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Embedded System

Design and Development of a Helmet Drying and Sterilization System Using the Fuzzy Logic Method

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A B S T R A C T

This study aims to design and develop an IoT-based helmet drying and sterilization system utilizing the Mamdani fuzzy logic method to maintain helmet hygiene, reduce humidity, and inhibit the growth of harmful microorganisms. The system integrates a DHT22 sensor to measure temperature and humidity, an ESP32 microcontroller for data processing, a fan heater for drying, and a UV-C lamp for sterilization. To handle dynamic environmental conditions, the Mamdani fuzzy logic algorithm adaptively controls the actuator outputs based on sensor inputs. Additionally, the system connects to the Blynk IoT platform via Wi-Fi for real-time remote monitoring through a smartphone application. Testing demonstrated that the DHT22 sensor achieved high accuracy, recording 99.71% for temperature and 97.17% for humidity. The ESP32 efficiently processed the fuzzy logic algorithm with an average latency of 556 µs, while maintaining stable IoT communication up to a 40-meter radius. The fan heater successfully reached the target drying temperature of 45°C, and the UV-C lamp effectively operated within the germicidal spectrum to ensure proper sterilization. Overall, the system dynamically adjusted to varying conditions and successfully completed the drying process in approximately 1 hour and 3 minutes. In conclusion, the proposed system successfully automates helmet maintenance, proving highly effective in drying and sterilizing helmets. The integration of fuzzy logic and IoT technology ensures adaptive performance and reliable monitoring, thereby enhancing user health, safety, and comfort.

INTRODUCTION

Motorcycles have become one of the most widely used modes of transportation in Indonesia due to their practicality, affordability, and ability to navigate various road conditions. According to Statistics Indonesia (BPS), the number of motorcycles in Indonesia reached 125,305,332 units in 2022, making motorcycles the dominant transportation mode for daily activities [1]. The high number of motorcycle users has increased concerns regarding riding safety, health, and comfort, which have become important issues requiring greater attention.

In addition to traffic safety risks, motorcycle riders also face challenges related to riding equipment, particularly helmets. Helmets are mandatory protective equipment designed to reduce the severity of injuries during accidents. However, the cleanliness and condition of helmets are often overlooked by users. Helmets exposed to rain, sweat, or frequent shared usage can create a humid environment that supports the growth of harmful microorganisms, potentially causing health problems on the scalp and skin.

A study investigating the cleanliness of motorcycle helmets reported that 392 bacterial isolates were identified from 130 helmet samples. The most dominant bacteria were *Staphylococcus aureus* (22.7%), followed by *Staphylococcus epidermidis* (19.6%) and *Escherichia coli* (13.8%) [2]. These findings indicate that daily-used helmets can serve as breeding grounds for pathogenic microorganisms, particularly when moisture accumulates inside the helmet due to perspiration or rain exposure. Such conditions may increase the risk of scalp irritation and other skin-related infections.

Fungal contamination is another significant concern associated with helmet hygiene. Research on motorcycle helmets used by online motorcycle taxi drivers revealed that 23.3% of the helmets were contaminated with Dermatophyte fungi, including *Trichophyton mentagrophytes*, *Trichophyton rubrum*, and *Microsporum canis* [3]. The study also found that contamination was more prevalent in helmets that were rarely cleaned and had been used for extended periods. These fungi are known to cause

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tinea capitis, a scalp infection characterized by itching, scaling, and hair loss. Therefore, inadequate helmet maintenance and prolonged moisture retention can increase the risk of fungal growth and disease transmission.

The issues described above highlight the need for a system capable of maintaining helmet hygiene by reducing moisture and inhibiting microbial growth after use. An effective drying process is required to lower the humidity level inside the helmet, while a sterilization process is necessary to suppress the growth of bacteria and fungi. The integration of both processes can help improve helmet cleanliness, user comfort, and health protection. Furthermore, advances in Internet of Things (IoT) technology provide opportunities to develop smart systems capable of monitoring environmental conditions and controlling devices automatically.

One approach suitable for adaptive environmental control is fuzzy logic. Fuzzy logic is capable of handling uncertain and dynamic conditions by mimicking human decision-making processes. In a helmet drying system, fuzzy logic can be utilized to determine the operating level of actuators based on temperature and humidity measurements. Unlike conventional on/off control methods, fuzzy logic allows the system to produce gradual and adaptive outputs, resulting in more efficient drying performance under varying environmental conditions.

Based on these considerations, this research proposes the design and development of an IoT-based helmet drying and sterilization system using the fuzzy logic method. The system employs a DHT22 sensor to measure temperature and humidity, an ESP32 microcontroller as the main controller, a fan heater for the drying process, and a UV-C lamp for sterilization. In addition, the system utilizes the Blynk IoT platform for real-time monitoring and control. The proposed system is expected to maintain helmet dryness and cleanliness effectively while reducing the risk of bacterial and fungal growth, thereby improving user health, safety, and comfort.

METHOD

This research focuses on the development of an IoT-based helmet drying and sterilization system using the Mamdani fuzzy logic approach. The system aims to maintain helmet hygiene by reducing humidity levels and inhibiting microbial growth through an automated drying and sterilization mechanism. The research methodology consists of two main stages: hardware design and fuzzy logic design. The hardware design includes the development of the sensing, processing, communication, and actuation subsystems, while the fuzzy logic design covers the determination of linguistic variables, membership functions, and fuzzy rules. The detailed methodology employed in this study is presented in the following sections.

A. Hardware Design

Figure 1 illustrates the block diagram of the proposed IoT-based helmet drying and sterilization system. The system utilizes a DHT22 sensor to measure temperature and humidity inside the helmet chamber. The acquired data are processed by an ESP32-WROOM microcontroller, which serves as the main controller of the system. Based on the processed data, the ESP32 controls three output devices: a fan heater for drying, a UV-C lamp for sterilization, and an LCD display for local monitoring. Furthermore, the ESP32 communicates with the Blynk server through a Wi-Fi connection, enabling real-time monitoring using the Blynk mobile application.

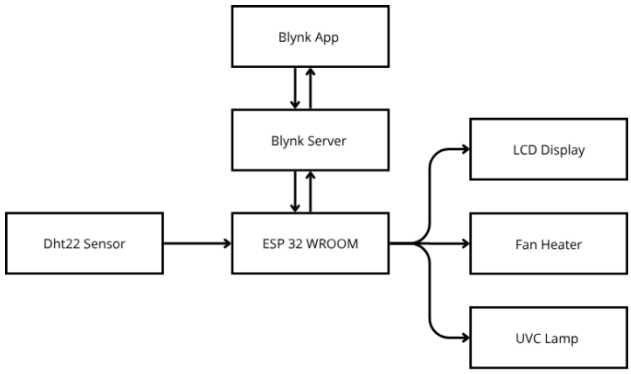


Figure 1. Block Diagram System

The operating principle of the system is illustrated in Figure 2. Initially, the DHT22 sensor is initialized and begins measuring temperature and humidity inside the helmet chamber. The measured values are processed using the fuzzy logic algorithm to determine the operating conditions of the fan heater and UV-C lamp. Subsequently, the processed data are transmitted to the Blynk server and displayed on both the LCD and smartphone application. The process continuously repeats until the helmet reaches the predefined dry condition.

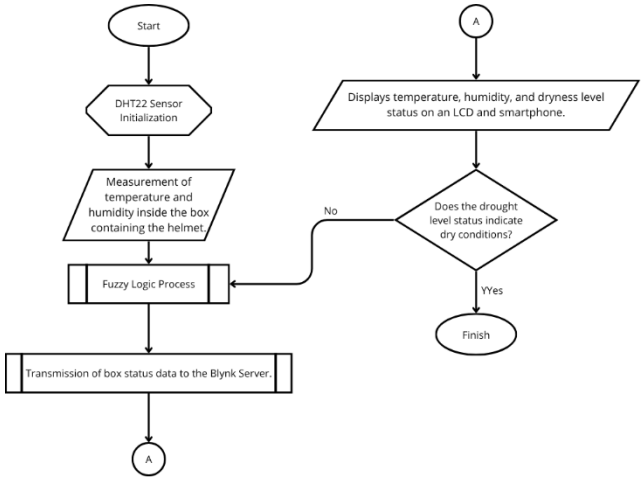


Figure 2. General system flowchart

Figure 3 presents the fuzzy logic process implemented in the system. The process begins by acquiring temperature and humidity data from the DHT22 sensor. The sensor readings are then converted into fuzzy linguistic variables through the fuzzification stage. Next, the inference mechanism evaluates the predefined fuzzy rule base to determine the appropriate control action. Finally, the defuzzification process converts the fuzzy output into crisp values that are used to control the fan heater, UV-C lamp, and system status.

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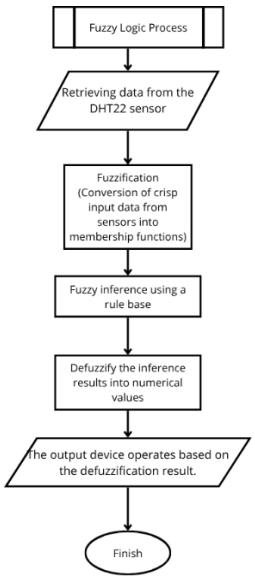


Figure 3. Sub Flowchart Fuzzy Logic

Figure 4 illustrates the data transmission process to the Blynk platform. After obtaining the fuzzy logic output, the ESP32 attempts to establish a Wi-Fi connection. If the connection is unavailable, the system continuously retries until a successful connection is established. Once connected, the temperature, humidity, and system status data are transmitted to the Blynk server and displayed on the user's smartphone in real time.

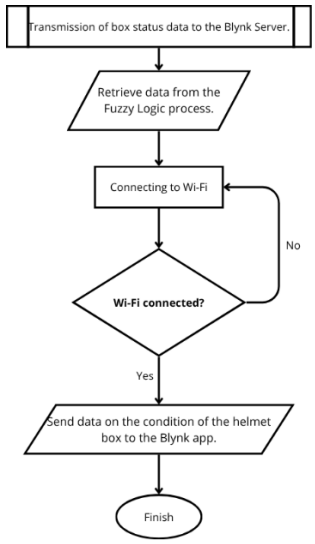


Figure 4. Sub Flowchart Blynk IoT

The proposed helmet drying and sterilization system consists of several hardware components that work together to monitor environmental conditions, perform data processing, and control the drying and sterilization processes. The main components used in this study include a DHT22 sensor, an ESP32-WROOM microcontroller, a fan heater, a UV-C lamp, an LCD display, relay, mosfet, LM2956 modul and a power supply unit. The overall hardware configuration of the system is shown in **Figure 5.**

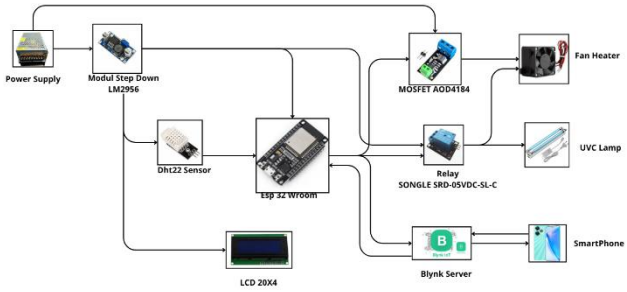


Figure 5. General System Hardware Design

The DHT22 sensor functions as the sensing unit responsible for measuring temperature and humidity inside the helmet chamber. The measured data are transmitted to the ESP32-WROOM microcontroller, which serves as the main processing unit of the system. The ESP32 executes the fuzzy logic algorithm and determines the operating conditions of the output devices based on the measured environmental parameters.

The drying process is performed using a fan heater that generates warm airflow to reduce humidity inside the helmet chamber. In addition, a UV-C lamp is utilized as a sterilization device to inhibit the growth of bacteria and fungi that may develop in humid helmet conditions. An LCD display is employed to provide local information regarding temperature, humidity, and system status. Furthermore, the system is connected to the Blynk IoT platform through a Wi-Fi network, enabling real-time monitoring via a smartphone application.

A regulated power supply is used to provide the required electrical power for all system components. Through the integration of these components, the proposed system is capable of automatically monitoring, drying, and sterilizing helmets while providing real-time information to users.

B. Fuzzy Logic Design

The proposed system employs the Mamdani fuzzy inference method to determine the operating conditions of the drying and sterilization devices. Two input variables and four output variables are used in the fuzzy logic controller. The fuzzy variables utilized in this research are summarized in **Table I.**

Table 1. Fuzzy Membership Function

Variable Type	Variable
Input	Temperature
Input	Humidity
Output	Fan
Output	Heater
Output	UV-C Lamp
Output	Status

The fuzzy controller consists of four stages: fuzzification, rule evaluation, aggregation, and defuzzification. Temperature and humidity values obtained from the DHT22 sensor are converted into fuzzy membership values. These values are then evaluated using a rule base consisting of nine rules. The resulting fuzzy outputs are aggregated and converted into crisp values to control the system actuators.

1. Fuzzy Rule Base

The rule base used in this study consists of nine rules derived from combinations of temperature and humidity conditions. The objective of these rules is to determine the appropriate operation of the fan heater, UV-C lamp, and system status according to the environmental conditions inside the helmet chamber. The rule base is shown in **Table 2.**

Table 2. Fuzzy Inference Rule Base

Temperature	Humidity	Fan	Heater	UV-C Lamp	Status
Cold	Wet	ON	Strong	Long	Not Dry
Cold	Humid	ON	Medium	Medium	Not Dry
Cold	Dry	OFF	Weak	Short	Nearly Dry
Warm	Wet	ON	Strong	Long	Not Dry
Warm	Humid	ON	Medium	Medium	Nearly Dry
Warm	Dry	OFF	Weak	Short	Dry
Hot	Wet	ON	Medium	Medium	Nearly Dry
Hot	Humid	ON	Weak	Short	Dry
Hot	Dry	OFF	Weak	Short	Dry

2. Membership Function

The input variable **temperature** is divided into three linguistic terms, namely *Cold*, *Warm*, and *Hot*, as shown in Figure 6. The input variable **humidity** is classified into *Dry*, *Humid*, and *Wet*, as illustrated in Figure 7.

For the output variables, the **fan** variable consists of two linguistic terms, namely *OFF* and *ON* (Figure 8). The **heater** variable is divided into *Weak*, *Medium*, and *Strong* levels (Figure 9). The **UV-C lamp** variable consists of *Short*, *Medium*, and *Long* operating durations (Figure 10). Finally, the **status** variable is represented by three linguistic conditions: *Not Dry*, *Nearly Dry*, and *Dry*, as shown in Figure 11.

The membership functions were designed and simulated using the MATLAB Fuzzy Logic Toolbox before being implemented on the ESP32 microcontroller. These membership functions allow the controller to generate adaptive outputs according to changes in temperature and humidity conditions inside the helmet chamber.

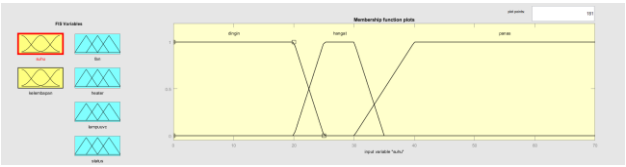


Figure 6. Temparature

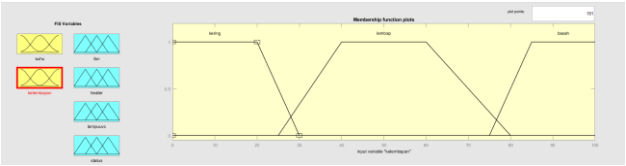


Figure 7. Humidity

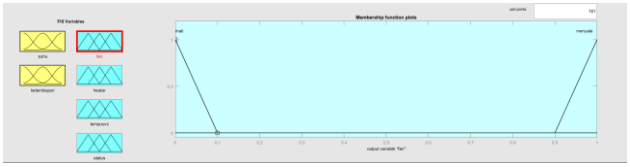


Figure 8. Fan

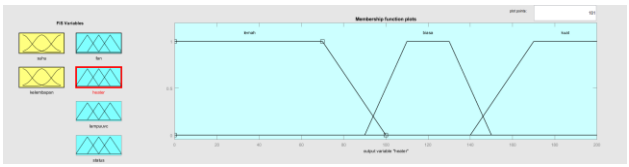


Figure 9. Heater

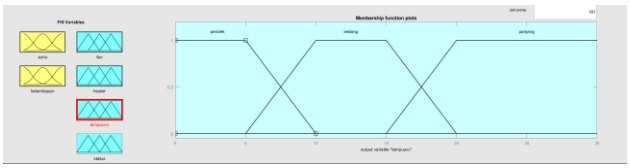


Figure 10. UVC Lamp

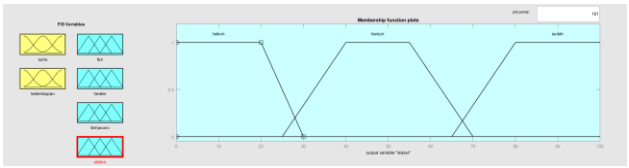


Figure 11. Status

RESULTS AND DISCUSSION

This section presents the implementation and evaluation of the proposed IoT-based helmet drying and sterilization system. The implementation stage focuses on the realization of both hardware and software components, including sensor integration, actuator installation, fuzzy logic implementation, and IoT communication. Subsequently, system performance is evaluated through several testing scenarios to verify the functionality of each subsystem and assess the overall effectiveness of the proposed solution.

A. System Implementation

The developed system was implemented by integrating the DHT22 sensor, ESP32-WROOM microcontroller, fan heater, UV-C lamp, LCD display, and Blynk IoT platform into a single prototype. The hardware components were assembled inside a helmet drying chamber designed to accommodate a motorcycle helmet during the drying and sterilization processes.

The DHT22 sensor was installed inside the chamber to continuously monitor temperature and humidity conditions. The measured data were processed by the ESP32-WROOM microcontroller using the Mamdani fuzzy logic algorithm to determine the appropriate operating conditions of the fan heater and UV-C lamp. The fan heater was utilized to reduce humidity inside the chamber, while the UV-C lamp was employed to perform sterilization by inhibiting the growth of microorganisms.

To enhance user interaction, an LCD display was integrated into the system to provide local information regarding temperature,

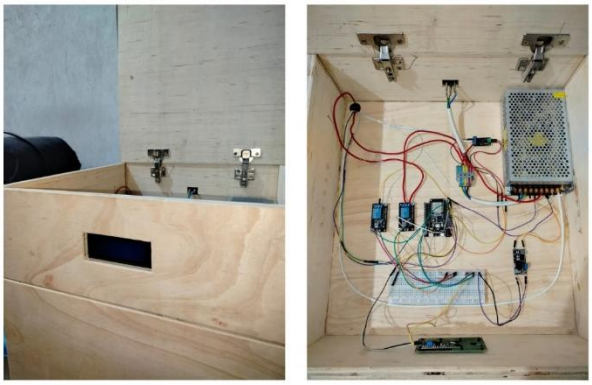
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humidity, and drying status. In addition, the system was connected to the Blynk IoT platform through a Wi-Fi network, allowing users to monitor system conditions remotely using a smartphone application. The implemented prototype of the proposed system is shown in Figure 12 and 13.



(a) (b)

Figure 12. Hardware Installation on Cabinets



(a) (b)

Figure 13. The entire system is visible.

B. System Testing

To evaluate the performance of the proposed system, several testing scenarios were conducted. The testing process was performed to verify the functionality of each subsystem and to assess the overall system performance in monitoring, drying, sterilizing, and transmitting data through the IoT platform.

The testing procedures include sensor performance testing, fuzzy logic validation, actuator testing, IoT communication testing, and overall system evaluation. The results obtained from each testing scenario are discussed in the following subsections.

1. Dht22 Sensor Testing

The DHT22 sensor was evaluated by comparing its temperature and humidity measurements with a hygrometer as the reference instrument. Data were collected 30 times at 1-minute intervals during the drying process. The results indicate that the DHT22 sensor produced measurements that were close to the reference values. The temperature difference ranged from 0.0°C to 0.8°C, while the humidity difference ranged from 0.0% to 9.2% RH.

Based on the error calculation results, the average temperature measurement error was 0.29%, whereas the average humidity measurement error was 2.83%. Consequently, the sensor achieved an accuracy of 99.71% for temperature measurements and 97.17% for humidity measurements. Furthermore, the standard deviation of the temperature and humidity errors was 0.45% and 1.96%, respectively. These relatively low values indicate that the DHT22 sensor provides stable and consistent measurements throughout the testing process.

The testing results demonstrate that the DHT22 sensor is capable of measuring temperature and humidity with high accuracy and good consistency, making it suitable for implementation in the proposed helmet drying and sterilization system.

Table 3. Comparison Average Error and Accuracy results between the DHT22 sensor and the hygrometer.

Parameter	Temperature (%)	Humidity (%)
Average Error	0.29	2.83
Accuracy	99.71	97.17

2. Esp 32 Wroom Testing

The ESP32-WROOM performance was evaluated to assess its capability in processing sensor data and executing the fuzzy logic algorithm. The testing results showed that the microcontroller operated at a stable frequency of 240 MHz throughout the operation. The processing latency, including sensor reading, fuzzification, rule evaluation, and defuzzification, ranged from 550 µs to 562 µs, with an average latency of 556 µs (0.556 ms). Compared to the system sampling interval of 2 seconds, the fuzzy logic process utilized only 0.028% of the available processing time. These results indicate that the ESP32 has sufficient computational resources to simultaneously handle fuzzy logic processing, actuator control, LCD updates, and IoT communication while maintaining real-time system performance.

In addition, Wi-Fi communication testing was conducted to evaluate the wireless connectivity between the ESP32 and the Blynk IoT platform. The results showed that the system maintained stable communication at distances of 10 m, 20 m, 30 m, and 40 m from the access point. At these distances, the ESP32 successfully received control commands and transmitted monitoring data in real time. However, at a distance of 50 m, communication could no longer be established due to signal attenuation and network limitations. Overall, the ESP32 demonstrated reliable wireless communication performance with an effective operating range of up to 40 m under the testing conditions.

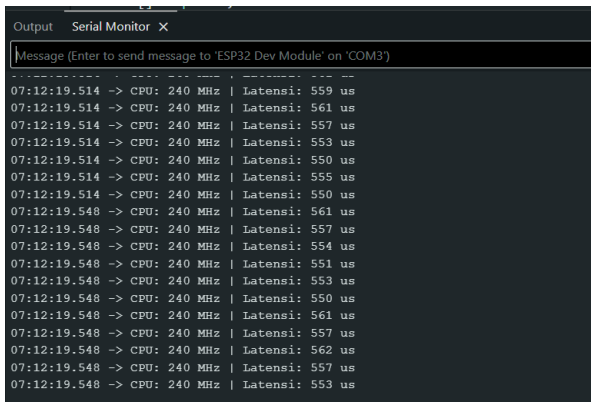
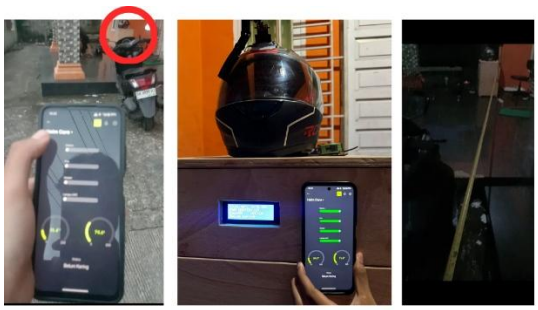


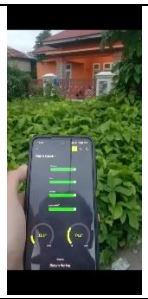
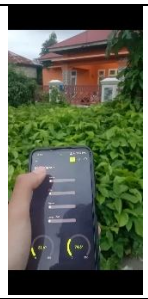
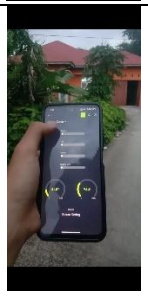
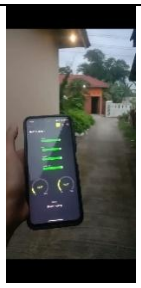
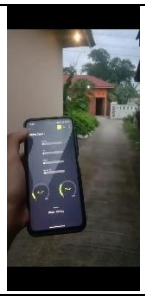
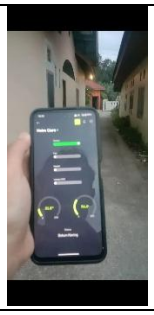
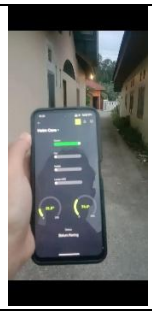
Figure 14. Shows the ESP32 Performance



(a) (b) (c)

Figure 14. Wi-Fi communication testing results.

Table 4. ESP32 Connection Range with 2.4 GHz Network

No	Distance (meter)	Switch ON	Switch OFF	Status
1	10			Connected
2	20			Connected
3	30			Connected
4	40			Connected
5	50			Not Connected

3. Fan Heater Testing

The fan heater was tested to evaluate its ability to achieve the target drying temperature of 45°C. Temperature measurements were observed using a hygrometer as the reference instrument and compared with the readings obtained from the DHT22 sensor. The results showed that the heater successfully reached the target temperature and continued increasing to a maximum temperature of approximately 52.4°C.

The testing results indicate that the fan heater provides sufficient heating performance for the helmet drying process. The small difference between the DHT22 sensor readings and the hygrometer measurements also confirms that the system can accurately monitor temperature changes during operation. Reaching temperatures above 45°C can accelerate moisture removal inside the helmet, thereby improving drying efficiency.

To ensure safe operation, the system employs a fuzzy logic controller that adjusts the heater output according to the measured temperature and humidity conditions. Additionally, a safety mechanism is implemented to automatically turn off the heater when the temperature reaches 70°C, preventing overheating and protecting the system components. Overall, the fan heater demonstrated adequate performance to support the drying process in the proposed Helmet Care system.



Figure 15. Fan heater temperature testing results

4. UVC Lamp Testing

The UV-C lamp was tested to verify that the lamp used in the Helmet Care system operates within the UV-C wavelength range (200–280 nm), which is effective for microorganism inactivation. The testing was performed using a UV-C test card by exposing the card directly to the lamp inside the sterilization chamber.

The results showed that the UV-C indicator on the test card changed and displayed the “UVC” mark, while the indicator for ordinary UV light showed no response. This confirms that the lamp used in the system emits UV-C radiation and is suitable for sterilization applications.

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The successful identification of UV-C radiation indicates that the lamp can support the sterilization process by helping reduce the presence of bacteria and fungi on helmet surfaces. Therefore, the UV-C lamp was verified to function properly and meets the requirements of the proposed Helmet Care system.



Figure 16. UV-C lamp testing using a UV-C test card.

5. Blynk IoT Testing

The Blynk IoT platform was tested to evaluate the communication performance between the Helmet Care system and the remote monitoring application. The testing was conducted by comparing the temperature, humidity, and drying status displayed on the LCD with the data shown in the Blynk IoT application.

The results demonstrated that the values displayed on the LCD were successfully transmitted and accurately displayed in the Blynk application. For example, a temperature of 30.9°C, humidity of 77.4%, and the status "Not Dry" were consistently shown on both interfaces, indicating successful data synchronization between the ESP32 and the Blynk platform.

Due to the limitations of the non-premium Blynk account used in this study, data transmission was configured to occur at 3-minute intervals to reduce data usage. Despite this limitation, the testing confirmed that the communication mechanism functioned properly and that the system was capable of performing remote monitoring effectively. These results verify the successful integration of the ESP32 microcontroller with the Blynk IoT platform for real-time helmet drying and sterilization monitoring.



Figure 17. Data transmission and monitoring results on the Blynk IoT application.)

6. Overall System Performance Testing

The overall system performance was evaluated by observing the drying process under different operating conditions. At 10 seconds of operation, the system recorded a temperature of 31.4°C and a humidity level of 86.9%, indicating a very wet helmet condition. Consequently, the fuzzy controller generated the maximum heater output of 180 PWM, while the fan and UV-C lamp remained active. The system status was classified as "Not Dry," demonstrating the ability of the controller to provide an immediate response by activating all actuators at high intensity.

At 1 minute of operation, the measured temperature increased to 36.3°C, while the humidity decreased to 80%. The heater output was reduced to 152 PWM, indicating that the fuzzy logic controller gradually adjusted the heating intensity according to the changing environmental conditions. The fan and UV-C lamp remained active, and the system status was still identified as "Not Dry" due to the relatively high humidity level. These results demonstrate that the proposed system can effectively respond to variations in temperature and humidity while adaptively controlling the drying and sterilization process.

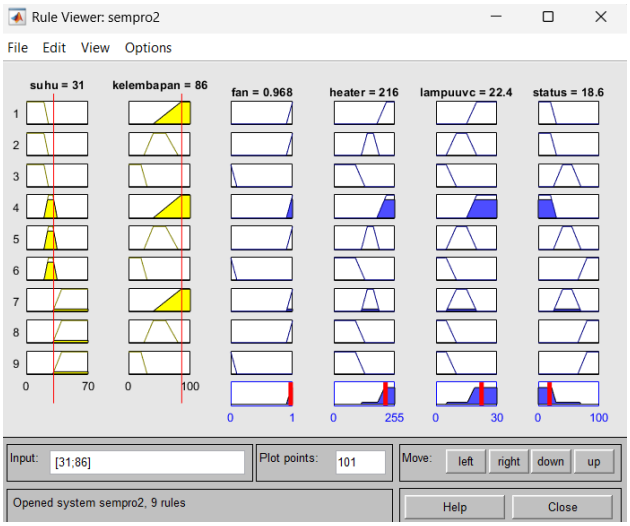


Figure 18. Overall system performance at 10 second

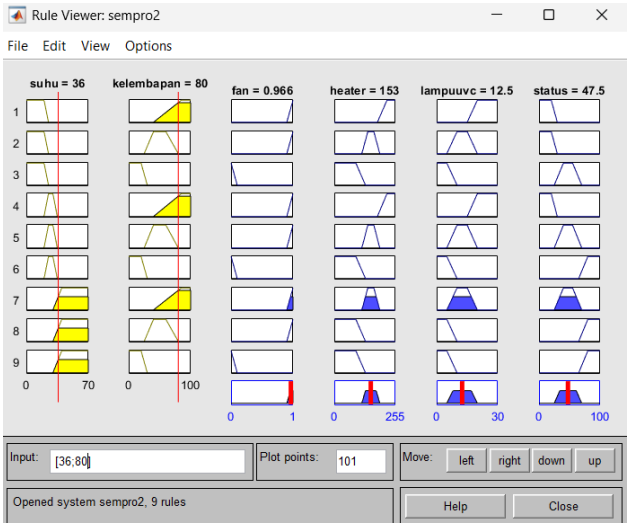


Figure 19. Overall system performance at 1 minute

CONCLUSIONS

This study successfully developed an IoT-based helmet drying and sterilization system using the Mamdani fuzzy logic method. The DHT22 sensor demonstrated high measurement accuracy, achieving 99.71% accuracy for temperature and 97.17% for

humidity, with low standard deviation values indicating good measurement consistency. The ESP32-WROOM microcontroller provided stable performance with a processing latency of approximately 550–562 µs, enabling real-time fuzzy logic execution.

The Wi-Fi communication system successfully supported IoT monitoring and control through the Blynk platform with an effective range of up to 40 m. The fan heater was capable of reaching temperatures above the 45°C target required for helmet drying, while the UV-C lamp was verified to operate within the UV-C spectrum suitable for sterilization. Furthermore, data transmission between the ESP32 and the Blynk application was successfully performed, allowing temperature, humidity, and system status information to be monitored remotely.

The implemented fuzzy logic controller operated according to the designed rule base and produced outputs consistent with MATLAB simulation results. Overall, the proposed system successfully performed automatic helmet drying and sterilization, completing the drying process in approximately 1 hour and 3 minutes under the tested conditions. These results demonstrate that the developed Helmet Care system is effective for maintaining helmet hygiene and supporting real-time monitoring through IoT technology.

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