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Design and Implementation Fuzzy Tsukamoto-Based Temperature and Humidity Control for Aeroponic Pakcoy Cultivation

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ABSTRACT

Aeroponics is a method of hydroponic cultivation where plant roots are suspended in the air and nutrients are supplied through misting. The temperature and humidity control system, along with the monitoring mechanism, was designed using an ESP32 microcontroller. Input was provided by DHT22 and HC-SR04 sensors, while actuators consisted of mini fans and pumps. Through the integration of an Internet of Things (IoT) system, data on temperature, humidity, and water levels in the nutrient solution were monitored via the Blynk IoT application on smartphones. The results indicated that the DHT22 sensor measured temperatures within the range of 25°C to 26°C, with an average error of 0.79, and humidity levels above 70%, with an average error of 0.34. The data were processed using the Tsukamoto fuzzy method to determine the pump operating time and the PWM value for the mini fan. The HC-SR04 sensor recorded water levels between 10.1 cm and 11.5 cm, with an average error of 0.46, which was displayed using red and green LED indicators. Monitoring via the Blynk IoT application successfully presented both data and graphs of sensor readings. The entire system functioned as designed, effectively maintaining the temperature and humidity in the aeroponic pakcoy plant watering container.

Keywords
Aeroponics;
Tsukamoto Fuzzy;
IoT (Internet of Things);
Blynk;
Pakcoy.

ABSTRAK

Aeroponik merupakan metode penanaman hidroponik dimana akar tanaman dibiarkan menjuntai di udara sehingga pemberian nutrisi dilakukan melalui pengabutan pada akar. Sistem pengendalian suhu, kelembapan, dan monitoring ini dirancang menggunakan mikrokontroler ESP32, dengan input dari sensor DHT22 dan HC-SR04, serta aktuator berupa mini fan dan pompa. Dengan menerapkan sistem Internet of Things (IoT), data suhu, kelembapan, dan ketinggian air larutan dapat ditampilkan pada aplikasi Blynk IoT yang tersedia di smartphone. Hasil penelitian menunjukkan bahwa sensor DHT22 mengukur suhu dalam rentang 25°C-26°C dengan rata-rata kesalahan 0.79, dan kelembapan di atas 70% dengan rata-rata kesalahan 0.34. Data tersebut diolah menggunakan metode fuzzy Tsukamoto untuk mengatur waktu operasi pompa dan nilai PWM pada mini fan. Sensor HC-SR04 mengukur ketinggian air dalam rentang 10.1

cm- 11.5 cm dengan rata-rata kesalahan 0.46, yang kemudian di tampilkan pada indikator LED merah dan hijau. Monitoring melalui aplikasi Blynk IoT berhasil menampilkan data dan grafik hasil pembacaan sensor. Keseluruhan sistem bekerja sesuai dengan perancangan untuk menjaga suhu dan kelembapan wadah penyiraman tanaman aeroponik pakcoy.

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1. Introduction

Indonesia is one of the countries experiencing rapid development in the agricultural sector. As time goes by, the increasing population has led to more land being used for infrastructure development and urban expansion. Consequently, the shrinking of agricultural land has become one of the main issues in this field. The reduction in the area of agricultural land is now a factor driving farmers to switch to soil-less planting techniques such as hydroponics, aeroponics, and aquaponics. These methods are considered more efficient in addressing the issue of limited land for certain crops, as they require less space and emphasize optimal nutrient delivery. Hydroponics is a planting method that involves providing nutrients through the plant's roots by dissolving them in flowing water. Meanwhile, hydroponics is further divided into two categories: aquaponics and aeroponics. Aquaponics is a combined method of hydroponic techniques with the cultivation of aquatic organisms such as fish and shrimp. On the other hand, aeroponics is a hydro ponic method that utilizes nutrient mist to control temperature and humidity at the plant roots. In various aspects, aeroponics is considered to have a lower risk of crop failure due to its advantages, which include faster and more efficient plant growth, high oxygen content in the nutrient solution, and the ability to reduce the risk of plant diseases [1].

In aeroponics, roots are a crucial factor in plant growth, so watering is done continuously or intermittently at different intervals for each plant over several hours to maintain the moisture of the plant roots [2]. Automatic misting based on a timer, commonly used by aeroponic farmers, is considered less effective for misting roots; the amount of nutrients provided without considering temperature and humidity can alter the condition of plants in aeroponics. Plants experiencing nutrient excess or deficiency will have suboptimal growth results; for example, in pakcoy, problems may manifest as yellowing leaves or drying stems [3]. Therefore, misting with a fuzzy logic approach that considers the temperature and humidity of plant roots could serve as a solution to timer-based misting, helping to prevent fluctuations or extreme climate changes in the growing medium. Each plant has different ideal temperature and humidity values for its roots. Previous research using strawberries as the research object found the ideal root temperature to be between 14°C and 24°C and the ideal root humidity between 85% and 95%. Fuzzy logic-based automatic misting showed better results by taking plant and environmental factors into account [1].

For this study, the plants used were pakcoy grown outdoors, with ideal root temperature values of 20°C to 25°C and ideal root humidity values of 60% to 80% [4]. In outdoor pakcoy aeroponics, the misting duration runs continuously for 1-15 seconds every 15 minutes, with a harvest period of 45 days plus a seedling period of 6-8 days until the seedlings grow 4 leaves [4]. From the data obtained in previous research, it can be concluded that farmers need to pay attention to the root misting system and monitor the temperature and humidity conditions of plant roots, thus requiring automatic watering with temperature and humidity control for the roots. Additionally, the height of the nutrient solution used should also be monitored so that the pump can operate more effectively, as the pump used for misting can only draw water to a certain height. Due to the limited data regarding plant conditions that can serve as a reference for aeroponic farmers, monitoring for remote observation is necessary, including recording temperature and humidity values as well as nutrient solution height, which will facilitate real-time monitoring of plant conditions by farmers [5].

The problem-solving approach in this research is based on the results of previous studies related to controlling the temperature and humidity of plant roots in aeroponic systems and monitoring plant conditions. The solution to address the complexity of the plant environment caused by climate fluctuations in the aeroponic planting method involves an approach derived from prior research. This approach includes automatic watering utilizing fuzzy logic as the main method in this study for automated plant irrigation control. The use of fuzzy logic in this research functions to manage uncertainties in sensor data by classifying it based on environmental changes to enhance plant quality. Classification in fuzzy logic is essential to achieve sufficient accuracy in nutrient misting at the plant roots to avoid excess or deficiency.

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The actuators in the control system generated by fuzzy logic are a DC jet pump and a mini fan, which function to regulate temperature and humidity within the growing box. Temperature and humidity values are obtained from the DHT-22 sensor, while the height of the nutrient solution is measured using the HC-SR04 sensor. Monitoring is done using an IoT (Internet of Things) approach with the ESP32 as the microcontroller, which can connect to Wi-Fi to transmit data obtained from the sensors to electronic devices capable of sending data over the internet [5]. This makes it easier for farmers to monitor plant conditions remotely using a smartphone integrated with the internet.

2. Related Work

Aeroponic cultivation has become one of the most promising technologies in modern agriculture because it enables plants to grow without soil while significantly reducing water and nutrient consumption. In aeroponic systems, plant roots are suspended in air and periodically sprayed with nutrient-rich mist, allowing efficient oxygen absorption and accelerating plant growth. Previous studies have demonstrated that aeroponic cultivation offers higher productivity than conventional soil-based farming while requiring considerably less cultivation area [6]. These advantages make aeroponic systems particularly suitable for urban farming and controlled environment agriculture. Despite these benefits, maintaining optimal environmental conditions remains one of the primary challenges in aeroponic cultivation. Temperature and relative humidity directly influence plant transpiration, nutrient uptake, photosynthetic efficiency, and overall crop development [7]. Environmental fluctuations caused by weather variations or greenhouse conditions may reduce plant growth and increase the risk of disease. Consequently, automatic environmental control systems have become an important component of smart agriculture.

The rapid advancement of the Internet of Things (IoT) has significantly improved the capability of environmental monitoring systems. IoT-based agricultural platforms integrate environmental sensors, wireless communication, cloud computing, and embedded controllers to provide real-time monitoring and remote management of cultivation systems. Sensors continuously collect environmental data that are processed by microcontrollers before being transmitted to web or mobile applications for visualization and analysis. Such systems improve operational efficiency while reducing labor requirements.

Although IoT technology provides reliable monitoring capabilities, intelligent decision-making algorithms are required to regulate environmental conditions automatically. Conventional threshold-based controllers generally operate using fixed setpoints. These methods are simple to implement but often produce oscillatory actuator behavior because they cannot adequately represent the nonlinear characteristics of agricultural environments. As environmental variables continuously fluctuate, threshold-based control frequently causes excessive actuator switching, reducing both system stability and component lifetime.

Artificial intelligence techniques have therefore become increasingly popular in smart agriculture. Among these techniques, fuzzy logic has attracted considerable attention because it effectively represents human reasoning without requiring complex mathematical models. Instead of relying on precise equations, fuzzy logic utilizes linguistic variables and expert knowledge to describe system behavior under uncertain conditions. This characteristic makes fuzzy logic particularly suitable for environmental control applications where multiple variables interact simultaneously. Several fuzzy inference methods have been proposed, including Mamdani, Sugeno, and Tsukamoto. The Mamdani method is widely recognized for its intuitive rule representation but generally requires computationally intensive defuzzification procedures [8]. The Sugeno method offers computational efficiency by producing mathematical output functions, making it suitable for optimization and adaptive control applications [9]. In contrast, the Tsukamoto method employs monotonic membership functions that generate crisp outputs from each inference rule, allowing efficient real-time implementation on embedded microcontrollers while maintaining relatively low computational complexity [10].

Previous studies have successfully applied fuzzy logic to greenhouse climate regulation, irrigation scheduling, hydroponic nutrient management, and smart farming systems. Most reported improvements include better environmental stability, reduced water consumption, and increased crop productivity compared with manual operation. However, many existing studies primarily focus on monitoring environmental parameters rather than implementing adaptive automatic control. Furthermore, several systems utilize only a single environmental variable, limiting their capability to respond to dynamic cultivation conditions. Recent developments in low-cost embedded systems have enabled the integration of fuzzy controllers into compact agricultural platforms. Microcontrollers such as the ESP32 provide sufficient processing capability to perform real-time fuzzy inference while simultaneously managing multiple sensors and actuators. Combined with wireless connectivity, these platforms offer affordable solutions for intelligent

agriculture, particularly for small-scale farmers and educational research laboratories. Although numerous studies have investigated fuzzy-based environmental control, relatively few have implemented the Fuzzy Tsukamoto algorithm for simultaneous temperature and humidity regulation in aeroponic Pakcoy cultivation. Most previous systems emphasize greenhouse applications or hydroponic cultivation rather than compact aeroponic environments. In addition, comprehensive evaluations involving sensor accuracy, control performance, and prototype implementation remain limited.

To address these limitations, this study proposes an intelligent environmental control system that combines temperature and humidity sensing with the Fuzzy Tsukamoto inference algorithm in an embedded ESP32 platform. Unlike conventional threshold-based approaches, the proposed system continuously adapts actuator operation according to changing environmental conditions, enabling more stable cultivation environments and reducing manual intervention. The integration of real-time sensing, intelligent decision making, and automatic environmental regulation represents the primary contribution of this work toward low-cost smart agriculture systems.

3. Method

This research uses the R&D (Research and Development) method to enhance knowledge and develop existing products. This method also provides an understanding of research involving hardware and software through a needs analysis procedure, followed by the development phase and concluded with evaluation. According to Borg and Gall, the meaning of this research model is a process used to develop and validate educational products [11].

3.1 Schematic Diagram

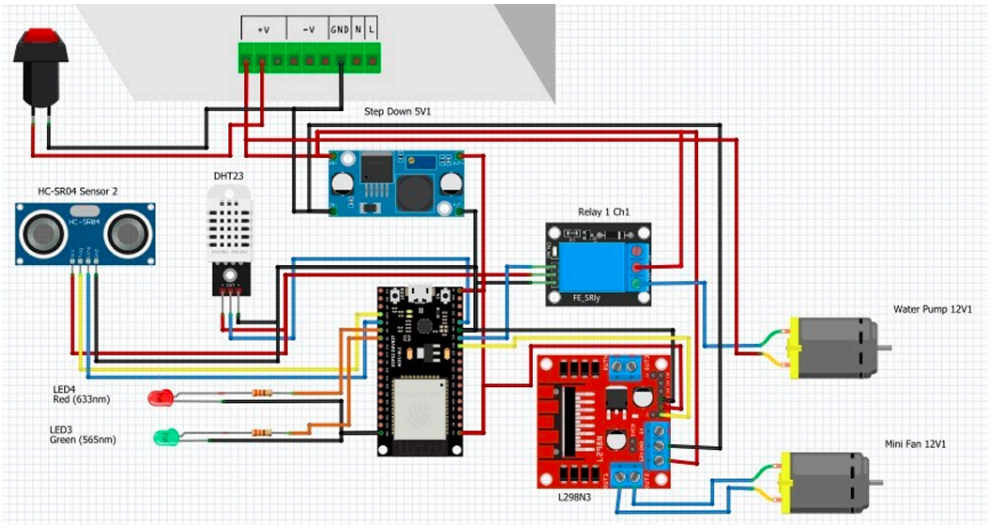

Fig.1 Schematic Diagram

The electronic circuit was designed based on the functional requirements of each component to support the automated monitoring and control processes. The system is powered by a 12 V power supply equipped with a switch button that functions as the main power switch to turn the system on and off. The output voltage from the power supply is distributed directly to the L298N motor driver through its 12 V and GND terminals and to a 12 V-to-5 V step-down converter via the Vin (+) and Vin (−) terminals to provide a regulated 5 V supply for components requiring lower operating voltages.

The ESP32 microcontroller serves as the central controller, coordinating data acquisition from the sensors and controlling all actuators. The ESP32 interfaces with a single-channel relay module, L298N motor driver, red and green indicator LEDs, DHT22 temperature and humidity sensor, and HC-SR04 ultrasonic sensor through dedicated GPIO pins according to their respective functions.

The DHT22 sensor is employed to measure ambient temperature and humidity. It is connected to the ESP32 with the VCC pin supplied by 5 V, the GND pin connected to ground, and the data pin connected to GPIO 13. Meanwhile, the HC-SR04 ultrasonic sensor is used for distance measurement and is connected through the 3.3 V, GND, TRIG (GPIO 15), and ECHO (GPIO 2) pins.

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Actuator control is performed using the L298N motor driver, which receives control signals from GPIO 14 of the ESP32. The driver operates a mini fan connected to the OUT1 and OUT2 terminals of the L298N. Additionally, the single-channel relay module is connected to the 3.3 V, GND, and GPIO 12 pins of the ESP32 to control electrical loads according to the predefined control logic implemented in the software.

All hardware components are integrated into a single electronic system, enabling coordinated operation from sensor data acquisition and processing by the ESP32 to automatic actuator control based on real-time environmental conditions. The detailed schematic diagram is shown in Figure 1.

3.2 Voltage Flow Design

The voltage flow design is used to determine the voltage pathway starting from the 12V 5A power supply. Based on the flowchart created, the voltage is divided into two pathways: 12V to power the L298N motor driver for the 12V mini fan and the DC pump. Meanwhile, the voltage is stepped down to produce 5V for the ESP32 microcontroller, which will supply power to the DHT22 sensor, HC SR04 sensor, green and red LED indicators, and a 1-channel relay. This voltage flow design serves to map the components that require 5V power, thus minimizing the risk of short circuits. The voltage block diagram is presented in Figure 2.

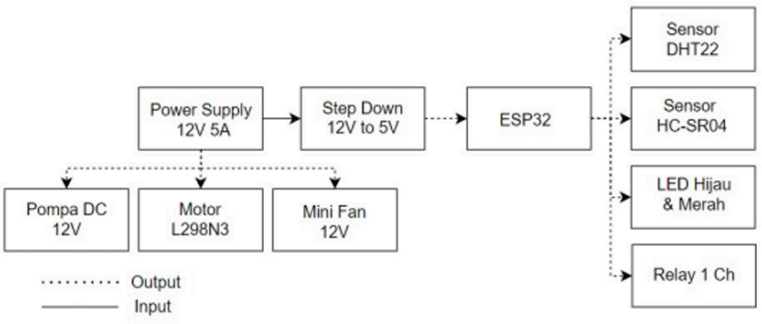

Fig.2 Voltage Block Diagram

3.3 3D Design of the Aeroponic Prototype

The prototype of the aeroponic temperature and humidity control system was designed using Tinkercad to create a three-dimensional (3D) visualization as a reference for the hardware development process. The prototype consists of two separate compartments with distinct functions. The first compartment serves as the aeroponic growing chamber and is constructed from transparent material to facilitate visual observation of the nutrient spraying process on the plant roots. The nutrient delivery system employs spray nozzles positioned beneath the suspended roots, with one nozzle assigned to each plant to ensure uniform nutrient atomization. In addition, a 12 V mini fan and a DHT22 temperature and humidity sensor are installed inside the growing chamber to support environmental monitoring and climate control. Figure 3 shows the 3D design of the proposed aeroponic system.

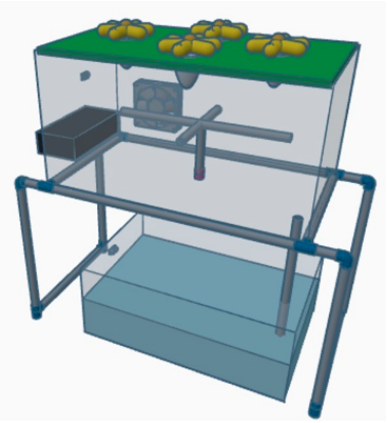

Fig.3 3D Design of Proposed Aeroponic System

The second compartment functions as the nutrient solution reservoir. After the nutrient solution is sprayed onto the plant roots in the growing chamber, the excess solution is returned to the reservoir through a

recirculation system, preventing nutrient accumulation within the cultivation chamber. An HC-SR04 ultrasonic sensor is installed in the reservoir to monitor the nutrient solution level continuously. Meanwhile, the electronic control unit, which houses the microcontroller and supporting electronic components, is placed in a separate enclosure outside the aeroponic system to protect it from water splashes generated during the spraying process.

The separation of the growing chamber, nutrient reservoir, and electronic control unit was intentionally implemented to improve system reliability and measurement accuracy. Positioning the DHT22 sensor inside the growing chamber enables accurate measurements of the environmental temperature and humidity surrounding the plant roots, thereby providing reliable input data for the fuzzy logic controller. Similarly, placing the HC-SR04 sensor in the nutrient reservoir prevents exposure to the mist generated by the spray nozzles, reducing the risk of measurement errors and potential sensor damage. The prototype is supported by a 35 cm-high PVC frame with a table-like structure, while the DC water pump is positioned adjacent to the electronic control unit to facilitate nutrient solution delivery to the spraying system.

3.4 Tsukamoto Fuzzy

The method used is the Tsukamoto fuzzy method. The selection of the Tsukamoto method is based on the consideration that the Mamdani and Sugeno methods have been used in previous re search, making Tsukamoto a choice for further research development. The Tsukamoto fuzzy method also has advantages in terms of simplicity of objective selection using IF-THEN rules, as it produces linear outputs, which facilitates implementation and understanding. This differs from decision making with classical logic, which emphasizes true or false values (0 or 1). Fuzzy logic makes decisions based on membership to measure the value of a statement or action.

Table 1. Temperature and Humidity Membership Function Intervals

Variable	Interval
Temperature – Cold	[15, 15, 18, 21]
Temperature – Normal	[20, 22.5, 25]
Temperature – Hot	[24, 28, 32, 32]
Humidity – Dry	[0, 0, 32.5, 65]
Humidity – Humid	[60, 72.5, 85]
Humidity – Wet	[80, 100, 100]

Table 1 presents the fuzzy membership functions used to transform numerical temperature and humidity measurements into linguistic variables during the fuzzification process. Each input variable is represented by three overlapping fuzzy sets, enabling smooth transitions between adjacent membership functions and providing more flexible decision-making than conventional threshold-based methods.

For the temperature variable, three fuzzy sets are defined: Cold, Normal, and Hot. The Cold membership function is represented by the interval [15, 15, 18, 21], indicating that temperatures below 15 °C have full membership ($\mu = 1$), while the membership value gradually decreases to zero at 21 °C. The Normal fuzzy set is defined by the interval [20, 22.5, 25], where the membership value increases from 20 °C, reaches its maximum at 22.5 °C, and decreases to zero at 25 °C. Meanwhile, the Hot fuzzy set is represented by the interval [24, 28, 32, 32], where the membership value begins to increase at 24 °C, reaches full membership at 28 °C, and remains fully active up to 32 °C.

Similarly, the humidity variable is divided into three fuzzy sets: Dry, Humid, and Wet. The Dry membership function is defined by the interval [0, 0, 32.5, 65], indicating high membership values at low humidity levels that gradually decrease to zero at 65%. The Humid fuzzy set is represented by the interval [60, 72.5, 85], with the highest membership value occurring at 72.5%, corresponding to the optimal environmental humidity for the aeroponic system. The Wet membership function is defined by the interval [80, 100, 100], where the membership value increases from 80% and reaches full membership at 100% relative humidity. The temperature and moisture level membership functions are shown in Figure 4 and Figure 5.

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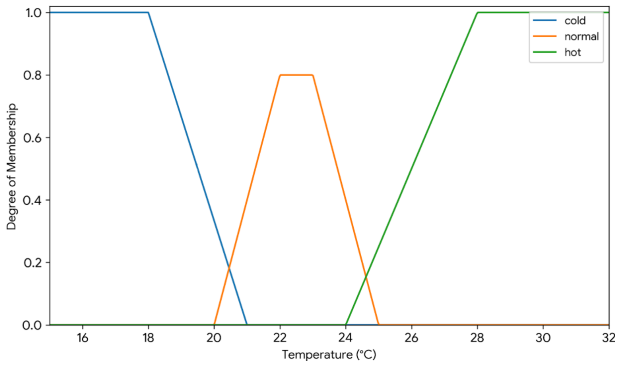

Fig. 4 Temperature Membership Functions

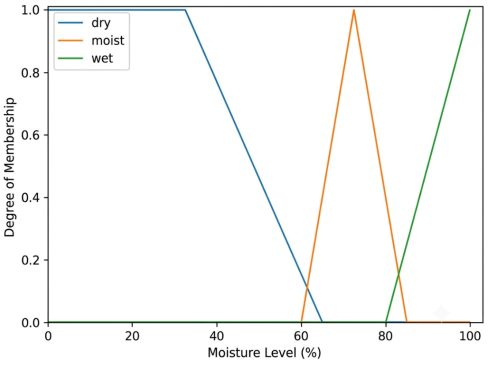

Fig.5 Moisture Level Membership Functions

The overlap between adjacent fuzzy sets allows a single sensor reading to simultaneously belong to multiple linguistic categories with different degrees of membership. For example, a temperature of 20.5 °C may partially belong to both the Cold and Normal fuzzy sets. This overlapping characteristic is one of the primary advantages of fuzzy logic, as it effectively represents gradual transitions observed in real-world environments and avoids abrupt changes in system responses.

Overall, the fuzzy intervals defined in Table 1 serve as the basis for the fuzzification process, in which crisp sensor measurements are converted into linguistic variables. These linguistic values are subsequently processed during the fuzzy inference stage to determine the appropriate control actions, such as regulating the cooling fan and nutrient spraying system, thereby maintaining optimal environmental conditions within the aeroponic cultivation system.

Table 2. Spraying Duration Based on Temperature and Humidity Conditions

Rule	Input	Spraying Duration (s)
1	Temperature **Cold** & Humidity **Dry**	Fast (5 s)
2	Temperature **Cold** & Humidity **Humid**	Normal (10 s)
3	Temperature **Cold** & Humidity **Wet**	Slow (15 s)
4	Temperature **Normal** & Humidity **Dry**	Normal (10 s)
5	Temperature **Normal** & Humidity **Humid**	Slow (15 s)
6	Temperature **Normal** & Humidity **Wet**	Slow (15 s)
7	Temperature **Hot** & Humidity **Dry**	Slow (15 s)
8	Temperature **Hot** & Humidity **Humid**	Normal (10 s)
9	Temperature **Hot** & Humidity **Wet**	Fast (5 s)

Table 2 presents the fuzzy rule base used by the proposed fuzzy inference system to determine the operating time of the nutrient spraying system and the rotational speed of the cooling fan based on the measured temperature and humidity conditions. The rule base consists of nine IF–THEN rules, which are derived from the combination of three temperature fuzzy sets (Cold, Normal, and Hot) and three humidity fuzzy sets (Dry, Humid, and Wet). Each rule produces two output variables: the spraying duration and the PWM value controlling the fan speed.

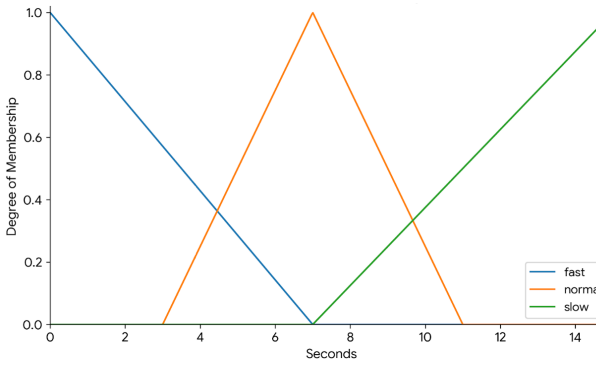

Fig.6 Spraying Duration Membership Function

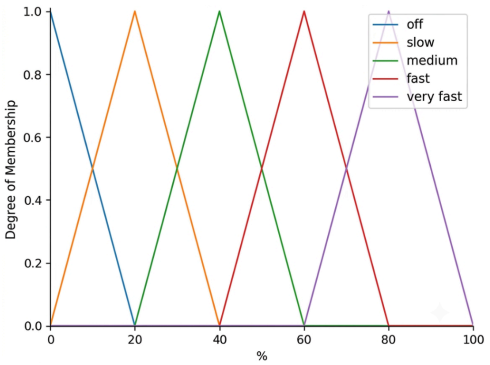

Fig.7 Membership Function for Fan Speed

The rules are formulated based on expert knowledge and the environmental requirements of the aeroponic cultivation system. When the environmental conditions are cold and dry (Rule 1), the spraying duration is set to Fast (5 s) while the fan operates at a Medium speed (PWM = 50). Under cold and humid conditions (Rule 2), the spraying duration is increased to Normal (10 s) while maintaining the same fan speed. If the environment is cold and wet (Rule 3), the spraying duration becomes Slow (15 s) and the fan speed is increased to High (PWM = 100) to reduce excessive humidity.

For normal temperature, the controller adjusts the outputs according to the humidity level. Under dry conditions (Rule 4), the spraying duration is Normal (10 s) and the fan is turned Off (PWM = 0). When the humidity is Humid (Rule 5), the spraying duration is increased to Slow (15 s) while the fan operates at a Medium speed (PWM = 50). Under Wet conditions (Rule 6), the spraying duration remains Slow (15 s), whereas the fan speed is increased to High (PWM = 100) to enhance air circulation.

When the temperature is classified as Hot, the controller prioritizes reducing the environmental temperature. Under dry conditions (Rule 7), the spraying duration is Slow (15 s) and the fan remains Off. When the humidity is Humid (Rule 8), the spraying duration is Normal (10 s) and the fan operates at a High speed (PWM = 100). Finally, under hot and wet conditions (Rule 9), the controller activates the Fast spraying duration (5 s) and the Very High fan speed (PWM = 255), representing the maximum cooling effort of the system. The spraying and fan speed duration membership function is presented in Figure 6 and Figure 7.

3.5 Monitoring Design

The monitoring design in this research uses the Blynk application with Wi-Fi connectivity. Based on the flowchart above, monitoring begins by initializing the ESP32, then connecting the ESP32 to the Blynk IoT application. If the connection is successful, the ESP32 will repeat the connection process. Once the ESP32 is connected to the Blynk IoT application, the device will operate, and the ESP32 will start reading the temperature and humidity from the DHT22 sensor, as well as the liquid level from the HC-SR04 sensor. Subsequently, the ESP32 will send the sensor data to the Blynk IoT application to be displayed on the Blynk IoT dashboard. The choice to use the Blynk application is based on several recommendations from previous studies, including the ease of access when switching devices, as the data remains stored in the cloud and can be accessed from other devices without losing information. Additionally, Blynk has a delay of around 3-5 seconds, allowing for real-time monitoring of sensor data. This application also supports stable connections with IoT devices like the ESP32 and features a user-friendly interface for monitoring and controlling devices. Monitoring is conducted by connecting the ESP32 to an Android device by entering the username and password provided in the Android personal hotspot.

4. Result and Discussion

4.1 Sensor Test

The temperature measurements obtained from the DHT22 sensor were compared with those recorded using a thermohygrometer as the reference instrument. The measurement difference ranged from 0.1 to 0.3 °C, with an average error of 0.79%. Based on the average percentage error, the sensor achieved an overall measurement accuracy of 99.21%, indicating good agreement with the reference instrument and demonstrating that the sensor is sufficiently reliable for temperature monitoring applications.

Table 3. Temperature Measurement Accuracy of the DHT22 Sensor

Minute	Sensor (°C)	Thermohygrometer (°C)	Difference	Error (%)
5	25.6	25.3	0.3	1.19
10	25.7	25.4	0.3	1.18
15	25.5	25.3	0.2	0.15
20	25.5	25.4	0.2	0.39
25	25.6	25.4	0.2	0.79
30	25.6	25.5	0.1	0.39
Average Error				**0.79**

The humidity measurements which presented in Table 3 obtained from the sensor were compared with those recorded using the thermohygrometer as the reference instrument. The measurement difference ranged from 0 to 0.9%RH, with an average error of 0.34%. Based on this result, the sensor achieved an overall measurement accuracy of 99.66%, indicating a high level of agreement with the reference instrument and demonstrating that the sensor is reliable for relative humidity monitoring. The temperature and humidity measurement accuracy of the DHT22 sensor are shown in table 3 and table 4.

Table 4. Humidity Measurement Accuracy of the DHT22 Sensor

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Minute	Sensor (%RH)	Thermohygrometer (%RH)	Difference	Error
5	99	99	0	0
10	98.9	98	0.9	0.91
15	98.4	98	0.4	0.40
20	98	98	0	0
25	97.5	97	0.5	0.51
30	97.2	97	0.2	0.20
Average error value				**0.34**

The ultrasonic sensor measurements were compared with those obtained using a ruler as the reference instrument. The measurement differences ranged from 0 to 1.0 cm, with an average error of 0.46 cm. Based on the average error, the sensor achieved an estimated measurement accuracy of 99.54%, indicating good agreement with the reference measurements and demonstrating that the ultrasonic sensor is suitable for distance monitoring applications. The distance measurement accuracy of the ultrasonic sensor can be found in table 5.

Table 5. Distance Measurement Accuracy of the Ultrasonic Sensor

Minute	Sensor (CM)	Ruler (CM)	Difference
5	11.5	10.8	0.7
10	11.1	10.5	0.6
15	11.1	10.1	1
20	10.5	10.1	0.4
25	10.1	10.1	0
30	10.1	10	0.1
Average error value			**0.46**

4.2 System Testing

The aeroponic prototype was designed with a multi-tier structure to maximize land-use efficiency while maintaining a compact cultivation system. The supporting frame was constructed from polyvinyl chloride (PVC) pipes, providing adequate structural strength and stability for the overall system. The completed aeroponic prototype is shown in Figure 8.

Fig.8 Implementation of the Aeroponic System Prototype

The testing of the entire system aims to determine whether there are any errors in the actuators during sensor readings and fuzzification. The temperature and humidity data collected are those displayed in the Blynk application, sent by the ESP32 microcontroller. The actuators involved are the pump and mini fan, which operate based on commands received after fuzzy processing. The testing was conducted over several days to achieve optimal results in accordance with the design. Below is the table of temperature and humidity control testing conducted over 105 minutes with 7 cycles of misting.

Table 6. Experimental Results of the Fuzzy Control System

Minute	Temperature (°C)	Humidity (%RH)	Fuzzy Pump (s)	Fuzzy Fan (PWM)
15	27.7	97.6	5	Very Fast (255)
30	27.5	87.7	10	Fast (100)

45	26.9	93.0	10	Fast (100)
60	26.8	96.1	10	Fast (100)
75	26.7	97.5	10	Fast (100)
90	26.4	98.2	10	Fast (100)
105	26.2	98.4	10	Fast (100)

Table 6 summarizes the performance of the proposed fuzzy control system over a 105-minute observation period. The recorded temperature gradually decreased from 27.7 °C to 26.2 °C, indicating that the control strategy effectively reduced the environmental temperature toward the desired operating range. Meanwhile, the relative humidity remained consistently high, fluctuating between 87.7%RH and 98.4%RH, which is suitable for aeroponic cultivation where high humidity is required to maintain healthy root development.

The fuzzy controller dynamically adjusted the spraying duration and fan speed according to the measured environmental conditions. At the beginning of the experiment (15 min), when both temperature and humidity were relatively high, the controller activated the pump for 5 s and operated the fan at the maximum PWM value (255) to rapidly stabilize the environment. As the temperature gradually decreased, the controller reduced the fan speed to PWM 100 while maintaining a 10 s spraying duration for the remainder of the experiment. This adaptive response demonstrates that the fuzzy inference system successfully modified the control outputs based on real-time sensor inputs rather than relying on fixed threshold values.

Overall, the experimental results indicate that the proposed fuzzy control algorithm provided stable environmental regulation by continuously adapting the pump operation and fan speed to changing temperature and humidity conditions. The gradual reduction in temperature without abrupt fluctuations suggests that the fuzzy-based control approach is effective for maintaining suitable environmental conditions in the aeroponic cultivation system.

4.3 Monitoring Testing

The purpose of the monitoring test is to check whether data is transmitted while the device is powered on, the Wi-Fi distance between the smartphone and the device, and to verify if the datastream readings are displayed while the device is running. The monitoring created in the Blynk application displays information in the form of temperature and humidity data obtained from the DHT22 sensor, as well as water level measurements using the HC-SR04 sensor, all presented in real-time. The programming developed commands the ESP32 to read and then send data from the sensors while the device is powered on.

Fig. 11. Aeroponic Monitoring Display

Fig.9 Aeroponic Monitoring Dashboard

The Blynk application successfully transmitted sensor data continuously while the device remained powered on. The monitoring system was able to display real-time environmental parameters, including temperature,

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relative humidity, and water level. In addition, the application provided graphical representations of the collected sensor data, enabling users to observe changes in environmental conditions over time. The monitoring results demonstrate that the developed system can reliably transmit, display, and visualize sensor data through the Blynk platform, as shown in Figure 9**.**

5. Conclusion

The proposed prototype of an automatic temperature and humidity control system for an aeroponic cultivation environment was successfully developed and implemented using a fuzzy logic controller. The experimental results demonstrated that the system was capable of maintaining the environmental temperature and humidity within the ranges required for optimal pakcoy growth under aeroponic conditions. The developed monitoring system, integrated with the Blynk IoT platform, successfully displayed real-time measurements of temperature (°C), relative humidity (%RH), and nutrient solution level (cm). Communication between the ESP32 microcontroller and the Blynk application exhibited an average latency of approximately 4 s, which was considered acceptable for real-time environmental monitoring.

Performance evaluation indicated that the proposed system achieved measurement accuracies of 99.2% for temperature, 99.6% for relative humidity, and 99.5% for nutrient solution level. Furthermore, the actuators, including the water pump and 12 V mini fan, operated according to the predefined fuzzy inference rules, enabling adaptive environmental control. During the experiment, the system successfully reduced the chamber temperature from 27.7 °C to 25.2 °C while maintaining the relative humidity within the range of 87%–90%, thereby creating favorable conditions for aeroponic cultivation.

In addition, the water-level indicator function operated as intended. The green LED was activated when the nutrient solution level exceeded 20 cm, whereas the red LED was illuminated when the water level dropped below 20 cm, indicating that the monitoring and warning functions performed correctly in accordance with the programmed control logic.

Author Contribution:

Fitria Alysa Yasmin: developed the hardware and software system, data collection, data analysis, interpretation of the results, and prepared the initial manuscript. Purno Tri Aji: preparation of the manuscript, and review and revision of the manuscript.

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Conflicts of Interest:

The authors declare no conflict of interest.

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