

Fuzzy logic based greenhouse temperature control for tropical tomatoes using ESP32

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ABSTRACT

Greenhouses play a crucial role in maintaining optimal environmental conditions for tropical tomato cultivation. However, temperature fluctuations in tropical climates often reduce crop quality and productivity. This study aims to design an automatic temperature control system based on the ESP32 microcontroller using the Mamdani fuzzy logic method to maintain stability within the optimal range of 25–30°C. The system employs a DHT11 sensor for temperature measurement, a relay to control the heater, and an L298N motor driver to regulate the cooling fan. Temperature data are displayed on a TFT screen and transmitted via Wi-Fi to the Blynk application for real-time remote monitoring. Experimental results show that the system maintained temperature stability with an average deviation of -0.8°C from the 30°C setpoint and response times ranging from 5 to 109 seconds. The fuzzy logic algorithm successfully adjusted fan speed (50–225 PWM) and heater status adaptively, making the system more efficient than conventional fixed setpoint control. Furthermore, wireless communication through Blynk demonstrated low latency (<6 seconds) and accurate data synchronization. Therefore, this system can improve energy efficiency, reduce manual supervision, and support optimal growth of tropical tomato plants in greenhouses.

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1. INTRODUCTION

Greenhouses are facilities designed to create controlled environmental conditions for the optimal growth of tropical tomato plants, including temperature, humidity, and light intensity [1]. Uncontrolled temperature fluctuations can negatively affect plant growth and fruit quality [2]. Tropical tomato cultivation is highly sensitive to environmental variability caused by solar radiation, weather, and external factors, which makes greenhouse management particularly challenging. The optimal temperature range for tropical tomatoes is $25\text{--}30^{\circ}\text{C}$ during the day and $15\text{--}18^{\circ}\text{C}$ at night. Temperatures above 30°C may cause heat stress, hinder fruit formation, and increase susceptibility to diseases such as blossom-end rot or cracking, while temperatures below 15°C may inhibit root growth and nutrient absorption, leading to yield reductions of up to 20–30% [3]. In tropical climates such as Indonesia, extreme temperature fluctuations highlight the importance of automatic temperature control to prevent economic losses and ensure stable food supply.

Conventional control systems for greenhouse temperature monitoring rely heavily on manual supervision, which is inefficient and prone to error [4]. Fixed setpoint control systems often result in overheating or underheating when environmental conditions change, leading to excessive energy use or failure to maintain optimal conditions [5]. Fuzzy logic offers a promising solution because it can handle environmental uncertainty using reasoning similar to human decision-making. This method integrates multiple input parameters to generate adaptive control decisions, reducing energy consumption and improving temperature stability compared to conventional systems [6].

The development of microcontroller technology, such as the ESP32, enables the implementation of intelligent solutions for tropical tomato greenhouses [7]. The ESP32's integration with wireless sensors supports real-time temperature monitoring with high accuracy and flexibility in sensor and actuator placement. Moreover, its built-in Wi-Fi allows remote monitoring and control, enabling farmers to manage their greenhouses without being physically present [8]. This approach increases productivity while reducing inconsistencies caused by human intervention, aligning with modern agricultural efficiency goals.

Several previous studies are relevant to this research. Bouketir et al. [9] developed a fuzzy logic-based greenhouse system for tropical tomato production in Algeria, using DHT22 sensors and Mamdani fuzzy logic to control ventilation and irrigation, showing effectiveness through MATLAB simulations. Hahn [10] designed a fuzzy controller to reduce tomato cracking by monitoring temperature and solar radiation, successfully reducing cracking rates from 52% to 17%. Therefore, this study aims to design and implement a fuzzy logic-based temperature control system using the ESP32 microcontroller for tropical tomato greenhouses. The proposed system integrates real-time monitoring through the Blynk platform to maintain optimal growth conditions, enhance energy efficiency, and provide scalable smart agriculture solutions.

2. METHOD

Design is a strategy or an activity aimed at creating a new system that can solve existing problems and provide effective solution [11]. After completing the design stage, the system is usually illustrated through a block diagram. A block diagram is a system representation that displays the main parts or main functions of a system in the form of boxes connected by lines [12]. Figure 1 shows the block diagram of proposed system.

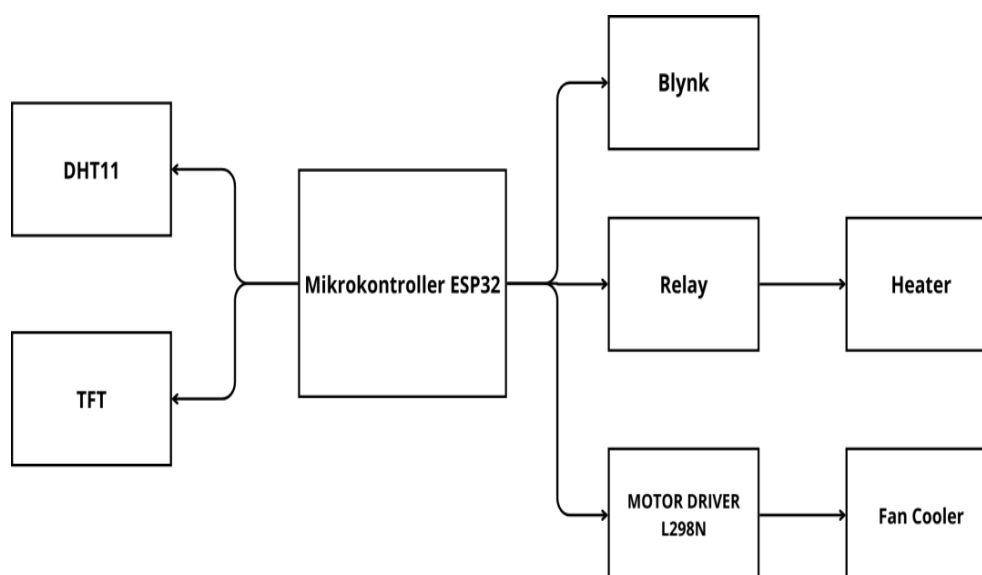


Figure 1. Block diagram of proposed system

This system begins with the Blynk application and a TFT display, which are used to set the temperature setpoint and display the data. The ESP32 microcontroller, as the processing unit, receives temperature input from the DHT11 sensor, which functions to read the environmental temperature. The ESP32 then processes this data using the Mamdani fuzzy logic method by comparing the actual temperature with the predetermined setpoint to generate control decisions. These decisions regulate two main actuators: a relay to control the heater when the temperature is too low, and an L298N driver to activate the fan cooler when the temperature is too high, ensuring that the greenhouse temperature remains stable.

The electronic circuits ensures that each component is connected to each other so that the system can work according to its respective functions. In depicting the circuit scheme, each component can be depicted in its own form or represented with symbols. Electronic circuit design of the greenhouse temperature control system using ESP32, integrating DHT11, TFT display, relay, and L298N motor driver for automatic fuzzy logic-based control. Figure 2 shows the circuit scheme of proposed system.

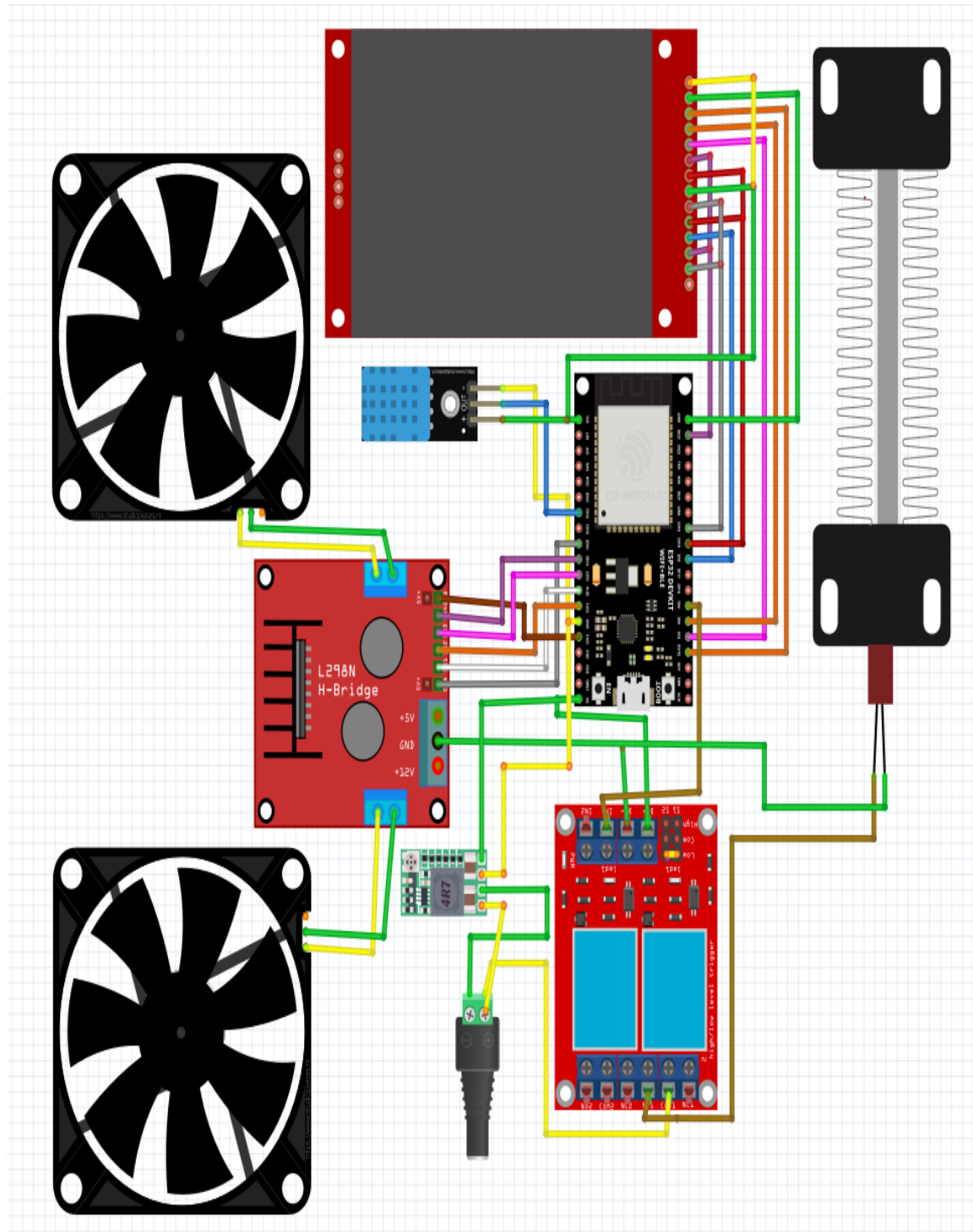


Figure 2. Electronic circuit of the temperature control system

Flowchart is a diagram or chart that describes the flow of processes or steps in a program, including the relationship between processes and statements involved in it [13]. Flowchart consists of several symbols connected by lines, with each symbol having its own meaning. Flowcharts are also used to represent the conceptual structure of complex software systems, serving as design documents used by system analysts to communicate, negotiate and represent the complexity of a process [14]. Flowchart of the ESP32-based greenhouse temperature control system using Mamdani fuzzy logic, showing the process from initialization, sensor data acquisition, fuzzy decision-making, to actuator control and real-time monitoring via TFT and Blynk. Figure 3 shows the flowchart of proposed system.

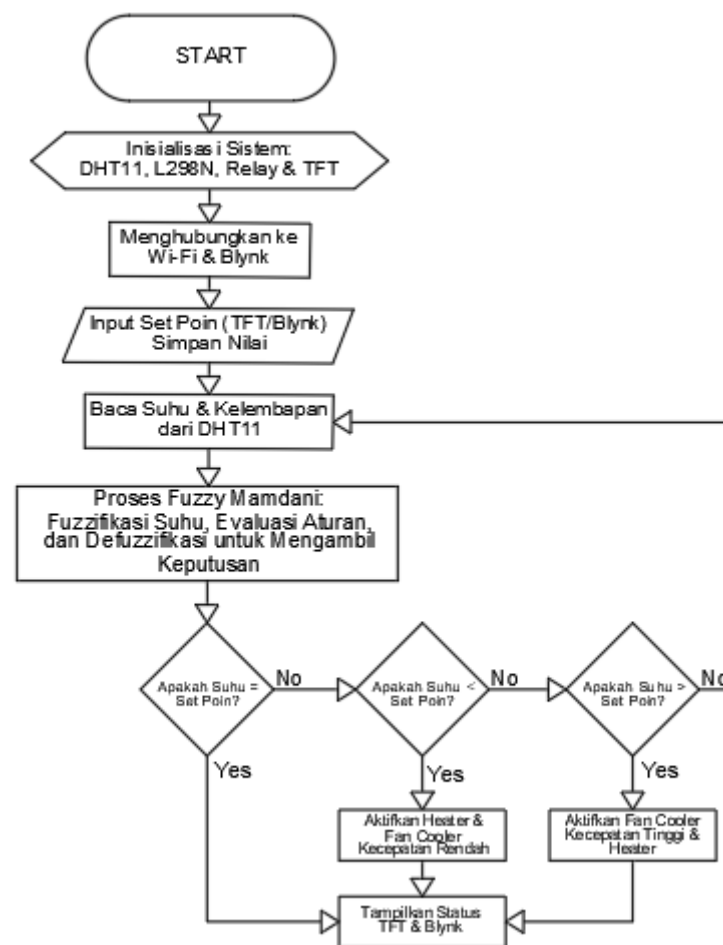


Figure 3. Flowchart

Hardware design is the process of designing, planning and developing the physical form of a system, including architectural design, component selection and technical specifications of the device to be made [15]. Figure 4 shows the mechanical design of proposed devices. Prototype design of a small-scale greenhouse ($50 \times 30 \times 25$ cm) integrating ESP32, sensors, display, relay, and fans for automatic fuzzy logic-based temperature control.

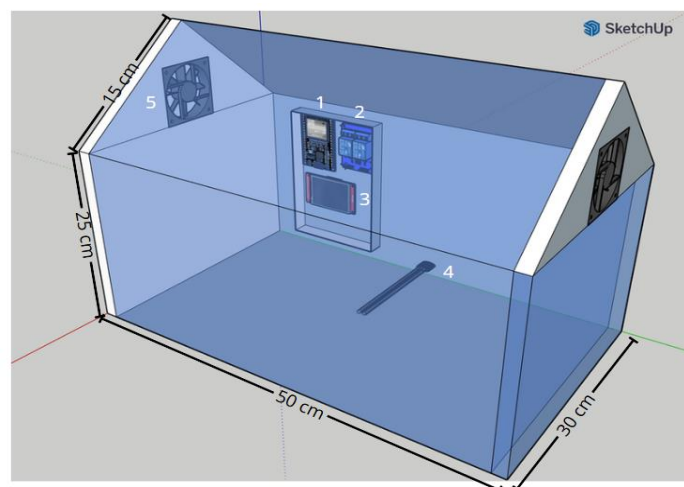


Figure 4. Hardware Design

3. RESULTS AND DISCUSSION

This test evaluates the capability of the fuzzy algorithm in adaptively managing the greenhouse temperature for tropical tomato plants using the ESP32 microcontroller. The fuzzy logic method is implemented to handle the uncertainty of temperature data from the DHT11 sensor through fuzzification, inference, and defuzzification processes..

Table 1. Testing of Fuzzy Logic-Based Temperature Control System

Experiments	Temperature (°C)	PWM Fan Motor	Speed category	Heater status	Error (°C)	Time (s)
1	32.7	225	High	Off	-2.7	109
2	31.5	225	High	Off	-1.5	87
3	31.0	225	High	Off	-1.0	64
4	30.4	225	High	Off	-0.4	35
5	29.9	50	Low	On	0.2	5.5
6	30.1	225	High	Off	-0.1	7.3
7	30.0	125	Medium	Off	0.0	4.1

The experiment was carried out by simulating variations in environmental temperature through the activation of the heater and fan cooler, with the temperature setpoint fixed at 30.0°C as the optimal range for tomato growth. Seven repeated trials were conducted to measure the system's response to temperature fluctuations, including motor speed (PWM), speed category (low, medium, high), heater status (ON/OFF), deviation from the setpoint, and response time, with data recorded via the ESP32 serial log and validated using an external multimeter.

The fuzzy logic-based temperature control system maintained adaptive performance with temperatures ranging from 29.9°C to 32.7°C around the 30.0°C setpoint. Motor speeds varied between 50–225 PWM, with high speeds dominating during overheating conditions, while the heater was mostly OFF except when the temperature slightly dropped below the setpoint. Deviations from the setpoint (–2.7°C to 0.2°C) and response times (109–4.1 s) indicate efficient control, though minor oscillations near the setpoint suggest further fuzzy rule optimization. Figure 5 shows the blink.

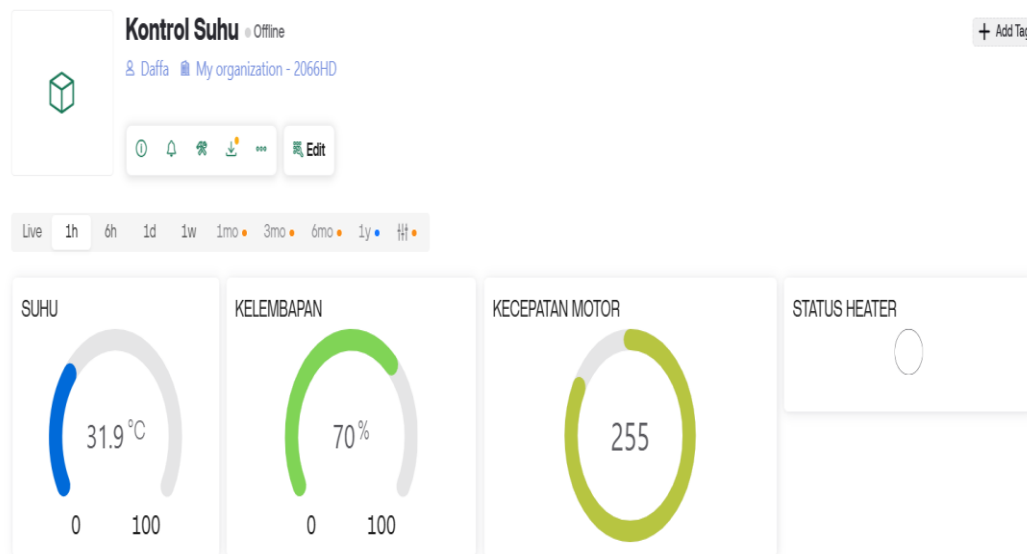
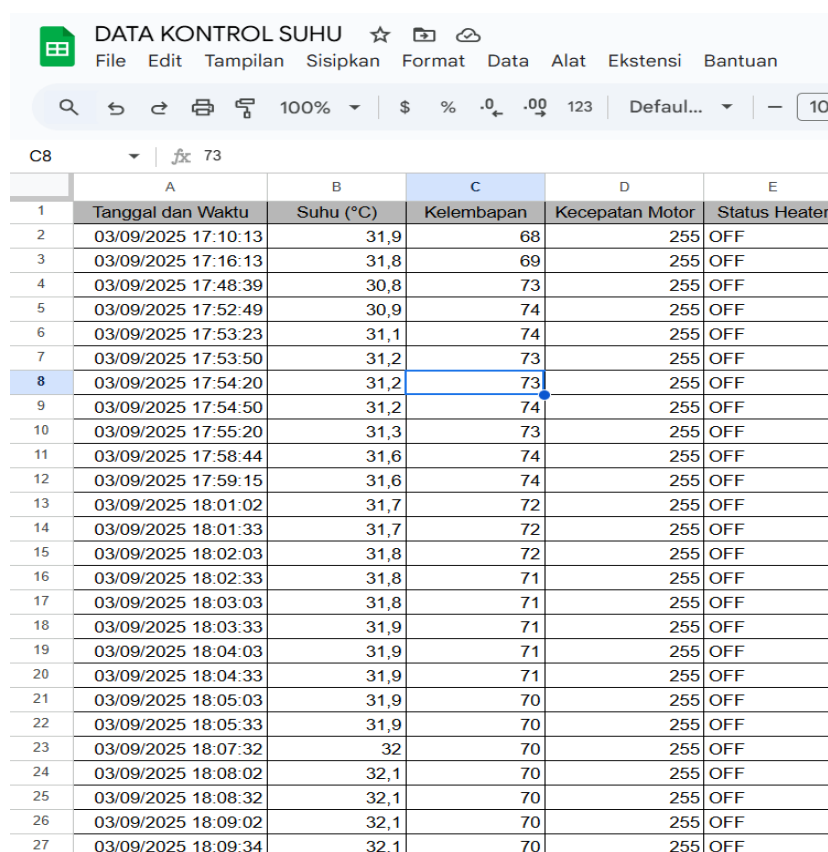


Figure 5. Data view from Blynk

Wireless communication testing via Blynk demonstrated that the application interface effectively presented temperature and humidity data measured by the DHT11 sensor integrated into the system, accurately reflecting real-time environmental conditions. The motor speed, displayed as 255 in the PWM scale, indicated operation in the 'High' category, representing the system's maximum cooling response to temperatures exceeding the optimal setpoint of 30.0°C. The heater status consistently remained 'OFF,' as determined by the fuzzy logic rules designed to prevent overheating, since the detected temperature was above the threshold. This ensured efficient stability of the greenhouse environment for tropical tomato plants. Figure 6 shows the data logger of proposed system.



The screenshot shows a Google Sheet titled "DATA KONTROL SUHU" with a menu bar (File, Edit, Tampilan, Sisipkan, Format, Data, Alat, Ekstensi, Bantuan) and a toolbar with various icons and a zoom level of 100%. The sheet contains a table with 5 columns: A (Tanggal dan Waktu), B (Suhu (°C)), C (Kelembapan), D (Kecepatan Motor), and E (Status Heater). The data spans from row 1 to row 27, showing a progression of time from 17:10:13 to 18:09:34. The temperature (Suhu) fluctuates between 30.8°C and 32.1°C, humidity (Kelembapan) increases from 68% to 74%, and motor speed (Kecepatan Motor) remains constant at 255. The heater status (Status Heater) is consistently OFF.

	A	B	C	D	E
	Tanggal dan Waktu	Suhu (°C)	Kelembapan	Kecepatan Motor	Status Heater
1					
2	03/09/2025 17:10:13	31,9	68	255	OFF
3	03/09/2025 17:16:13	31,8	69	255	OFF
4	03/09/2025 17:48:39	30,8	73	255	OFF
5	03/09/2025 17:52:49	30,9	74	255	OFF
6	03/09/2025 17:53:23	31,1	74	255	OFF
7	03/09/2025 17:53:50	31,2	73	255	OFF
8	03/09/2025 17:54:20	31,2	73	255	OFF
9	03/09/2025 17:54:50	31,2	74	255	OFF
10	03/09/2025 17:55:20	31,3	73	255	OFF
11	03/09/2025 17:58:44	31,6	74	255	OFF
12	03/09/2025 17:59:15	31,6	74	255	OFF
13	03/09/2025 18:01:02	31,7	72	255	OFF
14	03/09/2025 18:01:33	31,7	72	255	OFF
15	03/09/2025 18:02:03	31,8	72	255	OFF
16	03/09/2025 18:02:33	31,8	71	255	OFF
17	03/09/2025 18:03:03	31,8	71	255	OFF
18	03/09/2025 18:03:33	31,9	71	255	OFF
19	03/09/2025 18:04:03	31,9	71	255	OFF
20	03/09/2025 18:04:33	31,9	71	255	OFF
21	03/09/2025 18:05:03	31,9	70	255	OFF
22	03/09/2025 18:05:33	31,9	70	255	OFF
23	03/09/2025 18:07:32	32	70	255	OFF
24	03/09/2025 18:08:02	32,1	70	255	OFF
25	03/09/2025 18:08:32	32,1	70	255	OFF
26	03/09/2025 18:09:02	32,1	70	255	OFF
27	03/09/2025 18:09:34	32,1	70	255	OFF

Figure 6. Test data on google sheet

The test results showed that the wireless communication system via Blynk was able to consistently transmit data to Google Sheets during the testing period, with temperatures ranging from 30.8°C to 32.1°C, humidity levels between 68% and 74%, and motor speed maintained at 255 PWM (High category) while the heater status remained consistently OFF. Figure 15 illustrates the synchronization of Blynk data with initial values such as temperature at 31.9°C, humidity at 68%, and motor speed at 255 PWM recorded at 17:10:13 WIB, which aligned with the datasheet values. Analysis indicated small temperature fluctuations (maximum 1.3°C) and a gradual increase in humidity (from 68% to 74%) over time, reflecting the system's responsiveness to environmental changes. The constant motor speed of 255 PWM suggests that the fuzzy logic prioritized maximum cooling as the temperature exceeded the 30.0°C setpoint, while keeping the heater OFF in line with the system design to prevent overheating. Transmission latency was estimated to be low (<5 seconds) based on the data intervals (around 5–10 minutes), with synchronization between TFT and Blynk appearing accurate given the minimal temperature deviation. However, further testing at greater distances (>50 meters) is required to evaluate signal stability and optimize the system for large-scale greenhouse applications.

4. CONCLUSION

The implementation of an ESP32-based fuzzy logic control system has proven effective in maintaining the temperature stability of a tropical tomato greenhouse. Experimental results showed an average deviation of -0.8°C from the 30.0°C setpoint, with adaptive response times to environmental fluctuations. The development of an adaptive setpoint method further enhanced system performance by automatically adjusting the temperature threshold. Wireless communication via Blynk ensured reliable remote monitoring with an average latency of 6 seconds and accurate data synchronization. In addition, fuzzy logic provided efficient control of motor speed (50–225 PWM) with short response times (5.1–10.3 seconds), achieving greater stability compared to conventional binary systems. Overall, the system demonstrates the potential of fuzzy logic-based smart control for improving energy efficiency, reliability, and productivity in greenhouse applications.

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