

Design and Development of an IoT-Based Indoor Air Quality Monitoring and Control System Using the Tsukamoto Fuzzy Algorithm on a Dual-Core ESP32 Architecture

***Estriadi Aditias**

Department of Electrical
Engineering, Faculty Of
Engineering, Universitas
Swadaya Gunung Jati Cirebon
estriadi.122220009@ugj.ac.id

Juju Juhaeriyah

Department of Electrical
Engineering, Faculty Of
Engineering, Universitas
Swadaya Gunung Jati Cirebon
juju_juhaeriyah@ugj.ac.id

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Abstract – Indoor air quality (IAQ) is a critical environmental health factor responsible for millions of cases of respiratory diseases each year. This study presents the design of an Internet of Things (IoT)-based indoor air circulation control system that integrates a BME680 sensor, an ESP32 microcontroller, and the Firebase Realtime Database platform with the Tsukamoto fuzzy logic algorithm as a control mechanism. This research implements a dual-core architecture on the ESP32, separating IoT communication tasks from sensor computation. This approach enables the BSEC algorithm to run consistently without interruption. The system uses two input variables (IAQ values and room temperature) as well as two actuators—a fan and a 12V DC blower—controlled via Pulse Width Modulation (PWM) signals based on 12 fuzzy rules. Testing was conducted in a miniature test chamber measuring $23.5 \times 16 \times 18$ cm with controlled pollutant introduction. The research results show that the BME680 sensor has an average accuracy of 99.3% for temperature and 98.0% for humidity. All 12 fuzzy testing scenarios met the rule base criteria. The system was able to reduce the IAQ value from a very dirty condition (IAQ = 500) to a clean condition (IAQ $\leq$ 80) in an average time of 281 seconds. Data synchronization between the local LCD display and the Firebase-based mobile application achieved 100% accuracy. These results demonstrate that the Tsukamoto fuzzy method is effective in producing rule-based, stable, and proportional control for indoor air circulation systems.

Keywords: IoT; indoor air quality; Tsukamoto fuzzy logic; ESP32; dual-core architecture; BME680; Firebase.



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I. INTRODUCTION

Indoor air quality is one of the most critical environmental health risks, accounting for approximately 3.2 million deaths each year, particularly in enclosed spaces with inadequate ventilation [1]. Recent global trends also indicate a

growing reliance on indoor spaces due to urbanization, remote work patterns, and lifestyle changes, resulting in individuals spending more than 90% of their time indoors [2]. Furthermore, new sources of pollutants such as e-cigarettes, volatile organic compounds (VOCs), and combustion residues have significantly increased air contamination in enclosed spaces [3]. Exposure to VOCs, cigarette smoke, and poor humidity levels is directly correlated with an increase in the incidence of Acute Respiratory Infections (ARIs) [4]. This underscores the fact that maintaining indoor air quality is becoming an increasingly critical global challenge, particularly in residential and commercial buildings, making smart and responsive IAQ control systems an urgent necessity.

Advances in IoT have enabled real-time IAQ monitoring using gas sensors [5]. However, most systems are still limited to monitoring functions without active automatic control mechanisms [6]. The reliability of IoT systems in processing sensor data in real time depends heavily on the efficiency of computational workload management at the microcontroller level. The use of a dual-core architecture on the ESP32 allows for the separation of processor core responsibilities for wireless communication and sensor data processing, thereby supporting parallel execution [7].

Previous research has demonstrated the effectiveness of single-actuator-based systems in controlling a single environmental parameter [8]. However, IAQ is simultaneously influenced by pollutant concentrations and thermal temperature, which have different characteristics. Controlling these two parameters independently within a single integrated system has not been extensively studied; therefore, this study proposes a dual-actuator approach—a blower to reduce pollutants and a fan to stabilize temperature—which enables a more differentiated response to both environmental variables simultaneously

In addition, commonly used fuzzy methods such as the Mamdani method involve a complex defuzzification process, which increases the computational load and makes them less suitable for real-time embedded applications [9]. Comparative studies have shown that the Tsukamoto fuzzy method achieves higher accuracy (99.35%) and faster response times than the Mamdani method (95.45%) in stabilizing air conditions [10]. The comparison between the Sugeno and Tsukamoto methods in temperature control systems also shows that the Tsukamoto method outperforms the Sugeno method in terms of response speed (rise time) [11]. This advantage stems from the weighted-average-based defuzzification, which is computationally lighter than Mamdani centroid integration [12].

This study aims to develop an IoT-based real-time indoor air quality control system using the Fuzzy Tsukamoto method, integrating environmental sensors (BME680), embedded dual-core processing, and cloud-based mobile monitoring.

The main novelty of this research lies in the implementation of an ESP32 dual-core architecture that separates sensor computation tasks from IoT communication to ensure the consistency of the BSEC algorithm, as well as the application of the dual-action control principle using two actuators that operate independently yet are integrated into a single Tsukamoto fuzzy control system.

II. BASIC THEORY

Research on indoor air quality monitoring and control continues to advance as awareness of the health impacts of IAQ grows. Various studies have developed Internet of Things (IoT)-based technologies using gas sensors to measure parameters such as VOCs, CO, temperature, and humidity [5]. The implementation of IoT concepts in this system enables the integration of sensors, microcontrollers, and cloud platforms to support real-time monitoring and control. IoT allows devices to connect with one another and exchange data over the internet, enabling users to monitor environmental conditions and control devices remotely [13]. These systems are generally capable of displaying real-time air quality data to monitor changes in environmental conditions [14]. In terms of IoT platforms, Firebase has proven to have a data transmission latency of less than 1 second, which is significantly lower than ThingSpeak (3.7–14 seconds) [15]. However, most of the systems developed still focus on monitoring functions without integrated automatic control. Previous research has emphasized that NodeMCU-based systems generally only provide data visualization without direct corrective actions [16]. This limits the system's ability to respond to changes in environmental conditions.

The application of fuzzy logic in air quality control has become a focus of research aimed at addressing the limitations of conventional control systems. Fuzzy logic is a mathematical framework that enables

decision-making in highly nonlinear systems, mimicking human reasoning and extending classical logic, which only recognizes true/false values, to degrees of truth between 0 and 1 [17]. The Mamdani method is commonly used because of its intuitive interpretation of rules [18]. The Fuzzy Logic method used is the Mamdani min-max method [19]. However, some research has shown that this method has limitations in terms of computational complexity, particularly in centroid-based defuzzification processes [12]. As an alternative, the Tsukamoto and Sugeno methods have begun to be widely adopted. Research shows that the Tsukamoto method has a faster response time than the Mamdani method because it uses weighted-average defuzzification [10]. Other research has found that the Tsukamoto method provides faster response times than the Sugeno method in temperature control, making it more suitable for air quality control applications that require rapid response [11], [20].

In the context of air quality, IAQ is a key indicator that reflects the level of indoor air quality and its impact on the health and comfort of occupants. The primary parameters that determine IAQ include temperature, humidity, and concentrations of pollutants such as carbon monoxide (CO), particulate matter, and Volatile Organic Compounds (VOCs). In this study, the IAQ classification is based on the index standards developed by Bosch Sensortec for the BME680 sensor [21], as shown in Table I.

Table 1. Indeks for Air Quality classification

IAQ Index	Air Quality	Impact (Long-Term Exposure)	Suggested Action
0 – 50	Excellent	Pure air; best for well-being	No measures needed
51 – 100	Good	No irritation or impact on well-being	No measures needed
101 – 150	Lightly Polluted	Reduction of well-being possible	Ventilation suggested
151 – 200	Moderately Polluted	More significant irritation possible	Increase ventilation with clean air
201 – 250	Heavily Polluted	Exposition might lead to effects like headache depending on type of VOCs	Optimize ventilation
251 – 350	Severely Polluted	More severe health issue possible if harmful VOC present	Contamination should be identified & maximize ventilation
> 351	Extremely Polluted	Headaches, additional neurotoxic effects possible	Avoid presence in room and maximize ventilation

A range of 0–100 is classified as good air quality and poses no health risks, making it the primary target of the control system developed. In addition, room temperature is regulated to remain within the thermal comfort range in accordance with applicable health standards [22].

The system was implemented using the ESP32 microcontroller, which features high processing power with a dual-core architecture and integrated Wi-Fi and Bluetooth connectivity. This capability allows the ESP32 to run sensor algorithms and fuzzy logic in real time while maintaining seamless data communication with the IoT server [23]. The ESP32's multitasking capabilities are essential in this system, given the need to read sensors, process data using fuzzy logic, and control actuators simultaneously [24].

In this study, the dual-core architecture of the ESP32 is utilized to address computational resource conflicts, which pose a challenge in real-time IoT systems [7].

This task separation is crucial because the BSEC algorithm requires periodic and consistent function calls [25]. In a single-core architecture, blocking communication processes can disrupt BSEC execution consistency, preventing proper sensor baseline formation and causing the IAQ Accuracy value to remain at level 0. By contrast, the dual-core approach allows both processes to run in parallel, maintaining algorithm consistency and improving IAQ data reliability.

As an environmental data acquisition device, this study uses the BME680 sensor, which is capable of measuring temperature, humidity, air pressure, and gas resistance in a single integrated module [26]. This sensor works in combination with the Bosch Software Environmental Cluster (BSEC) algorithm, which converts gas resistance data into an IAQ value on a scale of 0–500 [21]. In addition, BSEC also provides an IAQ Accuracy parameter that indicates the reliability of the data based on the sensor's baseline establishment process. Compared to conventional gas sensors such as the MQ series, the BME680 offers the advantage of detecting various types of VOCs more comprehensively, making it more representative in assessing overall air quality [27].

Based on the literature, this study proposes an IoT-based indoor air quality control system with a dual-input and dual-output approach using the Tsukamoto fuzzy method. The system accepts two main input parameters: the IAQ value, which represents the level of air pollution, and temperature, which serves as an indicator of thermal comfort. These two parameters are processed simultaneously to generate two control outputs: blower speed to reduce pollutants and fan speed to stabilize room temperature. This approach allows for the independent control of two environmental variables while keeping them integrated within a single system.

III. METHOD

This study uses a quantitative experimental method, in which a system is designed, implemented, and tested through a series of structured experiments to obtain measurable data. The testing was conducted by applying various controlled environmental conditions (temperature and VOC pollutants) in a

6,768 cm³ test chamber, which served as a controlled prototype environment for validating the algorithm. There is a gap in external validity between this test scale and implementation in a real room. On a real-room scale, the actuator needs to be replaced with a larger-capacity ventilation fan adjusted to the room volume, and the fuzzy membership function parameters need to be recalibrated. However, the 12 fuzzy rules designed based on IAQ value categories from the Bosch Sensortec standard (0–500 scale) are independent of the physical room scale, as the rules are based on IAQ index values, not air volume. This makes the developed control architecture relevant as a foundation for larger-scale implementation.

A. Hardware Design

The air quality control system is designed using hardware components integrated into a single miniature test chamber measuring 23.5 × 16 × 18 cm (volume 6,768 cm³).

The connection diagram is shown in Figure 1. The BME680 sensor is connected to the ESP32 via the I2C interface. The blower is a 12V brushless DC centrifugal fan (4020 form factor, 40×40×20 mm) and, based on reference specifications for equivalent form factor components, typically operates at 4,000–6,000 RPM and 2.9–4.9 CFM [28], while the fan is a 12V brushless DC axial fan (5010 form factor, 50×50×10 mm) typically operates at 5,000 RPM and 10.3 CFM [29]. Both actuators are controlled via PWM signals (0–255) through an L298N driver, allowing proportional speed adjustment based on the fuzzy algorithm output. A DC step-down module reduces the 12V supply to 5V for the ESP32 and supporting devices.

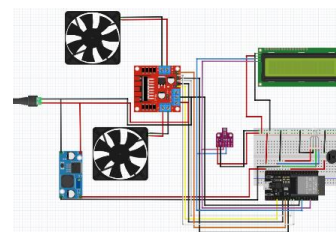


Figure 1. Wiring Diagram

B. System Architecture and Workflow

The system uses a closed-loop control architecture. The BME680 sensor periodically reads environmental conditions to provide real-time feedback. The data is sent to the ESP32 to be processed by the Tsukamoto fuzzy algorithm, which generates a PWM signal to drive the actuator. Changes in environmental conditions are detected again by the sensor, forming a closed-loop feedback control. The architectural block diagram is shown in Figure 2.

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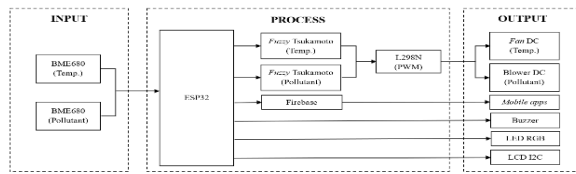


Figure 2. Architecture Block Diagram

The ESP32 utilizes a dual-core architecture based on FreeRTOS. In the early stages of development, the single-core implementation prevented the BSEC algorithm from completing its full computational cycle due to the blocking nature of Firebase communication processes, causing the IAQ Accuracy value to remain at level 0. By separating sensor and computational tasks on Core 1 and communication tasks on Core 0, This approach allows the BSEC execution to run continuously, ensuring the sensor baseline is properly established and the IAQ Accuracy improves to level 3. The Firebase platform also serves as a feedback control channel, through which manual commands from a mobile app (MIT App Inventor) can be sent to the ESP32 to control the RGB LED and buzzer. The complete system workflow is shown in Figure 3.

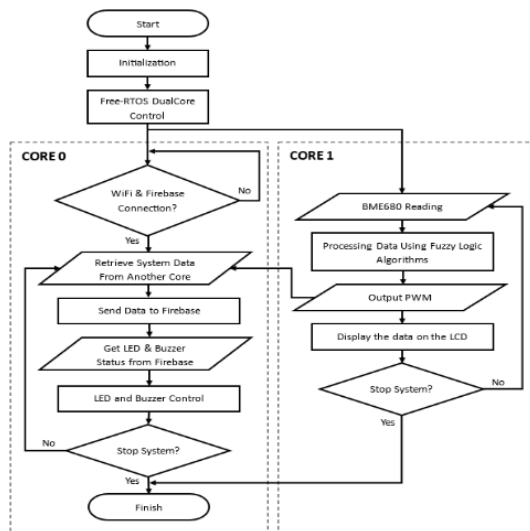


Figure 3. system flowchart

C. Implementation of the Tsukamoto Fuzzy Logic Algorithm

The Tsukamoto fuzzy algorithm is applied to control two actuators independently based on two input variables. The computational process is illustrated in the block diagram in Figure 4.

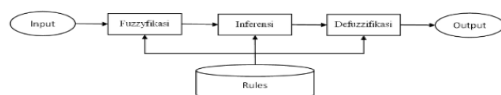


Figure 4. Fuzzy Logic System Block Diagram

1) Fuzzification

Fuzzification converts the crisp values from the sensor into linguistic membership degrees, as shown in the table below.

Table 2. Fuzzy Logic Criteria of IAQ

Fuzzy Sets	Parameter	Membership Function
Clean	0, 80, 100	Semi Trapezoidal Infimum
Light	80, 100, 125, 150	Trapezoidal
Moderate	125, 150, 180, 200	Trapezoidal
Dirty	180, 200, 500	Semi Trapezoidal Supremum

The IAQ value is used as one of the input variables in the fuzzy system to determine the level of air circulation control in the room. The membership function curve for the IAQ variable is shown in Figure 5.

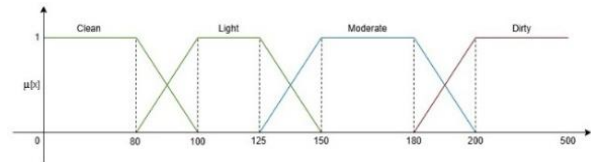


Figure 5 Variable IAQ Membership Curve

In addition to IAQ parameters, the indoor air circulation control system in this study also uses room temperature as an input variable in the fuzzy system.

Table 3. Fuzzy Logic Criteria of Temperature

Fuzzy Sets	Parameter	Membership Function
Cold	0, 18, 20	Semi Trapezoidal Infimum
Normal	18, 20, 24, 30	Trapezoidal
Hot	24, 30, 40	Semi Trapezoidal Supremum

The temperature parameter is used to determine the level of thermal comfort indoors and serves as the basis for adjusting fan speed. The membership function curve for the temperature variable is shown in Figure 6.

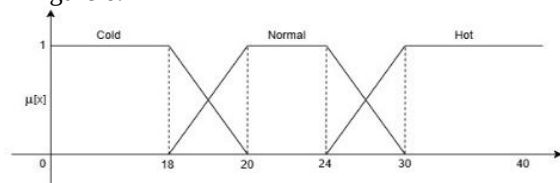


Figure 6. Variable Temperature Membership Curve

The resulting PWM values must also be grouped into fuzzy sets based on range criteria and represented using membership function graphs.

Table 4. Fuzzy Logic Criteria of PWM Output

Fuzzy Sets	Parameter	Membership Function
Slow	0, 85, 170	Semi Trapezoidal Infimum
Medium	85, 170, 255	Triangular
Fast	170, 255, 255	Semi Trapezoidal Supremum

The graph of the membership function for the output variable PWM value, based on Table 4 above, is illustrated in Figure 7 below.

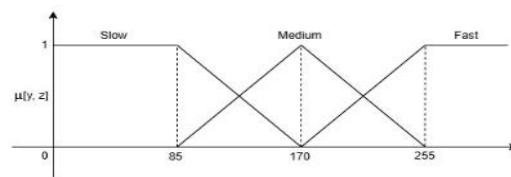


Figure 7. Variable PWM Output Membership Curve

2) Inference

The inference process applies the MIN operator to 12 IF-THEN rules to obtain the α -value of each rule.

$$\alpha_i = \min(\mu A(x), \mu B(x)) \quad (1)$$

$\mu A(x)$ is the membership degree of the IAQ variable, and $\mu B(y)$ is the membership degree of the temperature variable. Twelve control rules were designed based on the dual-action control principle, whereby the blower output is entirely determined by IAQ, while the fan output is entirely determined by temperature, so that the two actuators operate independently.

Rule	Input IAQ	Input Temp.	Output Blower	Output Fan
1	Clean	Cold	Slow	Slow
2	Light	Cold	Medium	Slow
3	Moderate	Cold	Medium	Slow
4	Dirty	Cold	Fast	Slow
5	Clean	Normal	Slow	Medium
6	Light	Normal	Medium	Medium
7	Moderate	Normal	Medium	Medium
8	Dirty	Normal	Fast	Medium
9	Clean	Hot	Slow	Fast
10	Light	Hot	Medium	Fast
11	Moderate	Hot	Medium	Fast
12	Dirty	Hot	Fast	Fast

3) Defuzzification

Defuzzification uses the weighted average method. For each active rule ($\alpha_i > 0$), the crisp output value z_i is obtained from the inverse of the output membership function using the value α_i . The final PWM value is calculated as:

$$Z = \frac{\sum(\alpha_i \times z_i)}{\sum \alpha_i} \quad (2)$$

This method produces PWM values that are proportional to all active rules. Compared to Mamdani defuzzification, which uses centroid integration, the Tsukamoto algorithm is much less computationally intensive, making it ideal for real-time implementation on the ESP32 microcontroller

IV. RESULT AND DISCUSSION

A. System Implementation

An air quality control system has been successfully implemented in a test chamber with dimensions of $23.5 \times 16 \times 18$ cm that simulates enclosed-room conditions. All hardware components specified in the research methodology have been integrated into a single system.



Figure 8. Test Chamber

On the software side, the Firebase Realtime Database was successfully configured as a low-latency IoT backend. The mobile interface was built using MIT App Inventor, which enables real-time monitoring of IAQ, temperature, humidity, pressure, and actuator status, while also providing remote manual control.



Figure 9. Mobile App Interface

B. Sensor BME680 Accuracy

Accuracy testing was conducted to validate the reliability of the BME680 sensor as a data source for the fuzzy algorithm. The sensor's output values were compared with those of the HTC-1 digital thermometer, which served as the reference measurement device. The evaluation was based on the absolute error, error rate, and accuracy level.

Table 6. Results of the BME680 Temp. Accuracy Test

No.	BME680 (°C)	HTC-1 (°C)	Error (%)	Accuracy (%)
1	29,1	29,3	0,7	99,3
2	31,2	31,0	0,6	99,4
3	27,8	27,7	0,4	99,6
4	28,0	28,1	0,4	99,6
5	27,9	28,1	0,7	99,3
Average			0,7	99,3

As shown in Table 6, the BME680 sensor demonstrated excellent performance in temperature measurements, with an average accuracy of 99.3% and an average error of only 0.7%. The minimal difference in readings between the BME680 and the HTC-1 thermometer indicates a high level of precision and linearity, meaning that the temperature data generated is representative of the actual room conditions.

Table 7. Results of the BME680 Humidity Accuracy Test

No.	BME680 (%)	HTC-1 (%)	Error (%)	Accuracy (%)
1	75	75	0,0	100,0
2	74	73	1,4	98,6
3	73	72	1,4	98,6
4	87	89	2,2	97,8

5	88	90	2,2	97,8
	Average		2,0	98,0

The humidity test results in Table 7 show an average accuracy of 98.0% with an average error of 2.0%. Larger discrepancies in some samples (max. 2.2%) were caused by fluctuations in environmental conditions during testing. Nevertheless, this accuracy value remains within an acceptable tolerance range for air quality monitoring applications. Given the high accuracy of both parameters, the sensor data is deemed valid as input variables for the Tsukamoto Fuzzy Logic algorithm.

C. Testing the Tsukamoto Fuzzy Logic Algorithm

This test aims to evaluate the algorithm's ability to determine the PWM output for fans and blowers based on variations in IAQ and temperature inputs. The test was conducted 36 times, with each rule tested three times to cover all 12 designed rules. The data presented in Table 8 represents one representative scenario for each rule selected to summarize the test results.

Table 8. Results of the Tsukamoto Fuzzy Logic Rules Test

No	IAQ	Temp. (°C)	PWM Blower	PWM Fan	Description
1	15	17,6	85	85	Fullfil Rule 1
2	122	18,5	136	107	Fullfil Rule 2
3	159	18,1	165	87	Fullfil Rule 3
4	335	17,8	255	85	Fullfil Rule 4
5	70	21,9	85	170	Fullfil Rule 5
6	113	23,6	170	170	Fullfil Rule 6
7	126	24,2	154	160	Fullfil Rule 7
8	433	21,4	255	170	Fullfil Rule 8
9	71	30	85	255	Fullfil Rule 9
10	118	29,4	170	255	Fullfil Rule 10
11	142	32,9	135	220	Fullfil Rule 11
12	353	30,1	255	255	Fullfil Rule 12

From the 12 scenarios tested, all produced outputs that matched the designed rule base. These results demonstrate that the fuzzification, inference, and defuzzification processes functioned correctly in the ESP32 microcontroller implementation.

D. IAQ Accuracy Testing and System Architecture Analysis

Tests were conducted to evaluate the performance of the BSEC algorithm in generating valid IAQ values, while also analyzing the influence of system architecture on the sensor baseline formation process, as represented by the IAQ Accuracy parameter. Two test scenarios were applied: single-core and dual-core architectures on the ESP32.

The test results show significant differences between the two architectures, as shown in Table 9. In the single-core implementation, the IAQ Accuracy value did not improve and remained at level 0 throughout the testing, indicating that the sensor baseline formation process was not functioning properly. Conversely, in the dual-core architecture, IAQ Accuracy successfully reached the maximum level (level 3) with an average time of 695 seconds.

Table 9 System Performance Comparison

No	System Mode	Maximum IAQ Accuracy	Average Time to Reach Level 3 (s)
1	Single-Core	0	Not reached
2	Dual-Core	3	695

This performance difference is caused by the blocking nature of Firebase communication processes on a single-core architecture, which disrupts the consistency of the BSEC algorithm's execution—an algorithm that requires periodic calls. This disruption results in suboptimal sensor baseline formation, preventing the IAQ Accuracy score from improving.

Conversely, in a dual-core architecture, the separation of tasks between communication and computation allows both processes to run in parallel without interfering with each other. This maintains the consistency of the BSEC algorithm's execution, ensuring that the sensor baseline formation process proceeds smoothly and produces valid IAQ data.

Table 10. Time to Reach IAQ Accuracy

No	Time	Acc. 0→1 (s)	Acc. 1→2 (s)	Acc. 2→3 (s)	Total (s)
1	Morning	288	261	79	628
2	Midday	294	218	195	707
3	Afternoon	291	345	143	779
4	Evening	285	248	133	666
	Average	290	268	138	695

Based on Table 10, the time required to reach IAQ Accuracy Level 3 is relatively consistent, with an average of 695 seconds. Variations in time are influenced by environmental conditions and pollutant concentrations during testing. This has practical implications: the system can be calibrated more quickly by introducing variations in air conditions at the start of operation. However, all scenarios demonstrate that the system is capable of stably reaching the sensor baseline, indicating that the BSEC algorithm performs well on a dual-core architecture.

E. System Response Testing

System response testing was conducted to evaluate the system's ability to reduce pollutant concentrations from a heavily contaminated state (IAQ = 500) to a clean state (IAQ ≤ 80). The data presented in Table 11 represent the average time for each session. The reduction process was divided into three stages: from heavily polluted to moderately polluted (IAQ 500→178), from moderately polluted to lightly polluted (IAQ 178→125), and from lightly polluted to clean (IAQ 125→80).

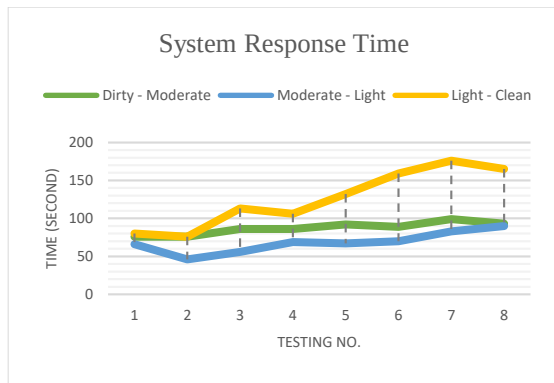


Figure 10. System Response Time Chart

The consistent slowdown during the Light to Clean phases (averaging 126 seconds) was analyzed from two perspectives. First, from the perspective of the control system's characteristics, the slower decrease in pollutant concentration during the final stage occurs because the fuzzy system generates lower PWM values according to the rule base as IAQ approaches the 'Clean' category. Second, from the perspective of fuzzy parameter design, the minimum PWM value in the 'Slow' fuzzy set, set at 85, is suspected to be too low, resulting in suboptimal pollutant removal rates at low concentrations. This indicates that the slowdown in the final phase is a potential weakness in the setting of the lower bound parameter for the "Slow" fuzzy set. Optimizing this parameter is recommended as a further development to speed up the response time in the 'Light' to "Clean" phases.

Table 11. Average System Response Time Results

No	Testing Time	INDEX AIR QUALITY			Total Dirty-Clean (s)
		Dirty-Moderate (s)	Moderate-Light (s)	Light-Clean (s)	
1	Morning	76	56	78	210
2	Midday	86	63	110	258
3	Afternoon	91	69	146	305
4	Evening	96	87	171	353
Total Average		87	68	126	281

Table 11 shows that the system exhibits an asymmetric yet structured response. Overall, the average total system time to reduce the IAQ from 500 to ≤ 80 is 281 seconds (~4 minutes 41 seconds). These results demonstrate good responsiveness for indoor air quality control applications, while also proving the effectiveness of the Tsukamoto fuzzy algorithm in producing rule-based, stable, and proportional control.

Variations in response times across testing sessions are believed to be influenced by differences in environmental conditions during each session, including humidity, temperature, and the composition of the pollutants administered. This is a limitation of the study that should be taken into account in future research, where testing should be conducted under more controlled environmental conditions.

F. IoT Synchronization and System Indicators

Synchronization testing was conducted to ensure data consistency between the local LCD and the

Firebase-based mobile app. A total of 4 test scenarios were performed under different IAQ conditions. All tests showed identical values between the two interfaces with no detectable delay. This success confirms that the Firebase Realtime Database, with latency < 1 second, is capable of meeting the requirements of a real-time control system.



Figure 11. IoT Synchronization Documentation

System indicator testing (RGB LED and buzzer) was performed across 4 air quality categories. The results are shown in Table 12.

Table 12. System Indicator Test Results

No	IAQ	LED	Buzzer
1	< 100 (Clean)	Green	OFF
2	101–150 (Light)	Green	OFF
3	151–200 (Moderate)	Blue	OFF
4	201–500 (Dirty)	Red	ON

G. Power Consumption

Power consumption testing was conducted to evaluate the system's operational efficiency while the ESP32 continuously runs both cores, including active Wi-Fi connectivity, Firebase synchronization, BME680 sensor readings, fuzzy logic computations, and actuator control. Current measurements were taken using a multimeter connected in series to the 5V supply line from the step-down module to the system, with a measured supply voltage of 5V. Measurements were taken 5 times after the system reached a stable state (IAQ Accuracy level 3).

Table 13. System Power Consumption Test Results

Testing No.	Current (A)	Power (W)
1	0,09	0,93
2	0,16	0,96
3	0,14	0,94
4	0,15	0,98
5	0,16	0,95
Average	0,14	0,7

Test results show that the system consumes an average of 0.7 watts under full operational conditions with both cores active. This power consumption includes the ESP32, LCD, RGB LED, and buzzer running simultaneously. This value is considered efficient for an embedded IoT system performing fuzzy computing and wireless communication in parallel, making the system potentially operable using battery power or a small solar panel in future implementations.

V. CONCLUSION

An IoT-based Indoor Air Quality (IAQ) control system using the Tsukamoto fuzzy method has been

successfully designed and implemented. The BME680 sensor achieved an average accuracy of 99.3% for temperature and 98.0% for humidity, confirming its reliability as a fuzzy input source. All 12 fuzzy rule scenarios were executed correctly, producing PWM output values consistent with the designed rule base.

The dual-core ESP32 architecture proved critical: the single-core implementation failed to improve IAQ accuracy beyond level 0, whereas the dual-core configuration successfully reached level 3 in an average of 695 seconds. The system reduced IAQ from a heavily polluted condition (IAQ = 500) to clean (IAQ ≤ 80) in an average of 281 seconds, while IoT synchronization between the LCD screen and the Firebase-based mobile app enabled real-time data synchronization. These results confirm that the Tsukamoto fuzzy algorithm with weighted average defuzzification is well-suited for real-time rule-based control in embedded systems, providing a fast, stable, and proportional response to changes in indoor air quality. Power consumption testing shows that the system consumes an average of 0.7 watts under full dual-core operating conditions, which is considered efficient for embedded IoT applications.

For further development, several specific recommendations are proposed based on the findings of this study. First, the parameters of the ‘Slow’ fuzzy set need to be optimized, specifically by raising the lower limit of the minimum PWM value from 85 to a more optimal value, or by adding a specific rule for ‘Light’ IAQ transition conditions approaching ‘Clean,’ to accelerate the system’s response time in the final phase without compromising control stability. Second, the system can be enhanced by adding PM2.5 particulate sensors and HEPA filters for more comprehensive pollutant detection and control. Third, testing in real-world room-scale environments and comparative studies with other methods such as PID or machine learning are needed to evaluate the system’s scalability. Fourth, the development of mobile app features such as historical data storage and notifications based on IAQ categories is recommended to enhance the system’s usability in daily use.

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