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Design And Development Of A Microcontroller-Based Air Pollution Monitoring System At Traffic Light Areas Using The Mamdani Fuzzy Logic Method

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ABSTRACT

Air pollution was a serious issue in Indonesia, particularly in areas with high vehicle density, such as Yogyakarta. In 2024, more than 164 million vehicles were recorded in Indonesia. Motor vehicle emissions contributed to approximately 85% of total air pollution in the country. The high activity of motor vehicles increased the concentration of harmful gases such as carbon monoxide (CO), which had adverse effects on public health. To assess air pollution levels in surrounding areas, a monitoring system of air quality was required to maintain acceptable environmental conditions. In this study, a system was designed by integrating the MQ-135 sensor to detect carbon monoxide (CO) in real-time. The data obtained from the sensor were transmitted to the ESP32, where data processing employed the Mamdani Fuzzy Logic method to classify air quality into three categories: Good, Moderate, and Poor. The process began with CO level detection and was followed by fuzzification, inference, and defuzzification stages, producing a crisp value as a reference for air quality classification. In addition, the system was equipped with a monitoring feature based on Firebase and an application developed with MIT App Inventor. Based on the results of testing, the air pollution monitoring system was successfully implemented. The MQ-135 sensor was able to read surrounding air conditions in real-time with an average error of 0.33%, resulting in a reading accuracy level of 99.67%. The Mamdani Fuzzy Logic method effectively processed ambiguous data; however, testing also identified limitations in the design of membership functions, which led to mismatches in category determination at threshold values. The system successfully transmitted data in real-time to Firebase and the MIT App Inventor application with a success rate of 80%.

Keywords
Air pollution;
ESP32;
Mamdani Fuzzy Logic;
Firebase.

ABSTRAK

Polusi udara di wilayah perkotaan, yang sebagian besar disebabkan oleh emisi kendaraan, merupakan ancaman signifikan bagi kesehatan masyarakat. Penelitian ini menjawab kebutuhan akan sistem pemantauan kualitas udara yang dapat diakses secara *real-time*, khususnya untuk area padat lalu lintas seperti persimpangan. Kontribusi utama dari penelitian ini adalah

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pengembangan prototipe berbasis *Internet of Things* (IoT) yang hemat biaya dan memanfaatkan metode Logika Fuzzy Mamdani untuk mengklasifikasikan kualitas udara, sehingga data lebih mudah dipahami oleh masyarakat umum. Sistem ini dirancang menggunakan sensor MQ-135 untuk mendeteksi kadar Karbon Monoksida (CO), mikrokontroler ESP32 untuk pemrosesan data, dan modul SIM800L untuk transmisi data *real-time* ke platform Firebase. Metode Logika Fuzzy Mamdani diimplementasikan untuk mengklasifikasikan konsentrasi CO yang terukur ke dalam tiga kategori: Baik, Sedang, dan Buruk. Hasil implementasi menunjukkan kinerja yang sangat positif. Sensor MQ-135 menunjukkan akurasi yang tinggi, dengan tingkat kesalahan rata-rata hanya 0.33% dan akurasi pembacaan keseluruhan sebesar 99.67% dibandingkan dengan detektor CO standar. Meskipun sistem logika fuzzy secara fungsional berhasil mengolah data ambigu di batas kategori, pengujian juga mengungkapkan adanya keterbatasan desain yang menyebabkan klasifikasi untuk nilai ambang batas tertentu (misalnya, 100 ppm) tidak selaras dengan standar ISPU. Lebih lanjut, sistem berhasil mentransmisikan data ke platform *cloud* Firebase dan aplikasi kustom MIT App Inventor dengan tingkat keberhasilan 80%. Sebagai kesimpulan, penelitian ini berhasil mengembangkan prototipe IoT yang fungsional untuk pemantauan polusi udara. Studi ini mengkonfirmasi kelayakan penggunaan metode Logika Fuzzy Mamdani untuk klasifikasi kualitas udara *real-time*, meskipun menyoroti kebutuhan krusial akan desain fungsi yang presisi untuk memastikan keselarasan dengan standar yang ada.

1. Introduction

Air pollution is a significant environmental challenge in Indonesia, which ranks as the third-largest user of motorized vehicles in Asia. The primary sources of this pollution are the high volume of vehicles exceeding 164 million units, with motorcycles comprising 83% and emissions from numerous industrial factories [1]. Consequently, vehicle emissions are identified as the leading cause of air pollution in Indonesia, contributing to approximately 85% of the total pollutants [2]. In addition to these sources, air pollution is exacerbated by common practices such as open waste burning. The resulting pollutants include particulate matter (e.g., dust and aerosols) and hazardous gases such as Carbon Monoxide (CO), Nitrogen Oxides (NOx), Sulfur Dioxide (SOx), and Hydrogen Sulfide (H2S) [3].

The consequences of this deteriorating air quality are severe for both human health and the environment. Prolonged exposure is linked to a range of conditions, including respiratory disorders, heart disease, and premature death. A 2021 study by the Health Effects Institute (HEI) attributed over 221,600 deaths in Indonesia to air pollution, with Acute Respiratory Infections (ARIs) being a leading cause of morbidity worldwide [4]. Beyond direct health impacts, air pollution alters the Earth's atmospheric structure, allowing harmful UV radiation to increase health risks like skin cancer [5]. Furthermore, pollutants trap heat in a phenomenon known as the greenhouse effect, which contributes to the rise in global temperatures [6].

In response to this crisis, the Indonesian government has established ambient air quality standards through Government Regulation No. 22 of 2021, which sets a threshold for pollutants like Carbon Monoxide at 10,000 $\mu g/m^3$ over an 8-hour period to safeguard public health. Despite these official regulations and the clear dangers, public awareness of the severe health and environmental risks remains critically low. This gap between established standards and public understanding highlights the need for accessible information to motivate community-level action.

To address this awareness gap, this project proposes the development of an Internet of Things (IoT) based air quality monitoring device. The system is designed to provide real-time, easily understandable data using an MQ-135 sensor for pollution detection, an ESP32 microcontroller for data processing, and a SIM800L

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module for remote communication [7]. Data is transmitted wirelessly to a Firebase database, ensuring that accurate and timely air quality information can be accessed. This technological solution aims to increase public consciousness and provide a practical tool for monitoring environmental health.

2. The Proposed Method/Algorithm

The core of the data processing in this system is a multi-stage fuzzy inference algorithm designed to convert quantitative CO concentration values (in PPM) into a qualitative assessment of air quality. This method ensures a more human-like and flexible decision-making process by handling imprecise data. The overall process, as illustrated in Figure 1, consists of four main stages: data collection, fuzzy set formation, fuzzy rule evaluation, and defuzzification.

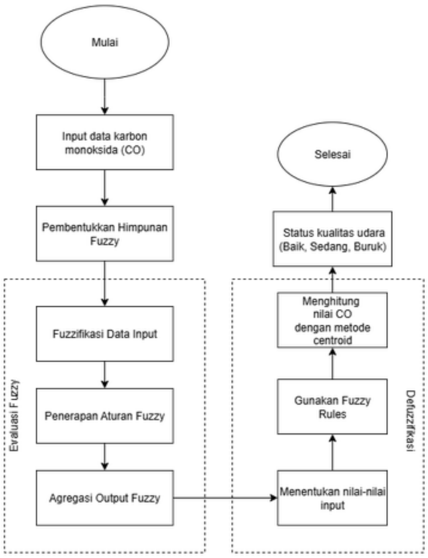

Fig. 1 Fuzzy logic mamdani method flowchart

The membership functions for each set are defined as follows:

- 'BAIK' (Good) Membership Function:

  $\mu Baik(x)\{1\ ;\ x\leq 30\ \frac{50-x}{20}\ ; 30\ <\ x\ <\ 50\ 0\ ;\ x\geq 50$

- 'SEDANG' (Moderate) Membership Function:

  $\mu Sedang(x) = \{0\ \ ; x\leq 40\ or\ x\geq 100\ \frac{x-40}{20}; 40\ <\ x\leq 60\ 1; 60\ <\ x\leq 80\ \frac{100-x}{20}; 80\ <\ x\ <\ 100$

- 'BURUK' (Poor) Membership Function

  $\mu Buruk(x)\{0; x\leq 90\ \frac{x-90}{30}; 90\ <\ x\ <\ 120\ 1; x\geq 90$

The process is divided into three main operational stages:

a. Fuzzification: This is the initial stage where the crisp input value from the MQ-135 sensor (e.g., 42 PPM) is converted into degrees of membership (μ) across predefined linguistic sets ('BAIK', 'SEDANG', 'BURUK'). This is achieved using trapezoidal and triangular membership functions, as defined in the system's design and shown in the equations below. For instance, an input of 42 PPM might result in μ_BAIK = 0.4 and μ_SEDANG = 0.1.
b. Inference (Aggregation): In this stage, the fuzzy rules are evaluated. The system uses a set of "IF-THEN" rules (e.g., "IF CO is SEDANG THEN air quality is SEDANG"). The degree of membership from the fuzzification stage determines the "strength" of each activated rule. The aggregation process then combines the outputs of all activated rules into a single fuzzy set. This is done using the MAX-MIN method, where the final composite area is the maximum envelope of all individual rule outputs that were clipped (MIN) by their activation strength.
c. Defuzzification: This is the final stage where the composite fuzzy set from the aggregation step is converted back into a single crisp numerical value. This research uses the Centroid method, which calculates the center of gravity of the composite area. This crisp value represents the final, decisive assessment of the air quality, which is then used to determine the final output category ('BAIK',

'SEDANG', or 'BURUK').

3. Method

The research methodology followed the Engineering Design Process (EDP), which includes defining the problem, designing a solution, building a prototype, and testing. The system's architecture is designed as an integrated unit for real-time pollution monitoring.

3.1 System Design and Hardware

The system comprises input, processing, and output components integrated into a cohesive unit.

- Input: An MQ-135 gas sensor serves as the primary input, detecting the concentration of CO in the ambient air.
- Processing: An ESP32 microcontroller with integrated Wi-Fi acts as the central processing unit, running the fuzzy logic algorithm and managing all system operations.
- Output: The system provides user feedback through a 16x2 LCD for displaying PPM values and status, and a buzzer for alerts when pollution levels are high.
- Communication: A SIM800L module is used for cellular data transmission to the cloud database, ensuring connectivity even without local Wi-Fi.
- Power: The system is powered by 18650 batteries regulated by an LM2596 step-down module to ensure stable voltage for all components.

3.2 Software and Model Development

- Firmware: The ESP32 was programmed using the Arduino IDE with C++. This includes the code for sensor reading, implementing the Fuzzy Logic Mamdani algorithm, and data transmission protocols.
- Data Management: The system utilizes a cloud-based Firebase Realtime Database to store and synchronize data instantly. This allows for remote access and real-time updates.
- Monitoring Application: A mobile application was developed using MIT App Inventor. This application connects to the Firebase database to display real-time air quality data (PPM and status) on an Android device, providing a user-friendly interface for monitoring.

4. Result and Discussion

4.1 Hardware Implementation and System Design

The system was physically realized in a custom enclosure designed for practical deployment. The design utilized a durable ABS plastic box with dimensions of 18 cm (length) x 11 cm (width) x 6 cm (height), which was manually customized to house all components. The front panel integrates the primary user interface and sensing components: a 16x2 LCD display, the MQ-135 gas sensor, and a buzzer for alerts. A dedicated compartment was fashioned on the side of the enclosure to hold the 18650 batteries, ensuring easy access for replacement. Internally, a custom PCB was designed and manually etched to neatly manage the connections for the ESP32 microcontroller, the SIM800L module, and the power regulation circuit. Subsequent hardware tests confirmed that all components—the ESP32 microcontroller, MQ-135 sensor, LCD display, buzzer, and SIM800L module—functioned correctly and reliably under operational loads.

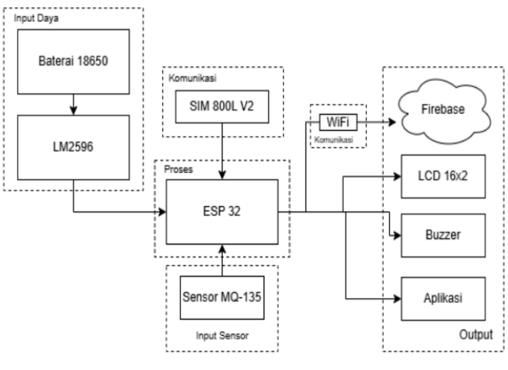

Fig. 2 Electronic architecture system

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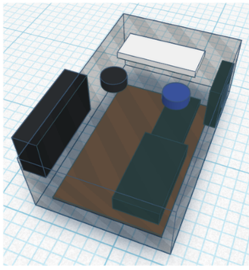

Fig. 3 Mechanics design

4.2 System Performance

The fully integrated system was tested in a real-world scenario at a busy traffic light intersection to evaluate its end-to-end performance. To determine the system's final accuracy, the error percentage was calculated for each set of test data by comparing its readings against a standard CO detector. This analysis confirmed the robustness of the hardware implementation, showing that the MQ-135 sensor demonstrated high accuracy, achieving an overall system accuracy of 99.67% with a mean error of only 0.33%. This result validates that the sensor calibration and data acquisition processes are reliable. The overall system accuracy was derived using the following formulas:

$$Error(\%)\frac{Device\ Reading - Standard\ Detector\ Reading}{Standard\ Detector\ Reading}\times 100\%$$

$$Total\ Error:\ 0.09\% + 0.04\% + 0.02\% + 0.03\% + 0.03\% + 0.02\% + 0.01\% + 0.01\% + 0.07\% = 0.33\%$$

$$Accuracy = 100\% - Mean\ Error$$

$$100\% - 0.33\% = 99.67\%$$

Table 1. System Performance Result

No.	CO Concentration (ppm)	CO Detector Reading (ppm)	Condition	Air Quality	LCD Display and Buzzer
1.	12	11	Green light, few vehicles	Good	Correct and Off
2.	24	25	Green light, few vehicles	Good	Correct and Off
3.	45	46	Green light, few vehicles	Good	Correct and Off
4.	53	55	Yellow light, vehicles begin to accumulate	Moderate	Correct and Off
5.	66	64	Yellow light, vehicles begin to accumulate	Moderate	Correct and Off
6.	77	79	Yellow light, vehicles begin to accumulate	Moderate	Correct and Off
7.	130	128	Red light, high vehicle density	Poor	Correct and On
8.	155	157	Red light, high vehicle density	Poor	Correct and On
9.	169	171	Red light, high vehicle density	Poor	Correct and On
10.	15	14	Green light again, few vehicles	Good	Correct and Off

4.3 Fuzzy Logic Performance

The performance of the Fuzzy Logic Mamdani method was a key focus of the evaluation. The basis for this logic is a set of membership functions designed for each category, as depicted in Fig.4. This graph illustrates how each PPM value is mapped to a degree of membership for the 'BAIK', 'SEDANG', and 'BURUK' sets.

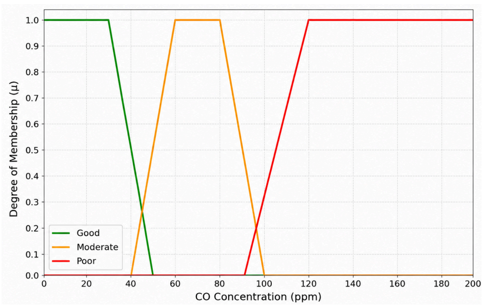

Fig. 4 Fuzzy membership graph

Functionally, the system was successful in processing ambiguous input values and producing a consistent output, as demonstrated in the detailed analysis of 42 PPM and 92 PPM inputs. However, the testing revealed a significant design flaw. A discrepancy was found between the system's output and the official Indonesian Air Pollution Standard Index (ISPU) at critical thresholds. For example, the system incorrectly classified a CO concentration of 100 PPM as 'BURUK', whereas the ISPU standard categorizes it as 'SEDANG'. This classification failure stems from a membership function design that is not perfectly aligned with the official standards.

The calculation follows three main stages of the Mamdani fuzzy inference system:

a. Fuzzification

The crisp input value (42 PPM) is converted into degrees of membership for the relevant fuzzy sets ('BAIK' and 'SEDANG') using the predefined membership functions:

- **μ_BAIK(x)** : For a CO level of 42 PPM, the degree of membership in the 'BAIK' set is calculated as:
  $\mu BAIK(42)\frac{50-42}{50-30} = \frac{8}{20} = 0.4$
- **μ_SEDANG(x)** : The degree of membership in the 'SEDANG' set is:
  $\mu SEDANG(42) = \frac{42-40}{60-40} = \frac{2}{20} = 0.1$
- **μ_BURUK(x)** : The degree of membership is **0** as 42 PPM is outside its range.

b. Inference and Aggregation

Based on the fuzzification results, two fuzzy rules are activated: "IF CO is BAIK THEN..." and "IF CO is SEDANG THEN...". The outputs of these rules are clipped at their respective degrees of membership (0.4 for 'BAIK' and 0.1 for 'SEDANG'). These clipped fuzzy sets are then combined (aggregated) using the MAX operator to form a single composite output fuzzy set. In this stage, a set of "IF-THEN" fuzzy rules are evaluated. The rules for this system are:

- IF CO concentration is 'BAIK', THEN air quality is 'BAIK'.
- IF CO concentration is 'SEDANG', THEN air quality is 'SEDANG'.
- IF CO concentration is 'BURUK', THEN air quality is 'BURUK'.

c. Defuzzification (Centroid Method)

The final step is to convert the composite fuzzy set back into a single crisp value using the Centroid method, which calculates the center of gravity of the composite area. The formula is:

$$x^{*} \frac{\sum xi \cdot \mu(xi)}{\sum \mu(xi)}$$

The calculation for the 42 PPM input yields:

- Numerator (sum of weighted values): 69.75
- Denominator (sum of membership values): 1.75

$$x^{*} \frac{69.75}{1.75} = 39.86$$

The resulting crisp value is 39.86 PPM. Since this value falls within the range defined for the 'BAIK' category (1-50), the system's final classification is 'BAIK'. A similar process for an input of 92 PPM (on the threshold of 'SEDANG' and 'BURUK') results in a crisp output of 89.56, correctly classifying it as 'SEDANG'. This demonstrates the method's robustness in handling ambiguous data through its internal fuzzy processing, ultimately producing a decisive and logical classification.

Table 2. Fuzzy Logic Method Result

No.	CO Concentration (ppm)	Fuzzy Output	Standard (Ditjen PPU)
1	12	Good	Good
2	24	Good	Good
3	45	Good	Good
4	50	Moderate	Good
5	66	Moderate	Moderate
6	77	Moderate	Moderate
7	100	Poor	Moderate
8	155	Poor	Poor
9	169	Poor	Poor
10	15	Good	Good

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4.4 Real-Time Data Transmission Testing

The system's IoT functionality was tested by transmitting data from the device to the Firebase database and the monitoring application. The system achieved an 80% success rate in data transmission over 10 trials. The two failures were attributed to temporary cellular signal disruptions at the test location, indicating that the transmission hardware and software are functional but dependent on network stability.

Table 3. Real-Time Data Transmission Result

No.	CO Concentration (ppm)	Transmission Status	Data Received in App
1	12	Success	12
2	24	Success	24
3	45	Success	45
4	53	Success	53
5	66	Fail	65
6	77	Success	77
7	130	Success	130
8	155	Success	155
9	169	Success	169
10	15	Fail	14

4.5 Discussion

The results demonstrate the successful development of a highly accurate sensor system and a functional IoT framework. The 99.67% accuracy of the sensor readings is a strong indicator of the system's capability for reliable environmental monitoring. The 80% data transmission success rate is acceptable for a prototype and highlights the importance of stable network connectivity for IoT devices.

The most significant finding is the mixed performance of the fuzzy logic implementation. While the algorithm worked correctly from a mechanical standpoint (handling ambiguous data through aggregation and defuzzification), the design of its core logic (the membership functions) was flawed. This highlights a critical lesson in designing expert systems: the underlying logic must be meticulously validated against established standards to ensure the output is not just consistent but also correct. By successfully automating the process of air quality sensing and data logging, the system addresses the core goal of providing real-time information, but the classification inaccuracy remains a key limitation.

5. Conclusion

Based on the research and implementation conducted, it can be concluded that the design of an air pollution monitoring system using the Fuzzy Logic Mamdani method has been successfully realized by effectively integrating hardware and software components. The system demonstrated strong performance, with the MQ-135 sensor achieving a high accuracy rate of 99.67% in real-time air quality readings. Furthermore, the system's performance in data transmission was proven to be functional and reliable; it successfully sent air quality data to the Firebase platform and monitoring application with an 80% success rate, ensuring data accessibility for users. The results achieved are consistent with the objectives stated in the introduction, where this system was proposed as a solution to provide real-time air quality information. The successful implementation provides an automated and integrated framework for environmental monitoring. The Fuzzy Logic Mamdani method proved to be functionally robust in processing ambiguous data at category boundaries, such as for 42 and 92 PPM values. However, a critical flaw was identified in the membership function design, which led to a classification failure at key thresholds, specifically misclassifying 100 PPM as 'BURUK' instead of 'SEDANG' according to the ISPU standard. For future development, several improvements can be made. To enhance classification accuracy, it is highly recommended to redesign and refine the fuzzy membership functions to be fully aligned with the official ISPU standards, particularly at critical boundary points. Additionally, to improve the reliability of data transmission, alternative communication protocols such as LoRa or MQTT could be explored to ensure a more stable connection with lower power consumption, especially for deployment in areas with fluctuating cellular signals.

Author Contribution:

All authors contributed equally as the main contributors to this paper. All authors read and approved the final manuscript.

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Conflicts of Interest:

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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