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Temperature and Humidity Control System for Quail Cages Based on Fuzzy Logic

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Abstract

Quails require stable environmental temperature and humidity to maintain health, reduce thermal stress, and support productivity. Conventional threshold-based control systems often show limited adaptability to dynamic environmental fluctuations in small-scale poultry farming. This study proposes an adaptive temperature and humidity control system for quail cages based on a Fuzzy Logic Controller (FLC) implemented on an ESP32 microcontroller using real-time feedback from a DHT22 sensor. The proposed system employs the Mamdani fuzzy method to control the heater and blower actuators via pulse-width-modulated (PWM) signals. The novelty of this study lies in the development of a low-cost adaptive fuzzy control framework specifically designed for small-scale quail cage environments with simultaneous heater–blower regulation based on combined temperature and humidity conditions. Experimental simulation results demonstrate that at low-temperature and dry-humidity conditions (18°Celcius, 40 relative humidity), the system produces a heater PWM of 223.3 and a blower PWM of 29.7. Under ideal environmental conditions (27°C, 60%RH), both outputs decrease to approximately 26.7 PWM, indicating energy-efficient operation. At high-temperature and high-humidity conditions (35°C, 80% RH), the heater decreases to 27.3 PWM while the blower increases to 224.6 PWM. These findings confirm that the proposed system provides adaptive, stable, and responsive environmental control for quail cages.

Keywords: Environmental Control, ESP32, Fuzzy Logic Control, Humidity, Temperature.

1. Introduction

Quail farming is one of the agribusiness sectors that has high economic potential because its production cycle is relatively short and market demand for eggs and meat is stable [1], [2]. The success of the quail farming business is strongly influenced by cage environmental management capable of maintaining optimal microclimate conditions [3], [4]. A stable cage environment plays an important role in supporting the metabolism, health, and productivity of quail birds sustainably [5].

Temperature and humidity are two main parameters that determine the comfort and health of quail birds [6], [7]. Temperature that is too low can inhibit activity and growth, while excessively high temperature and uncontrolled humidity can trigger stress, reduce egg productivity, and increase the risk of disease [8]. Therefore, a system is needed that is not only able to monitor cage environmental conditions, but also actively control temperature and humidity so that they remain within the ideal range through a responsive control mechanism [9], [10].

In practice, most farmers still use manual methods or simple control systems based on fixed threshold values in regulating heaters and cage ventilation [11]. This approach has limitations in dealing with dynamic environmental fluctuations, so it often results in inappropriate or delayed responses [12]. In addition, conventional control systems are generally less flexible and difficult to adapt for small- to medium-scale farmers due to cost limitations, device complexity, and relatively high-power consumption [13], [14]; therefore, an intelligent adaptive control system is required.

The Fuzzy Logic Controller (FLC) algorithm is one of the artificial intelligence methods widely used for controlling temperature and air humidity [15]. Previous studies indicate that this approach can improve environmental control system performance. Several researchers have investigated the operational characteristics of fuzzy logic controllers in variable-speed direct expansion air conditioning systems to simultaneously regulate indoor temperature and humidity [16]. Demir et al. [17] examined independent temperature and humidity control in a pre-cooled desiccant air-conditioning system using proportional controllers combined with proportional-based fuzzy logic. Zhong et al. [18] also conducted a simulation-based performance evaluation of a novel fuzzy logic algorithm designed to simultaneously regulate indoor air temperature and humidity. Furthermore, Yao et al. developed an HVAC (Heating, Ventilation, and Air Conditioning) control system based on reinforcement learning combined with fuzzy reasoning to optimize temperature, airflow rate, and supply air velocity [19]. Efforts to reduce energy consumption in air-conditioning systems through a fuzzy logic–based optimization approach were also investigated by Pagare et al. [20]. In addition, fuzzy logic has been implemented in a real-time plant monitoring platform and automated irrigation system using Internet of Things (IoT) and the Fuzzy Sugeno algorithm, as studied by Wijayakusuma et al. [21]. Meanwhile, Yi et al. explored adaptive thermal comfort control in electric vehicle air-conditioning systems using a fuzzy Proportional–Integral–Derivative (PID) controller optimized with the Grey Wolf Optimizer (GWO) method [22].

Çinar and Abut [23] developed a Fuzzy Linear Quadratic Regulator (LQR) based control method to maintain thermal comfort in HVAC systems with two different zones. Liu et al. [24] designed an adaptive fuzzy controller for an air handling unit (AHU). The application of fuzzy logic in evaporative cooling systems to improve energy efficiency and thermal comfort in buildings has also been experimentally validated using a cyber-physical system by Shrivastava et al. [25]. Safdari et al. [26] further developed a weather-adaptive fuzzy setpoint control strategy to enhance energy efficiency in HVAC systems within urban buildings.

Beyond HVAC systems, fuzzy logic has also been applied to simultaneous temperature and humidity regulation and thermal comfort applications. Li et al. [27] proposed a new fuzzy logic–based controller combined with a proportional–derivative (PD) control law to simultaneously regulate indoor temperature and humidity using a direct expansion air-conditioning system. Marvuglia et al. [28] combined a neural network–based temperature predictor with a fuzzy logic controller to regulate thermal comfort in office buildings. In addition, Khanghah et al. [29] conducted an IoT-based experimental validation of fuzzy logic control applied to solar thermal collector systems.

Based on the limitations identified in previous studies, this research proposes the design and development of an adaptive temperature and humidity control system for quail cages using an ESP32 microcontroller unit (MCU) and a fuzzy logic approach as a real-time decision-making mechanism [30]. Although fuzzy logic has been widely applied in thermal and environmental control systems, most previous studies mainly focused on Heating, Ventilation, and Air Conditioning (HVAC) systems, industrial processes, and large-scale environmental regulation. Consequently, adaptive and cost-effective control systems specifically designed for small-scale quail cage environments remain limited. Therefore, the research gap addressed in this study lies in the lack of low-cost and adaptive control systems capable of simultaneously regulating temperature and humidity according to quail environmental requirements in real time. Based on this gap, the research question of this study is: How can a fuzzy logic–based control system be designed to adaptively regulate temperature and humidity in quail cages using real-time environmental feedback while maintaining stable environmental conditions? Accordingly, the aim of this study is to design and evaluate an adaptive fuzzy logic–based environmental control system that integrates a DHT22 temperature and humidity sensor, heater, and blower actuators using pulse-width modulation (PWM) control to maintain cage environmental stability [31].

The novelty of this study lies in the development of a quail-specific fuzzy control framework capable of simultaneously regulating heater and blower outputs based on combined temperature and humidity conditions in real time using an ESP32 platform. The main contribution of this research is the development of a simple, adaptive, energy-efficient, and easy-to-implement environmental control system for small-scale quail farming. In addition, this study contributes practical insight into the implementation of fuzzy logic–based environmental regulation for improving cage stability, quail comfort, and farming productivity.

2. Method of the Research

The research methodology carried out in this study is Research and Development (R&D) with systematic flow stages from the design, implementation, and testing of a temperature and humidity control system for a fuzzy logic-based quail cage. The approach used is experimental and system engineering, where hardware and software are designed, integrated, and tested to evaluate adaptive temperature control performance.

2.1. System Design

The developed system is a closed-loop control system that utilizes feedback of cage environmental temperature and humidity as the basis for control decision-making. The block diagram (Fig. 1) shows that the cage environment acts as the controlled object, while the sensor functions as the measurement element. Environmental temperature and humidity are measured continuously using a DHT22 sensor [32], [33], which produces temperature data in degrees Celsius (°C) and humidity data in percent (%). The measurement data are then sent to the ESP32 microcontroller as the main input of the control system.

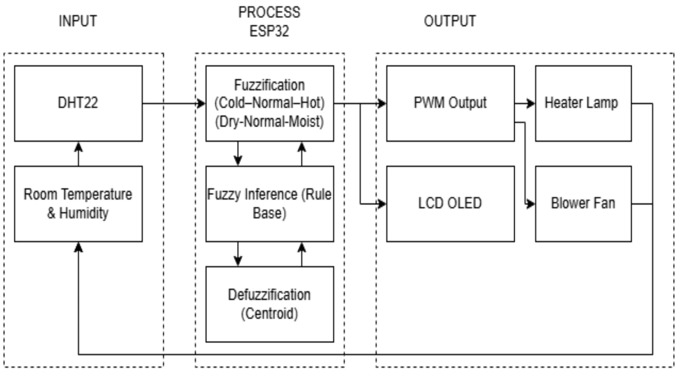

Figure 1. Block Diagram.

Inside the ESP32 microcontroller, temperature and humidity data are processed using a fuzzy logic algorithm. The initial stage carried out is fuzzification, which is the process of converting crisp temperature values into degrees of membership in the linguistic sets cold, normal, and hot, and converting crisp humidity values into degrees of membership in the dry, normal, and humid sets. This fuzzification process allows the system to represent environmental conditions in linguistic form that resembles human reasoning, so it is more adaptive to changes in dynamic environmental conditions.

Next, the fuzzification results are processed in the fuzzy inference stage using a rule base that has been designed. These rules determine the relationship between temperature and humidity conditions and the required intensity level of the heater lamp and blower fan. Inference is carried out using the Mamdani method to produce fuzzy output based on active rules. Through this mechanism, the system can determine the appropriate control magnitude to keep the cage temperature and humidity in optimal conditions.

The final stage in fuzzy logic processing is defuzzification, which aims to convert fuzzy output into crisp values. The centroid method is used to obtain numerical values representing heater intensity level and blower speed. The mathematical values from the fuzzy calculations are then converted into pulse signals, also known as PWM, which are sent to the actuator. These PWM variations will then regulate the heat generated by the lights and the fan speed to control humidity, ensuring stable conditions in the enclosure. If environmental conditions change, the DHT22 sensor will provide continuous feedback to the system to evaluate the fuzzy values. Data on temperature, humidity, fuzzy logic, and PWM parameters will then be displayed on the Organic Light-Emitting Diode (OLED) display in real time.

It should be noted that the thermal requirements of quails vary according to age and feather development. Newly hatched quails generally require higher environmental temperatures, which gradually decrease as the birds mature. In this study, the proposed fuzzy control system was designed and evaluated for near-mature/adult quail cage conditions, where relatively stable environmental temperature and humidity ranges are required. Therefore, age-dependent temperature adaptation was beyond the present study scope and is considered for future system enhancement.

2.2. Hardware and Circuit Design

The fuzzy control system circuit in the quail cage can be seen in Fig. 2, where the ESP32-C3 serves as a microcontroller that reads the sensor data and sets the output value of the aquarium, as well as displays the data in one integrated system. The selection of the ESP32 in this study is based on fast data processing capabilities for fuzzy algorithms, supports PWM capabilities, and has low power consumption, making it suitable to be used and applied according to the designed research flow.

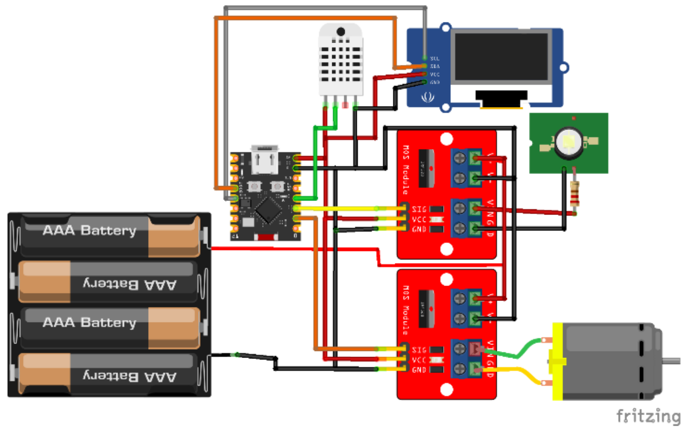

Figure 2. Circuit System.

DHT22 Sensor is used to read the temperature and humidity data in the environment of the quail cage. This Sensor is connected to the same voltage source as the ESP32-C3, and the DHT Data pin is connected to digital pin 3 of the ESP to read the sensor data in digital values. The sensor Data will be input feedback for the fuzzy algorithm in controlling the heater and blower. Then the OLED LCD functions to display temperature data, humidity, fuzzy inference values, and PWM values that are output to the aquarium. This is so that the running process of the system can be monitored in real time by the user without the addition of other devices.

The actuator in the system is designed to consist of a heating element and a blower fan, each of which is controlled by a PWM driver. This aims to power the amplifier at the same time so that there is no large backflow to the ESP, which can damage the components inside. The PWM signal is output to 2 different PWM drivers for each aquator, and this PWM duty cycle will later regulate the heat level and blower speed so that the temperature and humidity parameters of the Quail cage can be controlled automatically.

2.3. Fuzzy Logic System Design

The flow diagram of the system prepared in this study is shown in Fig. 3, which is a fuzzy logic-based learning control work process that is run on the ESP32-C3. The device, sensor, LCD, Aquator, and Fuzzy method are used; after that, the program will keep repeating.

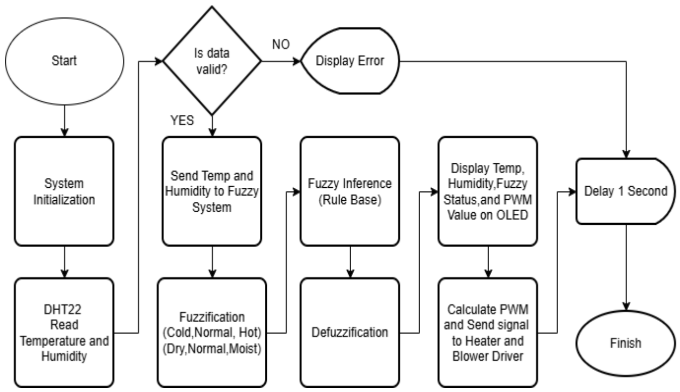

Figure 3. Flowchart.

In each cycle, the ESP32-C3 reads temperature data from the DHT22 sensor. If the temperature and humidity data are valid, the values are processed by the fuzzy logic system through the stages of fuzzification, inference based on the rule base, and defuzzification to produce crisp output values. This output value is used to regulate the PWM signal sent to the heater and blower drivers, so heater intensity and blower speed can be adjusted to the temperature and humidity conditions of the environment. Temperature and humidity information, fuzzy status, and PWM values are then displayed on the OLED as a monitoring medium. If the data are not valid, the system displays an error message on the OLED. This process takes place continuously while the system is active, so temperature control can be carried out adaptively and in real time.

Fuzzy logic applied in this research uses the Mamdani method because of its simplicity and its ability to represent human linguistic knowledge. The system input variables are environmental temperature and humidity obtained from the DHT22 sensor, while the output variables are the intensity level of the heater lamp and the blower speed represented in PWM values.

2.3.1. Membership function formulation

The fuzzy input variables are represented using triangular membership functions to provide smooth transitions between environmental conditions. Temperature is categorized into three linguistic sets, namely cold, normal, and hot, while humidity is divided into dry, normal, and humid conditions. The use of overlapping triangular membership functions allows one environmental condition to partially belong to multiple linguistic sets, thereby improving control flexibility and adaptability. The triangular membership function used in this study is mathematically expressed as follows:

$$\mu(x) = \begin{cases} 0, x \leq a \\ (x-a)/(b-a), a < x \leq b \\ (c-x)/(c-b), b < x < c \\ 0, x \geq c \end{cases} \quad (1)$$

where a, b, and c represent the lower limit, peak value, and upper limit of the triangular membership function. The membership function parameters used in this study are shown in Table 1.

Table 1. Input Membership Function Parameters.

Variable	Linguistic Set	Membership Type	Range
Temperature (°C)	Cold	Triangular	[15], [20], [26]
Temperature (°C)	Normal	Triangular	[24], [27], [31]
Temperature (°C)	Hot	Triangular	[27], [32], [40]
Humidity (%RH)	Dry	Triangular	[30], [40], [55]
Humidity (%RH)	Normal	Triangular	[50], [60], [75]
Humidity (%RH)	Humid	Triangular	[65], [80], [90]

The selected membership ranges were determined according to the physiological requirements of quails and environmental characteristics inside the cage. The overlapping regions between adjacent membership functions allow the system to perform gradual control transitions, thereby reducing sudden actuator responses and improving environmental stability. As shown in Table 2, the output variables consist of heater intensity and blower speed represented through PWM values. Each actuator output is categorized into four linguistic sets to ensure adaptive control performance.

Table 2. Output Membership Function Parameters.

Variable	Linguistic Set	Range
Heater PWM	Off	[0, 0, 100]
Heater PWM	Low	[50, 100, 150]
Heater PWM	Medium	[125, 175, 225]
Heater PWM	High	[200, 255, 255]
Blower PWM	Off	[0, 0, 100]
Blower PWM	Low	[50, 100, 150]
Blower PWM	Medium	[125, 175, 225]
Blower PWM	High	[200, 255, 255]

2.3.2. Fuzzy rule base

The fuzzy inference mechanism employs a rule base consisting of nine rules to determine heater and blower responses according to environmental temperature and humidity conditions. The fuzzy rule table is presented in Table 3.

Table 3. Fuzzy Rule Base for Heater and Blower Control.

Temperature	Humidity	Heater Output	Blower Output
Cold	Dry	High	Off
Cold	Normal	High	Off
Cold	Humid	Medium	Low
Normal	Dry	Low	Off
Normal	Normal	Off	Off
Normal	Humid	Off	Low
Hot	Dry	Off	Medium
Hot	Normal	Off	Medium
Hot	Humid	Off	High

The fuzzy rules are designed to prioritize heating during low-temperature conditions and cooling during high-temperature conditions. Under ideal environmental conditions, the heater and blower outputs remain at minimum levels to reduce unnecessary energy consumption and actuator workload. This fuzzy mechanism enables adaptive responses to dynamic environmental changes inside the quail cage.

2.3.3. Output scaling and PWM normalization

The fuzzy output values generated through the inference process are converted into PWM signals for direct implementation in hardware. Since the ESP32-C3 microcontroller utilizes an 8-bit PWM resolution, the output values are normalized into a range between 0 and 255. The PWM normalization process is formulated as follows:

$$PWM = \frac{Output\ Fuzzy}{Output\ Max} x\ 255 \quad (2)$$

The PWM output categories used in this study are presented in Table 4.

Table 4. PWM Output Scaling.

Linguistic Output	PWM Range
Off	0–40
Low	41–100
Medium	101–180
High	181–255

Following fuzzy inference, the centroid defuzzification method is applied to convert fuzzy outputs into crisp numerical values. This method is selected because it provides stable and smooth output transitions, thereby minimizing oscillations commonly found in conventional threshold-based ON–OFF control systems. Consequently, the proposed fuzzy logic system can regulate heater intensity and blower speed adaptively according to changing environmental conditions in the quail cage.

2.4. System Testing Procedure

System design testing was conducted by evaluating fuzzy logic performance in the context of controlling heater lamp intensity and blower speed based on variations in environmental conditions. Starting with hardware and software testing that works according to the research design, including fuzzy logic designed.

Then the system is tested in a variety of temperature and humidity conditions and monitors the output value of the heater and blower lights. Changes in ambient temperature and humidity will later be recorded and observed with PWM output values. This is done gradually to see the response of the system to the specified set point value.

The test results were then analyzed by looking at the value of output stability, transitions between conditions, and the suitability of the response to the fuzzy logic rules designed. The test results will then be elaborated, evaluated, and discussed in the next chapter.

3. Results and Discussion

3.1. Membership Function of the Fuzzy System

It can be seen in Fig. 4 that the results of the design of the membership function in the fuzzy logic system for temperature and humidity control in Quail cages. This membership function is a basic parameter in fuzzy logic, in which the parameter will interpret numerical values into linguistic variables. The determination of membership function parameters is based on the characteristics of the cage environment and physiological needs of quail so that the control system can work adaptively and stably.

For the temperature membership function, its variables are divided into 3 linguistic sets, namely cold, normal, and hot. The cold set represents low temperature conditions that inhibit Quail metabolism. At the same time, the normal set represents the ideal temperature range for the comfort and productivity of Quail. The set of heat describes the high temperature conditions that can cause thermal stress. The form of the membership function used is sigmoidal and trapezoidal; it aims to stabilize the transition between conditions that occur suddenly.

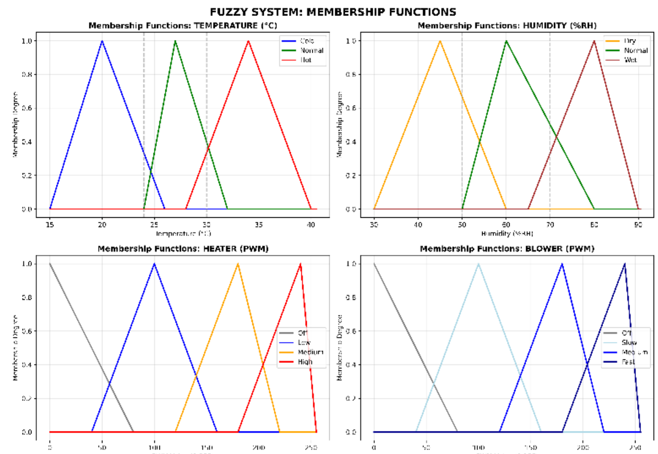

Figure 4. Fuzzy Membership Function.

The function of moisture membership is divided into three linguistic sets, namely dry, normal, and moist. This division aims to interpret the variation of humidity conditions in the cage that affect the comfort and health of Quail. The dry set represents low humidity conditions that tend to potentially cause dehydration, while the moist set indicates the risk of microorganism growth. The presence of intersecting areas between sets allows the system to quickly respond to changes in humidity in the cage.

At the output of the system, the membership function for the heater and blower is represented in the condition of four linguistic sets, namely off, low, mid, and high. The set is used to regulate the intensity of the PWM output sent to the heater driver and blower. This approach is designed to regulate the temperature level and air flow velocity to regulate humidity.

Overall, the results of the membership function design have shown that fuzzy Systems are created with a balanced structure between the number of sets, their range of values, and transitions. It aims to produce adaptive control decisions with changing approaches to temperature and humidity in the cage environment. With these characteristics, the system is expected to maintain quail cage environmental conditions to remain stable in the optimal range, and improve control effectiveness compared to conventional fixed-threshold control methods.

3.2. Simulation Results of the Fuzzy Control System

3.2.1. Basic simulation test results of the system

Basic simulation testing is carried out to evaluate the response of the fuzzy control system to various combinations of temperature, as shown in Table 5, and humidity, as shown in table 2 conditions of the quail cage environment. This testing aims to ensure that the system is able to generate appropriate control actions through the heater and blower actuators based on the designed fuzzy rules.

Based on Table 5 and Table 6, it can be seen that the fuzzy control system is able to produce a consistent and logical control response to variations in environmental conditions. In cold temperature conditions with dry or normal humidity, the heater PWM value is at a high level, while the blower is in an almost off condition. This shows that the system prioritizes increasing the cage temperature when environmental conditions are below the ideal range.

In normal temperature and normal humidity conditions, which represent the ideal cage condition, the system produces low PWM values for both heater and blower. This response shows that the fuzzy system is able to recognize environmental conditions that are already optimal and automatically minimizes actuator work, so it has the potential to improve energy efficiency and reduce device wear. Conversely, in hot temperature conditions, especially when humidity is at the humid level, the system shows the opposite response, namely the heater is almost off, while the blower works at high intensity.

3.2.2. Temperature Transition Analysis with Constant Humidity.

The next test is carried out to analyze the system response to gradual temperature changes with humidity kept constant at 60% RH, as shown in Table 7. This test aims to evaluate the stability and linearity of the fuzzy system response to changes in environmental temperature.

The results in Table 7 show that the fuzzy control system has smooth and gradual response characteristics to temperature changes. At low temperatures up to approaching normal conditions, the heater works at high intensity, then decreases significantly when the temperature enters the ideal range. Within the ideal temperature range, both the heater and the blower operate at minimal settings, indicating that the system succeeds in maintaining environmental stability without excessive intervention.

When the temperature rises above the specified normal limit, the system will gradually reduce the output value of the heater and increase the output level of the blower. This transition can occur without any surge in the PWM value; it can be concluded that the fuzzy system can minimize the occurrence of oscillations that often occur in traditional control systems based on ON-OFF. This is also the advantage of the adaptive and dynamic fuzzy logic Control System.

Table 5. Fuzzy Control System for Heaters.

Environmental Condition	Temperature (°C)	Humidity (%RH)	Heater (PWM)
Cold & Dry	18.0	40.0	223.3
Cold & Ideal	20.0	60.0	172.8
Cold & Humid	25.0	75.0	91.4
Ideal & Dry	27.0	45.0	100.0
Ideal	27.0	60.0	26.7
Ideal & Humid	27.0	75.0	28.9
Hot & Dry	32.0	45.0	28.9
Hot & Ideal	32.0	60.0	28.9
Hot & Humid	35.0	80.0	27.3

Table 6. Fuzzy Control System for Blower.

Environmental Condition	Temperature (°C)	Humidity (%RH)	Blower (PWM)
Cold & Dry	18.0	40.0	29.7
Cold & Ideal	20.0	60.0	28.9
Cold & Humid	25.0	75.0	80.0
Ideal & Dry	27.0	45.0	26.7
Ideal	27.0	60.0	26.7
Ideal & Humid	27.0	75.0	86.2
Hot & Dry	32.0	45.0	172.8
Hot & Ideal	32.0	60.0	172.8
Hot & Humid	35.0	80.0	224.6

Table 7. Temperature Transition Analysis Results (Humidity 60%RH).

Temperature (°C)	Heater (PWM)	Blower (PWM)
18.0	172.6	29.7
20.0	173.3	26.7
22.0	172.8	28.9
24.0	171.6	33.8
26.0	28.9	28.9
28.0	27.6	27.6
30.0	32.7	104.9
32.0	28.9	172.8
34.0	26.7	173.3
36.0	28.9	172.8
38.0	33.8	171.6

3.2.3. General discussion of system performance.

Simulation results show that the temperature and humidity control system designed with fuzzy logic is able to run adaptively and stably. The system can automatically adjust the variation of heater and blower output control based on the temperature and humidity input on the enclosure in real time, and the system response is better than the ON-OFF control method. From this, it is expected to improve the comfort of Quail, Quail health, and environmental stability of the cage.

Although the proposed fuzzy control system demonstrated adaptive PWM responses under varying environmental conditions, several classical control performance indicators such as temperature settling time, overshoot, and steady-state error were not experimentally quantified in this study. The present work primarily focused on validating the feasibility of adaptive fuzzy-based environmental regulation through heater and blower actuation in response to temperature and humidity variations. Nevertheless, based on the gradual PWM transitions observed in Table 7, the proposed system exhibited smooth control behavior without abrupt actuator switching, indicating a low possibility of excessive overshoot commonly found in conventional ON–OFF control systems.

The proposed fuzzy logic algorithm was implemented on an ESP32-C3 microcontroller, which provides sufficient computational capability for real-time environmental control. Although execution time was not explicitly measured, the control process was successfully executed continuously without observable processing delay during experimental operation.

3.2.4. Comparison with conventional ON–OFF control

Compared with conventional threshold-based ON–OFF control systems, the proposed fuzzy logic controller provides smoother actuator transitions by adjusting heater and blower outputs gradually according to environmental conditions. Conventional ON–OFF methods generally operate using binary switching, which may lead to frequent oscillations around temperature thresholds and increased actuator wear. In contrast, the fuzzy control system generates adaptive PWM outputs, allowing gradual thermal regulation and minimizing abrupt environmental fluctuations, as shown in Table 8.

Based on Table 8, the proposed fuzzy logic controller demonstrates several advantages over conventional ON–OFF control for quail cage environmental regulation. The ON–OFF method operates using binary switching, which may lead to abrupt actuator transitions and higher temperature oscillation around threshold values. In contrast, the proposed fuzzy control system provides gradual PWM-based regulation for heater and blower actuators, enabling smoother environmental adjustments according to temperature and humidity conditions. This adaptive response potentially improves environmental stability, reduces unnecessary actuator operation, and enhances energy efficiency under varying cage conditions.

Table 8. Comparison between ON–OFF and Proposed Fuzzy Control.

Parameter	ON–OFF Control	Proposed Fuzzy Control
Response Type	Binary	Gradual
Adaptability	Low	High
Oscillation Risk	High	Low
PWM Regulation	No	Yes
Temperature Stability	Moderate	Better
Energy Efficiency	Moderate	Potentially Higher

3.3. Surface Response (3D) Analysis of the Fuzzy Control System

Analysis of the system response on a visual surface showed adaptive evaluation of fuzzy control system behavior under variations in enclosure temperature and humidity. Surface 3D response can be seen in Fig. 5, which defines the relationship between two input variables, namely temperature and humidity, and two PWM outputs on the heater and blower. The figure shows the pattern of fuzzy control system characteristics that cannot be observed through a single variable test.

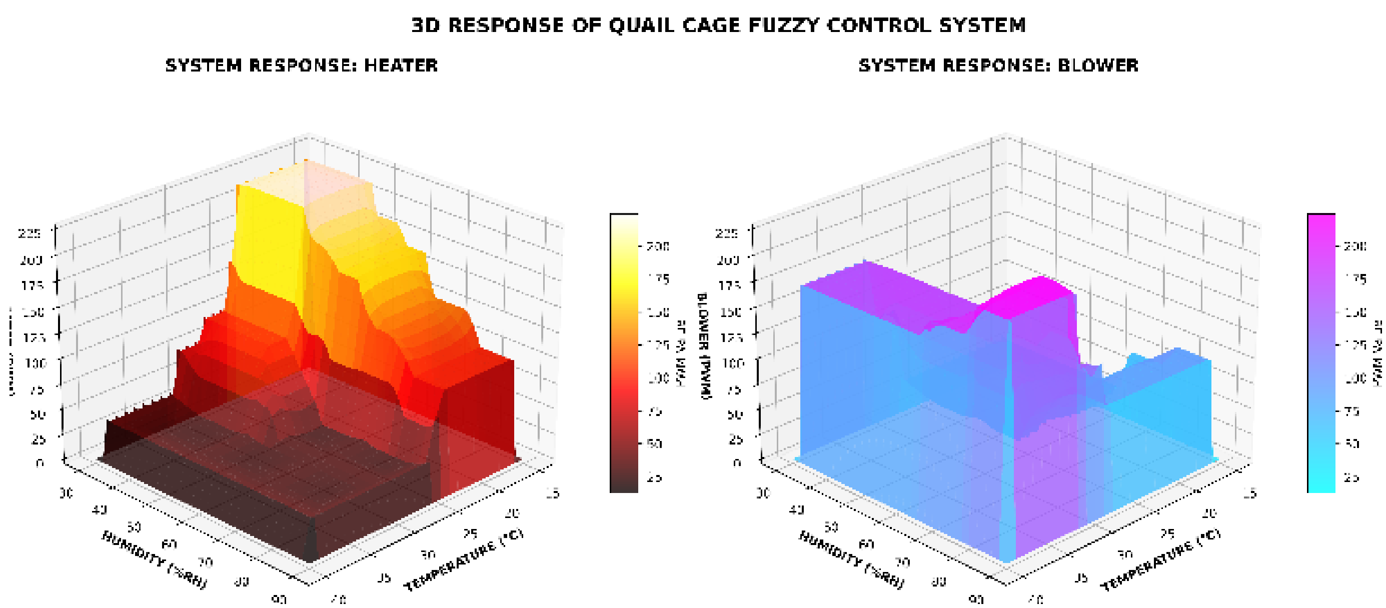

Figure 5. Fuzzy Membership Function.

In the heater output response, the PWM value reaches its maximum at low temperatures and relatively low humidity. Surface visualization of the system response also shows the gradient decreasing slowly as temperature and humidity increase. This explains that the system can automatically reduce the intensity of the PWM heater when the temperature approaches and exceeds the setpoint. The transition between control conditions looks smooth without sudden changes in values; this indicates that the fuzzy inference mechanism works optimally and automatically.

Then the blower system's response shows an inverted pattern compared to the heater's. The PWM blower value tends to increase significantly in high temperature and humid conditions, which is indicated by the high surface response in the set. This correlates with the relationship of the blower as an actuator for cooling and humidity control. At low humidity and normal temperature conditions, the blower response will be low in order to minimize blower work when cooling is not needed.

The interaction of temperature and humidity on the two response surfaces shows that the fuzzy system can take into account the input variables to determine the control action of the aquator in the form of PWM signals. There are no sharp discrete boundaries between control regions, but rather overlapping transitions in accordance with the fuzzy logic principle. This characteristic becomes the main advantage compared to threshold-based control systems, which generally produce sudden output changes.

Overall, the results of the 3D surface response analysis show that the designed fuzzy control system has adaptive, stable, and consistent control characteristics to changes in cage environmental conditions. The smooth response surface indicates that the system is able to avoid oscillations and extreme fluctuations in the heater and blower actuators. Thus, this system is considered capable of maintaining cage temperature and humidity stability optimally, and supporting quail comfort and productivity in the long term.

3.4. Contour Response Analysis of the Fuzzy Control System

Contour response analysis is carried out to provide a more detailed understanding regarding the distribution of fuzzy control system outputs to combinations of temperature and humidity of the quail cage environment. Unlike three-dimensional surface visualization, two-dimensional contour maps allow identification of control regions more clearly and are easier to interpret, especially in seeing transition boundaries between control conditions.

In the heater response contour (Fig. 6), it can be seen that the highest PWM value is in the low temperature region, especially in the temperature range below 22 °C with low to medium humidity. This region is marked with bright color, indicating that the system prioritizes intensive heater activation when environmental conditions are far below the ideal condition. As temperature increases toward the normal range, the contour shows a gradual decrease in PWM value, which indicates that the system adaptively reduces heater power to prevent excessive temperature increases.

In the region where temperature approaches and exceeds the ideal range, especially above 28 °C, the heater response contour is dominated by dark colors representing low PWM values close to zero. This shows that the system consistently deactivates the heater in high-temperature conditions, regardless of humidity variations, so the risk of overheating can be avoided. Variations in color transitions on contour maps can be observed that look smooth, and there is a gradient that shows the character of fuzzy control is not discrete.

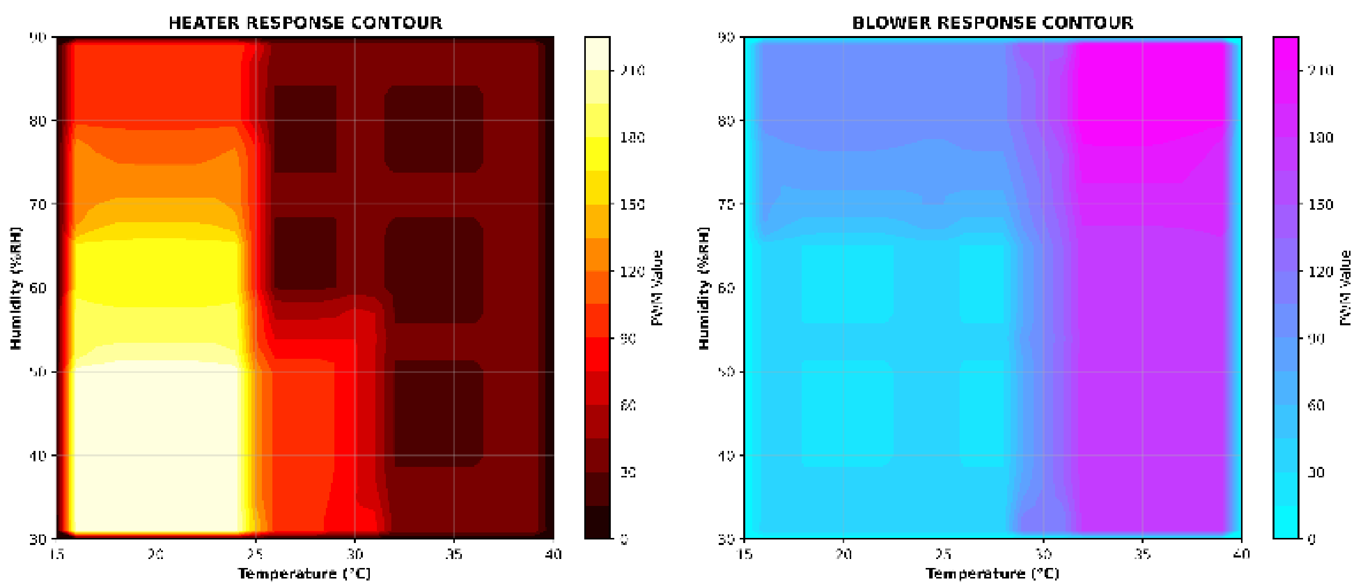

Figure 6. Heater and blower response contour.

Conversely, the blower response contour shows a pattern opposite to the heater. The blower PWM value is low in the low-to-normal temperature region, which is marked with cool colors. In these conditions, the system assesses that the cooling process is not yet needed. However, when temperature increases past the normal threshold, especially in high humidity conditions, the contour shows a significant increase in blower PWM value. Brighter colors in the high temperature and high humidity region show that the blower is activated at high intensity to reduce temperature and help reduce the level of air humidity inside the cage.

Comparison between the heater and blower contour responses shows a complementary control mechanism. When the heater works at high intensity, the blower is at minimum condition, and vice versa. This pattern shows that the fuzzy system is able to avoid work conflicts between actuators and ensure that the given control action is efficient and directed. In addition, the transition boundary between control regions is not determined by straight lines or fixed thresholds, but by continuous color gradients, which reflects the fuzzy system's ability to handle uncertainty and variations in environmental conditions.

Overall, the contour response analysis results show that the fuzzy control system is able to classify cage environmental conditions into appropriate control regions adaptively. This characteristic strengthens the results of the previous analysis on the 3D surface, and confirms that the designed system has high stability and flexibility in maintaining quail cage temperature and humidity at optimal conditions.

4. Conclusions

This study proposed and evaluated an adaptive temperature and humidity control system for quail cages based on a Mamdani Fuzzy Logic Controller (FLC) implemented on an ESP32-C3 microcontroller. The developed system demonstrated the ability to provide adaptive and stable environmental regulation through simultaneous heater and blower control based on real-time temperature and humidity conditions.

The simulation results confirmed that the proposed fuzzy system generated logical and consistent control responses under varying environmental conditions. Under low-temperature and dry-humidity conditions (18°C and 40%RH), the system produced a high heater output (223.3 PWM) and a low blower output (29.7 PWM), indicating dominant heating action. Conversely, under hot and humid conditions (35°C and 80%RH), the heater output decreased to 27.3 PWM, while the blower output increased to 224.6 PWM, indicating effective cooling regulation. In ideal environmental conditions (27°C and 60%RH), both heater and blower outputs remained low (26.7 PWM), demonstrating the system's capability to recognize stable cage conditions and minimize unnecessary actuator operation.

Furthermore, the temperature transition analysis under constant humidity conditions showed smooth and gradual actuator responses without abrupt PWM fluctuations, indicating that the proposed fuzzy system has the potential to reduce oscillation effects commonly observed in conventional ON–OFF control systems. These findings suggest that the proposed system can contribute to improved environmental stability, adaptive control performance, and potential energy efficiency in small-scale quail farming environments.

One limitation of this study is that the fuzzy membership parameters were designed for a fixed environmental range and have not yet incorporated age-dependent thermal requirements of quails. Future studies may develop adaptive fuzzy setpoints based on bird age and physiological development stages.

Future studies should include real-time thermal response measurements to quantify settling time, overshoot characteristics, and steady-state error under controlled environmental disturbances. Since this study mainly focused on adaptive environmental control feasibility, detailed energy consumption analysis of the heater and blower actuators was not included. However, the low PWM outputs observed during ideal environmental conditions indicate the potential for reduced power consumption and improved energy efficiency.

Long-term reliability evaluation under continuous operation was beyond the scope of this study and remains an important direction for future research to assess actuator durability and environmental stability over extended periods.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Yosi Nugraha Adi and Iswanto Suwarno: proposed the research problem and formulated the research objectives.

Yosi Nugraha Adi: developed the theoretical framework and Mamdani fuzzy logic control strategy.

Iswanto Suwarno: verified the analytical and control methods and supervised the research findings.

Widyasmoro Widyasmoro: designed and implemented the system architecture and hardware–software integration.

Nia Maharani Raharja: performed the simulations, computations, and data analysis.

Muhammad Hafid Alkarim: conducted the experimental evaluation and investigated the adaptive control performance under different environmental conditions.

Alfian Maarif: contributed to the development and verification of the fuzzy control methodology and supervised the technical aspects of the study.

All authors: discussed the results, contributed to the final manuscript, reviewed and revised the manuscript, and approved the final version.

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