IoT and cloud computing for adaptive water management. While effective for irrigation control, the system does not address the complete hydroponic nutrient management process, particularly pH regulation and plant growth stage adaptation.

In addition, Studies has shown that The higher the temperature, the higher the electronic conductivity and TDS values due to greater ion mobility. Experiment confirms a strong correlation between temperature, EC, and TDS [11], highlighting the importance of temperature monitoring and control to maintain optimal nutrient conditions in automated hydroponic systems.

So far, many studies have successfully introduced automation into hydroponic systems, they focus on specific components such as TDS monitoring, water refill control, or fixed schedule dosing. Most do not incorporate adaptive systems that adjust nutrient and water delivery based on plant type and age. Furthermore, few systems integrate pH sensors for real-time regulation, despite the critical role of pH in nutrient availability and plant health.

This research aims to fill these research gaps by developing a fuzzy logic based hydroponic automation using microcontroller. The system integrates TDS, pH, and actuators such as nutrient pumps. It uses a combination of time based, rule based, and fuzzy logic control techniques to regulate nutrient solution delivery dynamically. The plant's age, type (specifically Pakchoy and lettuce), and sensor readings will serve as input to the fuzzy inference system. The rule base will be configured using ideal ranges, with TDS levels maintained with a concentration of 700 ppm for the first two weeks and 1,200 ppm for the next two weeks for pakcoy [8], and for lettuce the nutrient solution is adjusted according to plant age: days 3–10: 200–400 ppm, days 11–20: 400–500 ppm, and days 21–35: 500–700 ppm [12], ensuring optimal nutrient availability for different growth stages.

By integrating adaptive control, this research contributes to the development of a more intelligent, sustainable, and efficient hydroponic system. It builds upon prior works such as those by Sneineh and Shabaneh [1], Hariono and Fanani [6], and Baharrudin et al. [8], but adds novel functionality through plant stage based fuzzy regulation and multi parameter integration that is yet to be fully realized in previous studies.

2. Research Methodology

Methodology

In conducting the development of the hydroponic automation system, this study follows a pipeline illustrated in Figure 3.1 There are several major stages in the process: system initialization, plant selection, sensor reading, fuzzy logic-based decision-making, and action

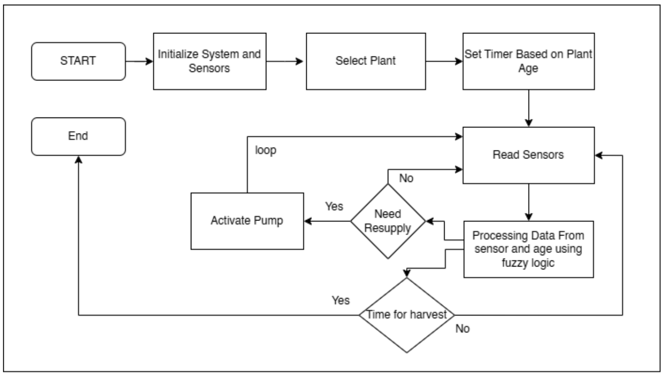

Figure 1. Research Methodology

This research begins with the initialization of the system and sensors, where the microcontroller is connected to several sensors. This first process is ensures that the components are working properly. Once the system is ready, the next steps is selecting plant types, which is selected through the keyboard user interface. This selection determines the ideal parameters according to plant type.

This study uses a Sugeno inference system, which is well suited for automatic control applications. In this approach, each fuzzy rule produces a numeric output, which is generally expressed as a constant value or a linear function.The fuzzy logic processes data through the following steps:

1. Fuzzification: Converts numerical values (TDS, plant age) into linguistic variables such as "low", "medium", or "high".
2. Rule Evaluation: Applies fuzzy rules IF THEN rules, such as:
   - IF TDS is low AND plant age is mature THEN nutrient pump duration is long.
   - IF water level is low AND plant age is young THEN water pump is activated briefly.
3. Inference: The Sugeno method is used to calculate the inference results, with each rule producing different weighted output.
4. Defuzzification: converting fuzzy inference results into numerical output, which directly determines the pump running time.

The prototype only activates the nutrition pump when fuzzy logic result indicates the need for adjustment. when fuzzy logic does not produce any output, the system only do monitoring. This approach adaptive control than conventional methods, which is beneficial for:

- Managing nonlinear nutrient requirements as plants grow.
- Reducing the risk of over or under dosing.
- Handling sensor noise or environmental fluctuations.

At the final evaluation stage, the system checks the current plant age against the ideal harvest duration based on the plant type. Through the Sugeno fuzzy inference method, this research aims to create an adaptive hydroponic control system, compared to those which only rely on static rules or fixed timers.

Dataset Collection

The data used in this research was manually obtained from the automation system every day, except weekend(Saturday&Sunday). All meausurement were obtained from sensor output. The recorded Parameters included pH, water temperature, Total Dissolved Solids (TDS), and the remaining nutrient, and data was collected once daily.

Data Pre-Processing

To evaluate the accuracy of the control system, the parameter used is the deviation between the actual tds value and the set tds value. Deviation is calculated using this following equation:

$$\boldsymbol{Di = PPMi - Si}$$

$\boldsymbol{Di}$ = Deviation on day-i (PPM)

$\boldsymbol{PPMi}$ = Actual Measurement Value (PPM)
$\boldsymbol{Si}$ = Set point Value (PPM)

To determine the stability level of the system during a testing period, the min and max deviation values are used:

$$\boldsymbol{Dmin} = min(\boldsymbol{D1}, \boldsymbol{D2}, \dots, \boldsymbol{Dn})$$
$$\boldsymbol{Dmax} = max(\boldsymbol{D1}, \boldsymbol{D2}, \dots, \boldsymbol{Dn})$$

$\boldsymbol{Dmin}$ value indicates the smallest deviation from setpoint, while $\boldsymbol{Dmax}$ indicates the largest deviation during test period.

Implementation

This stage covers the integration of hardware components,fuzzy logic algorithm, and data communication mechanisms between two microcontroller to ensure the accuracy of nutrient regulation and monitoring. First, the microcontroller and sensors are initialized to eensure the components are functional and ready for operation. Once the system is set up, the user selects the plant type via the LCD to see the plants option and keypad to chose plant type, and the system will run according to the type of plant that we chose before which sets the ideal parameters.

The collected data is processed using a Sugeno-type fuzzy inference model to determine the appropriate pump activation duration. During this process, numerical inputs such as TDS and crop age are converted into linguistic variables (fuzzification), evaluated based on predefined IF THEN rules, and then converted into a weighted output (inference). The final crisp output (defuzzification) directly determines the operating time of the nutrient or water pump. Based on the fuzzy output, the both pump for nutrient A and B will turned on.

Result

Table 1. Lettuce observation Data

Day	Date	Temp	pH	Tds(PPM)	Nutrient A	Nutrient B
1	Selasa, 28 Oktober 2025	28°C	6	407	518 ML	518 ML
2	Rabu, 29 Oktober 2025	28°C	6	404	517 ML	517 ML
3	Kamis, 30 Oktober 2025	28°C	7	405	515 ML	515 ML
4	Jumat, 31 Oktober 2025	28°C	6	405	514 ML	514 ML
5	Sabtu, 01 November 2025	Weekend	Weekend	Weekend	Weekend	Weekend
6	Minggu, 02 November 2025	Weekend	Weekend	Weekend	Weekend	Weekend
7	Senin, 03 November 2025	28°C	6	407	509 ML	509 ML
8	Selasa, 04 November 2025	28°C	7	407	507 ML	507 ML
9	Rabu, 05 November 2025	28°C	7	407	505 ML	505 ML
10	Kamis, 06 November 2025	28°C	6	415	500 ML	500 ML
11	Jumat, 07 November 2025	28°C	7	528	490 ML	490 ML
12	Sabtu, 08 November 2025	Weekend	Weekend	Weekend	Weekend	Weekend
13	Minggu, 09 November 2025	Weekend	Weekend	Weekend	Weekend	Weekend
14	Senin, 10 November 2025	28°C	7	682	450 ML	450 ML
15	Selasa, 11 November 2025	28°C	6	632	450 ML	450 ML
16	Rabu, 12 November 2025	28°C	6	632	450 ML	450 ML
17	Kamis, 13 November 2025	27°C	7	639	450 ML	450 ML
18	Jumat, 14 November 2025	26°C	7	630	450 ML	450 ML
19	Sabtu, 15 November 2025	Weekend	Weekend	Weekend	Weekend	Weekend
20	Minggu, 16 November 2025	Weekend	Weekend	Weekend	Weekend	Weekend
21	Senin, 17 November 2025	30°C	7	634	450 ML	450 ML

According to the results of lecctuce plants observation data for about 21 days, from day 1 to day 10 the set ppm value ranging from 200 to 400 ppm, the difference between the actual value and the set value was in the range of 4 ppm to 15 ppm. however, during day 11 to day 21, with a set value of 400-500 ppm, the difference between the actual value and the set value ranged from 28 ppm to 182 ppm. Furthermore, observations over a period of approximately 21 days showed a gradual reduction in the volume of nutrients A and B. This decrease indicates that the nutrients were used by the system during process.

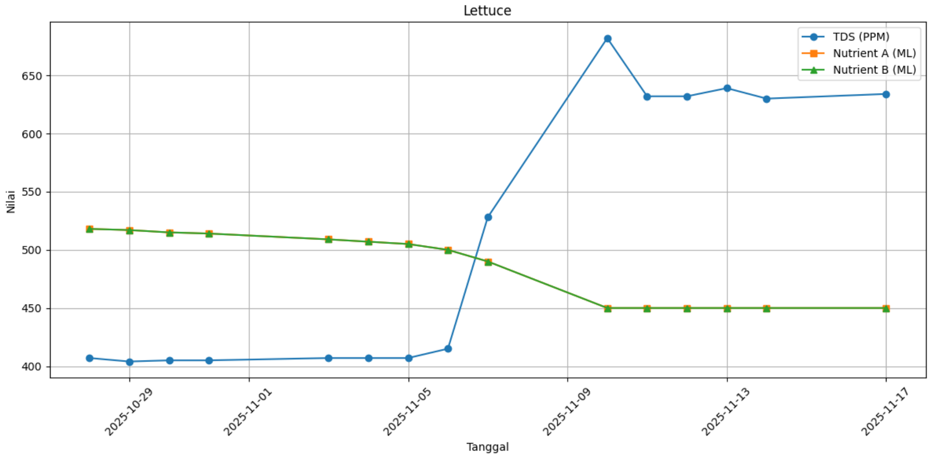

Figure 2. Relationship between the increase in TDS (PPM) values and the decrease in nutrient volume during the Lettuce observation period.

According to measurement data, the nutrient volume decreased from 518 mL to 450 mL. This shows that the system is able to distributing nutrients according to plant needs. Therefore, it can be concluded that the nutrient delivery mechanism in the system works well and is directly proportional to the downward trend in nutrient volume and the increase in PPM value, as shown in Figure 2.

Table 2. Pakcoy Observation Data

Day	Date	Temp	pH	Tds(PPM)	Nutrient A	Nutrient B
1	Sabtu, 22 November 2025	Weekend	Weekend	Weekend	Weekend	Weekend
2	Minggu, 23 November 2025	Weekend	Weekend	Weekend	Weekend	Weekend
3	Senin, 24 November 2025	29°C	-6	701	470 ML	470 ML
4	Selasa, 25 November 2025	27°C	8	731	470 ML	470 ML
5	Rabu, 26 November 2025	29°C	6	701	470 ML	470 ML
6	Kamis, 27 November 2025	31°C	5	730	470 ML	470 ML
7	Jumat, 28 November 2025	32°C	6	743	470 ML	470 ML
8	Sabtu, 29 November 2025	Weekend	Weekend	Weekend	Weekend	Weekend
9	Minggu, 30 November 2025	Weekend	Weekend	Weekend	Weekend	Weekend
10	Senin, 01 Desember 2025	29°C	6	724	470 ML	470 ML
11	Selasa, 02 Desember 2025	25°C	5	1190	450 ML	450 ML
12	Rabu, 03 Desember 2025	29°C	5	741	450 ML	450 ML
13	Kamis, 04 Desember 2025	26°C	5	726	450 ML	450 ML
14	Jumat, 05 Desember 2025	27°C	6	713	450 ML	450 ML
15	Sabtu, 06 Desember 2025	Weekend	Weekend	Weekend	Weekend	Weekend
16	Minggu, 07 Desember 2025	Weekend	Weekend	Weekend	Weekend	Weekend
17	Senin, 08 Desember 2025	29°C	6	1046	430ML	430ML
18	Selasa, 09 Desember 2025	28°C	6	1157	420ML	420ML
19	Rabu, 10 Desember 2025	28°C	6	1373	400ML	400ML
20	Kamis, 11 Desember 2025	33°C	5	1288	400ML	400ML

Based on pakcoy observations data over a period of 20 days, during the period from day 1 to day 10 with a set ppm value of around 700 ppm, the difference between the actual PPM value and the set value was 1 to 43 ppm. This shows that the system is able to maintain nutrient concentrations with relatively small and stable deviations. Conversely, during the period from day 15 to day 20 with a set value of 1200 ppm, the difference between the actual PPM value and the set value was 43 ppm, while the maximum deviation reached 173 ppm. Meanwhile, the gradual decrease in the volume of nutrient A and nutrient B and the increase in TDS (PPM) values indicate that the nutrients are being used by the system while the process is still ongoing.

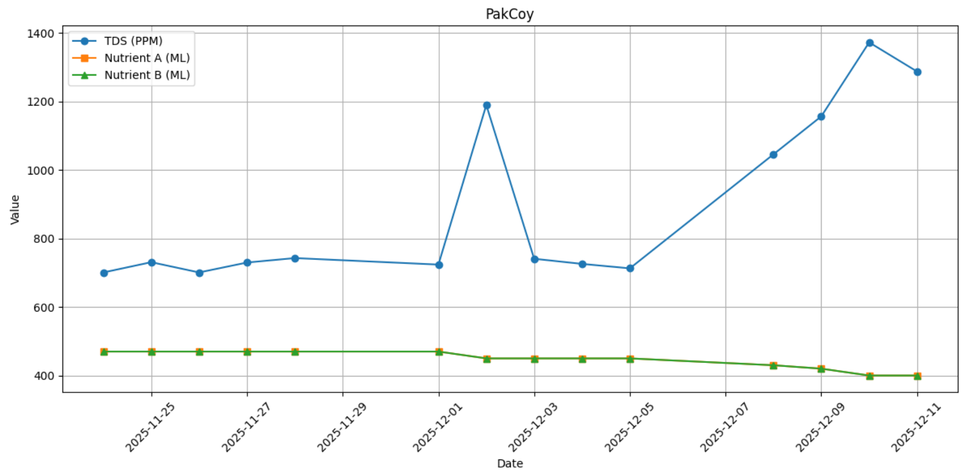

Figure 3. Relationship between the increase in TDS (PPM) values and the decrease in nutrient volume during the Pakcoy observation period.

Similar to the results shown in **Figure 2**, Measurement data shows that the nutrient volume decreased from 500 mL to 400 mL. This trend indicates that the system consistently distributes nutrients according to plant needs. Thus, it can be concluded that the nutrient delivery mechanism in the system works well and that there is a direct correlation between the decrease in nutrient volume and the increase in PPM value, as shown in **Figure 3**.

Discussion

Based on the testing conducted on two types of plants, the fuzzy logic-based hydroponic automation system demonstrated quite good performance and was able to adjust nutrient delivery according to plant age. During the testing process, TDS values changed dynamically depending on environmental conditions and the plant's growth phase. The system responded to the changes by activating the nutrient pump according to the result of fuzzy output.

For lettuce, Table 4.1 shows that the system operated pretty good within the established parameters for the first eleven days. However, temperature data from Day 1 to Day 16 were not recorded. Therefore, an imputation process was performed using the average temperature values from Days 17, 18, and 21 which are available, resulting in an estimate of 28°C. This average imputation method was chosen because the hydroponic system was placed outdoors but protected by UV plastic, so maintaining a relatively stable microenvironment with minimal temperature fluctuations.

Furthermore, nutrient distribution had been carried out since first planting, nutrient concentrations were only recorded starting from Day 9. To fill the missing data on Days 1–8, linear regression was performed using the TDS value and planting day as predictors. This method was chosen based on the observed linear relationship in the early growth phase, in line with the increase in TDS along with a decrease in the volume of nutrient addition to the system.

On the 14th day, a temperature sensor malfunctioned, preventing any data from being recorded. This resulted in abnormal calculations of nutritional parameters because the algorithm did not receive a valid temperature value. After maintenance and replacing the sensor, the system returned to normal operation and the temperature readings became accurate, and after the disruption, the water in the system was neither reduced nor recirculated.

for pakcoy plants , the system managed to maintain an average TDS value of close to 700 ppm in the first two week, but there were several problems with the hardware that caused errors such as on the after the sensor was replaced the pH reading on the next day was normal at 5-6 as in Table 4.2. Additionally, other errors were also observed. On Day 11 (Tuesday, December 02, 2025), the temperature and pH measurements were recorded normally at 25°C and pH 5. However, an anomaly occurred in the TDS reading using the primary TDS sensor. The sensor produced two inconsistent values, 119 ppm and 258 ppm, indicating unstable measurement results and not reflecting the typical nutrient concentration for the early vegetative stage in hydroponic systems.

To ensure data accuracy, a cross-check was performed using an external TDS meter, which showed a value of 1190 ppm. This significantly higher result is considered more valid and logical, supported by a noticeable reduction in the nutrient solution volume inside the reservoir, which indicates an increase in nutrient concentration. Therefore, the TDS value used for analysis on Day 11 is 1190 ppm, as it more accurately represents the actual nutrient condition of the pakcoy hydroponic system.

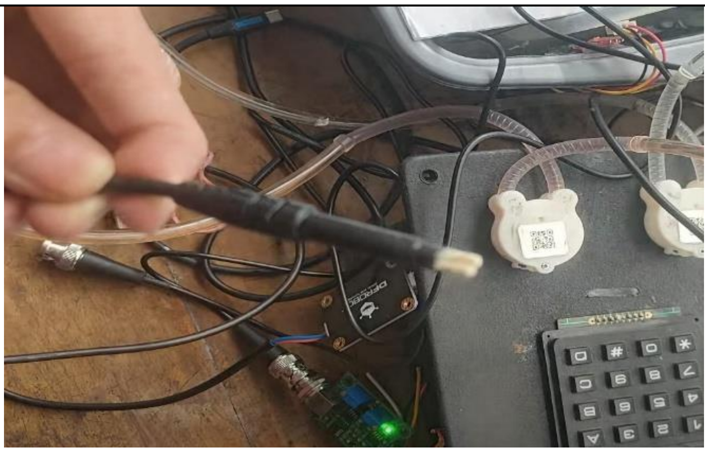

Figure 4. Accumulation of mineral and nutrient deposits on the probe surface.

To ensure the accuracy of sensor reading, regular maintenance was carried out on Ph and Tds Sensor . especially for Tds Sensor, recalibrated at least once every two weeks to ensure the measured values remained close to actual condition. Additionaly, the probe were cleaned regularly as long term use can lead to crystallization caused by mineral build up on the probe surface. This accumulation can potentially to reduce sensor sensitivity, leading tp deviations in measurement results. Through scheduled and continuous maintenance, the reliability of sensor readings and the stability of the nutrient control system can be maintained during the cultivation period.

However, the system still has limitations, particularly in storing plant growth day data and the type of crops being cultivated. When a power outage occurs, this information is not stored in the system, requiring the system to be reconfigured when power is restored. This condition can impact the continuity of the nutrient control process and requires manual intervention to ensure that the system return to operating normally with the correct parameters. Therefore, further development is needed to enable the system can store data in non volatilely memory and retain critical information even of a power outage.

Conclusion

The conclusion of this study show that the development of fuzzy logic–based hydroponic automation system successfully achieved its primary objectives, namely to automatically controlling nutrient levels based on TDS sensor readings and Plant ages, also provide a user interface that facilitates monitoring and selection of plant type which enable. The system performance showed promising results. For lettuce deviation between actual PPM and the setpoint during Days 1–10 ranged from 4 ppm to 15 ppm, during Days 11–20 with a setpoint of 400–500 ppm, the deviation increased to 28 ppm–182 ppm. for pakcoy, during the initial phase with a setpoint of approximately 700 ppm, the deviation ranged from 1 ppm to 43 ppm, demonstrating stable control. In contrast, during Days 15–20 with a setpoint of 1,200 ppm, the deviation increased to 43 ppm–173 ppm. Overall, the system performs more reliably at lower setpoints, while higher setpoints require further optimization to improve stability and accuracy.

This study still has chance for further research, such as integration of data storage mechanisms or IoT connectivity to ensure realtime information continuity which can be accessed from anywhere , as well as a more compact device design to simplify maintenance, and under various conditions. With these improvements, the system has potential to become more effective, reliable, and easy to implement hydroponic automation solution for both household and commercial scales, and can support more efficient and modern cultivation practices.

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