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Impact of Smart Greenhouse Using IoT for Enhanced Quality of Plant Growth

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ABSTRACT

Greenhouses play a crucial role in manipulating environmental conditions for optimal plant growth. While existing greenhouses enhance control over environmental factors, manual controls such as watering and humidity regulation often lead to suboptimal production and increased costs. This study proposes the development of a smart greenhouse with an automatic control system using fuzzy logic, specifically fuzzy Sugeno, to regulate watering and lighting based on soil moisture, temperature, and light intensity. The system's architecture involves sensor inputs, microcontroller processing, and the activation of actuators, such as UV lights and water pumps. Fuzzy logic is applied to interpret soil moisture and temperature inputs and determine optimal irrigation durations. The system's functionality is tested and validated through functional testing, Blynk application testing, and fuzzy Sugeno testing. Results indicate the successful implementation of the proposed smart greenhouse system. Functional testing demonstrates accurate sensor readings, including temperature and soil moisture. The Blynk application enables real-time monitoring and control of environmental conditions. Fuzzy Sugeno testing validates the irrigation control system, with an average error rate of 1.3%, affirming the system's alignment with desired specifications. Plant testing in different conditions showcases the effectiveness of the smart greenhouse in supporting plant growth and development.

1. Introduction

A greenhouse, known as "rumah kaca" in Indonesia, is generally defined as a structure designed to manipulate the environmental conditions for desired plant growth [1], [2]. In its use, a greenhouse demonstrates that the environment becomes more controlled, leading to more optimal yields compared to crops grown without the use of a greenhouse [3], [4]. Environmental conditions within a greenhouse, such as temperature, humidity, and light, can be controlled according to the growth requirements of the cultivated plants [5]-[8]. However, greenhouse construction has not yet fully adapted to the required climate due to the prevalence of manual controls, such as watering plants and humidity regulation [9]. This can result in quantity of production, accompanied by high costs. Considering the advancements in technology, particularly in the field of the Internet of Things (IoT) [10], [11], can be applied to greenhouses, enabling automatic control and remote monitoring [12], [13].

Numerous studies have been conducted by researchers related to the use of IoT to control environmental conditions in greenhouses, including research conducted by Sujin et al. (2021), discussing an IoT-based greenhouse control system. The system in this study monitors and controls environmental parameters in the greenhouse, such as temperature, humidity, and light intensity, through IoT [14]. NodeMCU esp8266 sends data to the cloud by activating actuators if parameters exceed set limits [15]. The research also includes mechanisms for managing soil humidity and controlling cooling and lighting systems. The results can be monitored through mobile phones and desktops. The system utilizes Arduino as the main controller with sensors like DHT11 [16] and LDR. In this research, it is concluded that the system is effective for monitoring and controlling the greenhouse, reducing physical activities and applicable in various locations. However, there are some shortcomings in this study, such as the use of on-off control in the system, leading to results that may not align with the desired set points.

The study by Mohabuts et al. (2023) discusses an IoT model for monitoring plant growth in a greenhouse [17]. The research suggests that IoT can be effectively utilized as a tool for automatically monitoring and controlling plant growth in unstable climatic conditions [18]. Despite the prevalent use of traditional greenhouse systems, there is still a need for technological integration. Traditional systems are susceptible to manual intervention, pose risks, and require accurate data to maintain plant health. Thus, the study introduces an automated greenhouse model with a microcontroller as the main controller, sensors, fans, and pumps designed to enhance yields and reduce human intervention [19]. This model is applicable in real-world environments with 240V AC power and allows for remote monitoring. Future developments, including mobile application versions and advanced component integration, could enhance system functionality. However, the study does not delve into the specific controls used to monitor the greenhouse environment, potentially limiting the attainment of desired real-time conditions, even though the system can be implemented in real-time [20]. Additionally, the monitoring of this system cannot be conducted using mobile devices.

The research conducted by Oguntosin et al. (2023) on an IoT-based Greenhouse Monitoring and Control System highlights a comparison between conventional farming and greenhouse farming [21]. Conventional farming requires high-frequency manual monitoring of various environmental parameters, often irregularly and less productively. In contrast, greenhouse farming integrates IoT technology for automatic monitoring and control, utilizing sensors such as temperature, humidity, light intensity, and soil moisture, along with an ESP32 development board with WiFi functionality [22]. With this automation, the greenhouse can be remotely controlled through the Internet of Things (IoT), providing an optimal environment for plant growth [23]. The study details the design and construction of a model greenhouse using wood and plastic film as covering, considering time efficiency and contributions to the Nigerian economy by ensuring year-round food availability. The data generated from this system can be used for further research to enhance the agricultural sector. However, the research conducted by Oguntosin et al. does not delve into the control mechanisms used, even though remote monitoring is possible, potentially limiting the effectiveness of the results.

The research by Dubey et al. (2021), focuses on IoT-based monitoring and control of greenhouse environments using Arduino. According to their findings, a greenhouse is an area with a controlled climate for optimal plant growth [24]. The aim of this study is to design a simple and cost-effective Arduino-based system to monitor and control environmental parameters in the greenhouse, such as temperature, humidity, soil moisture, light intensity, and soil pH. Key sensors, including DHT11, soil moisture, LDR, and pH sensors, simultaneously provide these values [25], [26]. All environmental parameters are sent online to an Android phone via Ethernet, and SMS notifications through a GSM modem alert users when sensor values exceed predefined limits. Farmers can control the system and actuators (fans, water pumps, lights, etc.) via SMS from anywhere. Ethernet is also utilized to send data to a server and store it in a database, enabling users to monitor and control parameters through a mobile application on Android using Blynk [27], [28]. The system does not discuss the use of control settings for greenhouse environmental conditions, indicating that optimization for desired set points has not been achieved yet.

Yajie Liu's (2022) research focuses on monitoring and controlling a smart greenhouse based on NodeMCU, addressing issues of food security due to a large human population and limited agricultural land, especially in uncertain situations like the rapid spread of COVID-19 [29]. To overcome these challenges, the study proposes a smart and cost-effective greenhouse monitoring and control system, utilizing sensors, actuators, an LCD display, and a microcontroller. The DHT22 sensor is employed to measure temperature and humidity in the greenhouse, with NodeMCU serving as the main microcontroller [30], [31]. Additional features, such as fans and heaters, are used to regulate the environment. The system is connected to the internet to monitor the growth environment and store data in the Thing Speak cloud. Users can view data directly through a web interface or a mobile application. If environmental conditions exceed predefined limits, the system can be adjusted automatically. Data analysis in the study shows a negative relationship between temperature and humidity. However, the research does not incorporate a control system, such as machine learning technology or fuzzy logic [32], that would enable the system to predict and adjust conditions automatically, reducing the risk of losses and human involvement.

From several descriptions of the above research, many studies are still related to smart Greenhouse that have not yet used an automatic control system that can regulate equipment in the greenhouse environment, such as machine learning technology, fuzzy logic, or other control systems [33], [34]. Therefore, in this study, an automatic control system is developed to regulate the watering and lighting of plants automatically based on soil moisture, room temperature, and incoming light intensity using fuzzy logic, especially fuzzy Sugeno. The system applied in the greenhouse is called a smart greenhouse [35]. The goal of developing this system is to facilitate and save time in managing the conditions of plants that require water, lighting, and other factors, where all monitoring factors and results are displayed on an LCD screen integrated with the system inside the greenhouse.

The discussion of this research paper is organized into four parts. The first part discusses previous research so that contributions made in this study can be identified. Part two examines the system design and research methods used. Part three explains the results of the experiments conducted, and part four concludes the findings and briefly provides further suggestions for improving this paper. Through this research, it is expected that the use of fuzzy logic control will ensure that the control of conditions in the greenhouse environment operates according to the desired conditions [36].

2. Method

2.1. System Design

The fuzzy control system to be designed will use the main inputs of soil moisture and temperature [37], [38]. The light sensor input will be used to automatically control the UV lights inside the greenhouse. The ultrasonic sensor HCSR04 input will be used to measure water height as an alarm when the water is depleted [39]. The sensor inputs will be processed by the microcontroller. The microcontroller will then control the UV lights, buzzer, and pump based on user-desired inputs, as seen in Fig. 1.

Fig. 2 explains the overall system architecture design. The system works by first reading the conditions in the greenhouse when the device is active. All sensor readings will be displayed on the LCD so that users can see the sensor values when the device is first activated.

Then, the readings from the temperature and soil moisture sensors in the greenhouse are processed by the fuzzy logic controller, and the output is a delay in milliseconds. This delay is converted into seconds and used to provide a delay or active time for the DC motor when it is in an active state. In terms of irrigation, one fixed drip can release 16 litters of water per hour, which means that each second, the fixed drip will release 4.4 ml of water. The light sensor output will be used as a reference set value, which will be processed to automatically turn on the UV lights. Similarly, the distance sensor will be used to activate the buzzer when the water in the water storage is about to run out. All systems in this final project run in parallel, so there will be three plants running automatically with the sensor inputs specified in Fig. 2.

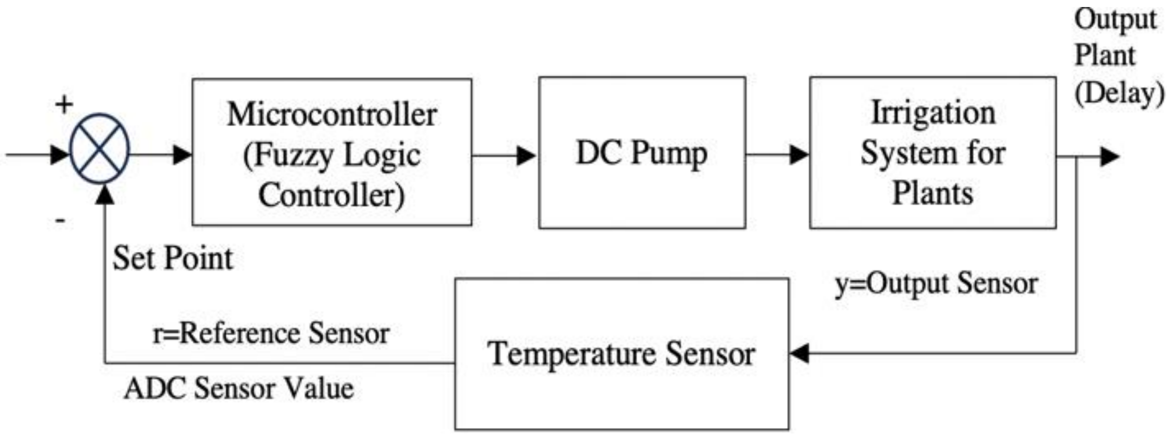


Fig. 1. System block diagram

Fig. 2. System architecture design

2.2. Fuzzy Design in the System

In this research, the Fuzzy Sugeno [40] method is employed to understand how the method functions in making decisions regarding the outputs of an IoT-based greenhouse system [41], [42]. In this study, the Fuzzy Sugeno method is specifically applied to the irrigation output using a water pump, focusing on chili plants. This choice is made due to the presence of two variables sensed by temperature and humidity sensors. For the environmental temperature cooling output using a fan and the light provision output using an LED strip, only one variable, temperature, is considered, and it is measured using a temperature sensor. The following outlines the programming design using the fuzzy method.

2.2.1. Fuzzification [43]

In this system, there are two types of variables, namely soil moisture and temperature [44]. Soil moisture variable has 3 criteria: dry, normal, and wet, while the temperature variable has 4 criteria: cold, cool, normal, and hot. From the generated results, 3 criteria are formed: fast, normal, and slow. The soil moisture variable has a measurement range from 0 to 100, representing the minimum and maximum average moisture. These values correspond to each input membership function of soil moisture, which is elaborated into 3 membership functions: dry, moist, and wet. Fig. 3 illustrates the membership functions of the soil moisture input [45].

Assuming the detected soil moisture value by the sensor is 66, then in Fig. 3, it can be observed that this value falls between moist and wet. If the value is manually calculated, the result will be obtained and illustrated as shown in Fig. 4.

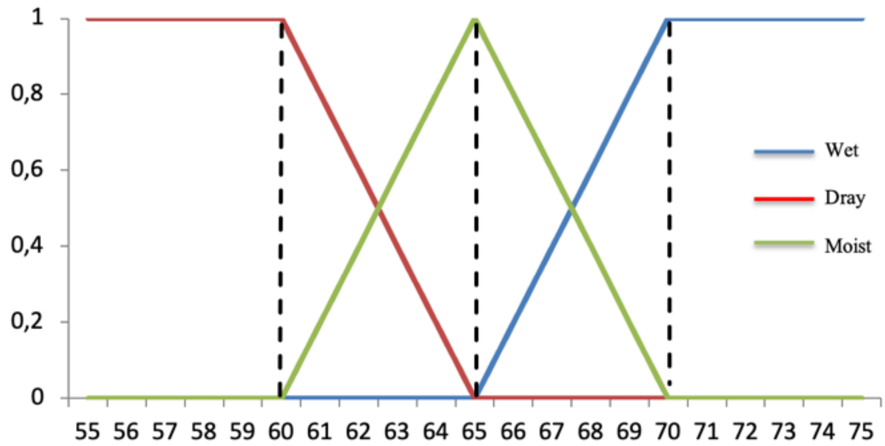


Fig. 3. Membership of soil moisture input

For Example, X = 66

U_moist = (c – x) / (c - b) = (70 – 66) / (70 – 65) = 4 / 5 = 0.8

U_wet = (x – a) / (b – a) = (66 – 65) / (70 – 65) = 1 / 5 = 0.2

Based on the calculations of the soil moisture variable, it can be concluded that the soil moisture value of 66 has a membership degree of 0.8 in the moist membership function and 0.2 in the wet membership function.

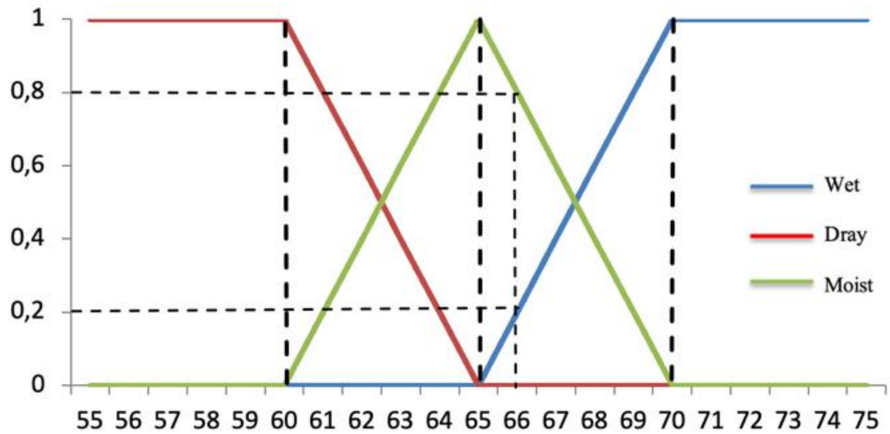


Fig. 4. Fuzzification condition of soil moisture

The temperature variable has a measurement range from 18°C to 30°C, representing the average values of the minimum and maximum temperatures. These values correspond to four membership functions: cold, cool, normal, and hot. Fig. 5 temperature input membership functions.

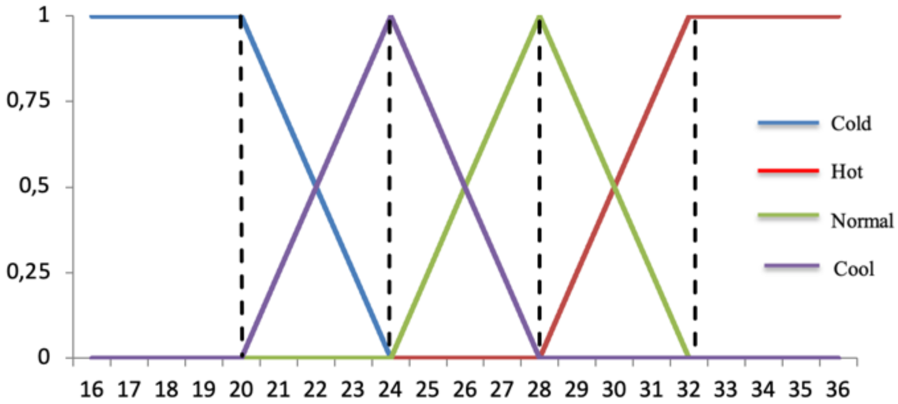


Fig. 5. Temperature input membership

If the assumed temperature value obtained by the sensor is 21°C, it can be seen in Fig. 5 that the value is located between cold and cool. If the value is manually calculated, the result will be obtained and illustrated as shown in Fig. 6.

For Example, X = 21

U_cold = (c – x) / (c – b)= (24 – 21) / (24 – 20) = 3/4 = 0.75

U_cool = (x – a) / (b – a) = (21 – 20) / (24 – 20) = 1/4 = 0.25

Based on the calculated temperature variable, it can be concluded that the temperature value of 21°C has a membership degree of 0.75 in the cold membership function and 0.25 in the cool membership function.

Time variable is a variable used as the final or output result obtained from the calculation of soil moisture variables and temperature variables. The time variable has a measurement range from 0 seconds to 10 seconds. These values represent each membership function of the temperature input, which is described by 3 membership functions: fast, moderate, and slow. Here is Fig. 7, which illustrates the membership function of the time variable.

2.2.2. Fuzzy Rule

The fuzzy rule process or inference is the process of combining rules based on data obtained from fuzzification results, resulting in the formation of 12 fuzzy sets as seen in Table 1.

Table 1. Fuzzy rule

Temp / Humidity	Cold	Cool	Normal	Hot
Dry	Medium	Medium	Long	Long
Moist	Fast	Fast	Medium	Medium
Wet	Fast	Fast	Fast	Fast

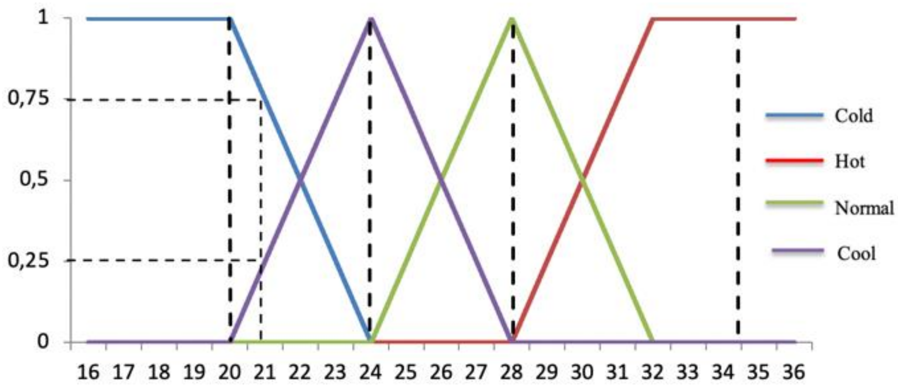


Fig. 6. Membership of soil moisture input

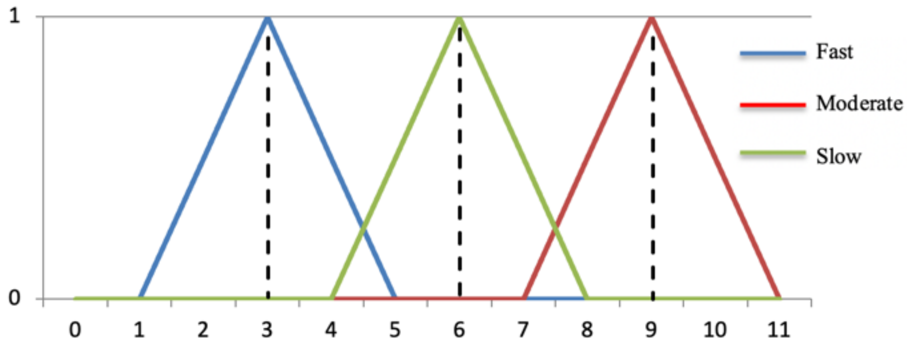


Fig. 7. Membership of the time variable

Based on the fuzzy rules provided in Table 1, the rules to be used in this research can be outlined as follows:

- (R1) If Dry Humidity AND Cool Temperature THEN Medium Time
- (R2) If Dry Humidity AND Mild Temperature THEN Medium Time
- (R3) If Dry Humidity AND Normal Temperature THEN Long Time
- (R4) If Dry Humidity AND Warm Temperature THEN Long Time
- (R5) If Moist Humidity AND Cool Temperature THEN Fast Time
- (R6) If Moist Humidity AND Mild Temperature THEN Fast Time
- (R7) If Moist Humidity AND Normal Temperature THEN Medium Time
- (R8) If Moist Humidity AND Warm Temperature THEN Medium Time
- (R9) If Wet Humidity AND Cool Temperature THEN Fast Time
- (R10) If Wet Humidity AND Mild Temperature THEN Fast Time
- (R11) If Wet Humidity AND Normal Temperature THEN Fast Time
- (R12) If Wet Humidity AND Hot Temperature THEN Fast Time

After formulating the rule base, the next step is to determine the implication function for each rule, which will then enter the defuzzification stage. In this study, the fuzzy method used is the Sugeno fuzzy method. The rules used in this method for implication functions involve using the MIN function and AND as the operator determining the smallest membership value. The formula is μA ∩ B = min (μA[x], μB[y]). Here are the explanations for some of the rules:

- (R5) If Moist Humidity AND Cool Temperature THEN Fast Time. α-Predicate 1 = μ Soil Humidity ∩ μ Temperature = min (μMoist [0.8] ∩ μCool [0.75]) = min(0.75)
- (R10) If Wet Humidity AND Mild Temperature THEN Fast Time. α – Predicate 1 = μ Soil Humidity ∩ μ Temperature = min(μWet [0.2] ∩ μMild [0.25]) = min(0.2)
- (R6) If Moist Humidity AND Mild Temperature THEN Fast Time. α – Predicate 1 = μ Soil Humidity ∩ μ Temperature = min(μMoist [0.8] ∩ μMild [0.25]) = min(0.25)
- (R9) If Wet Humidity AND Cool Temperature THEN Fast Time. α – Predicate 1 = μ Soil Humidity ∩ μ Temperature = min(μWet [0.2] ∩ μCool [0.75]) = min(0.25)

2.2.3. Defuzzification

After the calculation for each rule by taking the MIN value of each variable corresponding to the existing rule conditions, the next step is to calculate the defuzzification using the following formula (1).

$$Z = \frac{\alpha - Predicate\ 1(z1) + \cdots + \alpha - Predicate\ n(z1)}{\alpha - Predicate\ 1 + \cdots + \alpha - Predicate\ n} \quad (1)$$

Here, Z is the defuzzification value, and α−Predicateα−Predicate represents the implication value of each rule in the previous stage, need to substitute α−Predicate 1(z1), α−Predicate 2(z1), α−Predicate 2(z1), α−Predicate 3(z1) and α−Predicate 4(z1) with the calculated implication values for specific rules. Similarly, α−Predicate 1, α−Predicate 2, α−Predicate 3, and α−Predicate 4 are the total implication values for all rules. Using the formula above, you can compute the defuzzification value Z based on the implications of the previously established rules.

$$Z = \frac{0.75\ (3) + 0.2\ (3) + 0.25\ (3) + 0.25\ (3)}{0.75\ + 0.2 + 0.25 + 0.25}$$

$$Z = \frac{2.25 + 0.6 + 0.75 + 0.75}{1.45}$$

$$Z = \frac{4.35}{1.45} = 3\ Second$$

2.3. Test Scenarios

Test scenarios involve the experimentation and evaluation of the assembled equipment according to the plan outlined in this research. The following are the results of the final examination, comprising Functional Testing and Fuzzy Sugeno Process Testing.

A. Functional Testing involves the examination of each component of the equipment used in this research.

- Device testing is conducted with the aim of testing all devices or components used to determine if they function correctly and as planned. This includes assessing the functionality of the temperature and soil moisture sensors, obtaining values that are then input into the system and connected to the Internet of Things (IoT). Additionally, testing is conducted on the outputs of this system, namely the Fan, LED Strip, and Water Pump.
- Blynk Application Testing This testing is performed to assess the functions and features used to view data collected by sensors and to control the equipment.

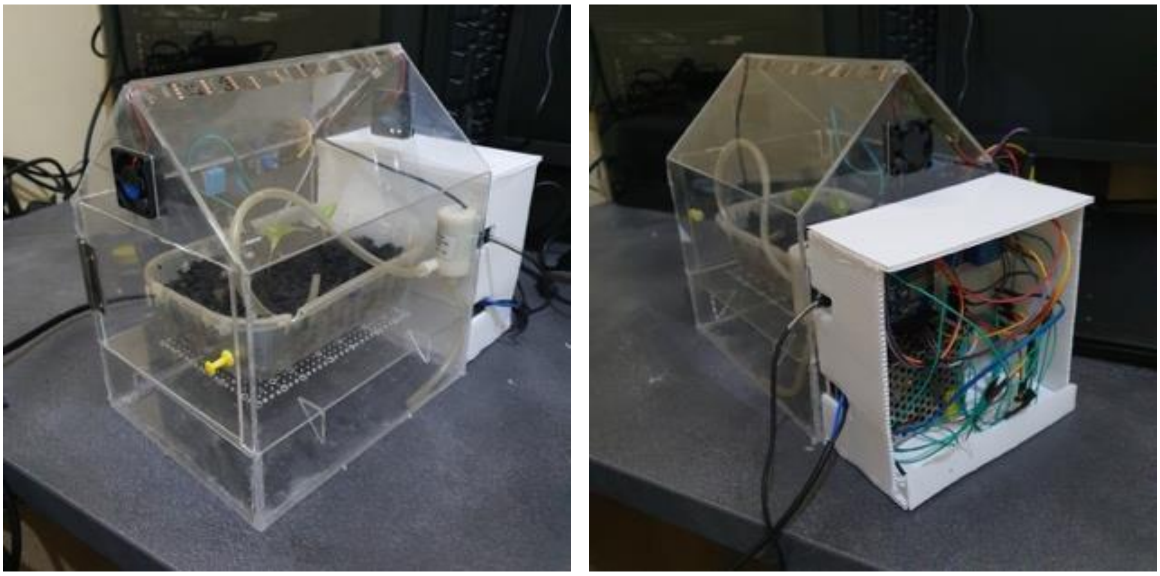
B. Fuzzy Sugeno Testing method testing involves evaluating how this method is applied to the irrigation control system to generate outputs in accordance with the pre-designed and calculated parameters.

3. Results and Discussion

This chapter will elaborate on the implementation of the hardware design, software implementation, functional testing, and analysis of the test results.

3.1. Testing Implementation of the Entire Equipment Circuit

In Fig. 8 (a) and Fig. 8 (b), the front and rear views of the entire equipment circuit for the IoT-based greenhouse system are presented. The equipment utilizes a container in the form of a simple model resembling a greenhouse, with dimensions of 17 cm in height, 15 cm in width, and 20 cm in length. It is equipped with a rectangular water storage tank underneath, measuring 15 cm in width and 20cm in length. Between the greenhouse model and the water tank, there is a partition in the form of a rectangular block with dimensions of 5 cm in height, 15 cm in width, and 20 cm in length. This partition has a small hole in the centre for the entry of water released by the incoming water pipe for the plants and also for the water droplets from the top, which are installed on the greenhouse. At the back of the greenhouse container, there is a compartment for the components used in this system, measuring 14cm in height, 8 cm in width, and 8cm in length. It contains several holes on the right and left sides for the entry of cables to the components inside. The components used in this system include the DHT11 temperature sensor, Soil Moisture sensor, Wemos D1R1, Breadboard, three relays, fan, LED strip, water pump, and a 5V power supply.



(a) (b)

Fig. 8. (a) Front view of the equipment circuit, (b) rear view of the equipment circuit

3.2. Software Implementation

In This part will delve into the software aspect of the project. It will outline the steps taken to translate the hardware design into functional software. This includes programming the Wemos D1R1, configuring the communication between sensors and the microcontroller, and integrating the control logic for the various output devices. The software architecture and code snippets may be provided to offer a comprehensive understanding of the implemented logic.

In the Blynk application testing, the functionality of monitoring and controlling the created IoT-based greenhouse system will be assessed. The purpose of using this application is to monitor the environmental conditions in the greenhouse model connected to the devices and to control each output of the system, such as the fan, LED strip, and water pump.

In Fig. 9 the initial view of the IoT-based greenhouse project using the Blynk application. This page displays real-time environmental condition monitoring, including air temperature in the greenhouse, air humidity, and soil moisture. The data displayed for air temperature and humidity is collected using the DHT11 temperature sensor, while the data for soil moisture is obtained using the soil moisture sensor. On the initial page of the IoT-based greenhouse project, there are also three control buttons for the output devices in the system: the fan used for temperature cooling, the LED strip used for lighting, and the water pump for irrigation.

3.3. Functional Testing of the Equipment

Functional testing involves testing each assembled component used in this research. The purpose of functional testing is to determine whether the assembled and integrated components and devices operate as intended.

3.3.1. DHT11 Temperature Sensor Testing

The temperature sensor testing using the DHT11 temperature sensor in the Arduino IDE yielded readings that were approximately the same as those obtained using a thermometer, which served as a temperature reference during simultaneous testing. The results of the testing will be documented in Table 2, where temperature readings using the DHT11 temperature sensor and the thermometer were conducted 10 times. After obtaining temperature values, the error percentage was calculated for each test, and the overall error results were averaged, according to formula (2). The temperature sensor readings for the DHT11 were 28.31, and for the thermometer, they were 28.

$$Error\ (\%) = \frac{\text{DHT11 Value} - Thermometer\ Value}{Thermometer\ Value} \times 100\%$$
$$Error\ (\%) = \frac{28.31 - 28}{28}\ 100\% = 1.10\% \tag{2}$$

To calculate the average error rate during the testing of the DHT11 temperature sensor, the following steps were taken and according to formula (3).

$$\sum error = \ Sum\ of\ individual\ error\ values\ from\ all\ tests \tag{3}$$

For example, if this test was conducted 10 times, ∑error would be the sum of the error values for each of the 10 tests, according to formula (4).

$$Error\ Average\ (\%) = \frac{\sum error}{\sum Trial}$$
$$Error\ Average\ (\%) = \frac{9.89}{10} = 0.989\% \tag{4}$$

Fig. 9. Initial view of the greenhouse project in the Blynk application

Table 2. Results of temperature testing with DHT11 temperature sensor and thermometer

No	DHT11 Temperature Sensor Data (°C)	Thermometer (°C)	Error (%)
1	28.31	28	1.10
2	31.28	31	0.90
3	33.63	33	1.9
4	30.15	30	0.5
5	26.07	26	0.26
6	27.25	27	0.92
7	30.08	30	0.26
8	31.28	31	0.90
9	29. 12	29	0.41
10	27.74	27	2.74
Average Error			0.989 %

From the calculation results obtained during the testing, it can be concluded that the DHT11 temperature sensor has an average error rate of 0.989%. Therefore, it can be inferred that the DHT11 temperature sensor is functioning well and in accordance with the desired specifications.

3.3.2. Soil Moisture Sensor Testing

The results of testing the soil moisture sensor using the soil moisture sensor on Arduino IDE are recorded in Table 3. The testing involved readings using the soil moisture sensor with a pot filled with soil. Subsequently, water was added in multiples of 30 ml to the pot. The testing was conducted 7 times. After obtaining soil moisture values, calculations were performed to convert sensor data into percentage data for each test. The following is the calculation of soil moisture percentage in the testing with a water volume of 30ml, where the soil moisture sensor value is 788.5, and the ADC value from the soil moisture sensor, which uses 10 bits, is 1023. After obtaining soil moisture values, calculations were performed to convert sensor data into percentage data for each test. The calculation formula (5) for soil moisture percentage is:

$$Soil\ Moisture(\%) = \frac{(ADCValue - Soil\ Moisture\ Sensor\ Value)}{DCValue}$$
$$Soil\ Moisture(\%) = \frac{(1023 - 788.5)}{1023} = 22.9\ \% \tag{5}$$

From the calculation results obtained during the testing, it can be concluded that the soil moisture sensor values have been converted into percentage values, which can be further processed in the system. Therefore, it can be inferred that the soil moisture sensor (soil moisture) is functioning well and in accordance with the desired specifications.

Table 3. Results of humidity testing with soil moisture sensor

No	Water Volume (ml)	Soil Moisture Sensor Value	Soil Humidity (%)
1	30	788.5	22.9
2	60	648.3	36.6
3	90	503	49.5
4	120	439.7	57
5	150	362	64.6
6	180	302.7	70.4
7	210	261.4	74.4

3.3.3. Testing of Temperature Cooling Control System

The results of testing the temperature cooling control system using the DHT11 temperature sensor on Arduino IDE can be seen in Table 4. The fan condition operated automatically and functioned properly; the fan operated according to the conditions specified based on the data collected by the temperature sensor. The testing results are recorded in Table 4. The testing was conducted over

2 days, with time divisions in the morning at 07:00 AM, noon at 12:00 PM, afternoon at 04:00 PM, and evening at 08:00 PM. From the obtained results of the testing, it can be concluded that the temperature cooling control system operates well in the greenhouse and aligns with the desired specifications.

Table 4. Results of temperature cooling control system testing with DHT11 temperature sensor

Testing	Testing Time	DHT11 Temperature Sensor (°C)	Fan Condition
1	Morning 07:00 AM	28	Off
	Noon 12:00 PM	33	On
	Afternoon 04:00 PM	30	On
	Evening 08:00 PM	26	Off
2	Morning 07:00 AM	27	Off
	Noon 12:00 PM	31	On
	Afternoon 04:00 PM	29	On
	Evening 08:00 PM	27	Off

3.3.4. Lighting Control System Testing

The results of the lighting control system testing using the DHT11 temperature sensor on the created device are presented in Table 5. The LED strip condition operated automatically and functioned properly; the LED strip operated according to the conditions specified based on the data collected by the temperature sensor. The testing results are recorded in Table 5. The testing was conducted over 2 days, with time divisions in the morning at 07:00 AM, noon at 12:00 PM, afternoon at 04:00 PM, and evening at 08:00 PM. Based on the obtained results from the testing, it can be concluded that the lighting control system operates well in the greenhouse and aligns with the desired specifications.

Table 5. Results of lighting control system testing with DHT11 temperature sensor

Testing	Testing Time	DHT11 Temperature Sensor (°C)	LED Strip Condition
1	Morning 07:00 AM	28	On
	Noon 12:00 PM	33	Off
	Afternoon 04:00 PM	30	Off
	Evening 08:00 PM	26	On
2	Morning 07:00 AM	27	On
	Noon 12:00 PM	31	Off
	Afternoon 04:00 PM	29	On
	Evening 08:00 PM	27	On

3.3.5. Irrigation Control System Testing

The results of the irrigation control system testing using fuzzy logic, aimed at determining the functionality of the fuzzy logic system in irrigation, are presented in Table 6. The testing is modelled as the accuracy of the irrigation duration, which is the output of the system implemented on the microcontroller. The obtained results from the fuzzy logic applied in Arduino IDE are compared with the simulation results using MATLAB. The testing results are recorded in Table 6. The testing was conducted over 3 days, with time divisions in the morning at 08:00 AM, noon at 12:00 PM, and afternoon at 05:00 PM. After obtaining the system output values and MATLAB output values, calculations were made to determine the percentage error for each test. The overall error was then averaged, according to formula (6). The calculation of the percentage error for the irrigation control system testing using fuzzy logic is as follows: the system output data is 5.63, and the MATLAB output data is 5.79.

$$error\ (\%) = \frac{Arduino\,Value - Matlab\,Value}{Matlab\,Value} \times 100\% \tag{6}$$

$$error\ (\%) = \frac{5.63 - 5.79}{5.79} \times 100\% = 2.7\ \%$$

This formula is used to calculate the average error rate during the irrigation control system testing. It involves summing up the individual error values and then dividing by the total number of tests conducted, according to formula (7).

$$Average\ Error\ Rate\ (\%) = \frac{\sum Error}{\sum Tests}$$
$$Average\ Error\ Rate\ (\%) = \frac{\sum 12.5}{\sum 9} = 1.3\% \tag{7}$$

The average error rate calculation during the irrigation control system testing is 1.3%. From the calculation results obtained during the testing, it can be concluded that the irrigation control system testing using fuzzy logic has an error rate of 1.3%, indicating that the system operates well and normally, aligning with the desired specifications.

3.3.6. Sunflower Plant Testing

In Fig. 10, plant testing is conducted based on 4 conditions. These conditions are:

- Automatic Irrigation and Lighting in the greenhouse.
- Manual Irrigation and Automatic Lighting in the greenhouse.
- Automatic Irrigation with Sunlight.
- Manual Irrigation and Sunlight.

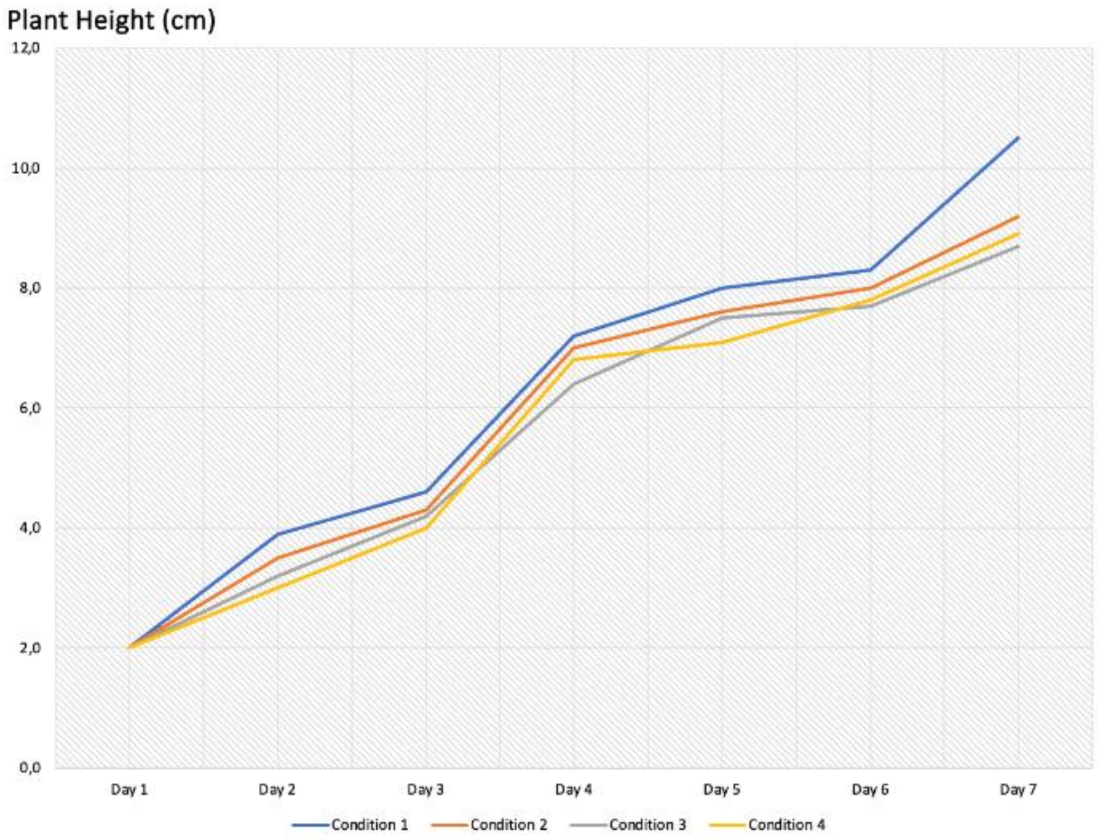


Fig. 10. Plant testing results

In Fig. 4, the testing results were conducted on different days but at the same duration, which is 7 days. Measurements were taken between 10:00 AM and 1:00 PM. The measurement results were obtained by summing the average plant height; the number of plants in each condition is 4 plants with an initial height of 2 cm. In Fig. 10, it can be said that the plant condition in the greenhouse is better due to the minimal factors that can interfere with the plant's growth and development.

Table 6. Results of irrigation control system testing by comparing Matlab simulation results with the device created using Arduino IDE

Testing	Time	Measurement Results		Water Pump Status (Seconds)	Manual Fuzzy Calculation Results (Seconds)	Matlab Simulation Output (Seconds)
		Temperature	Soil Moisture			
Day 1	08.00	29oC	413	3	2.68	2.75
	12.00	31oC	277	7	6.43	6.36
	16.30	30oC	463	2	1.1	1.17
Day 2	08.00	30oC	642	0	0	0
	12.00	32oC	690	0	0	0
	16.30	30oC	716	0	0	0
Day 3	08.00	28oC	674	0	0	0
	12.00	31oC	703	0	0	0
	16.30	27oC	649	0	0	0

4. Conclusion

Based on the conducted research on the monitoring and control of IoT-based greenhouse environmental conditions using fuzzy logic algorithms, several conclusions can be drawn, including: IoT-based greenhouse devices can facilitate control and monitoring of the greenhouse, tested in real-time and automated integration with the Blynk application on smartphones. Based on the conducted tests on the system, such as temperature cooling, lighting, and irrigation systems, they have functioned well and operated according to predefined conditions. The IoT-based greenhouse device using the Fuzzy Sugeno method can be considered to have functioned effectively. According to the results in the irrigation control system testing table using fuzzy logic, the average error is 1.3%, indicating the successful functioning of the fuzzy logic method in this system.

Suggestions for the development of this research include, among others, that this IoT-based greenhouse system still relies on third-party applications, so it is expected that in future research, control and monitoring can be conducted using a specific application.

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