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Fuzzy Sugeno Based Temperature and Humidity Control for a Hybrid PLC-ESP32 Based Automatic Chili Drying Machine

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A B S T R A C T

Maintaining stable temperature and relative humidity during chili drying is essential to produce high-quality dried products while reducing moisture content efficiently. This study presents a hybrid PLC–ESP32-based automatic chili drying machine employing a Fuzzy Sugeno controller for simultaneous regulation of temperature and humidity. The proposed system utilizes a Mitsubishi FX3U programmable logic controller (PLC) for real-time actuator control and an ESP32 for executing the Fuzzy Sugeno inference algorithm. Temperature error and relative humidity error are used as the controller inputs, while the outputs consist of PWM signals for the heater and the circulation fan. Communication between the ESP32 and PLC is established through the Modbus RTU protocol, enabling intelligent decision-making while maintaining industrial-grade control reliability. Experimental results demonstrate that the proposed controller successfully maintained the drying chamber temperature at the 60 °C setpoint with a maximum overshoot of 0.1 °C and a steady-state error of approximately ±0.17 °C. Compared with the conventional ON–OFF method, the proposed controller produced a more stable thermal response and improved drying performance. After four hours of drying, the average moisture content of the chili decreased to 2.6% on the upper rack and 1.0% on the lower rack, indicating relatively uniform drying throughout the chamber. Visual comparison with commercially available dried chili also showed that the proposed drying process produced a brighter red color, suggesting better preservation of product appearance under controlled drying conditions. Although no chemical composition analysis was conducted, these observations indicate that maintaining stable drying conditions contributes to improved visual quality. Overall, the proposed hybrid PLC–ESP32 architecture integrated with the Fuzzy Sugeno controller provides an effective solution for intelligent agricultural drying applications.

Keywords: Automatic Chili Dryer, Fuzzy Sugeno, PLC-EPS32, Humidity Control, Temperature Control.

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1. Introduction

Drying is one of the most important post-harvest preservation processes for agricultural commodities because it reduces moisture content, inhibits microbial growth, and extends product shelf life [1]. Chili (*Capsicum annuum* L.) is a highly perishable commodity with an initial moisture content of approximately 80–90%, making it susceptible to rapid deterioration after harvest[1],[5]. According to the Indonesian National Standard (SNI 3389:2023), the maximum allowable moisture content for dried chili is 11% to ensure product quality and prevent fungal growth[19]. Furthermore, previous studies have reported that drying temperatures between 50 and 60 °C are optimal for reducing moisture while maintaining the color, aroma, and nutritional quality of chili [6],[15],[16]. Therefore, maintaining stable drying conditions is essential to produce high-quality dried chili while minimizing quality degradation.

Conventional sun drying remains widely used because of its low operating cost [1],[5]. However, this method is highly dependent on weather conditions, requires long drying times, and is vulnerable to contamination by dust, insects, and microorganisms[1],[5]. In addition, uncontrolled temperature fluctuations often result in non-uniform drying and discoloration, reducing the commercial value of the final product [4],[15]. These limitations have encouraged the development of automatic drying systems capable of providing controlled thermal conditions and improving drying consistency throughout the process.

Various intelligent control methods have been proposed to improve the performance of agricultural drying systems[4]. Azis and Sinadia demonstrated that a Fuzzy Expert controller effectively maintained drying conditions and improved energy efficiency in a chili drying system[7]. Several previous studies have demonstrated that fuzzy logic can effectively improve temperature stability and drying performance in agricultural drying systems[4],[7],[8]. In addition, PLC-based temperature control systems have demonstrated excellent reliability and deterministic real-time performance for industrial automation applications[9]. Nevertheless, most previous studies have either implemented fuzzy control on standalone microcontrollers or focused on regulating a single process variable. The integration of industrial PLCs with intelligent fuzzy control for simultaneous temperature and humidity regulation in chili drying systems remains limited.

To address these limitations, this study proposes a hybrid PLC–ESP32-based automatic chili drying machine employing a Fuzzy Sugeno controller for simultaneous regulation of drying temperature and relative humidity. A Mitsubishi FX3U PLC is utilized as the primary real-time controller for actuator sequencing and PWM generation, while an ESP32 performs the Fuzzy Sugeno inference process[9],[10],[11]. The controller receives two input variables, namely temperature error and relative

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humidity error, and directly generates PWM commands for the heater and circulation fan through Modbus RTU communication. Unlike conventional approaches that require PID parameter tuning, the proposed controller directly determines actuator outputs based on fuzzy rules, enabling a simpler control structure while maintaining adaptability to nonlinear drying conditions[2],[3].

The contributions of this work are threefold. First, a hybrid PLC–ESP32 architecture is developed to combine industrial-grade reliability with the computational capability required for intelligent control. Second, a dual-input dual-output Fuzzy Sugeno controller is implemented to regulate heater and fan operation simultaneously based on temperature and humidity conditions. Third, the proposed system is experimentally evaluated through sensor validation, temperature stability, drying uniformity, moisture reduction, and visual comparison with commercially available dried chili. Although the comparison with commercial products is limited to visual characteristics because the drying method and chemical composition of commercial samples are unknown, it provides practical evidence that controlled drying at stable temperatures can better preserve the appearance of dried chili[15].[16],[17],[18]. The proposed system is therefore expected to provide an effective and reliable solution for intelligent agricultural drying applications.

To the best of the authors' knowledge, studies investigating the implementation of a Fuzzy Sugeno controller within a hybrid PLC–ESP32 architecture for automatic chili drying remain limited. Most existing studies either employ standalone microcontrollers for fuzzy computation or implement fuzzy control solely for temperature regulation, while industrial PLC-based implementations capable of simultaneously regulating both heater and circulation fan through direct PWM commands are rarely reported. Furthermore, previous works primarily emphasize controller performance, with limited discussion on the resulting product quality. Therefore, this study addresses these gaps by developing a hybrid PLC–ESP32 automatic chili drying system in which the ESP32 executes a dual-input dual-output Fuzzy Sugeno controller based on temperature and relative humidity errors, while the Mitsubishi FX3U PLC performs deterministic real-time actuator control via Modbus RTU communication. The proposed system is experimentally validated through comprehensive evaluations of temperature stability, moisture reduction, drying uniformity, and visual comparison with commercially available dried chili, providing both control performance and practical product-quality assessment for intelligent agricultural drying applications.

2. Materials and Methods

This section describes the methodology employed in developing the proposed automatic chili drying machine. The study consists of the design of a hybrid PLC–ESP32 control architecture, hardware integration, implementation of the Fuzzy Sugeno controller, Modbus RTU communication, and experimental validation. The developed system regulates the drying chamber temperature and relative humidity by simultaneously controlling the heater and circulation fan using pulse width modulation (PWM). The overall research methodology is illustrated in Fig. 1.

2.1. System Architecture

The overall architecture of the proposed automatic chili drying system is illustrated in Fig. 1. The system employs a hybrid control architecture by integrating a Mitsubishi FX3U programmable logic controller (PLC) with an ESP32 microcontroller. This architecture combines the deterministic real-time control capability of an industrial PLC with the computational efficiency of the ESP32 for implementing the Fuzzy Sugeno algorithm.

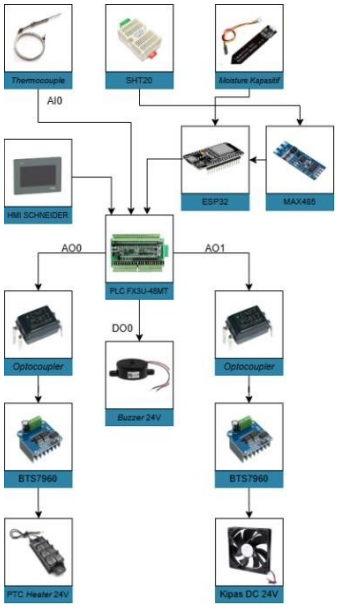


Figure 1. Simplified Electrical Wiring of the Control System

As shown in Fig. 1, the Mitsubishi FX3U PLC serves as the primary controller responsible for system sequencing, PWM signal generation, actuator control, safety interlocks, and Human–Machine Interface (HMI) communication[9]. Meanwhile, the ESP32 functions as the intelligent processing unit that executes the Fuzzy Sugeno inference algorithm[10]. Communication between the ESP32 and the PLC is established through the Modbus RTU protocol using an RS485 interface, enabling reliable bidirectional data exchange while maintaining deterministic real-time operation[11].

The drying chamber incorporates three sensing devices to monitor the drying process. An SHT20 sensor continuously measures the chamber temperature and relative humidity, providing the primary feedback variables for the control algorithm[13]. A PT100 resistance temperature detector (RTD) is employed as an independent safety sensor to detect excessive chamber temperatures and activate the protection mechanism when necessary[12]. In addition, a capacitive moisture sensor is used to evaluate the final moisture content of the dried chili. Unlike the SHT20 sensor, the moisture sensor is not included in the feedback control loop and is utilized solely for post-drying performance evaluation[13].

During system operation, the measured temperature and relative humidity are transmitted from the SHT20 sensor to the ESP32, where the temperature error and relative humidity error are calculated. These variables are processed by the Fuzzy Sugeno controller to directly generate PWM commands for the heater and the circulation fan. The calculated PWM values are periodically transmitted to the Mitsubishi FX3U PLC through Modbus RTU communication[11]. The PLC

subsequently produces PWM signals to drive the BTS7960 motor drivers, which regulate the PTC heater and DC circulation fan[14]. This control strategy enables simultaneous regulation of heating power and air circulation, allowing the drying chamber to maintain stable thermal conditions throughout the drying process.

2.2. System Architecture

The hardware configuration of the proposed automatic chili drying system is summarized in Table I. The selected components were chosen based on measurement accuracy, industrial reliability, communication compatibility, and suitability for implementing the proposed Fuzzy Sugeno-based control system. The combination of industrial-grade controllers, environmental sensors, and power drivers enables stable temperature and humidity regulation throughout the drying process.

Table 1. Hardware Configuration

Component	Function
Mitsubishi FX3U PLC	Main controller and PWM generation
ESP32	Fuzzy Sugeno computation
PT100 RTD	Over-temperature protection
SHT20	Temperature and humidity feedback
Moisture Sensor	Moisture content evaluation
BTS7960	PWM driver for heater and fan
PTC Air Heater	Heat generation
DC Fan	Air circulation

The Mitsubishi FX3U PLC was selected as the primary controller because of its high reliability, deterministic execution, and suitability for industrial automation applications[9]. The PLC is responsible for executing the control sequence, generating PWM signals, handling safety interlocks, and communicating with the Human–Machine Interface (HMI)[9]. To overcome the computational limitations of PLCs in executing intelligent algorithms, an ESP32 microcontroller is integrated as a dedicated processing unit for the Fuzzy Sugeno controller. This hybrid architecture combines the robustness of industrial control with the computational flexibility of embedded systems[9],[10].

The sensing subsystem consists of an SHT20 sensor, a PT100 RTD, and a capacitive moisture sensor[12],[13]. The SHT20 continuously measures chamber temperature and relative humidity, which serve as the input variables for the Fuzzy Sugeno controller[3],[13]. The PT100 RTD is employed independently as a safety sensor to detect excessive chamber temperatures and activate the protection mechanism when the operating temperature exceeds the allowable limit. In contrast, the capacitive moisture sensor is used only to evaluate the final moisture content of the dried chili and is not incorporated into the control loop[12].

A 24 V PTC heater is utilized as the primary heating element because of its self-regulating characteristics and operational safety, while a 24 V DC fan provides forced air circulation inside the drying chamber to improve heat distribution and moisture removal. Both actuators are driven by BTS7960 motor drivers, allowing the PLC to regulate their operating power through pulse width modulation (PWM)[9],[11]. This configuration enables independent adjustment of heating intensity and airflow according to the control commands generated by the Fuzzy Sugeno algorithm.

2.3. Fuzzy Sugeno Controller

The proposed automatic chili drying system employs a Fuzzy Sugeno controller to simultaneously regulate the heater and circulation fan based on the thermal conditions inside the drying chamber[3]. Unlike conventional PID-based approaches that require gain tuning, the proposed controller directly generates PWM commands for both actuators according to the temperature and relative humidity conditions. The controller utilizes two input variables, namely the temperature error and the relative humidity error, while the outputs correspond to the PWM values of the heater and circulation fan[3]. The overall control strategy is illustrated in Fig. 2.

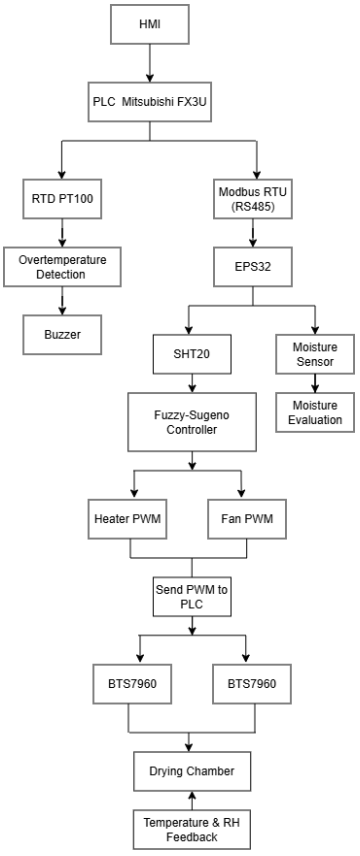


Figure 2. Block Diagram of The Proposed Fuzzy Sugeno Controller

As shown in Fig. 2, the controller continuously compares the measured temperature and relative humidity with their respective setpoints to calculate the control errors. These error values are processed by the Fuzzy Sugeno inference system to directly determine the PWM commands for the heater and the circulation fan. The generated PWM values are periodically transmitted to the Mitsubishi FX3U PLC through Modbus RTU communication, enabling real-time adjustment of heating power and airflow without requiring intermediate PID parameter tuning.

2.3.1 Fuzzy Sugeno Controller

The control inputs are obtained by calculating the deviations between the desired setpoints and the measured process variables[3]. Two error variables are employed as the inputs to the Fuzzy Sugeno

controller, namely the temperature error and the relative humidity error[3].

$$e_T = T_{SP} - T_{PV} \quad (1)$$

where:

T_{SP} = temperature setpoint (℃)

T_{PV} = measured temperature (℃)

$$e_{RH} = RH_{SP} - RH_{PV} \quad (2)$$

where:

RH_{SP} = relative humidity setpoint (%RH)

RH_{PV} = measured relative humidity (%RH)

The calculated error values are continuously updated throughout the drying process and serve as the input variables for the fuzzification stage[3].

2.3.2 Fuzzification

The fuzzification stage transforms the crisp input variables obtained from the error calculation into linguistic variables that can be processed by the Fuzzy Sugeno inference mechanism[3]. In this study, two input variables are employed, namely the temperature error and the relative humidity error[3]. Each input variable is represented using five linguistic terms: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB)[3]. These linguistic variables enable the controller to interpret the drying conditions in a manner similar to human reasoning, thereby improving control performance under nonlinear operating conditions[3].

Triangular and trapezoidal membership functions are adopted because of their simple implementation and low computational complexity, making them suitable for real-time execution on the ESP32 microcontroller. The temperature error and relative humidity error membership functions are illustrated in Fig. 3 and Fig. 4, respectively, while their corresponding parameters are summarized in Table II and Table III.

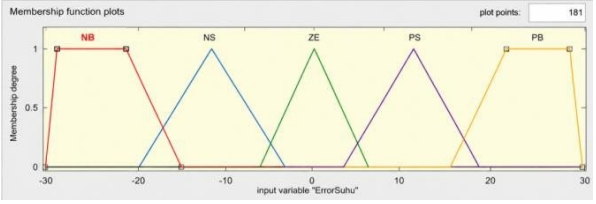


Figure 3. Membership Functions of Temperature Error

The temperature error represents the difference between the desired temperature setpoint and the measured chamber temperature. Negative error values indicate that the measured temperature exceeds the setpoint, whereas positive error values indicate that the measured temperature is below the desired value. Five overlapping membership functions are employed to provide smooth transitions between adjacent linguistic regions, thereby avoiding abrupt changes in the controller output.

Table 2. Parameters of Temperaure Error Membership Functions

Linguistic Variable	Membership Function
NB	Trapmf(-30,-30,-15,-8)
NS	Trimef(-15, -8,0)
ZE	Trimf(-5,0,5)
PS	Trimf(0,8.15)
PB	Trapmf(8,15,30,30)

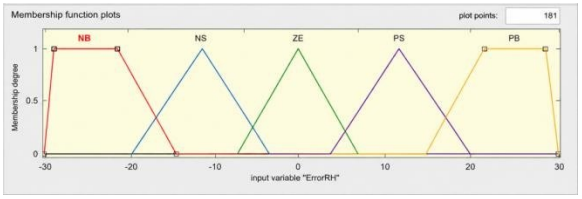


Figure 4. Membership Functions of Relative Humidity Error

The relative humidity error is defined as the difference between the desired and measured humidity values inside the drying chamber. Similar to the temperature error, five linguistic variables are employed to represent different operating conditions. The use of identical linguistic partitions for both input variables simplifies rule development while maintaining adequate sensitivity to environmental changes during the drying process.

Table 3. Parameters of Relative Humidity Error Membership Function s

Linguistic Variable	Membership Function
NB	Trapmf(-30,-30,-20,-10)
NS	Trimef(-10, -10,0)
ZE	Trimf(-8,0,8)
PS	Trimf(0,10.20)
PB	Trapmf(10,20,30,30)

2.3.3 Rule Base

The fuzzy rule base defines the relationship between the input variables and the corresponding control actions[3]. In the proposed controller, the rule base was established based on the thermal characteristics of the drying process and empirical observations obtained during preliminary experiments. The objective of the rule design is to increase the heating power when the chamber temperature is below the desired setpoint while simultaneously adjusting the circulation fan speed according to both temperature and relative humidity conditions.

The proposed controller employs two input variables, namely the temperature error and the relative humidity error, each represented by five linguistic variables: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB)**)[**3]. Combining these linguistic variables results in 25 IF–THEN rules, which determine the PWM outputs for the heater and circulation fan. The complete rule base is presented in Table IV**.**

Table 4. Rule Based PWM Heater

Error_Temp /Error_RH	NB	NS	ZE	PS	PB
NB	550	550	520	500	480
NS	450	420	400	350	320
ZE	250	220	180	150	120

PS	80	50	30	20	10
PB	0	0	0	0	0

Table 5. Rule Based PWM Fan

Error_Temp /Error_RH	NB	NS	ZE	PS	PB
NB	220	200	180	160	140
NS	180	160	140	120	100
ZE	140	120	100	80	60
PS	100	80	60	40	30
PB	60	50	40	30	20

Each rule consists of an antecedent formed by the combination of temperature error and relative humidity error, and a consequent representing the PWM commands for the heater and circulation fan. For example, when both the temperature error and humidity error are classified as Positive Big (PB), the controller increases the heater output to accelerate temperature rise while adjusting the fan speed to improve moisture removal[3]. Conversely, when the temperature error approaches Zero (ZE), the controller gradually reduces the heater PWM and maintains an appropriate fan speed to preserve stable drying conditions and avoid unnecessary temperature fluctuations[3].

Unlike conventional Fuzzy Mamdani controllers that produce fuzzy output sets requiring centroid defuzzification, each rule in the proposed Fuzzy Sugeno controller directly assigns a numerical output value. This approach significantly reduces computational complexity and is well suited for real-time implementation on the ESP32 microcontroller.

2.3.4 Sugeno Interface

After the fuzzification process, the controller evaluates all activated rules using the Sugeno fuzzy inference mechanism[3]. The firing strength of each rule is determined using the minimum (MIN) operator to represent the logical AND relationship between the temperature error and relative humidity error membership degrees[3].

For the *i*-th rule, the firing strength is calculated as

$$\omega_i = \min(\mu_T, \mu_{RH} \quad (3)$$

where:

ω_i = firing strength of the *i*-th rule,

μ_T = membership degree of the temperature error,

μ_{RH} = membership degree of the relative humidity error

The calculated firing strengths indicate the contribution of each rule to the final control action. Since multiple rules may be activated simultaneously, each rule participates proportionally according to its corresponding firing strength.

2.3.5 Defuzzification

The proposed controller employs the weighted average method to obtain crisp output values from the activated Sugeno rules[3]. Unlike the centroid method commonly used in Mamdani inference systems, the weighted average approach directly combines the numerical consequents of all activated rules, resulting in lower computational complexity and faster execution suitable for embedded systems[3].

The crisp output is calculated as

$$z = \frac{\sum_{i=1}^{n} \omega_i z_i}{\sum_{i=1}^{n} \omega_i} \quad (4)$$

where:

z = crisp output,

ω_i = firing strength of the *i*-th rule,

z_i = numerical consequent associated with the i-th rule,

n = total number of activated rules.

The weighted average calculation is independently performed for the heater and circulation fan, producing two crisp outputs that represent the desired PWM values for each actuator.

2.3.6 PWM Generation

The crisp outputs generated by the Fuzzy Sugeno controller correspond to the desired operating levels of the heater and circulation fan[3]. These values are converted into pulse width modulation (PWM) commands before being transmitted to the Mitsubishi FX3U PLC through Modbus RTU communication[9],[11],[14]. The PLC subsequently generates the corresponding PWM signals to drive the BTS7960 motor drivers, which regulate the heating power of the PTC heater and the rotational speed of the DC circulation fan[9],[14].

By directly generating PWM commands, the proposed control strategy eliminates the need for intermediate PID gain calculation or parameter tuning. Consequently, the controller provides a simpler implementation while maintaining adaptive responses to variations in temperature and relative humidity throughout the drying process.

2.4. System Operation

The operational sequence of the proposed automatic chili drying system is illustrated in Fig. 5. The drying process begins with system initialization, during which communication between the Mitsubishi FX3U PLC, ESP32, sensors, and Human–Machine Interface (HMI) is established[9],[10]. Once all devices are successfully connected, the operator specifies the drying parameters, including the desired temperature setpoint and drying duration, through the HMI before initiating the drying process.

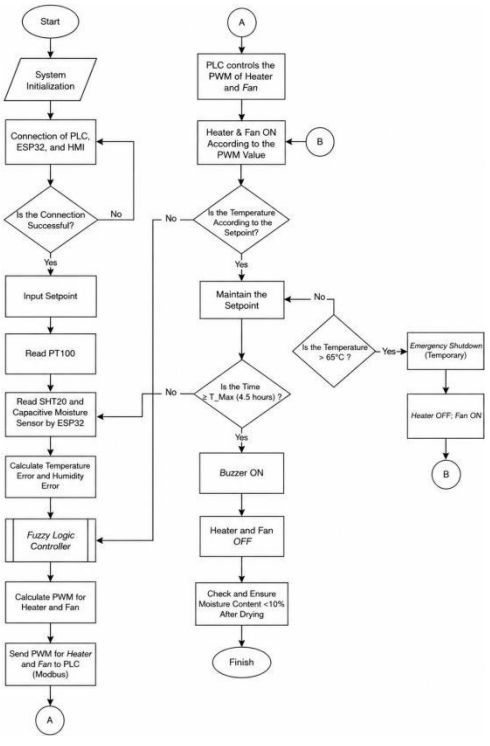


Figure 5. Flowchart of The Proposed Automatic Chili Drying System

As shown in Fig. 5, the SHT20 sensor continuously measures the temperature and relative humidity inside the drying chamber, while the PT100 RTD independently monitors the chamber temperature for safety purposes[12],[13]. The measured temperature and relative humidity are transmitted to the ESP32, where the temperature error and relative humidity error are calculated with respect to their predefined setpoints. These error values are subsequently processed by the Fuzzy Sugeno controller to determine the appropriate PWM commands for the heater and circulation fan.

The generated PWM values are periodically transmitted to the Mitsubishi FX3U PLC through Modbus RTU communication. The PLC converts these values into PWM signals that drive the BTS7960 motor drivers connected to the PTC heater and the DC circulation fan[14]. By continuously adjusting both actuators according to the controller outputs, the system maintains stable thermal conditions and promotes uniform heat distribution throughout the drying chamber.

To ensure safe operation, an over-temperature protection mechanism is incorporated into the control system. The PT100 RTD continuously supervises the chamber temperature independently of the fuzzy controller. If the measured temperature exceeds the predefined safety threshold, the PLC immediately disables the heater while maintaining fan operation to accelerate cooling. The heating process resumes automatically after the chamber temperature returns to the permissible operating range, thereby preventing overheating and protecting both the drying equipment and the agricultural product.

The drying process continues until the predefined drying duration is completed. At the end of the process, the heater and circulation fan are turned off automatically, and the final moisture content of the dried chili is measured using the capacitive moisture sensor for performance evaluation. The experimental results are subsequently analyzed in terms of temperature stability, moisture reduction, drying uniformity, and visual product quality.

2.5. PLC-ESP32 Communication

Reliable communication between the ESP32 and the Mitsubishi FX3U PLC is essential for ensuring stable and real-time operation of the proposed automatic chili drying system. Since the intelligent control algorithm and actuator control are executed on different hardware platforms, an efficient communication mechanism is required to synchronize data exchange between both devices. In this study, Modbus RTU communication over an RS485 interface is employed because of its simplicity, high reliability, and excellent noise immunity in industrial environments. Compared with conventional serial communication, Modbus RTU provides a standardized communication protocol that facilitates data exchange between devices from different platforms while maintaining deterministic communication performance.

Within the proposed architecture, the ESP32 functions as the Modbus master, performing sensor acquisition, fuzzy inference, and PWM computation, whereas the Mitsubishi FX3U PLC operates as the Modbus slave, receiving the calculated PWM values and executing real-time actuator control. This separation of computational and control tasks reduces the processing burden on the PLC while allowing the ESP32 to efficiently execute the Fuzzy Sugeno algorithm. Consequently, the hybrid architecture combines the computational capability of embedded systems with the robustness and reliability of industrial PLC-based control. The overall communication architecture between the ESP32 and PLC is illustrated in Fig. 6.

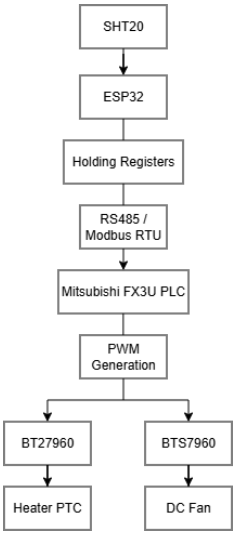


Figure 6. PLC-ESP32 Communication Architecture Using Modbus RTU

The ESP32 continuously receives temperature and relative humidity measurements from the SHT20 sensor and computes the corresponding temperature and humidity errors. These variables are processed by the Fuzzy Sugeno controller to determine the PWM commands for the heater and circulation fan. The calculated PWM values are then written to predefined Modbus holding registers, allowing the PLC to update the actuator outputs periodically during the drying process.

Conversely, the PLC periodically reads the transmitted register values and converts them into PWM signals for the BTS7960 motor drivers. This communication mechanism enables the PLC to execute deterministic actuator control while the computationally intensive fuzzy inference is handled by the ESP32. Consequently, the hybrid architecture combines the flexibility of embedded intelligent control with the reliability of industrial PLC operation.

Table 6. Modbus Register Mapping

Register	Description	Data Type
D100	Chamber Temperature (×10)	Integer
D101	Relative Humidity (x10)	Integer
D102	Heater PWM	Integer
D103	Fan PWM	Integer
D104	Moisture Sensor Value	Integer
D105	Moisture Percentage (%)	Integer

To ensure stable communication, sensor values and PWM commands are transmitted as scaled integer data. Temperature and relative humidity values are multiplied by a scaling factor before transmission to preserve decimal precision while maintaining compatibility with the integer-based Modbus registers of the Mitsubishi FX3U PLC. The PLC subsequently performs the

corresponding scaling operation before using the received values for monitoring and actuator control.

2.6. Hardware Configuration

The developed automatic chili drying system consists of a laboratory-scale drying chamber integrated with sensing devices, actuators, and industrial control hardware. The prototype was designed to provide uniform heat distribution while enabling real-time monitoring and control of the drying process. Figure 7 presents the three-dimensional design of the proposed drying chamber, whereas the completed hardware prototype is shown in Fig. 8.

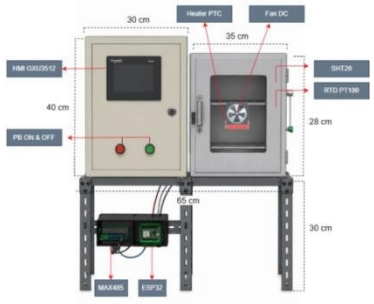


Figure 7. Three-Dimensional Design of the Proposed Automatic Chili Drying System

As illustrated in Fig. 7, the drying chamber has overall dimensions of 30 cm × 25 cm × 28 cm and is equipped with two drying racks to improve airflow distribution around the chili samples. A 24 V PTC heater is installed on the right side of the chamber, while a 24 V DC circulation fan is positioned at the bottom to distribute heated air uniformly throughout the drying chamber. The SHT20 sensor is mounted inside the chamber to continuously measure temperature and relative humidity, whereas the PT100 RTD is installed independently to provide over-temperature protection. This arrangement enables effective thermal regulation while maintaining measurement accuracy during the drying process.



Figure 8. Developed Automatic Chili Drying Machine

Figure 8 shows the completed prototype of the automatic chili drying system. The prototype integrates the Mitsubishi FX3U PLC, ESP32 microcontroller, HMI, BTS7960 motor drivers, sensors, and actuators into a compact laboratory-scale drying unit. During operation, the ESP32 executes the Fuzzy Sugeno algorithm using the measured temperature and relative humidity as inputs and periodically transmits the calculated PWM commands to the PLC via Modbus RTU communication. The PLC subsequently regulates the heater and circulation fan according to the received commands, ensuring stable drying conditions throughout the process.

The developed prototype provides a practical platform for validating the proposed hybrid PLC–ESP32 control architecture under actual drying conditions. The integration of industrial control hardware with an embedded intelligent controller enables the proposed system to operate in a reliable and real-time manner while maintaining flexibility in implementing the Fuzzy Sugeno algorithm. During the experimental evaluation, the prototype was used to assess the overall system performance, including communication reliability, actuator response, and the effectiveness of the proposed control strategy in regulating the drying chamber conditions. In addition to evaluating the controller performance, the prototype enables continuous observation of temperature stability, relative humidity reduction, moisture content, and the visual quality of the dried chili throughout the drying process. These comprehensive evaluations demonstrate the feasibility and practical applicability of the proposed system as an intelligent agricultural drying solution capable of producing dried chili with stable processing conditions and satisfactory product quality.

3. Result and Discussion

This section presents the experimental results and discusses the performance of the proposed automatic chili drying system. The evaluation covers sensor validation, communication performance, temperature and relative humidity control, actuator response, drying effectiveness, and the quality of the dried chili produced. The obtained results are analyzed to demonstrate the effectiveness of the proposed Fuzzy Sugeno controller in maintaining stable drying conditions while producing dried chili with satisfactory moisture content and visual quality.

3.1. Temperature and Humidity Validation

The accuracy of the sensing system is an essential factor in ensuring the reliability of the proposed Fuzzy Sugeno controller. Since the controller relies on temperature and relative humidity measurements as feedback variables, the performance of the SHT20 sensor was experimentally evaluated prior to the drying experiments. The validation was conducted by comparing the sensor readings with those of a calibrated commercial thermo-hygrometer under various operating conditions. The validation results are summarized in Table 7.

Table 7. Validation Results of the SHT20 Temperature and Relative Humidity Sensor

Temp (°C)	SHT20 (°C))	Temp_err (%)	RH (%)	SHT20 (%)	RH_err (%)
31.6	31.8	0.6	60.0	60.3	0.5
31.8	32.0	0.6	61.0	61.7	1.1
32.0	32.3	0.9	65.0	65.5	0.8
32.5	32.8	0.9	67.0	67.1	0.1
32.9	33.1	0.6	68.0	67.3	0.4
33.3	33.5	0.9	68.0	68.5	0.7
34.0	34.2	0.5	68.0	68.7	1.0
34.4	34.7	0.8	69.0	69.2	0.2
35.1	35.3	0.5	70.0	70.2	0.2
35.3	35.5	0.5	71.0	71.4	0.5
Avarage Error	-	0.68	-	-	0.55

As presented in Table VII, the SHT20 sensor exhibited satisfactory measurement accuracy for both temperature and relative humidity. The average temperature and relative humidity errors were 0.68% and 0.55%, respectively, indicating good agreement with the reference thermo-hygrometer. The small measurement deviations demonstrate that the SHT20 sensor provides reliable environmental data for the proposed Fuzzy Sugeno controller. Since the controller relies on temperature and relative humidity as its input variables, accurate sensor measurements are essential to ensure stable control performance throughout the drying process.

3.2. Temperature Performance Analysis

The temperature response of the proposed drying system was evaluated by comparing the conventional ON–OFF control strategy with the proposed Fuzzy Sugeno controller under identical operating conditions using a temperature setpoint of 60 °C. The comparison is presented in Fig. 9, while the corresponding dynamic response characteristics are summarized in Table 8.

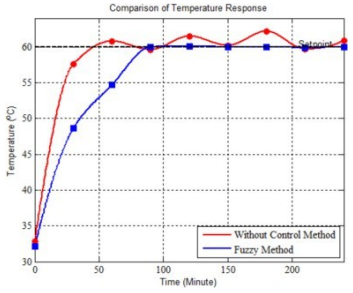


Figure 9. Comparison of Temperature Response Between the Conventional System and the Proposed Fuzzy Sugeno Controller

As shown in Fig. 9, the conventional control system increased the chamber temperature rapidly during the initial heating stage because the heater operated at full power until the setpoint was reached. However, after reaching the desired temperature, the chamber exhibited noticeable oscillations around the setpoint due to the repetitive ON–OFF switching of the heater combined with the thermal inertia of the heating element. These fluctuations resulted in unstable drying conditions throughout the experiment.

In contrast, the proposed Fuzzy Sugeno controller produced a smoother temperature response. Instead of operating the heater at full power continuously, the controller gradually adjusted the heater PWM according to the temperature error and relative humidity error. Consequently, the chamber temperature approached the 60 °C setpoint more gradually and was subsequently maintained within a narrow range of approximately 59.9–60.1 °C with only minor fluctuations. This behavior demonstrates the capability of the proposed controller to provide a more stable thermal environment during the drying process.

Table 8. Comparison of Dynamic Temperature Response

Parameter	Conventional ON-OFF	Proposed Fuzzy Sugeno
Rise Time	±60 min	±90 min
Settling Time	Not archieved	±90 min
Overshoot	2.2 °C (≈3.7%)	0.1 °C (≈0.2%)
Steady-State Error	±1.5 °C	±0.1 °C

As summarized in Table 8, the conventional system achieved a shorter rise time because the heater continuously operated at maximum power during the heating stage. Conversely, the proposed Fuzzy Sugeno controller required approximately 90 minutes to reach the setpoint since the heater output was continuously modulated according to the fuzzy inference results. Although this resulted in a slower heating process, it effectively prevented excessive temperature rise and significantly reduced temperature oscillations around the desired operating point.

The superiority of the proposed controller becomes more apparent from the overshoot and steady-state characteristics. The conventional ON–OFF system exhibited an overshoot of approximately 2.2 °C, whereas the proposed controller limited the overshoot to only 0.1 °C. Likewise, the steady-state error was reduced from approximately ±1.5 °C to ±0.1 °C, indicating excellent temperature regulation. These improvements are attributed to the ability of the Fuzzy Sugeno controller to continuously generate appropriate PWM commands for both the heater and the circulation fan based on real-time temperature and humidity conditions, rather than relying on binary switching. As a result, the proposed system maintained a more stable drying temperature, which is beneficial for achieving uniform moisture removal while minimizing thermal degradation of the chili during the drying process.

To evaluate the thermal uniformity inside the drying chamber, temperature measurements were conducted at two different locations, namely the upper and lower drying racks. Each measurement was repeated three times under the conventional ON–OFF control strategy, and the average values are summarized in Table 9 and Fig. 10.

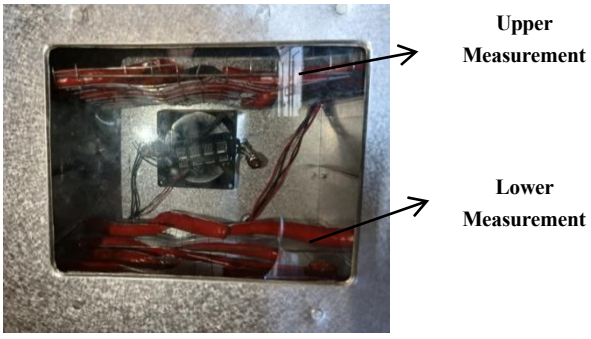


Figure 10. Temperature measurement locations inside the drying chamber

Table 9. Temperature Distribution Inside the Drying Chamber

Measurement Position	Trial 1 (°C)	Trial 2 (°C)	Trial 3 (°C)	Mean (°C)
Upper Section	59.4	59.8	59.6	59.6
Lower Section	61.8	62.1	61.7	61.8

As shown in Table 9, the average temperature at the lower rack was 61.8 °C, whereas the upper rack exhibited an average temperature of 59.6 °C, resulting in a temperature difference of approximately 2.2 °C. This non-uniform temperature distribution is mainly attributed to the placement of the PTC heater and the circulation fan near the lower section of the drying chamber. Consequently, heated air initially accumulated around the lower rack before being circulated toward the upper section, leading to a noticeable temperature gradient inside the chamber.

In addition, the conventional ON–OFF control strategy contributed to the non-uniform temperature distribution because the heater repeatedly switched between fully ON and OFF states. Such abrupt heating cycles caused periodic fluctuations in the chamber temperature, preventing the hot air from being distributed evenly throughout the drying space. As a result, the lower rack consistently experienced higher temperatures than the upper rack during the drying process.

These observations indicate that the drying chamber did not achieve completely uniform thermal conditions under the conventional control strategy. The existence of a temperature difference between the two drying racks suggests that product samples placed at different locations may experience different drying rates. Therefore, maintaining stable temperature regulation and improving air circulation are important factors in achieving a more uniform drying process and consistent product quality.

3.3. Relative Humidity and PWM Control Performance

The performance of the proposed Fuzzy Sugeno controller was further evaluated by analyzing the relative humidity (RH) response together with the corresponding PWM outputs generated for the heater and circulation fan. Since the controller simultaneously utilizes temperature error and relative humidity error as its input variables, the RH profile and actuator responses provide important insights into the adaptive behavior of the proposed control strategy. The experimental results are presented in Fig. 11 and Fig. 12, while the corresponding measurement data are summarized in Table 10.

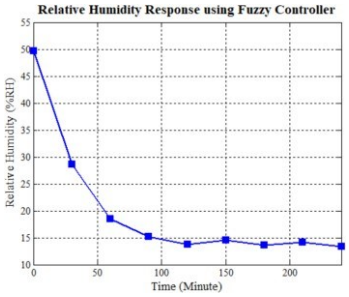


Figure 11. Relative Humidity Response During the Drying Process

As illustrated in Fig. 11, the relative humidity gradually decreased from 49.7%RH at the beginning of the drying process to approximately 13.4%RH after 240 minutes. This continuous reduction indicates that moisture was progressively removed from the drying chamber as heat was transferred to the chili samples. The decreasing RH confirms that the proposed control system was able to maintain favorable drying conditions throughout the experiment.

Small increases in RH were observed at 150 minutes and 210 minutes, where the humidity temporarily increased from 13.8%RH to 14.5%RH and from 13.6%RH to 14.1%RH, respectively. These temporary increases are attributed to the evaporation mechanism occurring inside the chili. As moisture migrated from the inner tissues to the surface, additional water vapor was released into the chamber, causing a slight increase in the measured RH. After sufficient air circulation removed the accumulated vapor, the RH gradually decreased again, indicating that the moisture removal process continued effectively[1],[4].

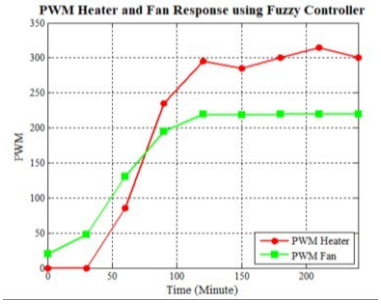


Figure 12. Heater and Fan PWM Responses Generated by the Proposed Fuzzy Sugeno Controller

The adaptive operation of the proposed controller can be clearly observed from the PWM responses shown in Fig. 11**.** At the beginning of the drying process, the heater PWM was maintained at 0, indicating maximum heating power to rapidly increase the chamber temperature from ambient conditions. Simultaneously, the circulation fan operated at a relatively low PWM value of 20 and gradually increased as the drying process progressed, enhancing air circulation and facilitating moisture removal from the chamber.

As the chamber temperature approached the 60 °C setpoint, the Fuzzy Sugeno controller progressively increased the heater PWM to approximately 285–315, thereby reducing the effective heating power and preventing excessive temperature rise. Meanwhile, the fan PWM stabilized at approximately 218–220, ensuring continuous circulation of heated air and efficient removal of water vapor generated during drying. This coordinated adjustment of both actuators demonstrates that the proposed controller continuously adapts its outputs according to the measured drying conditions instead of employing fixed operating values.

Table 10. Experimental Results of the Proposed Fuzzy Sugeno Controller

Time (min)	Temp (°C)	RH (%RH)	Heater PWM	Fan PWM
0	32.1	49.7	0	20
30	50.8	28.6	0	61.8
60	57.5	18.5	85	130
90	59.6	15.2	18.5	195
120	60.0	13.8	295	220
150	59.9	14.45	285	218
180	60.0	13.6	300	220
210	60.1	14.1	315	220
240	60.0	13.4	300	220

The measured data presented in Table X further confirm the effectiveness of the proposed controller. As the chamber temperature gradually increased toward the desired setpoint, the heater PWM was continuously adjusted to avoid excessive heating, while the circulation fan operated at higher PWM values to maintain adequate air exchange inside the chamber. The coordinated regulation of both actuators enabled stable temperature control while simultaneously maintaining a low relative humidity, thereby creating favorable conditions for continuous moisture evaporation throughout the drying process.

Overall, the RH response and PWM characteristics demonstrate the adaptive capability of the proposed Fuzzy Sugeno controller in regulating both heat input and air circulation simultaneously. Unlike conventional ON–OFF control, which relies on binary actuator operation, the proposed controller continuously modulates the heater and fan outputs according to real-time temperature and humidity conditions. This coordinated control strategy contributes to stable drying chamber conditions, minimizes unnecessary fluctuations, and supports a more efficient and uniform drying process.

3.4. Drying Performance Evaluation

The effectiveness of the proposed Fuzzy Sugeno controller was further evaluated by comparing the physical appearance of dried chili produced using the conventional ON–OFF control strategy and the proposed control method. Both experiments were conducted under identical drying conditions with a temperature setpoint of 60 °C and a drying duration of 240 minutes. The comparison of the dried chili products is presented in Fig. 13, while the overall drying performance is summarized in Table 11.

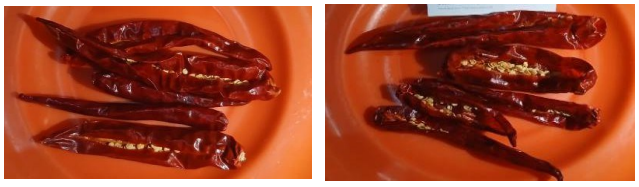


Figure 13. Comparison of Dried Chili Produced by (a) Conventional ON–OFF Control and (b) Proposed Fuzzy Sugeno Controller

As illustrated in Fig. 13, both drying methods produced dried chili with a generally similar visual appearance. However, the chili processed using the proposed Fuzzy Sugeno controller exhibited a noticeably higher degree of shrinkage, indicating that a greater amount of moisture had been removed during the drying process. In contrast, the chili dried using the conventional ON–OFF control strategy appeared slightly less dehydrated, suggesting that additional drying time would be required to achieve a comparable level of dryness.

Table 11. Comparison of Drying Performance Between the Conventional System and the Proposed Fuzzy Sugeno Controller

Parameter	Conventional ON-OFF	Proposed Fuzzy Sugeno
Temperature Setpoint (°C)	60	60
Initial Moisture Content (%)	78.5	78.5
Final Moisture Sensor Reading (%)	8.2	0.0*
Temperature Response	Fluctuating	Stable
Overshoot (°C)	2.2	0.1
Steady-State Error (°C)	±1.5	±0.17
Drying Uniformity	Less uniform	More uniform (±1% moisture difference)

*The 0% value represents the minimum detectable limit of the capacitive moisture sensor and does not indicate that the actual moisture content of the chili reached zero.

The observations shown in Fig. 13 are consistent with the quantitative results presented in Table 11. Although both systems operated for the same drying duration, the conventional system produced a final moisture sensor reading of 8.2%, whereas the proposed Fuzzy Sugeno controller reached the minimum measurable value of the capacitive moisture sensor. This result indicates that the proposed controller provided more effective moisture removal by maintaining stable drying conditions throughout the experiment[1],[6].

The improved drying performance is primarily attributed to the stable temperature regulation achieved by the proposed controller. As discussed in the previous sections, the Fuzzy Sugeno controller maintained the chamber temperature close to the desired setpoint while simultaneously regulating the heater and circulation fan outputs according to the measured drying conditions. Consequently, heat transfer and moisture evaporation occurred more consistently than in the conventional ON–OFF system, which experienced larger temperature fluctuations and less uniform heat distribution[1],[5].

Overall, the visual observations and quantitative measurements consistently demonstrate that the proposed Fuzzy Sugeno controller improved the effectiveness of the drying process. The combination of stable temperature regulation, adaptive actuator control, and more uniform moisture removal enabled the production of dried chili with better drying characteristics under the same processing time.

3.5. Qualitative Viual Comparison with Commercial Dried Chili

To further evaluate the quality of the dried product, a qualitative visual comparison was performed between the chili dried using the proposed Fuzzy Sugeno controller and a commercially available dried chili product. Since the drying conditions and processing methods employed in the commercial product are unknown, the comparison presented in this study is limited to observable physical characteristics without drawing quantitative conclusions. The comparison aims to provide a visual assessment of the product quality achieved by the proposed drying system.

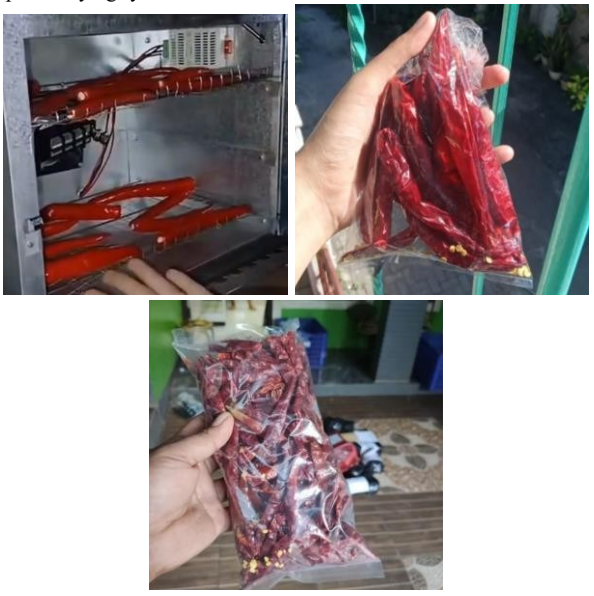


Figure 14. Visual comparison of (a) fresh chili, (b) dried chili produced using the proposed Fuzzy Sugeno controller, and (c) commercially available dried chili.

As illustrated in Fig. 14, the chili dried using the proposed system retained a bright red appearance with relatively uniform shrinkage after the drying process. In comparison, the commercially available dried chili exhibited a darker red color and a less uniform surface texture. Although

both products can be classified as dried chili, the proposed drying system produced a product with a fresher visual appearance.

The better color retention observed in the proposed drying method is closely related to the stable drying conditions achieved by the Fuzzy Sugeno controller[15[,[16],[17],[18]. As discussed in the previous sections, the controller maintained the chamber temperature close to the desired setpoint while minimizing temperature fluctuations through adaptive regulation of the heater and circulation fan. These stable operating conditions reduce unnecessary thermal exposure during drying, thereby helping preserve the natural appearance of the chili.

It should be emphasized that the comparison presented in this study is qualitative and is based solely on visual observations. Because the processing conditions of the commercial dried chili, including drying temperature, drying duration, airflow, and production method, are unknown, no direct quantitative performance comparison can be established. Therefore, the observations presented here are intended only to demonstrate the visual quality that can be achieved using the proposed drying system.

Nevertheless, the visual observations indicate that the proposed drying system is capable of producing dried chili with an attractive appearance while maintaining effective moisture removal. The combination of stable temperature regulation, adaptive control of the heater and circulation fan, and consistent drying conditions contributes to a product with good visual quality, demonstrating the practical potential of the proposed Fuzzy Sugeno controller for agricultural drying applications.

4. Conclusion

This paper presented the development of an automatic chili drying system based on a hybrid PLC–ESP32 architecture employing a Fuzzy Sugeno controller for simultaneous regulation of the heater and circulation fan. The proposed control strategy successfully maintained the drying chamber temperature at the desired setpoint of 60 °C with a maximum overshoot of only 0.1 °C and a steady-state error of approximately ±0.17 °C, demonstrating significantly better temperature stability than the conventional ON–OFF control strategy.

Experimental results showed that the adaptive adjustment of the heater and fan PWM enabled stable drying conditions, allowing the relative humidity to decrease gradually from 49.7%RH to 13.4%RH during the 240-minute drying process. Compared with the conventional system, the proposed controller produced more uniform drying characteristics and achieved a lower final moisture sensor reading within the same drying duration, indicating more effective moisture removal.

Qualitative visual observations further demonstrated that the proposed drying system produced dried chili with a more uniform appearance and better color retention than the conventional drying method. Although no quantitative comparison with commercially available dried chili was performed due to the unknown processing conditions, the visual assessment indicates that the proposed drying system is capable of producing dried chili with satisfactory product quality while maintaining stable drying conditions.

Future work may include laboratory analysis of the final moisture content, color parameters, and nutritional properties of the dried chili to quantitatively evaluate product quality. In addition, optimization of the fuzzy rule base and implementation of intelligent optimization techniques may further improve the drying performance and energy efficiency of the proposed system.

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