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Design and Development of an IoT-Based Air Quality Monitoring System to Support Inspection Processes

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ABSTRACT

Air quality degradation caused by industrial activities, urbanization, and increasing transportation has become a significant environmental issue affecting human health and ecosystem sustainability. Conventional air quality inspection methods often require lengthy measurement processes and are unable to provide real-time information, resulting in limitations in continuous monitoring and decision-making. This research aims to design and develop an Internet of Things (IoT)-based air quality monitoring system integrated with the Mamdani Fuzzy Logic method to support real-time inspection processes and improve air quality classification accuracy. The research employed a Research and Development (R&D) approach using the ADDIE development model, which consists of the analysis, design, development, implementation, and evaluation stages. The developed system utilizes an ESP32 microcontroller integrated with multiple sensors to measure particulate matter (PM2.5 and PM10), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3) parameters. Data transmission is conducted through GSM/LTE communication and visualized using a web-based monitoring platform. The results indicate that the system successfully performs real-time data acquisition, storage, visualization, and air quality classification based on Indeks Standar Pencemar Udara (ISPU) standards. The implementation of Mamdani Fuzzy Logic shows that air quality conditions were predominantly categorized as Good, with the highest ISPU value of 67 recorded at 12:00 due to increased PM2.5 and PM10 concentrations. The findings demonstrate that the proposed IoT-based monitoring system can provide an effective, automated, and structured solution to support air quality inspection processes. Future improvements are recommended through sensor calibration, the addition of environmental parameters, and integration with predictive intelligence models.

INTRODUCTION

Air quality is one of the important indicators for safeguarding environmental and human health. Along with industrial growth, urbanization, and the increasing use of motorized vehicles, air pollution has become a serious environmental problem (Borrego A. M.; Ginja J.; et al., 2021). Increasing concentrations of air pollutants can negatively affect human health and the environment. The decline in air quality occurs in various areas with high population density, intensive transportation activities, and industrial activities (Majidah, 2024). Exposure to air pollution not only affects respiratory health but can also affect skin health and reduce overall environmental quality. Therefore, air quality monitoring is essential due to its direct impact on public health and environmental sustainability (Pebralia, 2024).

Air quality monitoring plays a vital role in supporting public health protection and decision-making related to air pollution control (Snyder T. H.; Solomon P. A.; et al., 2013). Common parameters used in air quality monitoring include particulate matter, such as PM2.5 and PM10, as well as gaseous pollutants, including ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO). Previous research has shown that increasing concentrations of particulate matter and gaseous air pollutants can be influenced by industrial activities and motor vehicle emissions in urban areas. In addition, high PM10 concentrations are considered one of the major factors contributing to the deterioration of air quality in urban environments (Setyono W.; Nancy N., 2020).

(Castell F. R.; Schneider P.; et al., 2017) In the air quality inspection process, several agencies still utilize conventional methods involving High Volume Air Sampler (HVAS) instruments with the gravimetric method. Although the HVAS method is recognized for its high accuracy and is widely used as a reference method, it has limitations because it cannot provide real-time air quality information and requires a relatively long analysis period to obtain monitoring results. This condition causes historical data management and reporting processes to become less efficient.

The development of Internet of Things (IoT) technology enables air quality monitoring processes to be conducted automatically and in real time (Choiri E.; Chandra F. H., 2022). Several previous studies have developed IoT-based air quality monitoring systems using ESP32 microcontrollers and various gas sensors (Jiao G.; Williams R.; et al., 2016). Research by [7] designed an IoT-based air quality monitoring device using MQ-7 and MQ-135 sensors to detect CO and CO_2 concentrations in real time, with a system capable of transmitting data to a website for remote monitoring (Ihsan, 2025; Dewangga, 2024). Research by [8] developed an ESP32-based air quality monitoring system equipped with five sensors capable of displaying air quality data in real time through a website. In addition, research by [9] designed an air quality monitoring system using an ESP32-based MQ-2 sensor capable of monitoring gas concentrations in real time and activating automatic ventilation when predefined thresholds are exceeded (De Vito M.; Martinotto L.; Di Francia G., 2012).

Other studies have also demonstrated the advancement of IoT implementation in air quality monitoring systems. Research by [10] developed an IoT-based indoor air quality monitoring system for direct monitoring of indoor environmental conditions. Research by [11] developed an ESP32-based air quality monitoring device with an open-source and low-cost design. Research by [12], [13], and [14] utilized IoT technology to support automated and real-time air quality monitoring processes. Research by [15] further demonstrated that an ESP32-based air quality monitoring system can support environmental policy development by providing continuous air quality data. Furthermore, research by [16] developed an IoT-based environmental information system for real-time monitoring of air conditions.

Although several previous studies have successfully developed IoT-based air quality monitoring systems, most studies still focus primarily on real-time monitoring and visualization of air quality data and have not yet provided centralized inspection data management for recording, storing, and evaluating air quality monitoring results. Furthermore, previous studies generally utilize limited sensor parameters, resulting in air quality data that does not represent a comprehensive range of particulate matter and gaseous pollutants (Rai P.; Pilla F.; et al., 2017). Research on air quality analysis through continuous monitoring indicates that particulate matter and nitrogen dioxide parameters are important factors in determining air quality conditions (Kumar L.; Martani C.; et al., 2015). However, the application of the Mamdani fuzzy logic method in IoT-based air quality monitoring systems remains limited, particularly for supporting air quality classification based on Indeks Standar Pencemar Udara (ISPU) standards in a structured manner (Morawska P. K.; Liu X.; et al., 2018).

Therefore, this research focuses on the design and development of an Internet of Things-based air quality monitoring system that applies the Mamdani fuzzy logic method to support air quality inspection processes. The proposed system utilizes an ESP32 microcontroller integrated with multiple air quality seFairnsors to monitor PM2.5, PM10, CO, NO_2, SO_2, and O_3 parameters in real time (Feenstra V.; Hasheminassab S.; et al., 2019). This research offers novelty through multi-sensor air quality integration, centralized inspection data management, and the application of the Mamdani fuzzy logic method for air quality classification based on Indeks Standar Pencemar Udara (ISPU) standards, thereby supporting inspection processes and decision-making more effectively and systematically (Kumar S.; Singh R., 2020).

METHOD

This research employed a Research and Development (R&D) method using the ADDIE development model, which consists of five stages: Analysis, Design, Development, Implementation, and Evaluation. The ADDIE model was selected because it was suitable for developing structured and iterative Internet of Things (IoT)-based systems.Stages in model ADDIE includes:

(1) Analysis, that is stage identification need system
(2) Design, that is design system good device hard and device soft
(3) Development, that is implementation design become system Which functioning
(4) Implementation, that is implementation system on environment test
(5) Evaluation, that is process evaluation to performance system Which has built.

Model development ADDIE Which used in study This shown on Picture 1

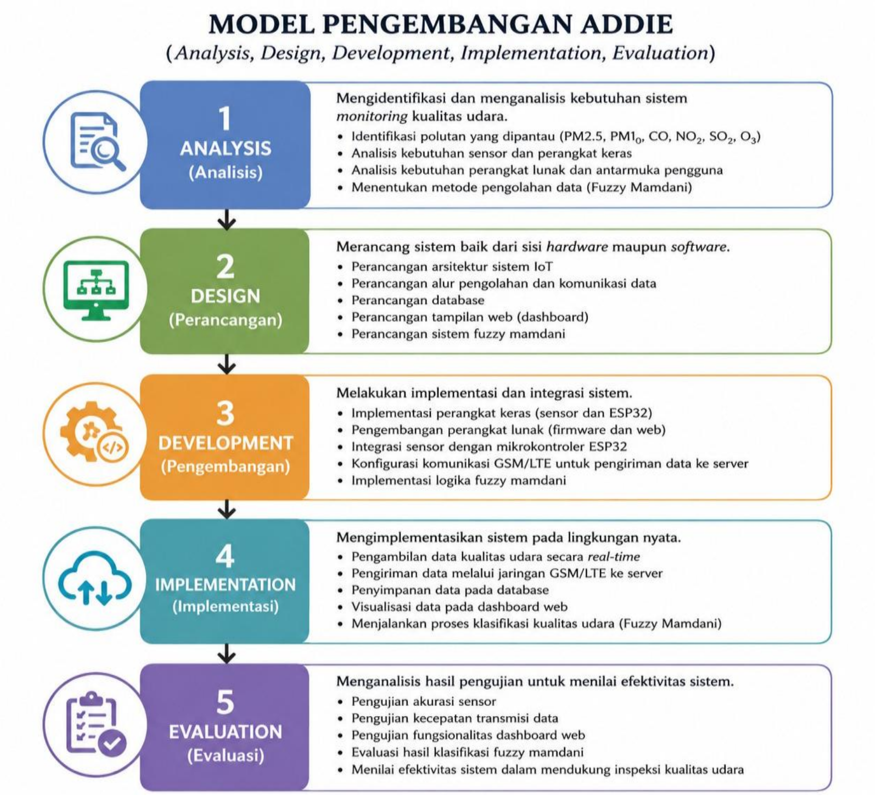


Figure 1. Model Development ADDIE

2.1 Design System

2.1.1 Design Internet of Things

The Internet of Things (IoT) system design in this study aims to build an air quality monitoring system capable of real-time and continuous data acquisition, transmission, and visualization. The system is designed so that the entire measurement and monitoring process is seamless. delivery data can walk in a way automatic without intervention manual.

The ESP32 DevKit V4 microcontroller is used as the system control center because it has a dual-core architecture, low power consumption, and supports Wi-Fi and Bluetooth Low Energy connectivity. Energy (BLE). Besides That, ESP32 own ecosystem library Which wide so that supports the integration of various sensors and communication modules in one integrated IoT system (Anshori R. M.; Manuhutu F., 2025; Perdana L.; Azizah P. N., 2025).

The sensors used are selected based on their ability to represent the main parameters. quality air in accordance standard ISPU. Sensor PMS5003 used For detect PM2.5 and PM10 particulates because they have a good level of accuracy in measuring fine particles in air. Temporary That, sensor gas MQ-7, MQ-135, MQ-136, And MQ-131 each used to detect carbon monoxide (CO), nitrogen dioxide (NO2), sulfur dioxide (SO2), and ozone (O3), which are the main indicators of air pollution in urban and industrial environments.

To support the overall data processing system, the system is equipped with several supporting components. The RTC DS3231 is used to provide precise time stamps on each measurement data, while a 16 GB microSD card is used as temporary local storage to anticipate network disruptions. The GSM/LTE SIM7000E module is used as the main communication medium for sending data to the server so that the system can operate in areas with limited Wi-

Fi networks. In addition, a 20x4 I2C LCD is used as a local interface to display sensor data directly.

The system is designed to be self-powered using a 30WP solar panel integrated with a 30A solar charge controller and four 18650 batteries for energy storage. This configuration allows the system to operate continuously in locations without stable electricity access, thus supporting field implementation (Pineda-Tobon A.; Branch-Bedoya J. W., 2024).

In a way overall, process Work system started from reading data by sensor Which connected to the ESP32. The data obtained is then timestamped by the RTC, temporarily stored on the microSD card, displayed on LCD, And sent to server through network GSM/LTE. The data received by the server is then stored in a database for further monitoring and analysis purposes.

Scheme overall architecture device hard system shown on Picture 2 .

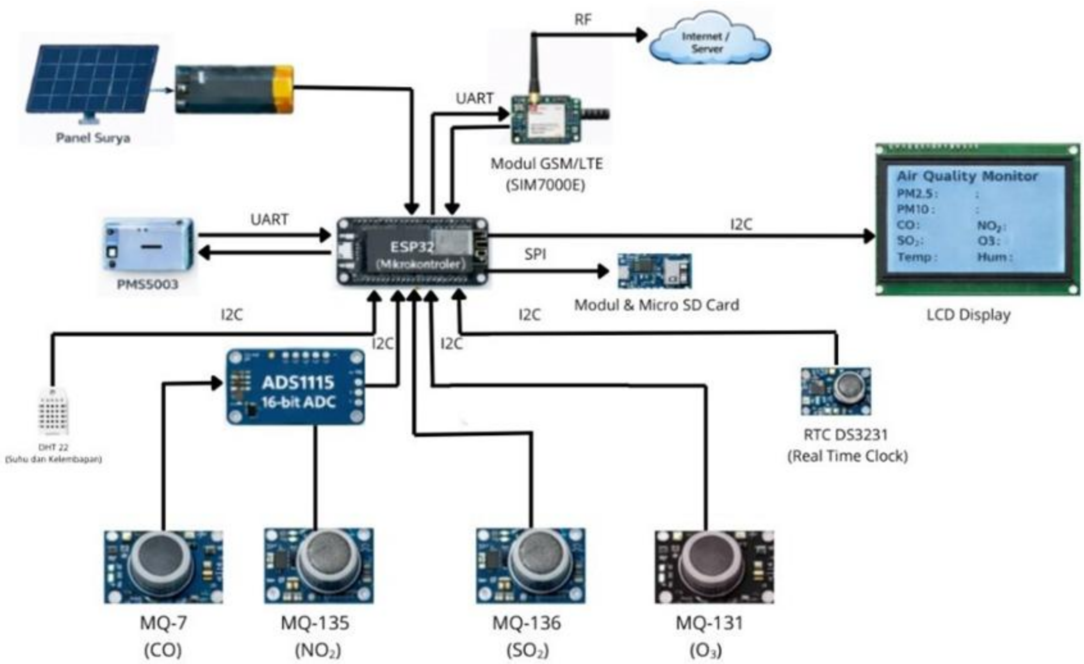


Figure 2. Architecture System Monitoring Quality Air Based IoT

2.1.2 Web System Design

The web system design aims to provide a user interface for real-time air quality monitoring and data management, so that users can access air quality information quickly, in a structured manner, and based on historical data without manual processes.

The web system provides several main modules that support the data monitoring and analysis process:

- Real-time Display Module: used to display sensor readings in real-time. The data is displayed in tabular and graphical formats, making it easier for users to monitor dynamic changes in air quality.
- Data Management: equipped with CRUD (Create, Read, Update, Delete)-based features that allow users to manage both current and historical measurement data. This feature supports the need for long-term analysis of air quality trends.

- Data Visualization Module: used to present information in the form of trend graphs and air quality category indicators based on the ISPU (Air Pollution Standards Index). Categories are visualized using color indicators — green for Good, yellow for Moderate, and red for Unhealthy conditions.
- Backend Integration: integrated with the backend using REST API and WebSocket. REST API is used for the data exchange process between the device and server, while WebSocket is used to support real-time data updates without the need to reload the page.

Overall, the design of this web system produces a responsive, integrated interface that is capable of presenting air quality data accurately and continuously, thus supporting the monitoring process and data-based decision-making.

2.2 Method Logic *Fuzzy* Mamdani

Method logic *Fuzzy* Mamdani used in study This For do classification quality air based on data results reading sensor. Method This chosen Because capable handle data uncertainty and provide results that are more adaptive to variations in environmental conditions.

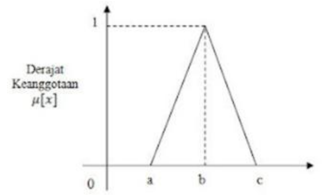
Process system *Fuzzy* Mamdani consists of from three stage main, that is fuzzification, inference (*rule base*), and defuzzification.

1.1.1 Fuzzification

Fuzzification is the process of transforming crisp values from sensors into membership degrees *in* fuzzy sets.

1) **Variables Input** Variables input Which used in system includes:
   - PM10
   - PM2.5
   - Sulfur Dioxide (SO2)
   - Nitrogen Dioxide (NO2)
   - Ozone (O3)
   - Carbon Monoxide (CO)
2) **Variables Output** Variables output Which produced is category quality air:
   - Good
   - Currently
   - No Healthy
   - Very No Healthy
   - Dangerous
3) **Set Fuzzy** Range mark ISPU Which used in study This is:
   - Good : 0–50
   - Currently : 51–100
   - No Healthy : 101–199
   - Very No Healthy : 200–299
   - Dangerous : >300
4) **Membership Functions** The membership functions used are triangular *and* trapezoidal *functions* .

Form general function triangle is:



$$\mu[x,a,b,c] = \begin{cases} 0 & x \leq a \text{ atau } x \geq c \\ (x-a)/(b-a); & a \leq x \leq b \\ (c-x)/(c-b); & b \leq x \leq c \end{cases}$$

Figure 3. Function Membership Triangle

Information: μ = degrees membership *a* = limit lower *b* = mark peak membership *c* = upper limit

1.1.2 Inference (Rule Base)

Process inference use rule IF–THEN with operator:

- AND use function minimum (min)
- OR using the maximum function

(max) The rule base used is as follows:

- **Rule 1** IF PM2.5 Good AND PM10 Good AND SO2 Good AND NO2 Good AND O3 Good AND CO Good THEN Status = Good
- **Rule 2** IF PM2.5 Currently OR PM10 Currently OR SO2 Currently OR NO2 Currently OR O3 Medium OR CO Medium THEN Status = Medium
- **Rule 3** IF PM2.5 Unhealthy OR PM10 Unhealthy OR SO2 Unhealthy OR NO2 Unhealthy OR O3 Unhealthy OR CO Unhealthy THEN Status = Unhealthy
- **Rule 4** IF PM2.5 Very Unhealthy OR PM10 Very Unhealthy OR SO2 Very Unhealthy OR NO2 Very Unhealthy OR O3 Very Unhealthy OR CO Very Unhealthy THEN Status = Very Unhealthy
- **Rule 5** IF PM2.5 Dangerous OR Dangerous PM10 OR SO2 is Dangerous OR NO2 Dangerous OR O3 Dangerous OR CO Dangerous THEN Status = Dangerous

1.1.3 Defuzzification

Defuzzification is process conversion results *fuzzy* becomes mark firm (*crisp value*) using the *Centroid (Center of Gravity) method* .

Defuzzification formula in a way continuous is:

$$z^* = \frac{\int z\,\mu(z)\,dz}{\int \mu(z)\,dz} \tag{1}$$

Because the implementation on the computer uses a discrete form, the equation is used. following:

$$z^* = \frac{\sum (z_i \cdot \mu_i)}{\sum \mu_i} \tag{2}$$

Caption: z^* = crisp output value z_i = representation value (category midpoint) μ_i = degree of membership

RESULTS AND DISCUSSION

Sensor Measurement Results

Table 1 shows the results of air quality measurements obtained from the IoT-based monitoring system. The data obtained includes PM2.5, PM10, CO, NO2, SO2, and O3 parameters.

Table 1. Air Quality Measurement Results

Time	PM2.5	PM10	CO	NO2	SO2	O3
06:00	20 μg/m³	20 μg/m³	0.50 ppm	20 μg/m³	11.85 μg/m³	56.63 μg/m³
09:00	30 μg/m³	30 μg/m³	0.51 ppm	20 μg/m³	12.15 μg/m³	58.59 μg/m³
12:00	72 μg/m³	78 μg/m³	0.58 ppm	28 μg/m³	15.21 μg/m³	65.00 μg/m³
15:00	64 μg/m³	72 μg/m³	0.51 ppm	25 μg/m³	10.21 μg/m³	58.00 μg/m³
18:00	45 μg/m³	40 μg/m³	0.51 ppm	20 μg/m³	15.12 μg/m³	60.90 μg/m³
21:00	30 μg/m³	30 μg/m³	0.51 ppm	20 μg/m³	15.01 μg/m³	68.09 μg/m³
00:00	20 μg/m³	20 μg/m³	0.50 ppm	20 μg/m³	11.85 μg/m³	56.63 μg/m³

Based on Table 1, the measurement results show that the concentration values of air pollutants fluctuated at each observation time. The PM2.5 and PM10 parameters are the main indicators that show the most significant changes compared to other parameters.

At 06:00, the air quality condition was in the Good category with an ISPU value of 33. This condition indicates that the concentration of pollutants was still low in the morning because human and vehicle activity was still relatively low.

At 09:00, the ISPU value increased to 44 but remained in the Good category. This increase indicates a rise in PM2.5 and PM10 particle concentrations due to increased community activity.

The highest ISPU value occurred at 12:00 with a value of 67, which falls in the Moderate category. This condition was influenced by a significant increase in PM2.5 of 72 μg/m³ and PM10 of 78 μg/m³. This increase indicates that daytime activities contribute to the increase in air pollutants (Fitriyah; Indriyani, 2022).

At 15:00, the ISPU value decreased to 54 and was still in the Moderate category. Furthermore, from 18:00 to 00:00, the ISPU value returned to decrease and fell in the Good category with a value range of 33–47. This condition indicates that air quality tends to improve in the afternoon and evening as vehicle and industrial activity decreases.

Overall, the dominant air quality is in the Good category with some conditions in the Moderate category during the day.

3.2 Hardware Implementation Results

The IoT-based air quality monitoring system has been successfully realized in the form of a hardware prototype. This device consists of several main components, such as air quality sensors, a microcontroller, and supporting modules used to process and send data to the monitoring system.

The hardware implementation demonstrates that the process of data acquisition from the environment can be done directly by sensors installed in the system. The data obtained is then processed by a microcontroller before being sent to an IoT-based monitoring platform.

Furthermore, the implementation results also demonstrate that the integration between hardware components is working well, enabling the system to function according to the initial design. This prototype serves as the basis for further development of the air quality monitoring system, especially in terms of improving sensor accuracy and data transmission stability.

3.3 System Output Results

The system generates a dashboard interface used to display real-time air quality data. This display includes sensor data, trend graphs, and air quality classification results based on the Mamdani Fuzzy Method.

Based on the system display data, the PM2.5 value was 30 µg/m³, PM10 was 30 µg/m³, CO was 0.51 ppm, NO2 was 20 µg/m³, SO2 was 12.15 µg/m³, and O3 was 58.59 µg/m³. These data show that most parameters are at a low level.

The system classification results show an ISPU value of 44 in the Good category. This shows that even though there are variations in values for several parameters, the dominance of membership values in the Good category is still higher so that the final result remains in that category.

Thus, the system has successfully carried out the process of data acquisition, visualization, and air quality classification in real-time via a web interface.

3.4 Mamdani Fuzzy Classification Results

The Mamdani Fuzzy Method is used to classify air quality based on PM2.5, PM10, CO, NO2, SO2, and O3 parameters. The inference process uses the MAX method and defuzzification uses the centroid method.

Table 2. Mamdani Fuzzy Calculation Results

Time	µ Good	µ Moderate	µ Unhealthy	ISPU	Category
06:00	1.00	0.18	0.00	33	Good
09:00	1.00	0.59	0.00	44	Good
12:00	1.00	0.28	0.49	67	Moderate
15:00	1.00	0.22	0.26	54	Moderate
18:00	1.00	0.80	0.00	47	Good
21:00	1.00	0.59	0.00	44	Good
00:00	1.00	0.18	0.00	33	Good

Based on Table 2, the Mamdani Fuzzy calculation results show that air quality is predominantly in the Good category.

The lowest ISPU value occurred at 06:00 and 00:00 with a value of 33, while the highest value occurred at 12:00 with a value of 67, which falls in the Moderate category.

The increase in the ISPU value at 12:00 was influenced by the increase in PM2.5 and PM10 concentrations compared to other times. In the fuzzification results, PM2.5 has an Unhealthy membership degree of 0.4857, while PM10 has a Moderate membership degree of 0.2800.

Inference results indicate that particulate matter (PM2.5 and PM10) has the most significant influence on changes in ISPU values compared to other gas parameters. This indicates that dust particles play a dominant role in determining air quality in the system being built.

3.5 Sample Fuzzy Calculation

For example, the calculation is performed on data at 12:00 with the following values: PM2.5 = 72, PM10 = 78, CO = 0.58, NO2 = 28, SO2 = 15.21, O3 = 65.00.

The fuzzification results show that PM2.5 has an Unhealthy membership degree of 0.4857, while the other parameters are dominated by the Good category.

Inference results using the MAX operator are:

- Good = 1
- Moderate = 0.28
- Unhealthy = 0.4857
- Very Unhealthy = 0
- Dangerous = 0

The defuzzification process using the centroid method produces:

$$ISPU = [(1 \times 25) + (0.28 \times 75) + (0.4857 \times 150)] / (1 + 0.28 + 0.4857) = 118.86 / 1.7657 \approx 67$$

Based on these results, the ISPU value at 12:00 is in the Moderate category.

CONCLUSION

This research successfully designed and developed an Internet of Things (IoT)-based air quality monitoring system integrated with the Mamdani Fuzzy Logic method to support real-time air quality inspection processes. The developed system combines an ESP32 microcontroller as the main controller with multiple sensors to measure air quality parameters, including PM2.5, PM10, CO, NO_2, SO_2, and O_3. The system utilizes GSM/LTE communication for automatic data transmission and a web-based platform for monitoring and data management. The implementation results demonstrate that the system is capable of acquiring, storing, visualizing, and classifying air quality conditions based on Indeks Standar Pencemar Udara (ISPU) standards. The Mamdani Fuzzy Logic method successfully classified air quality conditions into several categories, with most observations categorized as Good, while moderate conditions occurred during periods of increased particulate matter concentrations. The highest ISPU value was recorded at 12:00, reaching a value of 67, which was primarily influenced by increased PM2.5 and PM10 concentrations. These findings indicate that particulate matter parameters play an important role in determining air quality classification. Therefore, the proposed IoT-based system provides an effective solution for improving the efficiency, accessibility, and accuracy of air quality inspection activities through continuous and automated monitoring.

Future research should focus on improving system reliability, measurement accuracy, and scalability for broader environmental monitoring applications. Sensor calibration against standardized air quality measurement instruments, such as reference monitoring stations, should be conducted to validate measurement accuracy and minimize sensor deviations. Further studies may expand the system by incorporating additional parameters, such as volatile organic compounds (VOCs), temperature, humidity, and meteorological factors, to provide a more comprehensive assessment of environmental conditions. In addition, future developments may integrate artificial intelligence approaches, such as machine learning or deep learning models, to enhance predictive capabilities and identify future air quality trends. The implementation of cloud-based data storage, mobile applications, and extensive field testing under various environmental conditions is also recommended to evaluate system performance and support large-scale deployment for governmental, industrial, and public health monitoring purposes.

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