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Design and performance of nutrient dosing control system for hydroponic chilli plant using fuzzy logic controller

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Abstract

The application of irrigation and nutrient provision is crucial for cultivating plants using hydroponic systems. This significance arises from the absence of natural nutrients in hydroponic growing media, which necessitates precise and tailored nutrient administration. This study aimed to discuss the design and construction of a nutrient dosing system employing both an on-off-based nutrient mixing control and a fuzzy logic-based fertigation control. Nutrient dosing system design entails establishing design criteria, functional and structural design, prototyping, programming, and testing. Performance testing involved a mixture of cocopeat and rice husk charcoal growing medium, with a 2-month-old chilli plant as the testing subject. The nutrient mixing control system resulted in a ready-to-use nutrient solution with a concentration of 1538.45 ppm, which slightly deviated from the 1500 ppm target. The total time required for nutrient mixing amounted to 3685.8 seconds. The calculations revealed a percentage error of 2.56 % for this nutrient mixing control system. The tested fertigation control system successfully maintained the moisture content of the growing medium within the available water zone with an error rate of 2.17 %. Observations over three days demonstrated that the control system activated fertigation processes twice daily, predominantly in the morning and evening. The total volume of fertigation administered ranged from 217 cm^3 to 287 cm^3 daily. All the components of the nutrient dosing system functioned effectively and performed well.

Keywords: control system; dosing nutrition; fertigation system; hydroponic system; nutrient mixing.

I. Introduction

Application of irrigation systems and nutrient provision is critical for hydroponic plant cultivation [1]. Hydroponic growing media lack natural nutrients, necessitating precise nutrient supplementation according to the plant requirements. In hydroponic cultivation using drip irrigation techniques, irrigation and fertilization can be executed simultaneously using nutrient-dosing control systems. Nutrient dosing systems can be categorized into two types: nutrient mixing control systems, which regulate the concentration of nutrient solutions, and fertigation control systems, which manage the volume of nutrient solutions provided to the plants. These control systems play a pivotal role in developing automation technology for drip-irrigated hydroponic cultivation, impacting production costs for farmers and ensuring optimal plant growth.

One control system applicable to nutrient mixing is an on-off control system [2]. Several methods exist for on-off-based nutrient mixing control systems. The first

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method uses sensors to read concentrations and adjust nutrient and raw water concentrations to create a ready-to-use nutrient solution [3]. The second method employs theoretical concepts and utilizes general dilution equations to determine the necessary concentrated volume to produce a ready-to-use nutrient solution [4]. The third method, a combination of these two, yields an on-off-based nutrient mixing control system with a relatively high level of accuracy [5].

Once the nutrient solution concentration aligns with the plant's requirements, it is distributed to the plants through fertigation processes. Concerning fertigation control systems, the irrigation water requirement is based on two parameters: evapotranspiration and moisture status of the growing medium [6]. Several studies have focused on creating automated irrigation systems for cultivation in both open-field and greenhouse settings. Various control systems have been employed, including the proportional integral derivative [7], fuzzy logic [8], and artificial neural networks [9].

The use of fuzzy logic as an irrigation control system offers its advantages because it does not require an accurate model of the plant object to be watered [10]. Jaiswal and Ballal [11] have explored the application of a fuzzy logic irrigation control system with several input parameters, such as soil moisture, temperature, water level, and air humidity, with the output parameter being the percentage of valve opening. Meanwhile, Krishnan [12] also explored the use of fuzzy logic in an irrigation control system, where the input parameters used are soil moisture, temperature, and humidity, with the output parameter being the motor status. In addition, Navinkumar [13] also used almost similar parameters, where temperature, humidity, wind speed, rainfall, and soil moisture were used to influence the water level as output parameters. However, in these studies, each environmental parameter stands independently as an input variable for fuzzy logic, without prior processing or conversion into evapotranspiration values.

Furthermore, the moisture status of the growth medium has not been adequately investigated. Fundamentally, the water that plants can absorb must be within the available water zone between the field capacity and wilting point. Another study related to smart nutrient dosing control systems, integrating nutrient mixing control systems with fertigation control systems, was conducted by Salih [14]. In their research, the prototype was designed to control the nutrient concentration using an on-off-based nutrient mixing control system. However, the fertigation control system was based solely on a schedule, without adjusting to the current plant conditions and requirements.

This study aimed to discuss the design and construction of a nutrient dosing system for hydroponic plant cultivation with drip irrigation. This study aims to design two control systems: a nutrient mixing control system and a fertigation control system. A nutrient mixing control system is expected to provide nutrient solutions with concentrations suitable for plant requirements. The fertigation control system is expected to distribute nutrient solutions to the growing medium according to the current plant conditions and needs, considering aspects such as the moisture of the growing medium and evapotranspiration

II. Materials and Methods

A. Research stages

This study used a functional and structural design approach based on the required design criteria [15]. This research began by identifying issues related to plant cultivation using hydroponic systems. Following this, design criteria were established to address the chosen problems. Subsequently, functional and structural designs were developed according to these design criteria. Then, prototyping is performed, including the construction of hardware and the creation of control system program codes per the designed framework. Finally, tests were conducted to evaluate the nutrient-dosing control system. If the test results did not meet the required design criteria, an iterative process was initiated, which involved a redesign process until an optimal outcome was achieved. The research stages are illustrated in Figure 1.

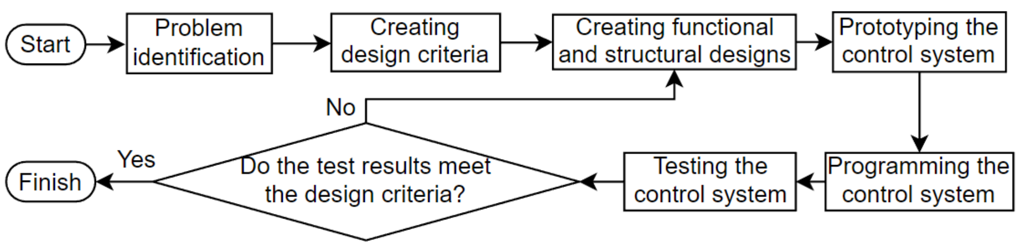

Figure 1. Flowchart of the research stages.

B. Design criteria

The design and development of fertigation and nutrient mixing control systems can be employed as nutrient dosing systems if they meet the following criteria:

- The nutrient mixing control system generated a mean absolute percentage error value of less than 5 % for the nutrient solution concentration.
- The growing media moisture is in the available water zone with a mean absolute percentage error value of less than 5 %.

C. Conceptual design

Two types of control systems were designed within the nutrient dosing system: an on-off-based nutrient mixing control system and a fuzzy logic-based fertigation control system. The design of the fertigation control system comprises three sensor nodes to measure moisture content, air temperature, air humidity, and solar radiation. One sensor node was allocated to measure wind speed. The server module serves as the central control system and database server. The design of the nutrient mixing control system consisted of an electrical conductivity (EC) sensor connected directly to the server module via a cable. Additionally, the server module is directly linked to actuators such as a peristaltic pump for pumping concentrated nutrients into the nutrient reservoir, two water pumps for the mixing and delivery of the nutrient solution from the nutrient reservoir to the growing medium, and a solenoid valve to regulate the flow of fertigation to the plant. The conceptual illustration of the design for the nutrient dosing system can be observed in Figure 2.

D. Functional design

The designed nutrient-dosing system consists of four components with distinct functions.

- Sensor nodes are responsible for reading the percentage of moisture content in the growing medium and measuring environmental parameters. This node comprises several components, such as the ESP32 as the microcontroller, a capacitive-based moisture sensor for reading the moisture value of the growing medium, a DHT22 sensor for measuring air temperature and humidity, a TSL2561 sensor for measuring solar radiation, an anemometer for measuring wind speed, and a 5-volt 3-ampere DC adapter as the power supply.
- The server module served as the central control system. The server module consisted of a Raspberry Pi as the central control unit, a monitor as an interface for displaying data, an SD card for data storage, a 12 volt power supply for converting AC electricity to DC 12 volt, a DC step-down 12 volt to 5 volt converter, a solid-state relay for powering on and off pumps and solenoid valves, and a miniature circuit breaker for disconnecting and reconnecting the power supply. The server module is also directly linked to the electrical conductivity sensor to detect the nutrient concentration value and an EZO conductivity circuit module to connect the EC sensor with the Raspberry Pi.

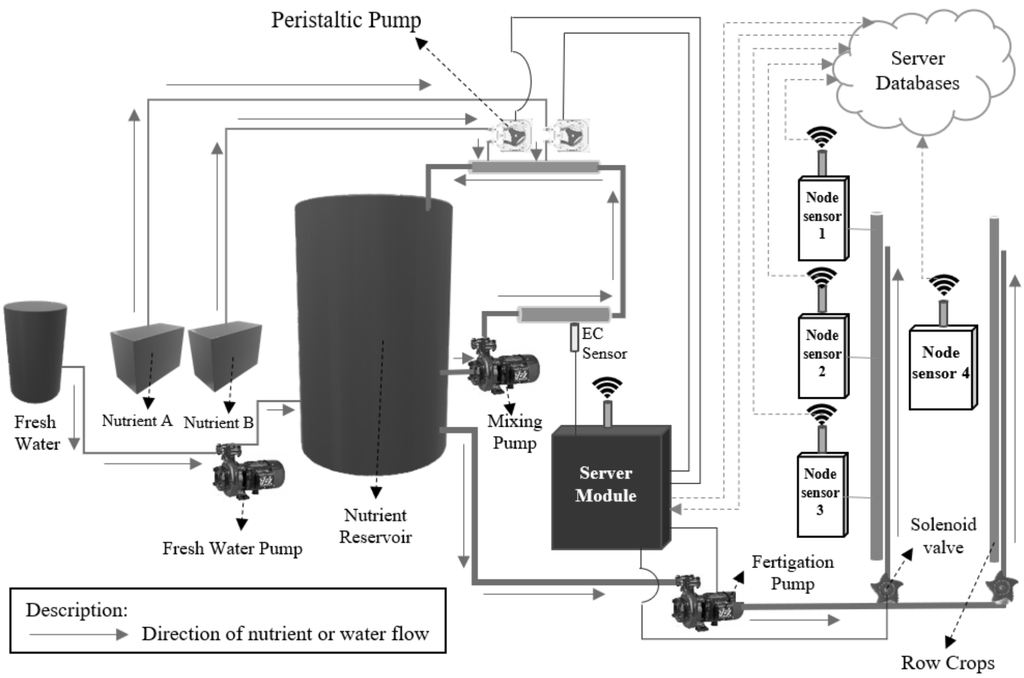

Figure 2. Conceptual scheme of nutrient dosing system for hydroponic cultivation with drip irrigation.

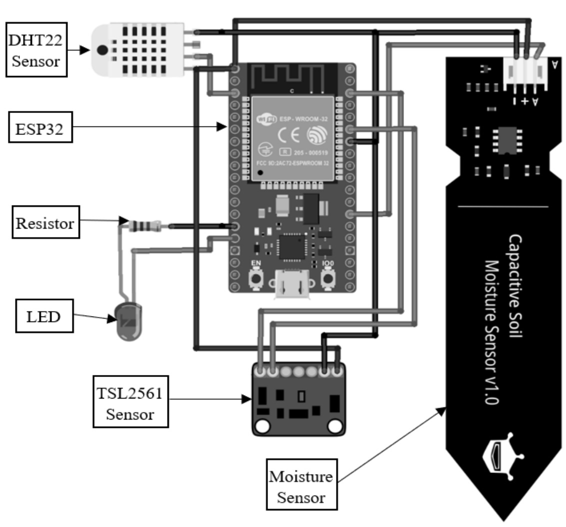

Figure 3. Component circuits of sensor nodes 1, 2, and 3.

- Irrigation consists of water pumps for pumping nutrient solutions to the plants, solenoid valves regulating the opening and closing of the fertigation flow to the growing medium, and a drip irrigation piping installation as the channel for nutrient distribution to the plants.
- The nutrient mixing installation consists of a reservoir containing a mixed nutrient solution, jerry cans containing concentrated nutrients, a peristaltic pump for transferring nutrients from the jerry cans to the reservoir, and a mixing pump for blending concentrated nutrients with fresh water.

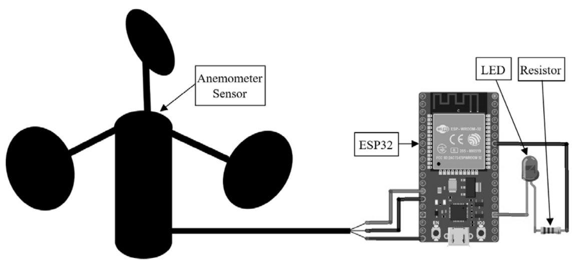

Figure 4. Component circuits of sensor node 4.

E. Structural design

1) Hardware design

The nutrient dosing control system has two types of sensor nodes and one server module. The structural design of sensor nodes 1, 2, and 3 is shown in Figure 3. Several sensors, such as a capacitive soil moisture sensor, a DHT22 temperature and humidity sensor, and a TSL2561 light intensity sensor, are all connected to the ESP32 microcontroller. An LED is also added to indicate the operation of the ESP32. The structural design of sensor node 4 is shown in Figure 4. This sensor node is placed at a height of 2 meters above the ground. A wind speed sensor is connected to the ESP32 microcontroller along with an LED to indicate the operation of the ESP32. The structural design of the server module is shown in Figure 5. A 12-volt power supply is used for the Raspberry Pi components. The electrical power is first regulated by a 12-volt DC step-down to 5 volts before entering the Raspberry Pi. An

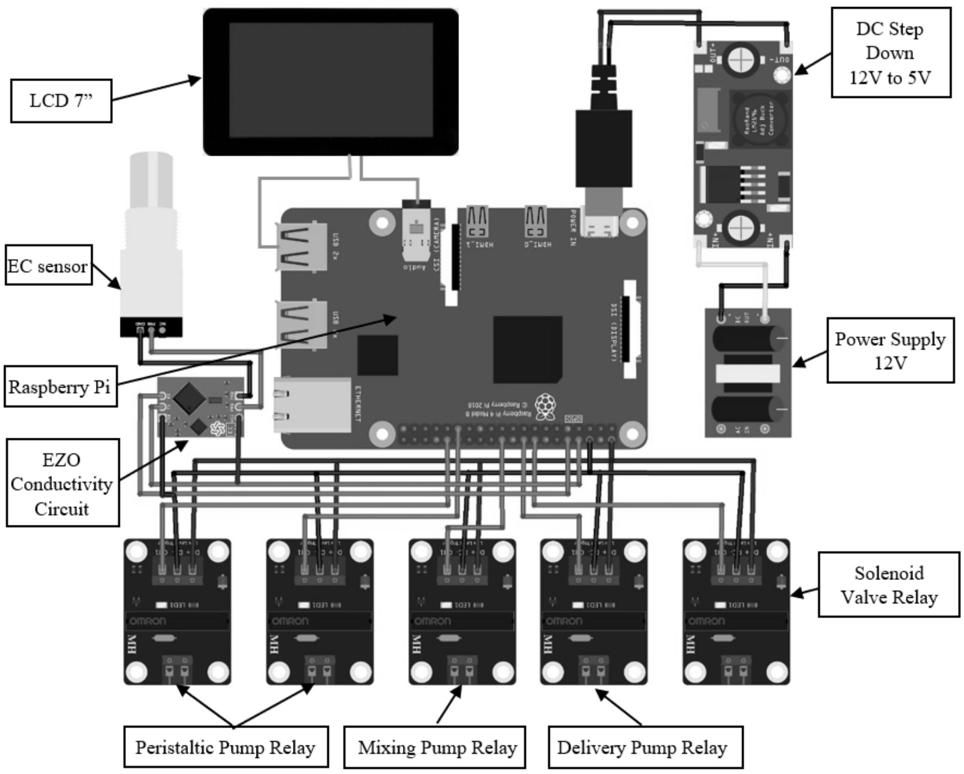

Figure 5. Component circuits of the server module.

electrical conductivity sensor is connected to the Raspberry Pi. Several solid-state relays are used as actuators to turn the pump on and off. A 7-inch LCD is used as a screen to display overall system information.

2) Software design

The operational mechanism of the nutrient-dosing control system is shown in Figure 6. The process began with the determination and input of several parameters and set points used in the nutrient mixing control system. The nutrient mixing control mechanism was executed using Python with an algorithm flowchart, as shown in Figure 7. Once the nutrient solution attains the appropriate concentration for the plants, distribution is conducted using the fertigation control system. Various parameters, such as membership functions and fuzzy rules, were incorporated into the programming of the fertigation control system.

The algorithm flowchart for the sensor node programming is shown in Figure 8. In addition to receiving and processing sensor reading data from each node and managing the calculation timing of the ETo value, a PHP program is required, as depicted in the algorithm flowchart in Figure 9. The designed PHP program retrieves data from each sensor node transmitted by ESP32 through the local host network. Furthermore, the designed PHP program will interact with Python programming to calculate the ETo value, as depicted in the algorithm flowchart shown in Figure 10. The fertigation control mechanism used fuzzy logic with Python programming, as illustrated by the algorithm flowchart in Figure 11.

In this control system, mixing was conducted between concentrated nutrient A, concentrated nutrient B, and freshwater. The nutrient mixing process within this control system begins by calculating the volume of concentrated nutrients that must be mixed with freshwater using equation (1) [4]. In equation (1), the concentration of the concentrated nutrients before mixing and the maximum volume of the nutrient reservoir must first be determined. The EC

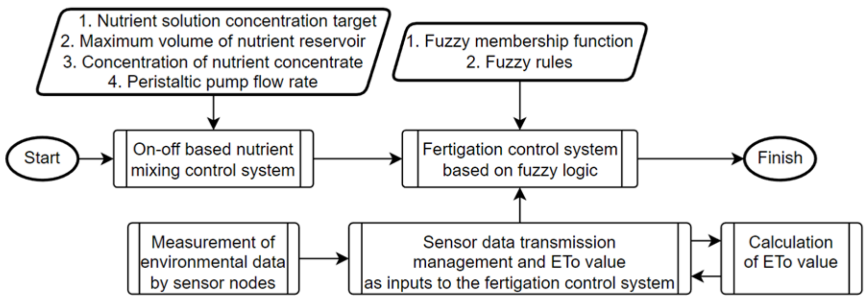

Figure 6. Flowchart of the nutrient dosing system mechanism.

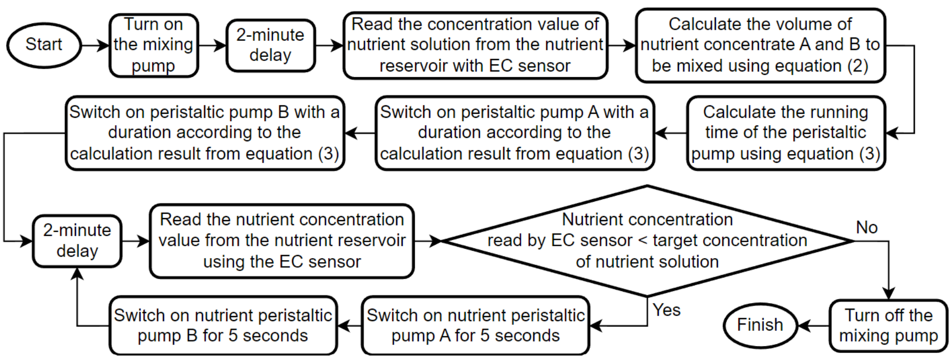

Figure 7. Flowchart of nutrient mixing algorithm.

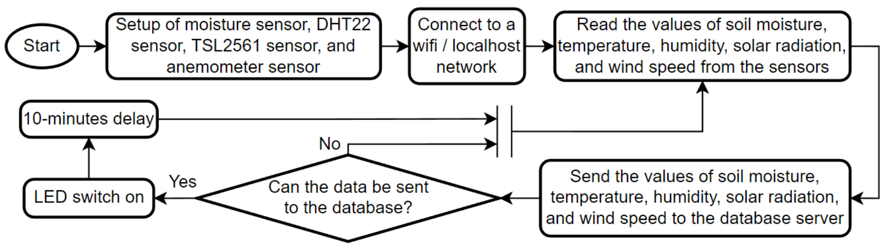

Figure 8. Flowchart of the program algorithm on sensor nodes.

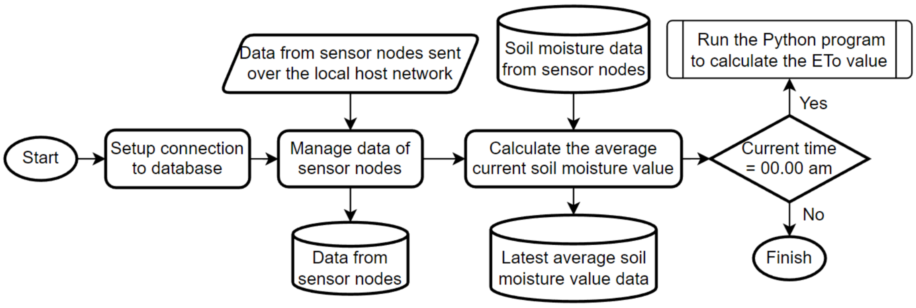

Figure 9. Flowchart of the PHP program algorithm on the server module.

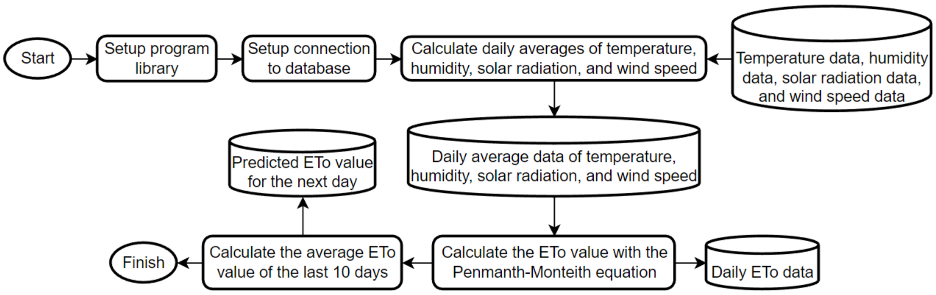

Figure 10. Flowchart of the Python program algorithm for calculating ETo values on server modules.

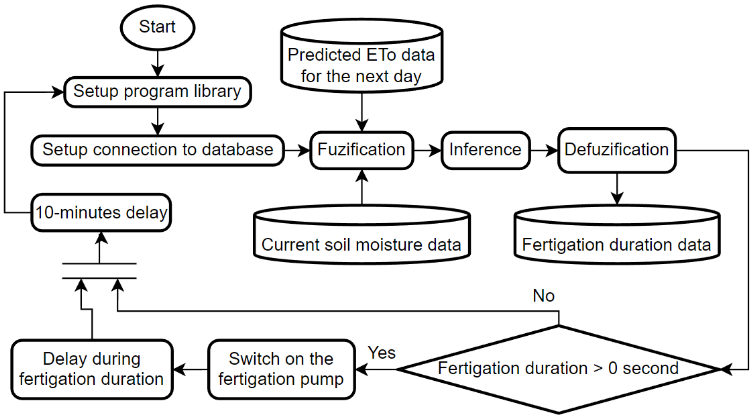

Figure 11. Flowchart of a Python program algorithm for calculating fertigation duration value with fuzzy logic on the server module.

sensor also reads the concentration value of available fresh water in the nutrient reservoir.

$$V_{concentrate} = \frac{(C_{target} - C_{now})\ x\ V_{max}}{(C_{concentrate}\ x\ 2)} \quad (1)$$

where $V_{concentrate}$ is the volume of each nutrient concentrate A and B to be mixed with fresh water (cm^3), C_{target} is the concentration target of nutrient solution (ppm), C_{now} is the current concentration of freshwater read by the sensor (ppm), V_{max} is the maximum volume of nutrient solution in the nutrient reservoir (cm^3), and $C_{concentrate}$ is the concentration of nutrient concentrate A and B in the jerry can (ppm).

The pump activation duration was determined by measuring the flow rate of the peristaltic pump. The pump flow rate test was conducted ten times by measuring the volume of the solution dispensed by the perstaltic pump every minute. The pump activatin duration was obtained using equation (2) [16].

$$t = \frac{V}{Q} \quad (2)$$

where t is the pump duration (s), V is the volume of the mixed concentrate (cm^3), and Q is the peristaltic pump flow rate (cm^3/s).

After the mixing process using equations (1) and (2), the EC sensor will again read the concentration of the mixed nutrient solution. If the obtained concentration value is less than the required target, the mixing mechanism continues with the sensor reading methods. The concentrated nutrients were added individually for 5 seconds each until the sensor read that the concentration value of the mixed solution had reached the required target. An algorithm flowchart for the nutrient mixing control system is shown in Figure 7.

As shown in Figure 6, the mechanism of the fertigation control system is complex and requires a considerable amount of hardware and programming design. Environmental data and the moisture content of the growing medium are needed as inputs to the fertigation control system. The sensor nodes are designed to read and send environmental and soil moisture data to the server module. A flowchart of the program algorithm for these sensor nodes is shown in Figure 8.

The programming of these sensor nodes employs the C programming language uploaded to the ESP32 microcontroller [17]. This program has two main functions: setup and loop functions. The setup function aims to configure the sensors/libraries used in the programming and then set up the wifi/local host connection to communicate with the server module. The setup function is processed only once at the start of the program. Once the connection is established, the ESP32 collects soil moisture, air temperature, relative humidity, solar radiation, and wind speed values from each of its sensors. These values are then encoded in JavaScript object notation (JSON) format, which allows for structured and efficient data transmission via POST requests. In this study, environmental data transfer from the sensor nodes to the server module is implemented using the hypertext transfer protocol (HTTP) with the POST method. This mechanism was chosen because it is simple, lightweight for microcontroller implementation, and compatible with standard web server technology. The ESP32 microcontroller acts as an HTTP client that periodically sends sensor readings to the Raspberry Pi, which serves as a local web server and database host. This process was repeated every 600 seconds.

Two programming languages were used in the server module: PHP and Python. PHP programming is used to receive sensor data transmitted by sensor nodes from within the greenhouse and then input into the database. The data from these sensor nodes were processed using Python programming with two different types of files. The first Python file calculated the standard evapotranspiration (ETo) value, whereas the second Python file calculated the fertigation requirements using fuzzy logic.

Figure 9 shows that there are three main functions of PHP programming for this server module. After the setup for the connection to the database is completed, the PHP program executes the first function to receive the sensor data transmitted by the sensor nodes. The server module receives incoming HTTP POST requests through a PHP-based API endpoint that remains active on the local server. A PHP script decodes the transmitted JSON payload, and the extracted sensor data is inserted into a local structured database stored in the Raspberry Pi's memory. Next, Raspberry Pi, as the microcontroller, performs the second function, which involves calculating the current average moisture content value according to the sensor reading data present in the database. Finally, when the time indicated 00:00 AM, the third function was executed to run the Python program to calculate the ETo value.

Figure 10 illustrates the flowchart of the Python program for calculating the ETo value used as the input for the fuzzy-logic-based fertigation control system. The process begins by setting up program libraries and connecting them to a local database. Subsequently, the Python program calculated the daily average values of environmental parameters, such as temperature, humidity, wind speed, and solar radiation. These daily average values were used as inputs when calculating the ETo using the Penman-Monteith equation [18]. To determine the ETo value for the next day, which functions as an input parameter for fuzzy logic, the predicted ETo is used by calculating the average ETo value over the last ten days.

Figure 11 depicts a flowchart of the Python program for calculating the fertigation duration value using fuzzy logic. The process begins by setting up program libraries and connecting them to a local database. The current moisture content data of the growing medium and predicted ETo values were used as inputs in the fuzzification process. In contrast, the fertigation duration is used as output in the defuzification process. The moisture content of the growing medium in the fuzzification process is divided into three categories: dry, moist, and wet. Evapotranspiration is then divided into three categories: low, medium, and high. Inference is the process of converting fuzzy inputs into fuzzy outputs by following predetermined rules. Fuzzy rules are the logic used for decision-making. In this study, the logic used is IF-AND logic. There are nine rules used in this inference process, as presented in Table 1. These nine rules are a combination of various categories in the moisture content of growing medium, evapotranspiration, and fertigation duration.

Defuzzification is the process of converting the results of the inference stage into a clear-cut output using a predefined membership function. In this study, the centre-of-area method was used for defuzzification. The fertigation duration range will be divided into four categories: off, short, medium, and long. The result of the fuzzy logic calculation will activate the fertigation pump if the generated duration is over 0 seconds; otherwise, the pump will not be activated. The control system then returns to the initial process by

Table 1.
Fuzzy rules of the fertigation control system.

Number	Rules
1	IF (moisture content = dry) and (ETo = high) THEN (duration = long)
2	IF (moisture content = moist) and (ETo = high) THEN (duration = medium)
3	IF (moisture content = wet) and (ETo = high) THEN (duration = off)
4	IF (moisture content = dry) and (ETo = medium) THEN (duration = long)
5	IF (moisture content = moist) and (ETo = medium) THEN (duration = short)
6	IF (moisture content = wet) and (ETo = medium) THEN (duration = off)
7	IF (moisture content = dry) and (ETo = low) THEN (duration = medium)
8	IF (moisture content = moist) and (ETo = low) THEN (duration = short)
9	IF (moisture content = wet) and (ETo = low) THEN (duration = off)

recalculating the fertigation requirements using fuzzy logic for 600 seconds.

F. Control system testing

Testing the nutrient control system is necessary to determine its performance of the control system. The test is performed by determining the error value of the control system for the desired target. Performance testing of the nutrient mixing and fertigation control systems was conducted within the greenhouse. Performance testing was conducted over three days, utilizing chili plant samples two months after planting (MAP). The growth medium comprised cocopeat (75 %) and husk charcoal (25 %). Initial testing was conducted on the nutrient mixing control system. The nutrient mixing control system will prepare a ready-to-use nutrient solution with a target concentration of 1500 ppm before being supplied to the plants. The results of nutrient mixing using this control system were evaluated for mean absolute percentage error (MAPE) using equation (3) [19].

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{A_i - F_i}{A_i}\right| x100\% \tag{3}$$

Figure 12. The nutrient dosing system prototype for hydroponic cultivation with drip irrigation.

where n is the number of observed data, A_i is the target nutrient solution concentration (ppm), and F_i is the concentration of the nutrient solution reached (ppm).

Following the completion of the performance test for the nutrient mixing control system, a performance test for the fertigation control system was conducted for three days. Testing was carried out by observing the performance of the control system in maintaining the moisture status of the growing medium between field capacity and wilting point. If the moisture condition of the growing medium exceeds these two points, this condition is declared an error. The error value was calculated using equation (3).

III. Results and Discussions

The prototype of the designed nutrient dosing system is shown in Figure 12 and Figure 13 The main components of the control system were housed within a dedicated indoor room, whereas the irrigation installation and sensor nodes were located within the greenhouse. Functionally, all the components of a nutrient dosing system can operate effectively.

A. Evaluation of the nutrient mixing control system

On the first day of testing, before the fertigation process began, the nutrient dosing system activated the nutrient mixing control system to prepare the plant nutrient solution. The nutrient concentration requirement for 2-month-old chili plants is 1500 ppm [20]. The total volume of the nutrient reservoir used was 0.435 m^3. Figure 14 shows the status of nutrient solution concentration in the mixing control. Based on the test results, the freshwater concentration measured by the nutrient mixing control system was 118 ppm. Subsequently, concentrated nutrients were added based on the calculation results using equation (1), with a total volume of concentrated nutrients of 3010 cm^3. The peristaltic pump was activated for 925.8 seconds.

(a)

(b)

(c)

Figure 13. (a) Solenoid valve that regulates the opening and closing of fertigation in the greenhouse; (b) sensor nodes to measure wind speed; (c) sensor nodes to measure soil moisture, air temperature, air humidity, and solar radiation.

Mixing the concentrated nutrients using equation (1) resulted in a nutrient solution concentration of 832.85 ppm. The error in the results of controlling nutrient mixing using this equation method is still high and far from the target concentration of the required nutrient solution. Therefore, the control system proceeded with nutrient mixing using the sensor reading method. The control system added concentrated nutrients stepwise, totaling 2730 cm^3, to reach the required nutrient concentration target over 2520 seconds. Mixing concentrated nutrients using this on-off-based control system yielded a ready-to-use nutrient solution concentration of 1538.45 ppm, with a total nutrient mixing time of 3685.8 seconds. The final result of this nutrient mixing control system had an error of 2.56 % and still fell within the required design criteria. The error value generated by this nutrient mixing control system was much smaller than that in the experiment conducted by Untoro [21], which was 11.25 %. However, compared with the nutrient mixing duration in the research undertaken by Suseno [22], this study required a much longer mixing time. This research placed a high priority on ensuring the correctness of the nutrition-mixing results. Therefore, the employed pump exhibited a consistent and limited fluid flow rate.

B. Evaluation of the fertigation control system

The design of the fertigation control system is deemed successful if it can maintain the moisture status of the growing medium within the available water zone between the field capacity and wilting point. The wilting point of the cocopeat and husk charcoal mixture was approximately 9 % [23]. Based on the test results, the field capacity of the cocopeat and husk charcoal mixed growing medium was 39.1 %, slightly lower than the research conducted by Nurlina [23], which was 52.34 %. According to Han [24], chilli plants can grow optimally when they receive irrigation of at least 55 % of field capacity, and this is called the critical point. If chilli plants receive irrigation below the critical point, the vegetative and generative growth of the plants will be hampered [24]. Hence, based on the calculated critical point value of the growth medium used, it was 21.5 %.

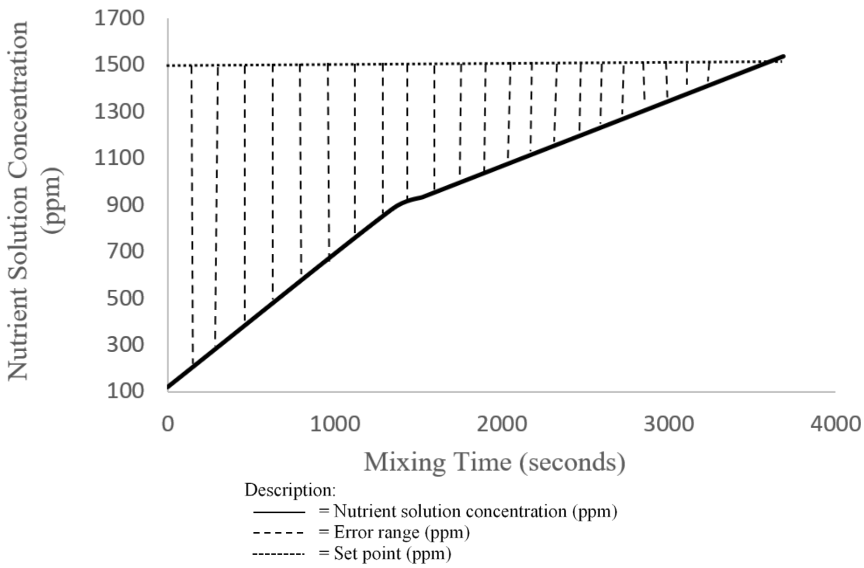

Figure 14. Status of nutrient solution concentration in mixing control.

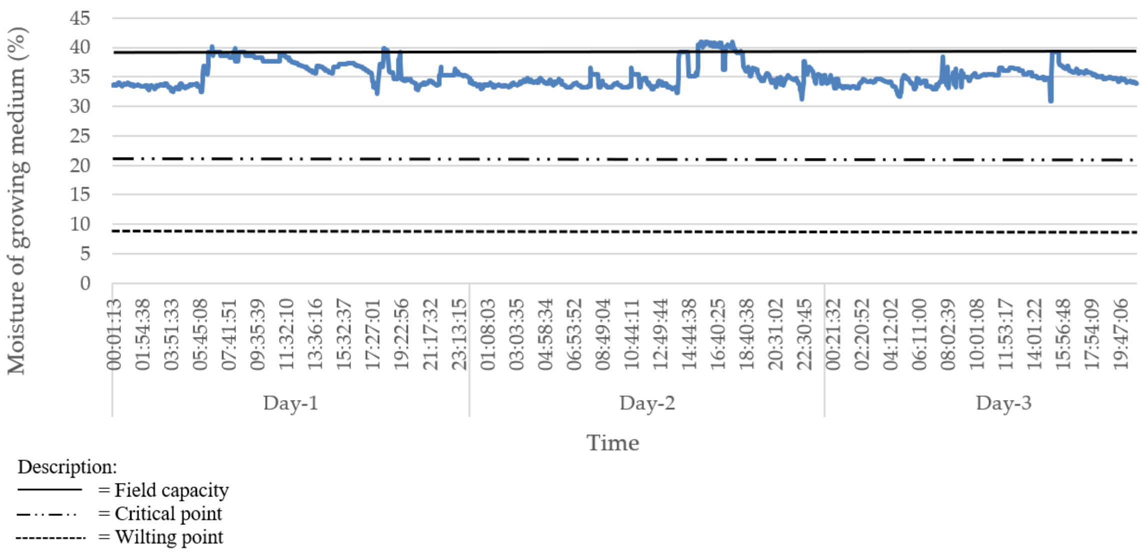

Figure 15. Moisture status of the growing medium.

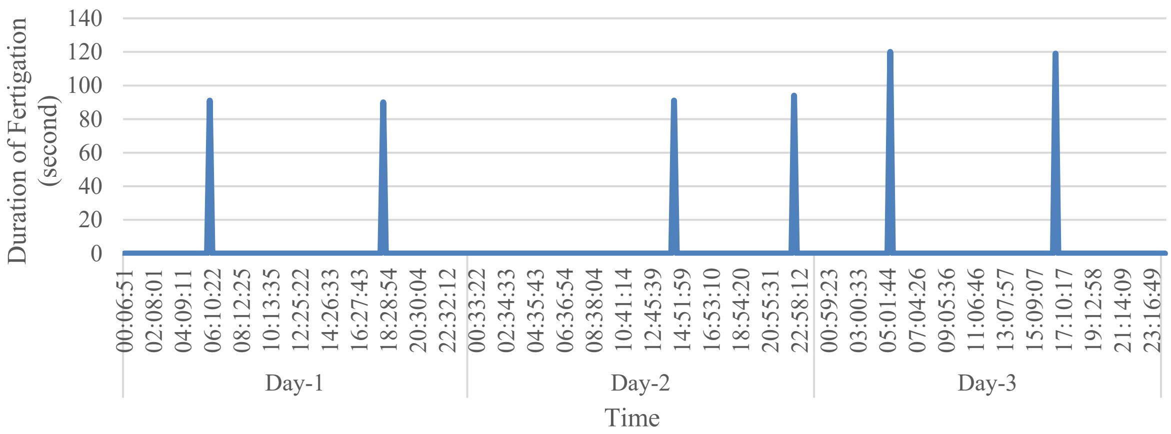

Figure 16. Fertigation time and duration during the test.

Figure 15 shows that the fertigation control system could maintain the moisture status of the growing medium within the available water zone. Although the test results still showed some errors, indicating that the moisture of the growing medium was above the field capacity in some periods, this was due to errors in the moisture sensor readings. Based on the sensor validation results, the average mean absolute percentage error of the moisture sensor readings was 3.85 %. Homogeneity of the growing medium mixture also affected the test results. Non-homogeneous planting media tend to have uneven moisture distribution, which can reduce irrigation efficiency [25]. However, the error in this test was relatively small (2.17 %) and still fell within the required design criteria. According to the results shown in Figure 16, the timing of fertigation varied each day during the testing period, depending on the predicted evapotranspiration value and the current moisture status of the growing medium. Fertigation was mainly administered in the morning and afternoon, suggesting that the moisture in the growing medium was at its lowest during these times. According to Warren [26], morning fertigation can reduce evaporation and ensure water reaches the root zone before temperatures rise. Meanwhile, afternoon fertigation can increase soil moisture in the shallow layers [27]. Increasing soil moisture levels in the shallow layers benefits chili plants, which have shallow root systems [28]. As shown in Table 2, the total volume of fertigation per day ranged from 217 cm^3/day to 287 cm^3/day. These results align with those of Aulia [29], where the fertility requirement based on daily evapotranspiration ranged from 82 to 507 cm^3/day

Table 2.
Total duration and volume of fertigation during the test.

Parameters	Day-1	Day-2	Day-3
Total duration (seconds)	181	185	239
Total volume (cm^3)	217.2	222	286.8

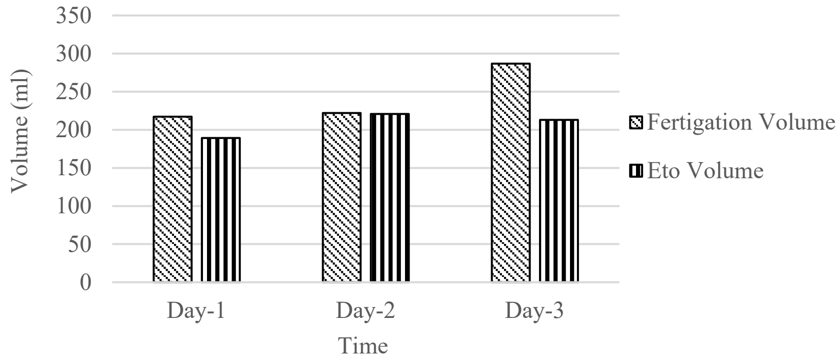

Figure 17. Comparison of the volume of fertigation produced by the fuzzy logic control system with the calculation of the volume of Eto.

under similar greenhouse conditions with an arch-type structure. The average fertigation volume with the fuzzy logic control system in this study was 242 cm^3/day, lower than the scheduled fertigation volume for chili plants, which was 576 cm^3/day [30]. Environmental climate conditions in the greenhouse directly affect the evapotranspiration value and humidity of the growing media, which causes the fertigation volume by the fuzzy logic controller to be lower than scheduled fertigation and varies daily [31].

One strategy for determining the daily fertigation volume is to calculate the evapotranspiration rate [32]. The data in Figure 17 indicate that the fertigation value delivered through the fuzzy logic control system marginally surpassed the standard evapotranspiration rate. According to Mahjoor [33], using different growing media for cultivation can result in variations in plant evapotranspiration rates. Compared with other growing media, plants grown in cocopeat exhibited relatively high evapotranspiration rates. The elevated evapotranspiration in cocopeat is due to its high water content. It possesses water-binding solid and retaining properties owing to its micropore structure, which hinders water movement and maintains water availability [34]. This phenomenon leads to a greater fertilization volume than the actual evapotranspiration rate.

IV. Conclusion

All the components of the nutrient dosing system functioned effectively. Performance testing was conducted using a mixture of cocopeat, husk charcoal growing medium, and 2-month-old chili plants. The nutrient mixing control system resulted in a nutrient solution concentration of 1538.45 ppm with a total nutrient mixing time of 3685.8 seconds. The final result for the nutrient mixing control system showed an error of 2.56 %. The tested fertigation control system maintained the moisture status of the growing medium within the available water zone with an error value of 2.17 %. Observations over three days indicated that the control system activated the fertigation process twice daily, with most applications occurring in the morning and evening. The total volume of fertigation administered ranged from 217 cm^3/day to 287 cm^3/day.

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Declarations

Author contribution

All authors contributed equally as the main contributor of this paper. All authors read and approved the final paper.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The use of AI or AI-assisted technologies

During the preparation of this work, the authors used Grammarly as an AI-assisted tool in order to check and improve grammar, spelling, and language clarity. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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