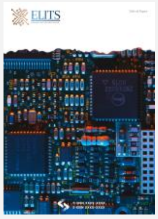
Electronics and Informatics Journal Vol. 1 No. 1 (2026)

P-ISSN: XXXX-XXXX
E-ISSN: XXXX-XXXX
ELITS Journal
journal.diginus.id/ELITS



Design and Implementation of an IoT-Based Roadside Air Quality Monitoring System Using ESP32 Multi-Sensor and Mamdani Fuzzy Logic Integrated with Blynk

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ABSTRACT

Increased volume of road transportation can worsen air quality and negatively impact the health of road users. The project aims to develop and implement a highway air quality monitoring system that leverages the Internet of Things (IoT), with multi-sensor integration and Mamdani's fuzzy logic for air quality evaluation. The system consists of an ESP32 microcontroller integrated with a BME280 sensor to measure temperature, humidity, and pressure, an MQ-135 sensor to detect gaseous pollutants, and a GP2Y1010AU0F dust sensor to assess particle concentration. Sensor data is sent in real-time to Blynk's IoT platform over Wi-Fi and displayed as numerical values, graphs, and time-series graphs. Gas and dust measurements are further processed through Mamdani's fuzzy logic system to generate a Fuzzy Air Quality (Fuzzy AQ) score, which ranges from 0 to 100 and is categorized into three levels: low, medium, and high. The experimental results showed that the system could consistently monitor air quality parameters and present up-to-date air quality status through the Blynk app, with fuzzy outputs that correspond to sensor fluctuations and open up opportunities for expansion to other roadside monitoring locations in the future.

ARTICLE INFO

Article History:

Received:
December 16th, 2025
Received in revised form:
December 27th, 2025
Accepted:
December 28th, 2025

Keywords:

Internet of Things (IoT);
ESP32;
Multi-sensor;
Blynk;
Logika Fuzzy Mamdani.

1. INTRODUCTION

Air quality on highways is one of the crucial elements that affect public health and the sustainability of the urban environment [1]. The increasing number of vehicles year on year has led to a significant spike in emissions of harmful gases such as carbon monoxide, carbon dioxide, nitrogen oxides, and fine dust particles [2]. These pollutants have serious adverse effects on human health and contribute to global climate change [3]. Long-term exposure to air pollution also contributes to worsening global climate change and reducing the comfort and quality of life of people in urban areas with heavy traffic. Therefore, sustainable air quality monitoring has an important role to provide direct information to the public and the government as a basis for decision-making related to environmental policies and transportation planning [4].

The development of Internet of Things (IoT) technology opens up huge opportunities for automatic environmental monitoring through sensors connected to the internet network [5]. IoT enables continuous collection and transmission of sensor data to servers, allowing monitoring to be carried out remotely with a high level of efficiency [6]. IoT-based systems offer effective solutions for monitoring air quality with wide coverage and high accuracy [7]. With this system in place, air condition analysis can be carried out in real-time, which helps in detecting changes in air quality around the vehicle as well as providing early warning if pollutant levels exceed certain limits. In addition, the combination of IoT with cloud computing services and mobile device applications allows for informative data visualization in the form of graphs, indicators, and historical reports that can be further analyzed.

The ESP32 microcontroller is one of the most frequently used devices in the development of IoT monitoring systems because it is equipped with a dual-core processor, as well as an integrated Wi-Fi and Bluetooth connection, in addition to having low power consumption [8]. The ESP32 is capable of supporting the integration of various types of gas sensors, such as the MQ-135 sensor which is commonly used to detect various air pollutants such as NH_3, NOx, benzene, and smoke [9]. With its multi-threading feature, the ESP32 can process information from multiple sensors simultaneously, making it suitable for on-road air quality monitoring applications that require multi-sensor systems [10]. The combination of ESP32 with gas sensors, temperature sensors, and ambient humidity gives the system the ability to generate more in-depth air quality data by considering the influence of environmental conditions on sensor data readings [11].

In the development of aerial monitoring systems, the Blynk IoT platform has been widely applied to present real-time, interactive sensor data [12]. The platform makes it easy for users to view air measurement results in the form of graphs, indicators, and automatic notifications through mobile devices [13]. The advantage of Blynk IoT compared to other platforms lies in the ease of configuration without the need for a manual server and the flexibility to integrate IoT devices such as ESP32 [14]. Through a user-friendly interface, users can monitor various air quality parameters at once, set thresholds for each parameter, and receive alerts when air conditions are in the unhealthy category. The Blynk IoT system also offers ease of displaying data from multiple sensors, making it ideal for use in environmental monitoring applications in dynamic locations such as highways [15].

Several previous studies have developed an air quality monitoring system in industrial areas using the ESP32 NodeMCU with MQ-7, MQ-8, and MQ-135 sensors to detect CO, NO_2, and H_2S gases, where the information is displayed on the LCD and website and is equipped with a buzzer as a warning sign when the gas concentration exceeds a predetermined limit [16]. This study shows that ESP32-based microcontrollers are quite effective for direct air quality monitoring applications in industrial environments, and are able to provide accurate data on the air conditions around the factory. Even so, the focus of the research is still limited to the industrial environment which has characteristics of different sources of pollutants that are quite significant compared to conditions on the highway, which are more influenced by emissions from motor vehicles.

Other research has created a monitoring and notification system regarding air quality on the streets using the Wemos D1 connected to the MQ-135 sensor and the Blynk app as an IoT platform. The system categorizes air quality into three classifications: Normal (0–400), Moderate (401–800), and Abnormal (>800) which are determined based on sensor output values at various highway locations in East Lombok [17]. The results of the test showed that the air quality in the tested area was generally in the Medium category, so there was still a risk of disturbing health if exposed for a long time. The study showed that the combination of microcontrollers, gas sensors, and Blynk IoT works well for monitoring air quality in road areas, but is still limited to one type of gas sensor and measurable air quality parameters.

In addition, a number of previous studies have emphasized indoor air quality monitoring. One of them is a study that introduced a comprehensive indicator for indoor air quality (CIAQI) that integrates various pollutant parameters such as CO, and PM_{10}, as well as utilizing the exponential moving average (EMA) method so that the system can react to changes in air quality directly with minimal computational demands on IoT devices [18]. Another study designed a system to monitor indoor air quality based on ESP8266, using MQ-4 and DHT11 sensors that transmit information about CO_2, temperature, and humidity to the ThingSpeak platform, store data on microSDs, and provide alerts when CO_2 levels exceed certain limits [19]. Both studies show that the use of multi-parameter approaches and IoT platforms can improve the quality of information delivered to users, although it is still limited to indoor conditions.

Based on these various studies, it can be seen that air quality monitoring systems based on IoT are generally focused on one type of gas sensor or one specific type of environment, such as industrial areas or enclosed spaces. In addition, many make use of web platforms or ThingSpeak which has limitations in terms of data update intervals and interface flexibility. On the other hand, highways as one of the main causes of air pollution in urban areas require a monitoring system capable of capturing dynamic changes in air quality affected by traffic density, peak times of vehicles, and other environmental factors. In this study, an ESP32-based Road Air Quality Monitoring System with Multi-Sensor and Blynk IoT has been developed, which utilizes the developed device to monitor various air quality parameters simultaneously in the road environment. In addition, the Blynk app is used as an interface for online monitoring and notifications on mobile devices. Thus, the proposed system is expected to provide more comprehensive information on highway air quality that can be easily accessed and responsive to changing traffic conditions.

The main objective of this research is to design and implement a highway air quality monitoring system that is able to acquire, process, and present air condition information in a sustainable manner. In addition, this study aims to evaluate the performance of the system in monitoring air quality based on the sensor data obtained, as well as assess the potential application of the system as a proof of concept solution for urban environmental monitoring.

2. METHOD

The method applied in this study is oriented towards the design, simulation, and testing of an Internet of Things (IoT)-based air quality monitoring system using the ESP32 microcontroller, BME280 environmental sensor, MQ-135 gas sensor, and SHARP GP2Y1010 dust sensor. The system is built to monitor air quality parameters online and transfer data via Wi-Fi connection to the Blynk IoT platform as a means of visualization. Furthermore, this study adopts Mamdani's fuzzy logic as a method to classify air quality categories based on data from various sensors, following the fuzzy-based air quality evaluation approach that has been used in previous studies [20]. The application of IoT technology in air quality monitoring systems has proven to be very effective, as it facilitates remote monitoring and provides quick information to users, as revealed in several studies on ESP32 and Blynk IoT-based air quality monitoring systems [21].

ELITS Journal
E-ISSN: XXXX-XXXX, P-ISSN: XXXX-XXXX

2.1 Research Flow

The research flow was prepared to describe the stages of developing a systematic IoT-based air quality monitoring system. The study uses a simulated experimental method, where system testing is carried out in a laboratory by simulating various air conditions using sources of smoke, aerosols, and dust particles. A quantitative approach was applied to analyze the numerical data obtained from sensor measurements, which included assessment of sensor performance, stability of IoT data transmission, and results of Mamdani's fuzzy classification. The research flow applied in this study for the development of an IoT-based air quality monitoring system is shown in Figure 1.

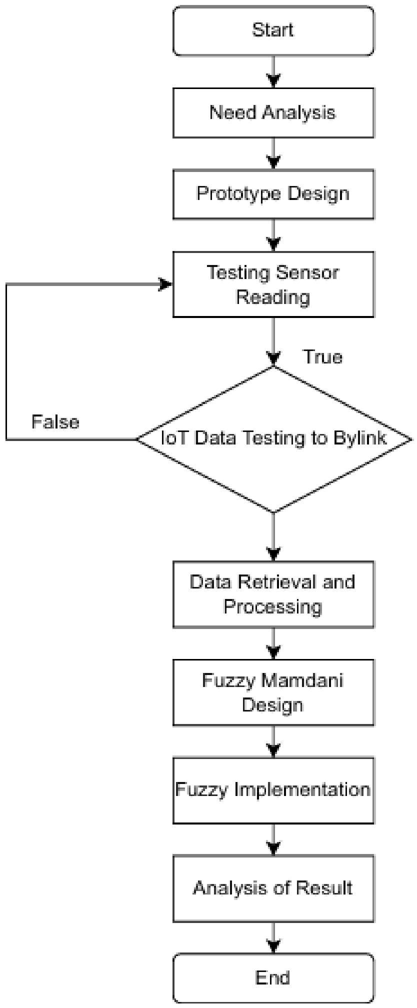

Figure 1. Research flow of the IoT-based roadside air quality monitoring system

The research stage begins with determining the required system, which includes the identification of the air quality parameters to be measured as well as the selection of critical components such as ESP32, BME280, MQ-135 sensors, and SHARP GP2Y1010 dust sensors. After that, the next stage is to design the hardware by combining all the components and conducting initial functional tests to ensure the system is functioning properly.

The next stage is to design the IoT and Blynk systems, which include programming ESP32 to obtain sensor data, transmit data over Wi-Fi, and develop a monitoring dashboard in the Bylnk application. After the data submission process went well, the research continued with the application of Mamdani's fuzzy logic, which included designing membership functions, determining input and output variables, compiling a rulebase, inference process, and defuzzification to automatically produce air quality categories.

The final stage of the study involves testing the system as well as the analysis of the information collected. In this test, a simulation experiment method was applied by changing the air conditions in the laboratory room. All data obtained from the sensor will be analyzed through quantitative means to evaluate the sensor's performance, IoT data stability, and compatibility of fuzzy results with real conditions.

2.2 Hardware Planning

The hardware design in this study is aimed at creating an air quality monitoring system that can continuously measure various environments with a high level of reliability and accuracy. The hard components are assembled by incorporating the ESP32 microcontroller as the brains of the system, along with three main sensor types, namely the BME280, MQ-135, and the SHARP GP2Y1010 dust sensor. Each element has different tasks and measurement properties according to the system requirements. An air quality monitoring system flowchart illustrating the relationship between hardware components and process flows is shown in Figure 2.

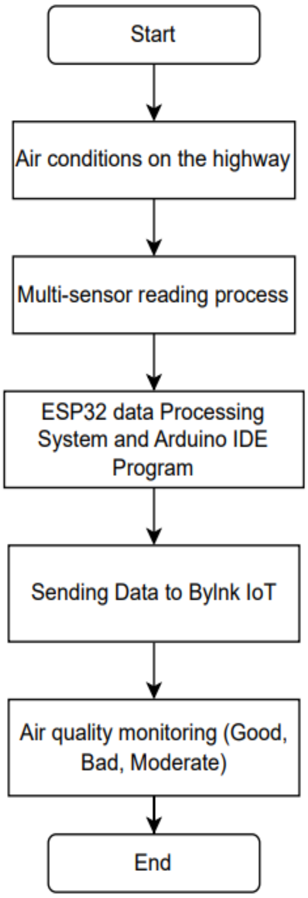

Figure 2. System Flowchart

The main components of the hardware used in the development of this air quality monitoring system are presented in Table 1.

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E-ISSN: XXXX-XXXX, P-ISSN: XXXX-XXXX

Table 1. Hardware components

No	Component Name
1	ESP32 DevKit V1 Module
2	Sensor BME280
3	Sensor MQ-135
4	Dust sensor SHARP GP2Y1010
6	Breadboard
7	Cable jumper
8	Cable USB

The circuitry and connections between the hardware components of the air quality monitoring system are shown in Figure 3.

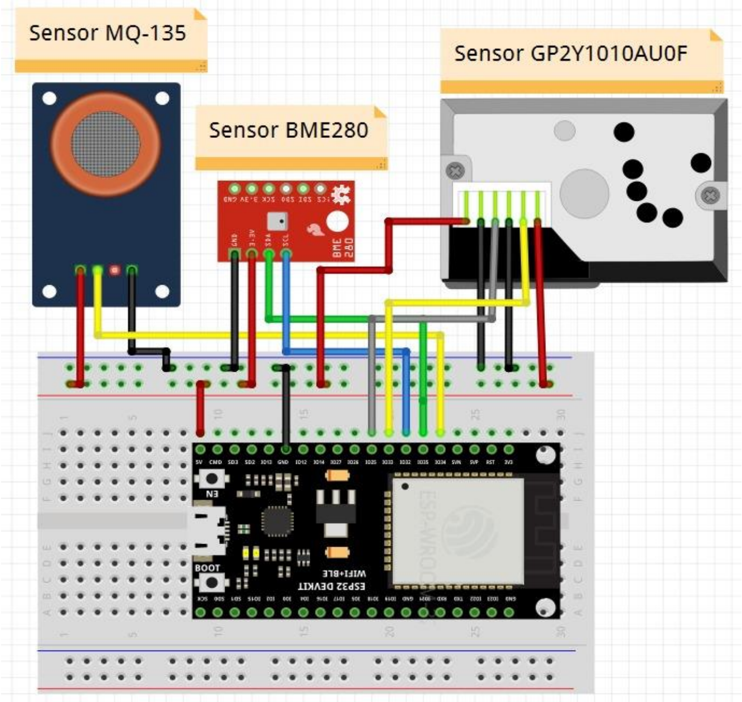

Figure 3. Hardware Wiring

The required core components can be seen in Table 1. The MQ-135 sensor is connected to one of the ADC pins on the ESP32 (e.g. GPIO34) with a 3V3 and GND power source to detect pollutant gas concentrations. The BME280 sensor is connected via the I2C protocol, where the SDA and SCL pins are connected to the I2C pins on the ESP32 (such as GPIO21 and GPIO22) and are supplied with a 3V3–GND power supply to measure temperature, humidity, and atmospheric pressure. On the other hand, the dust sensor GP2Y1010AU0F connected to another ADC pin on the ESP32 (e.g. GPIO35) to measure a voltage signal reflecting the concentration of dust particles, with the LED pin and photodiode adjusted according to the datasheet guidelines. All components are attached to the breadboard using jumper cables to make the assembly and testing process easier. The ESP32 gets power and connection for programming via the USB port on the laptop. The complete connection between all components is shown in Figure 3 as the basis for the hardware implementation before being combined with Blynk's IoT programming and Mamdani's fuzzy logic.

2.3 IoT and Bylnk System Planning

The design of the Internet of Things system in the developed system aims to ensure that data on air quality captured by the ESP32 collection and monitoring devices can be accessed directly via the internet. The system structure consists of three main elements, namely a sensor node based on the ESP32, a Blynk Cloud server, and the Blynk application on a smartphone as an interface for users. This kind of architectural model is often applied in air quality monitoring studies using ESP32 because it is considered easy, flexible, and supports two-way interaction between devices and users.

On the device side, the ESP32 is coded using an Arduino IDE with the addition of the Blynk library. In the program schema, Wi-Fi connection parameters such as SSID and password are specified, as well as the Blynk authentication token obtained from the Blynk application when the project starts. Once the ESP32 connects to a Wi-Fi network and successfully authenticates to the Blynk Cloud, the microcontroller routinely reads data from the BME280, MQ-135, and GP2Y1010AU0F sensors, and then sends those readings to Blynk's servers via virtual pins. For example, temperature, humidity, and pressure data can be sent via V0–V2, MQ-135 gas concentrations via V3, dust levels via V4, and Mamdani fuzzy outputs (Good/Moderate/Poor air quality category) via V5. The frequency of data transmission is adjusted in seconds (such as every 5–10 seconds) so that users can observe changes in air quality almost immediately.

On the user side, Blynk's interface is developed using a variety of widgets such as Gauge, Labelled Value, Chart, and LED/Indicator to represent sensor data as well as the results of fuzzy classifications. The Chart widget serves to show historical trends of air quality parameters, while the air quality status indicator (Good/Moderate/Poor) is presented in an easy-to-understand text or color format. In addition, Blynk can be set up to send notifications to the smartphone if the gas or dust content exceeds a certain limit according to the fuzzy analysis results. With this design, the system can provide information about air quality on the highway in a sustainable and easily accessible manner, as well as serve as a basis for further integration with other IoT features if needed.

2.4 Implementation Fuzzy

The Mamdani fuzzy method was chosen because of its ability to handle the uncertainty of sensor data. Furthermore, this method is applied to classify air quality based on multi-sensor data. The air quality evaluation system has been widely applied in various previous studies, both for indoor air quality control and to determine pollution indexes based on several pollutant parameters. Overall, these studies show that the Mamdani fuzzy has the ability to model the non-linear relationships between gas concentrations, dust, and air quality indices flexibly compared to the commonly used strict limits.

Referring to the idea applied in an IoT-based indoor air quality monitoring system, which utilizes mamdani's fuzzy logic to rely on exhaust fan operation [22], As well as in an air pollution monitoring system powered by IoT with inputs of CO and CO_2 gases processed using Mamdani fuzzy to produce an Air Pollution Standard Index (ISPU) [23], The approach used is the same as making adjustments to the context of air quality on the highway. In addition, the design of membership functions and rule bases also refers to the method of determining fuzzy air quality index (fuzzy AQI) designed in air quality evaluation studies using a fuzzy inference system with several pollutant parameters [24].

In the created system, the fuzzy input variables include the concentration of pollutant gases (ppm) measured by the MQ-135 sensor as well as the concentration of dust particles (μg/m³) detected by the

GP2Y1010AU0F sensor. The result variable is the air quality value in the range of 0 to 100 which is then grouped into three linguistic categories, namely low, medium, and high. The value serves as an air quality threshold and is sent to Bylnk to be displayed as an indicator of air conditions on the road. Air quality evaluation is carried out through four main stages, including fuzzification, rule-based inference, rule composition, and defuzzification as described in the literature on Mamdani fuzzy for air quality. The determination of fuzzy variables and the speaker universe used in this system is presented in Table 2.

Table 2. Determination of variables and speaker universe

Function	Variable Name	Speaker Universe	Remarks
Input	Gas concentration	0 – 400 ppm	Pollutant gas concentration values read by MQ-135 sensor
Input	Dust concentration	0 – 300 µg/m³	The concentration value of dust particles read by the sensor GP2Y1010AU0F
Output	Air quality score	0-100	Fuzzy score representing air quality conditions (low–high)

The range of numbers in Table 2 is determined based on the nature of the sensor used and refers to the range of gas and particulate concentrations that are often used in air quality monitoring studies with a fuzzy approach.

The fuzzy sets for each input and output variable are presented in Table 3.

Table 3. Himpunan Fuzzy

Function	Variable Name	Fuzzy set name	Interval
Input	Gas concentration of MQ-135	Low	0, 0, 75, 150
		Rendh low	100, 175, 250
		High	200, 300, 400, 400
Input	Dust concentration	Low	0, 0, 50, 100
		Rendh low	75, 150, 200
		High	150, 250, 300, 300
Output	Air quality score	Low	0, 0, 30, 40
		Rendh low	30, 50, 70
		High	60, 80, 100, 100

The fuzzy sets listed in Table 3 are formed by a combination of triangular and trapezoidal membership functions, following the design pattern of the membership function on the fuzzy system for pre-existing air quality. For the output variable, the low category indicates a fairly good air condition, indicating a decrease in air quality that is still within safe limits, while the high category indicates polluted air conditions that can endanger the health of road users.

The basis of Mamdani's fuzzy rule used to determine the air quality score is presented in Table 4.

Table 4. Fuzzy Rule

No	Gas concentration (Input)	Dust concentration (Output)	Air quality score (Output)
1	Low	Low	Low
2	Low	Rendh low	Rendh low
3	Rendh low	Low	Rendh low
4	Rendh low	Rendh low	Rendh low
5	High	Rendh low	High
6	Rendh low	High	High
7	High	High	High

The structure of the rules contained in Table 4 adheres to the fundamental principles in the formulation of the rulebase on the Mamdani fuzzy system for determining air quality, where a mixture of inputs with both levels results in a low air quality classification, while the combination of inputs with both high levels results in a high air quality category. These rules have been adapted to the characteristics of the data obtained from the MQ-135 sensor and the GP2Y1010AU0F located in the highway environment.

In practice, the concentrations of gases and dust detected by ESP32 are categorized into low, medium, and high groups. The result of combining the fuzzy output is then converted back to a crisp value using the centroid method to obtain an air quality score in the range of 0 to 100. These values are then reconnected with the low, medium, or high linguistic labels and sent to the Blynk dashboard as an indicator of the road air quality status that can be monitored directly.

3. RESULTS AND DISCUSSION

3.1 System Design Results

The results of the system design show that the process of preparing the hardware for the ESP32-based highway air monitoring system system has been successfully carried out in accordance with the architecture and specifications that have been set. All elements, from the ESP32 microcontroller, the BME280 sensor, the MQ-135 gas sensor, to the SHARP GP2Y1010AU0F dust sensor have been integrated into a single series of prototypes on the breadboard and successfully passed the initial tests to ensure the functionality and stability of the sensor readings. Initial testing also indicated that the circuit can be well connected to the WI-FI network and transmit data to the Bylnk IoT platform as the basis for applying Mamdani's fuzzy logic. The concrete form of the hardware of this system can be seen in Figure 4.

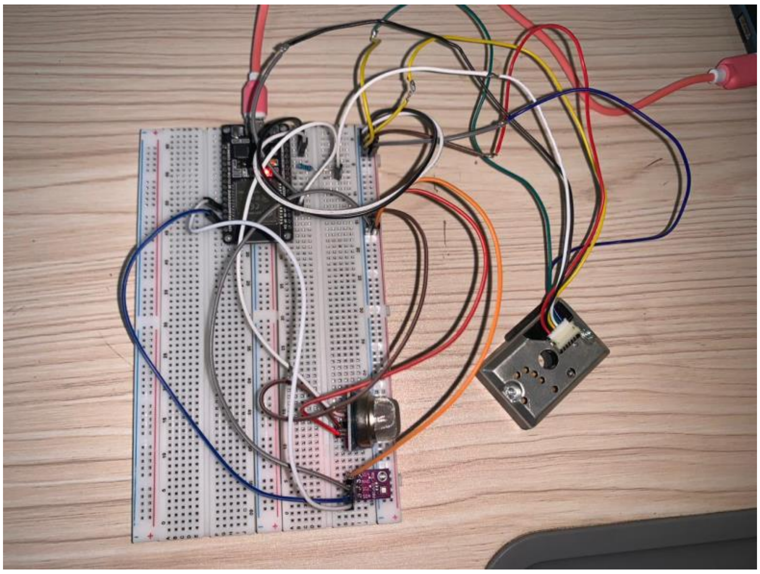

Figure 4. Hardware Prototype

3.1.1 ESP32 Microcontroler

The ESP32 DevKit V1 serves as the main controller that reads information from various sensors and sends that data to Blynk's IoT platform over a WI-FI connection. The ESP32 was selected based on its outstanding capabilities in data processing, low power usage, and integrated WI-FI connectivity features making it ideal for IoT applications. Previous research has also shown that ESP32 is an efficient and effective platform for IoT-based air quality monitoring systems, as it can quickly capture data and pre-process before sending it to the cloud [25].

3.1.2 BME280 Sensor (Temperature, Humidity, and Air Pressure)

The BME280 sensor serves to measure various environmental parameters such as temperature in degrees Celsius, relative humidity in percent, and atmospheric pressure in hPa. The appliance is connected to the ESP32 via an I2C connection, with the SDA pin installed in GPIO 21 and SCL in GPIO 22. BME280 was chosen because it has a high level of sensitivity to changes in the environment and has proven to be reliable in ESP32-based air monitoring systems according to previous research [26].

3.1.3 MQ-135 Sensor (Gas Pollutant Detection)

The MQ-135 sensor is designed to identify the presence of various hazardous gases such as ammonia (NH_3), nitrogen oxide (NO_x), carbon dioxide (CO_2), smoke, and volatile organic vapors (VOCs). These sensors have high sensitivity and fast response, making them ideal for air quality monitoring. The output of the sensor is in the form of an analog signal which is then converted to ppm units using the ADC on the ESP32. Various studies support the fact that the MQ-135 sensor is a sensor that is often used in air quality monitoring systems due to its reliability in detecting hazardous gases as well as compatibility with IoT modules [27].

3.1.4 SHARP GP2Y1010 Dust Sensor (Dust Particle Concentration)

This sensor functions to determine the concentration level of dust particles (PM) in the atmosphere by utilizing the principle of light scattering. The sensor produces an analog signal that varies based on the number of particles crossing the optical space. By connecting it to the ADC pin on the

ESP32, the system is able to measure the dust value in µg/m³. This dust measurement is a crucial indicator because particles in the air have a huge impact on the air quality around the highway.

3.1.5 Breadboard and Cable Jumper

This component serves as a tool for compiling a temporary circuit before the system is refined. Breadboard makes it easy to test sensors and incorporate hardware without the need for permanent soldering.

3.2 IoT Monitoring Result Using Bylnk

The results of the system monitoring showed that the transmission and broadcasting of air quality data using the Blynk IoT platform was carried out as planned. The data generated from the MQ-135 sensor, GP2Y1010AU0F dust sensor, and BME280 sensor was successfully transferred by ESP32 to Blynk's servers and displayed in the form of numbers, gauges, and graphs directly in the smartphone app. With the interface, users can more easily and informatively monitor the concentration levels of gases, dust, temperature, humidity, air pressure, as well as Fuzzy AQ values and air quality categories (low, medium, or high). This visualization also proves that the collaboration between sensor nodes, Wi-Fi connections, and Blynk dashboards works well as a means of monitoring air quality on the road, as illustrated in Figure 5.

Figure 5. Bylnk dashboard view

Figure 5 shows the Blynk dashboard interface used to monitor the state of air quality directly. In this view, there are various gauge widgets that display the levels of Dust, GasIdx, VoutMQ, Fuzzy AQ, Humidity, Temperature, and Pressure. When the data was collected, the dust level was 0 mg/m³, the gas index (GasIdx) was recorded at 40 in the range of 0–255, the voltage output of the MQ-135 sensor (VoutMQ) was at 0.46 V, the air humidity was measured at 64%, the temperature reached 27.3 °C, and the pressure was recorded at 100.96 kPa. The fuzzy output value (Fuzzy AQ) is recorded as 27 on a scale of 0–100 and the system categorizes it as "Good", as seen in the Categories section. The green indicator next to the device name (Quickstart Device) indicates that the ESP32 has been successfully connected to Blynk's servers and the data has been successfully transmitted. These findings show that the integration between sensor nodes and IoT platforms has been successfully carried out according to plan and is able to provide information about air quality directly through smartphones.

3.3 Results of Mamdani's Fuzzy Logic Simulation

The results of the application of Mamdani's fuzzy logic show that the way to determine air quality categories based on the combined values of gas and dust has worked according to the design that has been made at the design stage. The values of the MQ-135 sensor and the GP2Y1010AU0F dust sensor were successfully put into the low, medium, and high linguistic groups, and then processed through the IF-THEN rule, thus producing a Fuzzy AQ value in the range of 0-100. This value is then remapped to a low, medium, or high air quality category that reflects the air conditions on the highway when measurements are taken. Tests showed that when gas and dust concentrations were low, the system consistently produced a Fuzzy AQ value below the medium threshold limit and categorized it as "Good", which corresponds to the display on the Blynk dashboard.

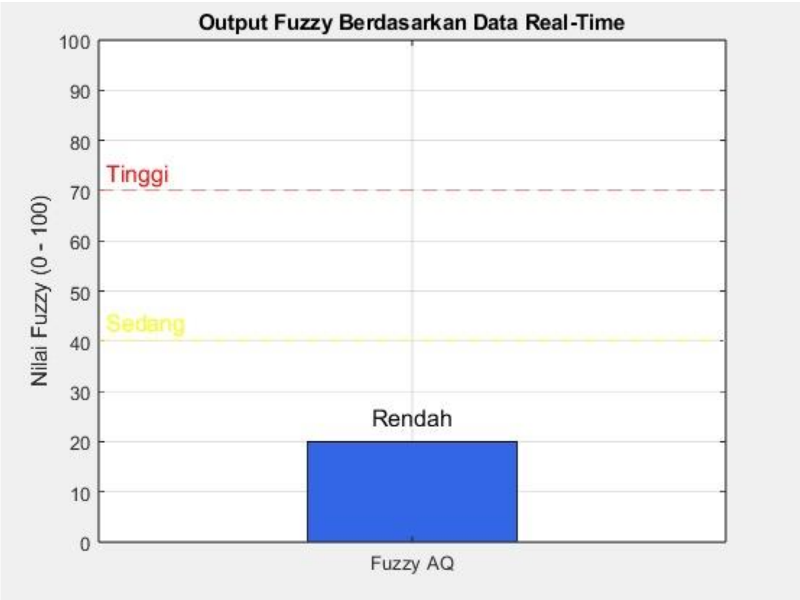

Figure 6. Air quality fuzzy logic simulation results

An example of a fuzzy calculation output can be observed in Figure 6, where the fuzzy values generated by the system are in the range of 20 to 27, which means they fall into the low category. On the chart, the yellow dotted line indicates the starting limit for the medium category, while the red dotted line indicates the starting limit for the high category. When the Fuzzy AQ value remains below the medium category threshold, the system assesses the air quality as "Good" condition which is in line with the category information in Figure 5 indicating that the Mamdani fuzzy model applied can integrate data from gas and dust sensors into a stable and easy-to-understand air quality indicator

3.4 Sensor Performance Evaluation and System Conceptual Validation

The assessment of the effectiveness of the air quality monitoring system in this study focused on the assessment of the features of the sensors utilized and the reliability of the data obtained during the simulation experiments. Taking into account the main objectives of the research which include the design and installation of IoT systems with multiple sensors and Mamdani's fuzzy logic, the sensor performance assessment is carried out conceptually referring to the technical details of the sensor and related literature sources, without involving calibration in the laboratory with standard reference instruments.

The MQ-135 gas sensor device used has the ability to respond to various types of pollutant gases such as NH_3, NO_x, CO_2, and other volatile compounds, and has an appropriate detection range for monitoring air quality in the environment. According to data from the specification sheet and previous research, the sensor exhibits non-linear response characteristics and is affected by temperature and humidity, so the value of the concentration of the gas produced is more accurate as a relative indicator of pollution levels than as an absolute value. In the system tests, readings from the MQ-135 sensor showed a stable and consistent pattern of change as the simulated air conditions varied, demonstrating the sensor's ability to detect changes in air quality directly.

As a way to validate the concept theoretically, the results of the gas and dust sensor measurements are then categorized into air quality classes using Mamdani's fuzzy logic, where the values are adjusted to commonly used air quality indices, such as the Air Pollution Standard Index (ISPU) and the Air Quality Index (AQI). This method provides the ability for the system to handle uncertainty and data changes from low-cost sensors and results in more consistent and easy-to-understand air quality values when compared to the implementation of a rigid single threshold.

In this way, the system created does not aim to replace existing air quality measuring devices, but serves as an early monitoring system that can provide data regarding air quality trends and categories directly in the highway area. For future research development, it is recommended that further evaluations be carried out that include calibration of sensors using reference instruments and testing over a long period of time under real environmental conditions.

3.5 Justification for Fuzzy Mamdani’s Logical Planning

The design of Mamdani's fuzzy logic in the approach used is aimed at addressing the uncertainties inherent in data from low-cost air quality sensors, as well as to describe the nonlinear relationships among various pollutant parameters. The fuzzy method was chosen because it can result in a smoother transition between different air quality states compared to methods that use rigid constraints.

The speaker universe range for gas (0–400 ppm) and dust (0–300 $\mu g/m^3$) concentrations is set taking into account the technical features of the MQ-135 and GP2Y1010AU0F sensors, as well as adjusted to the range of standard values commonly applied to air quality indices such as ISPU and AQI. This range includes air situations ranging from moderately clean to polluted, making it relevant for environmental surveillance on the road.

The set of fuzzy inputs is grouped into three categories, namely low, medium, and high, which indicates the level of air quality from safe to potentially hazardous. The triangular and trapezoidal membership functions were chosen for their simple nature and ability to depict gradual changes in sensor values, and are suitable for application in resource-constrained IoT systems.

The basis of the fuzzy rule was formed on the basis of the logic of experts and previous research that combined more than one pollutant parameter. The IF–THEN rule is made in such a way that an increase in the concentration of gases and dust leads to a gradual improvement in the air quality score, thus avoiding sudden changes in classification due to small fluctuations in sensor data.

Observations of the system's output reactions show that the variation in input values around the boundaries between fuzzy sets results in fairly smooth output transitions, which indicates the design stability of fuzzy parameters for use in air quality monitoring.

3.6 Limitations of Exeriments and System Implementation Context

The system test in this study was carried out in a laboratory using road condition simulation. This method was chosen so that the test can be carried out in a structured and repeatable way, so that the system performance, sensor integration, and performance of Mamdani's fuzzy logic can be clearly assessed.

Although the test results show that the system can detect and classify changes in air quality in real time, it does not fully reflect the complexity of the actual road situation. Elements such as variations in traffic density, weather conditions, and airflow can impact sensor readings as well as system stability. Therefore, this study is considered a first step (proof of concept), and it is recommended to proceed with field testing in actual highway conditions.

3.7 Reserch Contribution and Comparison with Related Studies

Various studies that have been conducted in the past have created an air quality monitoring system based on the Internet of Things using one or more environmental measuring devices as well as platforms for data visualization. However, most of these studies prefer to monitor one type of parameter or use classification methods that rely on fixed thresholds, which tend to be less responsive to changes in data from sensors in dynamic environments.

The main contribution of this research lies in the combination of several air quality sensors with the Mamdani fuzzy logic method which aims to produce more responsive and easy-to-understand air quality values. The system not only shows the sensor values raw, but also combines data on gas and dust concentrations to provide a more linguistic and continuous interpretation of air quality, so as to better reflect conditions in the highway environment.

In addition, this study explains the application of a comprehensive system, starting from sensor data collection using ESP32, data processing through Mamdani's fuzzy inference, to data presentation directly through the Blynk application. This end-to-end cohesion is a hallmark of this study, in contrast to previous studies that typically focused only on a few elements of the system, such as sensor measurements or data delivery separately.

Thus, although each element used in this study has been widely found in various literatures, the innovation of the system developed lies in integrating these elements into a comprehensive, responsive, and easy-to-implement highway air quality monitoring system as an initial solution for environmental monitoring with an IoT approach.

4. CONCLUSIONS

This research has been successful in designing and implementing an air quality monitoring system on the highway that is integrated with the Internet of Things (IoT), utilizing the ESP32 microcontroller, BME280 sensor, MQ-135 gas sensor, GP2Y1010AU0F dust particle sensor, Blynk platform, and Mamdani's fuzzy logic framework. The main goal of the system is to present a monitoring method that is able to continuously record air quality parameters and group them into several descriptive categories (low, medium, and high), so that users can evaluate the state of air quality around the road area in a simpler and more informative way.

The results of the tests showed that the integration between the ESP32 and the BME280, MQ-135, as well as GP2Y1010AU0F sensors can detect changes in air quality directly and transmit information related to temperature, humidity, pressure, gas concentration, and dust to the Blynk platform at regular intervals with a stable connection. The data displayed on the Blynk dashboard can be viewed in the form of numbers, gauges, and graphs over a certain period of time. The values from the sensor are then processed using the Mamdani fuzzy framework to produce a Fuzzy AQ output on a scale of 0-100, which is grouped into low, medium, or high air quality categories. The resulting fuzzy output pattern shows consistency with changes in sensor values, so that the fuzzy rules and existing membership functions can depict the transition of air conditions from good to polluted more gradually than using a rigid single limit. This visualization that combines sensor data and fuzzy output demonstrates the concept of a more "intelligent" and intuitive air quality monitoring system, as it allows for remote monitoring and interpretation of live air conditions.

Although the system has been operating according to design and successfully achieved the main research objectives, its current implementation is still limited to a single measurement location and test scenarios conducted in a laboratory setting to simulate conditions on the road. Further research could extend this system by placing multiple sensor nodes in a variety of different highway locations, sending fuzzy categorization results to a server as a representation of a map of air quality conditions in the area, as well as adding actuators such as buzzers or visual indicators to provide automatic alerts when air quality enters a category of health hazard. In addition, more in-depth calibration of sensors and testing in a variety of real-world environmental conditions is essential to obtain more measurable performance data, including accuracy, reading stability, and system response time during longer monitoring periods.

5. AKNOWLEDGMENT

The author would like to thank all parties who have provided support and facilities so that this research can be carried out properly.

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