Journal of Engineering Research and Education
Volume 17, 2025 [154-168]

Enhanced Hydroponic Nutrient Dosing Control System Using Consensus Method Combining PID and Fuzzy Logic

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ABSTRACT

Agriculture is important in Malaysia to ensure food security and prevent shortages. Hydroponic systems, present a viable solution to enhance agricultural productivity and sustainability. Conventional hydroponic systems face challenges such as time delays in nutrient concentration adjustments and the risk of nutrient concentration overdose. the paper aims to investigate the performance of the dosing system for four different control systems: proportional-integral-derivative (PID) control, fuzzy logic control, and a consensus control algorithm. This work utilizes Electrical Conductivity (EC) sensors and a NodeMCU 32 microcontroller to monitor and manage nutrient levels in the hydroponic solution. The data from the sensor is transmitted to the microcontroller and stored in an MSSQL database. This data is subsequently downloaded for analysis. The performance of these four control systems is investigated through the comparative evaluation of two key parameters, the step for nutrient concentration to reach the setpoint and the overshoot of EC values. The results reveal that the consensus algorithm gives the most optimum time to reach the setpoint and the overshoot of the EC value.

Keywords: PID, Fuzzy, Consensus Algorithm, Nutrient Concentration, Hydroponic

1. INTRODUCTION

As of December 2023, the global population stands at around 8 billion. The United Nations forecasts that this number will rise to 9 billion by 2037 [1]. The latest United Nations data shows that Malaysia's population is estimated at 34.5 million as of January 2024. The increasing world population will become an issue of food deprivation [2]. The swift population growth will result in a 70% to 100% increase in food demand by 2050 [3]. Transforming Malaysia's agricultural sector to meet the rising food demand and ensure long-term food security for future generations is essential.

Emphasizing sustainable food production is a global concern as one of the United Nations' Sustainable Development Goals (SDGs) is to achieve zero hunger by 2030 [4]. To achieve these goals, it is necessary to boost food production by incorporating modern agricultural techniques, such as hydroponic farming with the Internet of Things (IoT).

In the hydroponic, plant nutrients are one of the important factors that need to be considered, as these factors are important for the reproduction and growth of the plant [5]. Monitoring and controlling the nutrient concentration is important in a hydroponic system as different levels of nutrient concentration are required for each type of hydroponic [6]. The hydroponic system frequently encounters significant challenges, including excessive overshooting of nutrient concentrations and long delay time for nutrient concentration to reach the desired nutrient levels, which can lead to nutrient imbalances and toxicity [7].

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Advanced control systems provide solutions to overcome the limitations of conventional hydroponics and basic IoT integration. This paper aims to develop a comprehensive framework for monitoring and controlling the fertilizer system in hydroponic cultivation using an advanced control system. By utilizing a mobile web application or web-based platform, users can actively monitor and control the Electrical Conductivity (EC) value of the plants. Data collected from IoT devices and sensors is processed through a model and algorithm known as the control system [8]. In this paper, a closed-loop algorithm is used, incorporating a hybrid approach of fuzzy logic and Proportional-Integral-Derivative (PID) control techniques called a Consensus algorithm.

2. RELATED WORK

2.1 Nutrient Management in Hydroponic

Hydroponic is a method of cultivating plants that do not require soil [9], so the use of nutrient solutions is important in hydroponic farming. The nutrient solution is a water-based mixture of essential nutrients required for plant growth. In a hydroponic mostly farming uses a combination of fertilizer A and fertilize B that are called AB mix. Fertilizer A includes potassium, whereas Fertilizer B encompasses sulfate and phosphate [10]. These fertilizers are mixed to create a nutrient solution with optimal concentration. Nutrient concentration refers to the amount of nutrients dissolved in the water solution, to measure nutrient concentration mostly use Electrical Conductivity (EC). Maintaining EC value within the optimal range is crucial for ensuring healthy plant growth as the higher EC level can result in the plant's ability to absorb nutrients effectively [11].

In [12] paper, Utilizing the NodeMCU microcontroller as a main brain that is integrated with a Total Dissolved Solids (TDS) sensor and Ultrasonic Sensor to measure nutrient concentration and water level. The efficiency of the system was validated by comparing the automation reading of the nutrient concentration with the manual measurement. The advantage of the system it is fully automated and easy to monitor ensuring convenience and timely adjustment. However, in terms of accuracy of nutrient concentration, although the system shows a low percent error compared to the manual, the reading needs to be compared against the desired nutrient concentration setpoints to evaluate the effectiveness of the system.

In [13] paper, the NodeMCU microcontroller also works as a main brain that is integrated with different sensors such as Digital Temperature and Humidity (DHT11) Sensors to calculate the temperature and humidity, and the ultrasonic sensor to calculate the level of nutrient solution in the container. Light Dependent Resistor (LDR) is used to detect the presence of algae in the hydroponic solution. The system allows continuous data collection that allows farmers to remotely monitor the hydroponic system. However, in terms of nutrient solution, it does not accurately measure the nutrient concentration as the system relies solely on ultrasonic sensors to detect the volume of nutrient solution, without utilizing an EC sensor or TDS sensor to measure the concentration of nutrients.

This paper [14], Provides a system that uses IoT to monitor different parameters and relays to control the flow of nutrients for hydroponic farming. This paper utilized the NodeMCU as the core of the system that is connected to various sensors and actuators. The Blynk app is integrated into the system for monitoring their data on temperature, humidity, and pH meter. The result shows the functionality of sensors that can be monitored through the Blynk application and the control button for nutrient concentration. This system offers significant advantages in terms of user convenience for monitoring and controlling the system remotely. However, the system uses relays to manage the flow of nutrient solution, it does not measure or adjust the nutrient concentration accurately according to the specific needs of the plants. This is because the system relies on the actuator of the relay without incorporating sensors for precise calculation and adjustment of nutrient concentration.

In paper [15], Build a system of Smart hydroponic for lettuce using nutrient film technique (NFT) that integrates with IoT. ESP32 is used as the core for the whole system with various sensors such as DHT11, TDS, power of hydrogen (pH), and BH1750 to monitor the parameters of the Light sensor, temperature, humidity, TDS, and pH. The actuators used in this system are fans that are triggered by temperature, water mist activated by humidity, and a water pump scheduled ON every 15 minutes and OFF for 5 minutes. The system is performed in repeating looping and delay for 3 seconds.

This paper [16], Proposed a system that can double the rate of crop growth by integrating an Arduino controller with various sensors such as TDS, pH Value Sensor, and Temperature. The data from the sensors were used to adjust the water solution in a hydroponic system. The user will get a notification if there are any issues with the water quality. Based on this notification, immediate action needs to be taken to correct the issues before plants get affected. This system allows users to get notified by the software regarding water quality and the user can monitor the parameters of sensors but there is no specific actuator that can control the parameters so the user might need to adjust it manually.

Various systems [12], [13], [14], [15] ,[16] used IoT and sensors to monitor different parameters such as nutrient concentration, temperature, pH, and humidity. Each system offers advantages in improving the modern agriculture sector, especially by utilizing monitoring and control benefits in hydroponic systems. However, there are still shortcomings in terms of accuracy in reaching nutrient concentration setpoints and the time taken for nutrients to reach these setpoints. Therefore, an IoT-based control system is needed in hydroponic dosing systems to address these challenges.

2.2 Advances Control System in IoT-Based Hydroponic

Basic IoT integration of hydroponic systems offers numerous advantages such as good monitoring of the parameters set. However, the system's reliance on a simple actuator without a proper feedback mechanism can lead to inaccurate nutrient delivery so choosing an appropriate control system can enhance the accuracy of nutrient delivery and optimize the plant's growth. One of the control systems that are mostly used in IoT hydroponics are PID control system.

[17] Proposed an automated hydroponic system for pH control by using Raspberry Pi as the core for the system that is connected to various sensors to measure the pH level, temperature, and water level. To control the pH level the PID control system is used. The real-time data of pH level is collected and handled by Raspberry Pi compared with the pH level set. Error is calculated and the PID controller is working and sends the instruction to the Motor Driver based on the calculation of PID.

[18] Proposed a method using LabView and an AVR microcontroller. There are various sensors used to measure the parameters such as humidity, temperature, pH level, and light. The PID control system is applied in this system to maintain the desired set points for various parameters. The simulation result of LabView provides the smooth and stable control action of the PID controller.

[19] Using STM32 Microcontroller to create pH control system, develop expert PID controller, and compare the performance of the controller with the conventional PID by using MATLAB Simulink. The result of expert PID shows less overshoot of pH level compared to the conventional PID controller. [20] Proposed the improved PID control system for a variable rate

fertilization system to enhance the accuracy and reduce time delay and overshoot. The result of the simulation shows that the improved PID controller reduced the maximum overshoot and shortened the delay time compared to the standard PID control system.

The other control systems that are mostly used in IoT hydroponics are fuzzy logic control systems. [21] Propose a system that controls nutrient concentration in a hydroponic system based on predetermined values using fuzzy logic. The controller takes in the error and the change in error as inputs. Based on these inputs, it adjusts the angle of the servo motor, which in turn controls the openings of the nutrient and water valves. [22] Design 2 levels of adjustment, first the system determines the appropriate duty cycle based on the measured inlet pressure. It then automatically adjusts the duty ratio for the PWM control of the solenoid valve. Then the second level, the fuzzy control algorithm further adjusts the PWM duty cycle, ensuring that the mixture concentration closely matches the target concentration. The result is compared to the PID by using simulation in MATLAB. It shows that fuzzy control is better than PID control in response speed and overshoot of EC value.

[23] Proposed a system that can monitor parameters such as EC, pH level, and water level. The data from the sensor is used as the input for fuzzy logic control and the control pump of fresh water and nutrient concentration will adjust depending on the fuzzy logic calculation. A hydroponic system based on the NFT method was designed by [11] using fuzzy logic control. The image processing of the HSV Histogram of the Pakcoy mustard plants is used to predict the setpoint value for the EC of nutrient solution. Experimental results demonstrated that the fuzzy logic control effectively supplied nutrients appropriate for the plant's age, with an error rate of 8.9%.

To improve the PID control system, fuzzy logic is combined with the PID control system to enhance the accuracy and responsiveness of nutrient delivery. [24], [25], [26] The integrated water and fertilizer control system employs a fuzzy PID adaptive control method. The system calculates the error (E) and rate of change error EC based on the difference between setpoint and actual values. E and error EC are used as the input for the fuzzy logic rules to perform fuzzy reasoning. From the Fuzzy output, it adjusts the PID parameters of proportional gain, integral gain, and derivative gain. The system adjusts the duty cycle of the PWM to regulate solenoid valves or servo motors, effectively controlling nutrient and water delivery.

[27] Integrates fuzzy logic with a PID controller, optimized using Particle Swarm Optimization (PSO) to regulate pH levels in an automated fertilization system. The fuzzy controller adjusts the PID parameters of proportional, integral, and derivative gain based on the error and the rate of change of the error. PSO is employed to optimize these parameters by initializing a swarm of particles that iteratively adjust their positions based on individual and collective experiences to minimize the absolute value integral of the error. The proposed approach was validated through simulations and experiments, demonstrating improved stability and responsiveness compared to traditional methods

3. METHODOLOGY

3.1 System Design and Setup

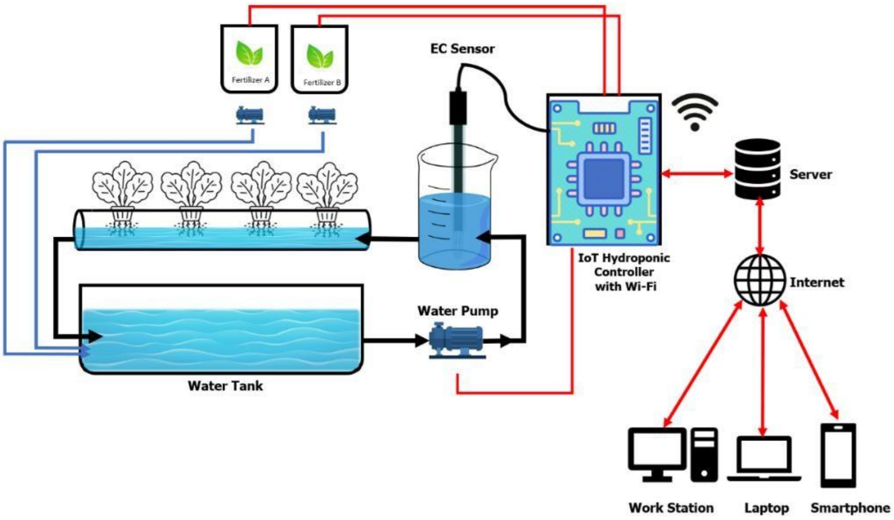

Figure 1. Overview of Hydroponic Dosing System

Figure 1 illustrates the IoT hydroponic dosing system for monitoring and controlling plant nutrient delivery. It comprises a water tank that serves as the main reservoir, with three water pumps, one linked to the tank to circulate water from it to the hydroponic beds, and the others connected to fertilizers A and B. Both fertilizer A and fertilizer B contain different types of fertilizer that are required for plant growth. The EC sensor is utilized to determine the nutrient concentration in water. The EC value is an indicator of the amount of dissolved salts (nutrients) in the water, which is critical for maintaining optimal plant growth conditions [28]. The hydroponic controller with Wi-Fi is the central control unit of the system. It receives data from the EC sensor and sends it to the server, the server stores the data and runs the algorithm to provide a command to adjust the operation of the fertilizer pumps to maintain the desired nutrient concentration. Since this system functions wirelessly and operates as a feedback loop system, data transmission may face some time lag between measurements and when the data is received by the server for computation. However, these aspects are not the primary focus of this study. The systems use the internet to facilitate communication between IoT controllers, servers, and user interfaces such as workstations, Laptops, or Smartphones. These devices allow users to remotely monitor and control the hydroponic system.

3.2 Control Algorithm

The control algorithm in this paper uses 4 control systems, namely a basic control system, PID control system, Fuzzy control system, and Consensus control system. All 4 control systems were compared to find the optimum performance for the Nutrient Concentration control system of an IoT-based hydroponic system.

3.2.1 Basic Control System

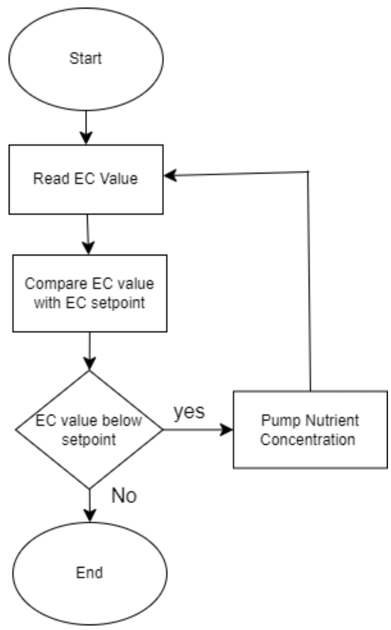

Figure 2. Flowchart of Basic Control System

The basic control system is the conventional hydroponic system that relies on straightforward predefined control strategies that manage the process of the hydroponic system. A simple feedback loop where the system's output is monitored and compared with the desired setpoint. If the differences are detected, adjustments are made to bring the output to the closer setpoint. This basic control system does not involve complex algorithms but relies on predefined rules to maintain the desired operation. The Fig 2 shows the flowchart of the basic control system. The EC sensors read the EC value and compare it with the EC setpoint. If the EC value is below the setpoint, the nutrient concentration is pumped into the hydroponic system. The system will continue looping until it reaches the setpoint value.

3.2.2 PID Control System

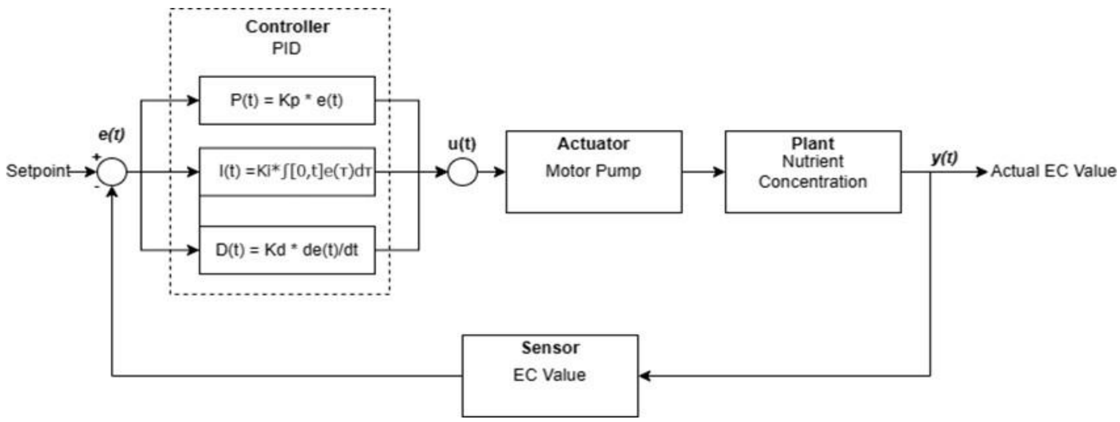

Figure 3. Block Diagram of PID Control System

The PID control system is widely used in engineering applications to maintain the desired output of the system. The PID control system is a closed-loop control system that regulates the output by combining Proportional, Integral, and Derivative to respond to the error signal [17]. Figure 3 illustrates the block diagram of the PID control system. EC sensor measures the current output of the process, then it compares the measured output with the setpoint to determine the error value based on Equation (1). Then based on the error the controller calculates the adjustment using PID formulae in Equation (2) and sends a control signal to the actuator.

$$e(t) = Setpoint - Current\ EC \quad (1)$$

$$u(t) = Kp * e(t) + Ki * \int_{0}^{t} e(\tau)\, d\tau + Kd * de(t)/dt \quad (2)$$

Based on Equation (2), Kp stands for proportional gain, which provides immediate corrective action based on the magnitude of the error. Ki stands for the integral gain, which eliminates any steady-state error that persists despite the proportional control. Kd stands for the derivative gain, which anticipates the future behavior of the error signal. The value of Kp, Ki, and Kd is Kp=0.5, Ki= 1, and Kd=1 [29].

3.2.3 Fuzzy Control System

The diagram of the Fuzzy control system in Figure 4 illustrates a feedback control system where a fuzzy is used to maintain the desired nutrient concentration in a hydroponic system by adjusting the nutrient level through a motor pump, The EC sensor measures the current EC and compares it to the setpoint EC based on Equation (1). Error e(t) is then processed in the fuzzy control system

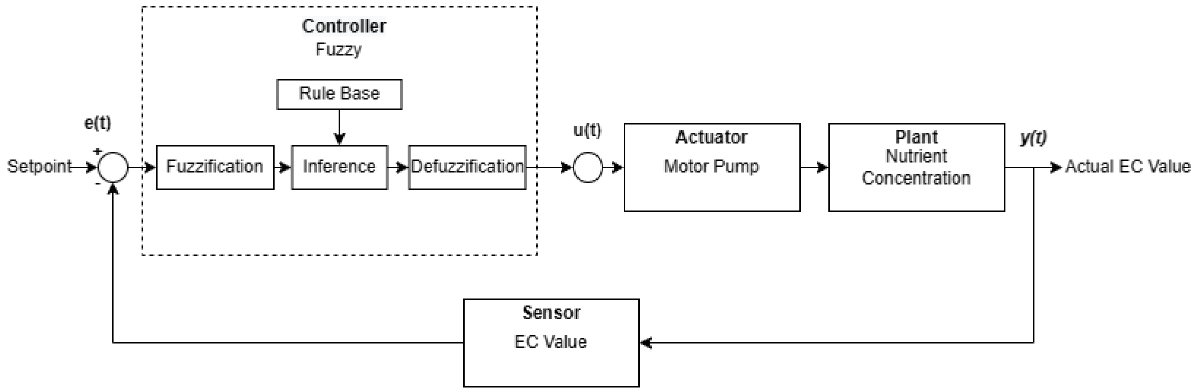

Figure 4. Block Diagram Fuzzy Logic Control System

In a fuzzy control system, the process of transforming numerical variable of non-fuzzy into linguistic variable of fuzzy is called fuzzification, since inputs need to be converted into fuzzy variables for processing within the fuzzy logic controller [30]. In this paper, the difference between the EC setpoint and the Current EC value is called error. The error is then fuzzification into three fuzzy sets: Low Membership, Medium Membership, and High Membership. The values of this membership in Table 1 refer to the previous research [11]. The table below shows the input and output of the membership function.

Table 1 Linguistic Variable

Variable	Condition			Unit
EC Value	Low Membership -2.5 – -0.5	Medium Membership -1 – 1	High Membership 0.5 – 2.5	mS/cm
Variable	Condition			Unit
Control Output	Decrease Significantly -10	Decrease Moderately -5	Increase Moderately 5	Second

These fuzzy sets are then evaluated using fuzzy rules during the inference stage to determine the appropriate control action. Table 2 below shows the fuzzy rules applied in this paper. Finally, defuzzification converts the fuzzy output back into a precise control signal u(t), which is sent to the actuator to adjust the nutrient concentration in the hydroponic solution.

Table 2 Fuzzy Rules

EC Value	Low Membership	Medium Membership	High Membership
Duration Control Output	Decrease Significantly	Decrease Moderately	Increase Moderately

3.2.4 Consensus Algorithm Control System

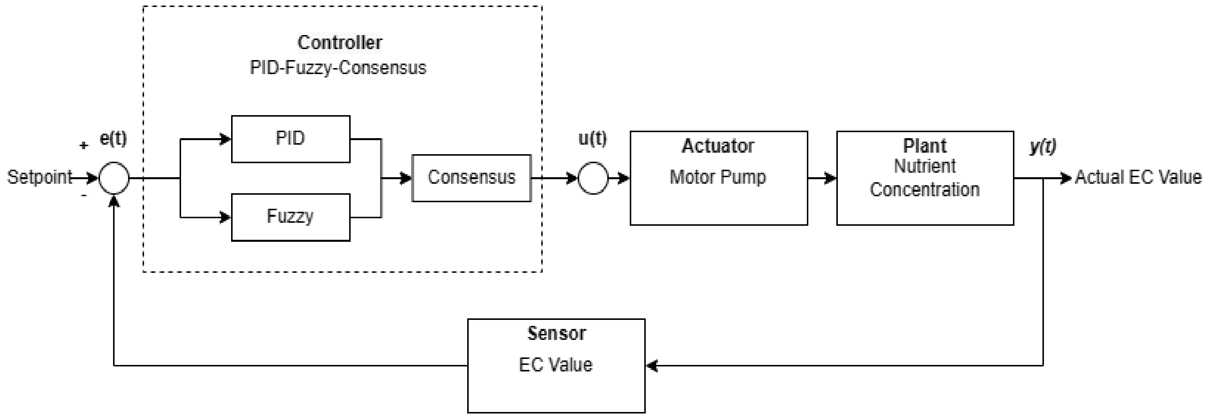

Figure 5. Block Diagram Consensus

Figure 5 illustrates a control system designed to manage the nutrient concentration in a hydroponic system using a hybrid approach combining a PID control system and a Fuzzy control system called Consensus algorithms. In this paper, the consensus method combines the outputs of the FUZZY and PID controllers by using a weighted ratio. The experiment was conducted to test the ratios of the consensus control system ranging from 100%, 80%, 60%, 40%, 20%, to 0%, with various nutrient concentration levels from 50 ml, 70 ml, 90 ml, 110 ml, 130 ml, and 150 ml. The average performance of each ratio was evaluated, and the results showed that an 80% ratio is the most optimal. In this case, the control system employs 80% PID control and 20% fuzzy control. This hybrid approach leverages the strengths of both methods to maintain the desired nutrient concentration in the hydroponic system. The setpoint represents the desired nutrient concentration, and the error e(t) is the difference between this setpoint and the current EC based on Equation (1). The PID and Fuzzy controllers process the error signal to generate control actions, which are then integrated by the Consensus algorithm to produce control signal u(t). This signal drives the actuator to adjust the nutrient concentration in the hydroponic solution. The actual EC value is continuously monitored by the sensor and fed back into the control loop, ensuring the system dynamically adjusts to maintain the desired nutrient levels.

4. RESULT AND ANALYSIS

4.1 Result of Basic Control System

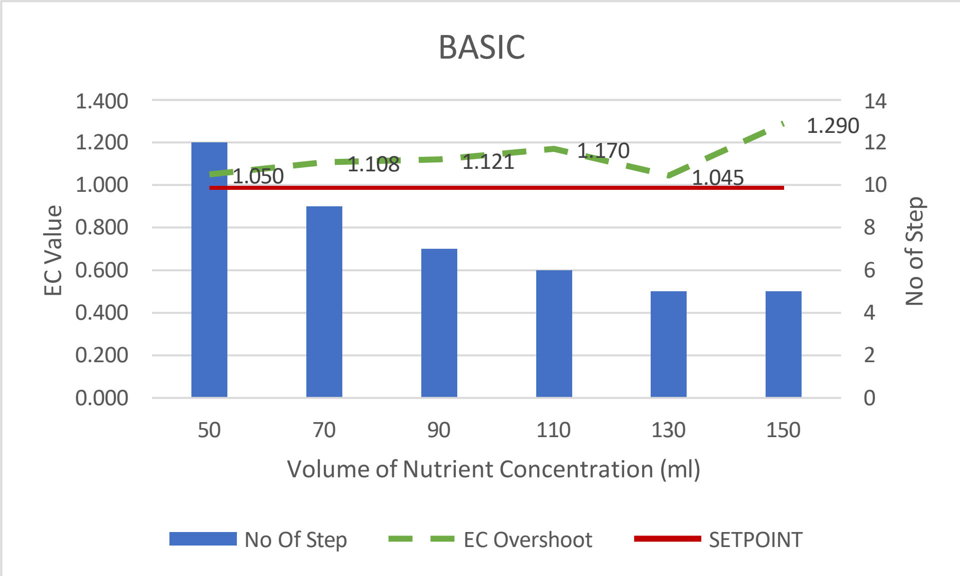

Figure 6. Result of Basic Control

The figure above illustrates the result of the basic control system. the setpoint is set at 1. For the basic control system, the longest time required to reach the setpoint occurs at 50ml with 12 steps, and the overshoot value is only ay 0.050, which is the second lowest overshoot value. As the volume of nutrient concentration increases to 70ml, the number of steps to reach the setpoint also decreases to 9 steps with an overshoot of 0.108. At 90ml, the system required 7 steps to reach the setpoint with an overshoot of 0.121, indicating a further increase in overshoot. At 110ml the basic control system required 6 steps to reach the setpoint with an EC overshoot of 0.170, showing a continued trend of increasing overshoot. The fastest times to reach the setpoint are at volume 130ml and 150ml by 5 steps. However, the overshoot value at 150ml is the highest among the basic control system measurements at 0.29, while at 130ml the lowest overshooting value is at 0.045. As the volume of nutrient concentration increases, the no of steps required to reach the setpoint decreases. From the graph, it can be concluded that higher volumes generally lead to faster responses however, in terms of overshoot behavior, that higher volume can result in a greater overshoot, although this is not consistently true for all volumes, as seen with the lowest overshoot value at 130ml.

4.2 Result of PID Control System

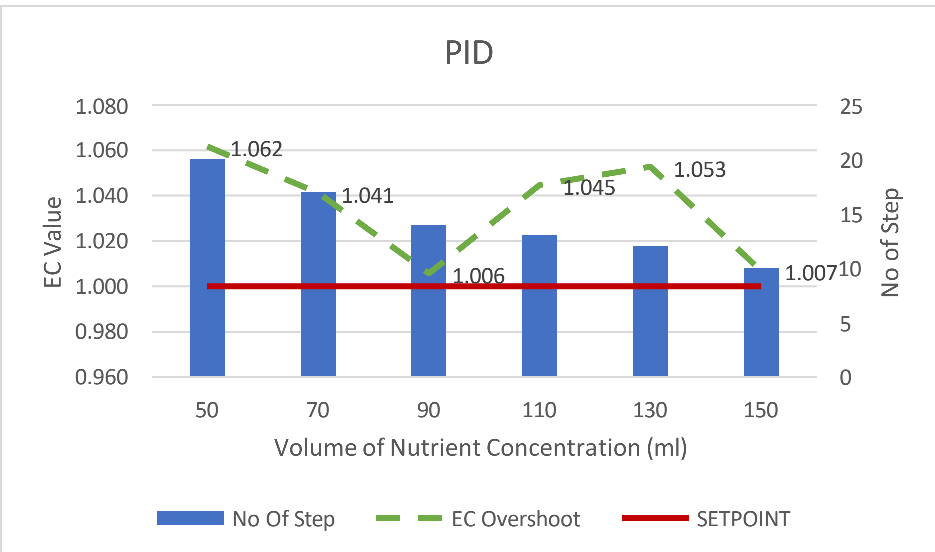

Figure 7. Result of PID Control

Based on the graph, the longest time required to reach the setpoint occurs at a volume of 50 ml, requiring 20 steps and exhibiting the highest overshoot value of 0.062. As the volume increases to 70ml, the PID control system requires fewer steps compared to 50ml with 17 steps and shows a reduced EC overshoot at 0.041. At 90ml PID performance improves further, requiring 14 steps to reach the setpoint with an overshoot of 0.006, which is very close to the setpoint. At 110ml, the PID system required 13 steps to reach the setpoint and has an EC overshoot of 0.045, indicating a slight increase in overshoot. At 130ml, the PID system required 12 steps, with an EC overshoot value of 0.053. The fastest to reach the setpoint is achieved at a volume of 150 ml, taking only 10 steps and displaying the second lowest overshoot value of 0.007. The graph indicates that higher volumes of nutrient concentration generally result in faster achievement of the setpoint. However, the overshoot behavior is not consistent, as the lowest overshoot value of 0.006 occurs at 90 ml.

4.3 Result of Fuzzy Control System

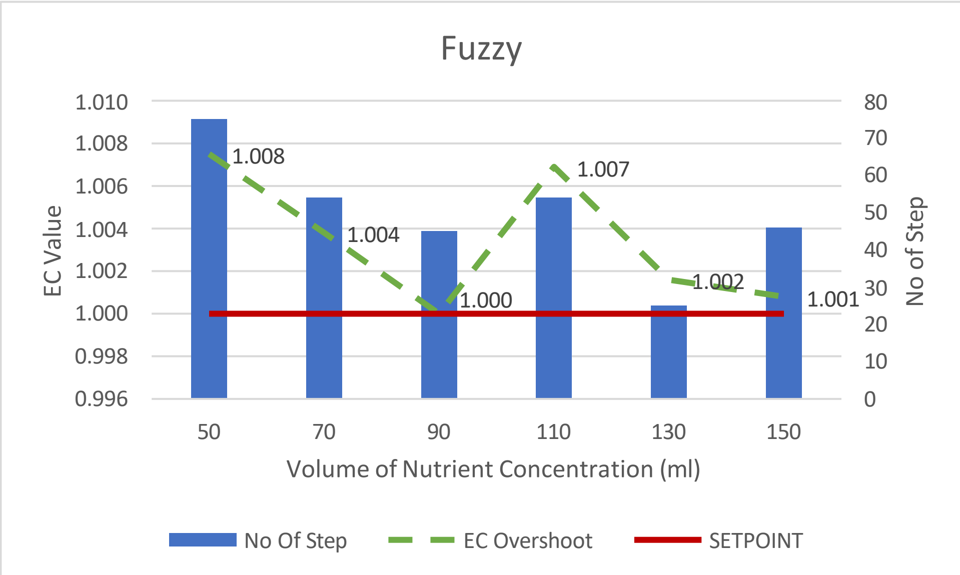

Figure 8. Result of Fuzzy Control

The result of Fuzzy in Figure 8 shows that at 50ml, the control system of fuzzy requires the highest number of steps by 75 steps to reach the setpoint and the EC overshoot at 0.008, indicating a significant overshoot above the setpoint. 70ml of nutrient concentration shows, the number of steps decreases to 45 steps and the EC overshoot also decreases to 0.004 showing an improvement in both response time and overshoot. At 90ml fuzzy control systems perform even better with reduced steps at 30 steps and EC 0 overshooting value observed. At 110ml, there is an increase in both the number of steps required to reach the setpoint by 60 steps and EC overshoot at 0.007, indicating a less optimal performance compared to 90ml. at 130ml the number of steps decreases significantly to 25 steps and the EC overshoot value is 0.002, indicating a quick response with a low overshoot. 150ml, the fuzzy requires 40 steps and has an EC overshoot of 0.001, demonstrating a relatively balanced performance with a low overshoot and a moderate number of steps.

4.4 Result of Consensus Control System

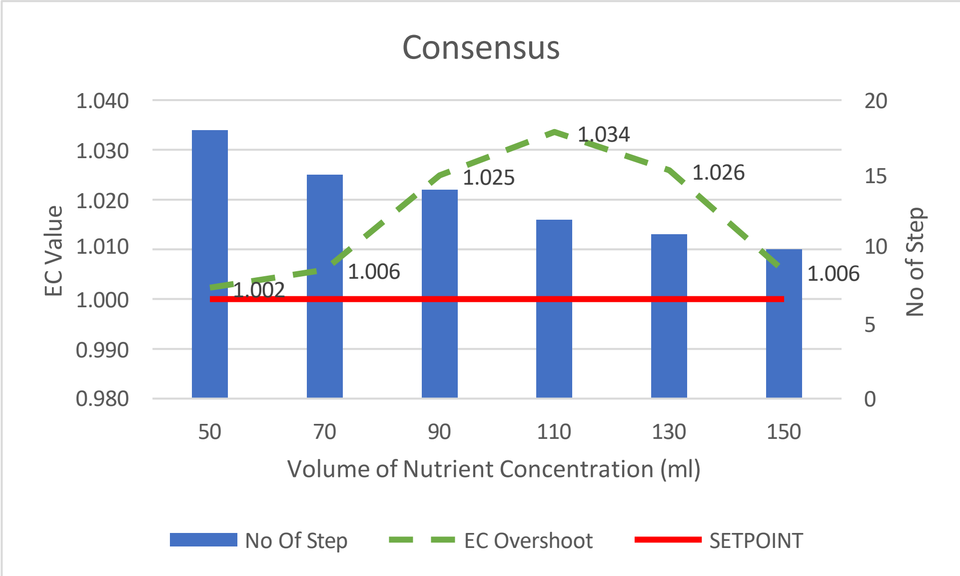

Figure 9. Result of Consensus Algorithm Control

Based on the graph above, at 50ml the consensus control system requires the highest number of steps by 18 steps with an EC overshoot of 0.002, indicating a minor overshoot above the setpoint. At 70ml the number of steps decreases to 15 steps with an overshoot of 0.006 showing a slight increase in overshoot. At 90ml, the number of steps decreases to 14 steps to reach the setpoint with an overshoot of 0.025. At 110ml, the consensus control system requires 12 steps to reach the setpoint with the highest number of overshooting at 0.034. 130ml, the number of overshoots decreased by 1 step at 12 steps with an overshoot decrease slightly compared to 110ml by 0.026. at 150ml, the consensus control system requires the fewest steps about 9 steps with an EC overshoot of 0.006, indicating a lower overshot after 50ml and quick response time.

4.5 Analysis and Discussion

To compare the four control systems: Basic control system, PID control system, Fuzzy control system, and Consensus control system, and determine which is the most optimal, the number of steps required to reach the setpoint and the corresponding EC overshoot for different volumes of nutrient concentration need to analyze.

Table 3 shows that the Basic, PID, and Consensus control systems generally require more steps at lower volumes, and as the volume of nutrient concentration increases, fewer steps are needed to reach the setpoint. The Fuzzy control system, however, consistently requires the most steps, with the highest number being 75 steps at 50 ml. The Consensus control system typically reaches the setpoint faster than the PID control system, while the Basic control system reaches the setpoint the fastest. However, considering EC overshoot is crucial for determining the optimum control system for nutrient concentration.

Table 3 Comparison Number of Step of Four Control System Results

Volume of Nutrient Concentration (ml)	50	70	90	110	130	150
Number of Steps Basic	18	6	5	5	5	6
Number of Steps PID	18	15	10	15	15	10
Number of Steps Fuzzy	75	45	30	60	25	40
Number of Steps Consensus	18	13	14	12	11	9

Table 4 Comparison Overshoot Value of Four Control System Results

Volume of Nutrient Concentration (ml)	50	70	90	110	130	150
EC Overshoot Basic (mS/cm)	0.050	0.108	0.121	0.170	0.045	0.290
EC Overshoot PID (mS/cm)	0.062	0.041	0.006	0.045	0.053	0.007
EC Overshoot Fuzzy (mS/cm)	0.008	0.004	0	0.007	0.002	0.001
EC Overshoot Consensus (mS/cm)	0.002	0.006	0.025	0.034	0.026	0.006

Table 4 compares the EC overshoot among the four control systems. The Basic control system exhibits the highest overshoot values, indicating it is not the optimal system despite its quick response time. Conversely, the Fuzzy control system, while achieving the most accurate setpoint with minimal overshoot, requires significantly longer to reach the setpoint. Despite focusing on EC parameters instead of pH levels, this study aligns conceptually with research comparing fuzzy and PID control in pH regulation, which found that fuzzy control exhibited slower peak time attainment and less overshoot compared to PID [31]. PID control system reaches the setpoint faster than the Fuzzy system but slower than the Consensus system, and it still has relatively high overshoot values. This observation aligns with findings from previous research, which reported that while the conventional PID controller achieves the fastest rise times across various flow rates, it also results in large overshoot values [32]. Thus, the Consensus control system appears to be the most optimal, as it effectively balances a quick response time with low overshoot values, maintaining superior performance in controlling nutrient concentration.

5. CONCLUSION

In this paper, four different control systems were tested on IoT-based Hydroponic systems. The experiment is run in various volumes of nutrient concentration for each control system. the data of the EC sensor is collected using MSSQL and comparative analysis is used to evaluate the performance of 4 different control systems. The time of nutrient concentration to reach the setpoint and the overshoot of EC value is used as the key parameter to evaluate the performance of each control system. The result shows that in terms of speed to reach the setpoint basic control system is the fastest however the overshoot value of EC is too high. While the fuzzy control system shows the least EC value to overshoot but the step it took to reach the setpoint is the longest compared to the other three control systems. PID and Consensus show the optimum in both times to reach the setpoint and EC value. However, Consensus performance is better than PID in both times to reach the setpoint and EC overshoot. These findings, show that the Consensus Algorithm can solve the time delay of nutrient concentration to reach the setpoint and also the overshoot of EC value. While the study provides valuable insights, several limitations need to be addressed in future research. These include adding more sensors, such as pH sensors, to gather more data for accurate analysis, and conducting long- term studies to evaluate the durability and consistency of the control systems over extended periods

ACKNOWLEDGEMENTS

This research was funded by a grant from University Malaysia Sabah (SKIM GERAN INOVASI SGI0192).

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