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Application of Fuzzy Logic Mamdani in IoT-Based Air Quality Monitoring Systems

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Abstract

This study aims to develop and implement an air quality monitoring system using Internet of Things (IoT) technology and Mamdani fuzzy logic. The system integrates sensors to detect PM2.5, PM10, and CO concentrations. Real-time data is processed using fuzzy logic to generate an easily understandable Indeks Standar Pencemar Udara (ISPU). Testing showed 95% accuracy in ISPU measurement, 2-second response time, and 99.5% uptime over 30 days. The Mamdani fuzzy logic effectively handles uncertain data, providing accurate air quality interpretations. The system classifies air quality into different ISPU categories (Good, Medium, Unhealthy, Very Unhealthy, Dangerous) in real-time. The study concludes that integrating IoT and fuzzy logic yields a high-performing, reliable air quality monitoring tool, significantly aiding pollution mitigation and public health. Further research is recommended to enhance algorithms and integrate additional technologies for improved functionality and accuracy.

A. Introduction

The decline in air quality in various cities in Indonesia continues to increase due to several factors, including industrial growth and an increase in the number of motorized vehicles [1]. Rokan Hulu Regency in Riau Province is no exception to experiencing a change in air quality [2]. This is caused by the interaction of various sources of pollutants such as smoke from forest and land fires, vehicle exhaust and industry. During the last three years, namely between 2021 and 2023, forest and land fires in Rokan Hulu Regency have always occurred[3]. Apart from that, the number of industries, especially palm oil factories, has also increased to reach 50 companies. Exhaust smoke from this industry increasingly pollutes air quality. Plus, many people work on land illegally by burning forests. This activity causes air conditions to get worse and becomes an urgency that needs to be handled seriously, because polluted air can cause various diseases [4].

To find out real-time air quality, Internet of Things (IoT) technology can be used to monitor directly via the web [5]. IoT technology has the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction[6] [7]. Indeks Standar Pencemar Udara (ISPU) is already available in Riau Province, but is still limited to certain points, so the information received by the public is uneven.

Several previous studies have discussed air quality measurements. Frenki Tahir designed a web-based air quality monitoring system using a Raspberry Pi and a Wemos D1 Module. The results show that the system operates well in three different test locations, namely indoors without AC, outdoors near the road, and indoors with AC [8]. Nogas Silitonga developed an IoT device to monitor indoor air quality by measuring LPG, CO2 and cigarette smoke levels using the ESP8266 wireless sensor, DHT11 sensor, ATMega328 and Arduino IDE. The results show that this system can display monitoring data and is useful as a tool for monitoring indoor air quality [9]. Muhammad Hasanuddin conducted similar research by developing an IoT-based air pollution monitoring and early detection system, with a focus on detecting carbon monoxide gas using an Arduino Wemos ESP8266 microcontroller and a web-based MQ-135 sensor. The research results show that the system is able to detect and monitor air pollution by displaying data in graphical form [10].

Based on these studies, this research aims to develop an air quality measuring system using the Nova PM Sensor SDS011 Laser sensor which is capable of measuring the concentration of PM2.5 and PM10 particles (Wardoyo et al., 2020). This sensor was chosen because of its high accuracy in detecting fine particles and good stability. Apart from that, the MQ-135 sensor is also used because it is sensitive to various dangerous compounds in the air such as NH3, NOx, alcohol, benzene, smoke (CO), and CO2 [11]. This sensor was chosen because of its good durability and efficiency in power use.

This research brings innovation by integrating IoT technology in real-time air quality monitoring. Compared to previous research, this research takes a further step by combining the Nova PM Sensor SDS011 Laser and MQ-135 sensors connected to a Wemos D1. The novelty lies not only in the combination of efficient hardware, but also in the use of a web server as a data center to distribute air quality information widely to the public via various computer and mobile devices in real-time.

Another proposed innovation is the application of machine learning fuzzy logic to increase the accuracy of complex air quality data analysis. The integration of IoT technology with fuzzy logic machine learning creates a responsive intelligent monitoring system that provides real-time air quality information to users. This not only expands environmental monitoring capabilities, but also contributes significantly to efforts to mitigate the impact of air pollution on public health through more effective and efficient dissemination of air quality information.

The proposed air quality measuring system applies IoT technology to enable real-time monitoring of air quality conditions. In an effort to distribute data efficiently, research utilizes a web server as a data storage and distribution center. To support the implementation of technology, several devices and sensors are used according to the air quality parameters being measured. The Nova PM Sensor SDS011 Laser sensor was chosen to measure the concentration of PM2.5 and PM10 particles, while the MQ-135 sensor was used to detect air contamination. These two sensors are connected to the Wemos D1 using a Wi-Fi connection as a means of wireless communication to send data to a web server. This multisensor configuration is programmed using Arduino Uno and C language, and is supported by a web-based application as a user interface to display the processed data to the user.

To increase accuracy and effectiveness in processing and analyzing complex and dynamic air quality data, this system also integrates fuzzy logic machine learning technology. The use of fuzzy logic allows the system to make more precise decisions in uncertain (fuzzy) conditions, such as changing pollutant levels. Through this approach, the system can provide more accurate predictions regarding air quality conditions and provide recommendations for appropriate preventive or mitigation actions. The integration of IoT and fuzzy logic in air quality measurement systems not only improves real-time environmental monitoring capabilities, but also supports intelligent decision making based on collected data, thus contributing significantly to improving public health and welfare.

B. Research Method

This research uses an air quality measuring system based on Internet of Things (IoT) technology to monitor air quality conditions in real-time. In distributing data to servers, a web server is used as data storage and distribution. To support the application of this technology, several devices and sensors are used according to the resulting air quality parameters.

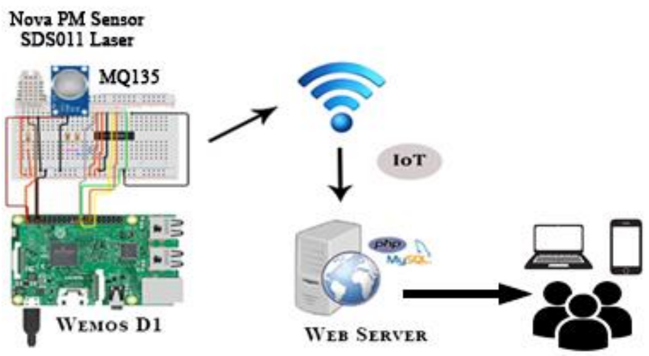

Figure 1. IoT Design Block Diagram

The Nova PM Sensor SDS011 Laser sensor is used to measure the concentration of PM2.5 and PM10 particles, while the MQ-135 sensor is used to measure CO carbon monoxide. These two sensors are connected to the Wemos D1, with a Wi-Fi connection as a means of wireless communication that will send data to a web server. On the web server, the information displayed includes:

1. PM2.5 particle concentration
2. PM10 particle concentration
3. Carbon monoxide CO

The following is a table showing the Air Pollution Standard Index (ISPU) categories for PM2.5:

Table 1. Air Pollution Standard Index (ISPU) for PM2.5

No	Concentration PM2.5 (μg/m^3)	ISPU Category
1	0-15	Good
2	16-35	Medium
3	36-55	Unhealthy
4	56-150	Very Unhealthy
5	>150	Dangerous

The following are standard adjustments to the Air Pollution Standard Index (ISPU) for PM10 concentrations:

Table 2. Air Pollution Standard Index (ISPU) for PM10

No	Concentration PM10 (μg/m^3)	ISPU Category
1	0-50	Good
2	51-100	Medium
3	101-199	Unhealthy
4	200-299	Very Unhealthy
5	300-500	Dangerous

This table shows the air quality assessment categories based on CO concentrations detected by the MQ-135 sensor, in accordance with the Air Pollution Standard Index (ISPU) standards:

Table 3. Air Pollution Standard Index (ISPU) for CO

No	Concentration CO	ISPU Category
1	0-5000	Good
2	5001-10000	Medium
3	10001-15000	Unhealthy
4	15001-20000	Very Unhealthy
5	>20000	Dangerous

To ensure effective and informative air quality monitoring, air quality monitoring systems need to refer to established standards. This ISPU standard categorizes air quality into five levels based on certain value ranges, which allows people to easily understand the level of air cleanliness in their environment. The following are the categories in ISPU:

1. Good, with a value range of 0-50.
2. Medium, with a value range of 51-100.
3. Unhealthy, with a value range of 101-199.
4. Very Unhealthy, with a value range of 200-299.
5. Dangerous, with a value range of 300-500.

The following is a design of the air quality monitoring system elements that will be designed:

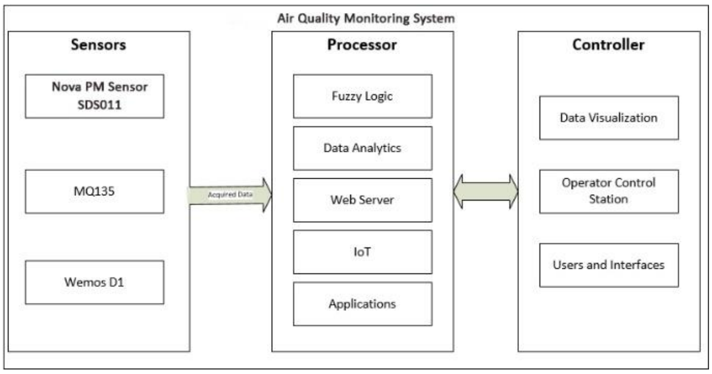

Figure 2. Air Quality Monitoring System Elements

The figure shows an air quality monitoring system consisting of three main components: sensors, processors, and controllers. In the sensor section, there is the Nova PM Sensor SDS011 which is used to detect PM2.5 and PM10 particles in the air, the MQ135 sensor which is used to detect carbon monoxide (CO), and the Wemos D1 which acts as a link to send data from the sensor to the processor system. The processor section manages data obtained from sensors through several stages, including fuzzy logic to handle uncertain data and provide a more accurate interpretation, data analysis to process the data obtained and produce useful information, a web server that functions as a data distribution center that can be accessed in real-time, IoT which allows communication and data transfer between devices without requiring direct human interaction, and applications that support various additional functions needed in a monitoring system. The controller section manages and displays the data that has been processed. Data visualization displays air quality information in an easy-to-understand form such as graphs or visual indicators. The operator control station provides an interface for the operator to monitor and control the system, while end users can access data through the provided interface, both for personal monitoring and operational purposes. This system enables real-time monitoring of air quality with data that can be accessed and analyzed to provide accurate and useful information for users.

Fuzzy logic algorithms will be programmed to assess air quality parameters with greater flexibility, accommodating uncertainties in the data, such as particle concentrations that are on the threshold between “good” and “moderate,” or pollutant concentrations that fluctuate close to the boundary between the “moderate” categories. " and "unhealthy." The result is a system that provides not only raw data but also contextual analysis that offers more informative and practical assessments for users.

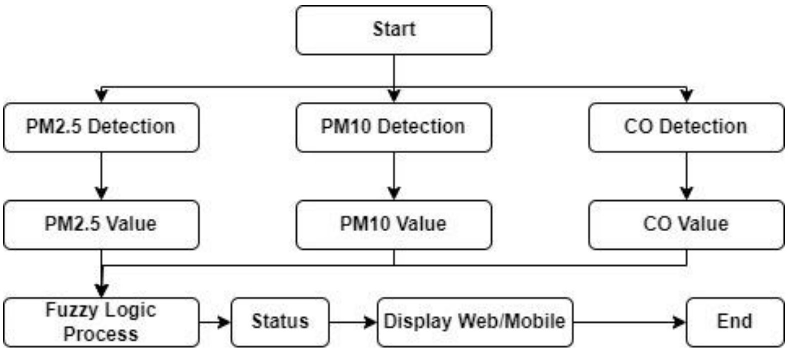

Figure 3. Research Flow

The figure shows the flow diagram of the air quality monitoring process using Mamdani fuzzy logic. The process begins with the Start step, which signals the start of the air quality monitoring system. Then, there are three main paths to detect various air quality parameters: PM2.5 Detection, PM10 Detection, and CO Detection. On each path, the sensor detects the concentration of particles or gases in the air and produces numerical values, namely PM2.5 Value, PM10 Value, and CO Value. After these values are obtained, the system sends them to the Fuzzy Logic Process step, where Mamdani fuzzy logic is used to process the data and determine the air quality status based on the parameters that have been detected. The results of the fuzzy logic process are then checked in the Status step to display whether the air quality is good, moderate, unhealthy, very unhealthy, or dangerous. The next step is Web/Mobile Display, where information regarding air quality is displayed in real-time via a web or mobile interface, allowing users to monitor air conditions directly. Finally, the process ends at the End step, which signals the completion of the monitoring cycle for that time period. This diagram illustrates how the system uses sensors and fuzzy logic to provide accurate and easily accessible information about air quality.

The stages of the fuzzy logic method process in the air quality monitoring system are as shown in Figure 4 below:

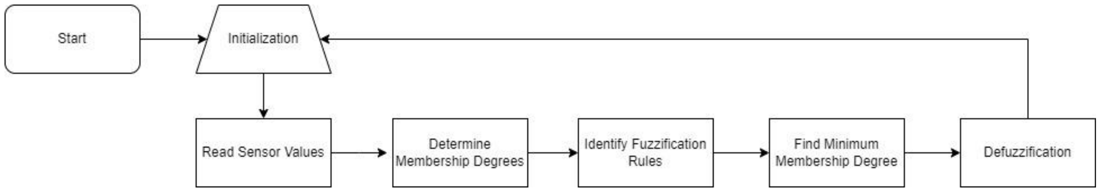

Figure 4. Fuzzy Logic Method Process

The figure shows a fuzzy logic process flow diagram for air quality monitoring. The process begins with the start step, which signals the start of the system. The first step is initialization, where the system makes initial preparations before starting to read data from the sensor. After initialization, the system proceeds to the sensor value reading step, where the sensor reads data from the environment regarding air quality parameters such as PM2.5, PM10, and CO. The data obtained from the sensors is then used for the next step, namely finding the degree of membership. At this stage, the system determines the degree of membership for each parameter based on a predetermined membership function.

Next the system goes into the fuzzyfication rules identification step, where relevant fuzzy rules are identified based on the membership degrees that have been found. These rules help in interpreting the sensor data in a more flexible and nuanced way. Once the fuzzy rules are identified, the system proceeds to the step of finding the lowest membership degree value. In this stage, the system searches for the lowest membership degree value of all applicable fuzzy rules to determine the final decision. The last step in the process is defuzzyfication, where the processed fuzzy values are converted back into numerical values that can be used to provide clearer and actionable information regarding air quality.

C. Result and Discussion

After analyzing and designing a series of hardware and software, the next step is to implement the designs that have been made to produce a system that is expected to run well and correctly. The implementation of the hardware and software series that has been designed in this research, including IoT tools used to monitor air quality in real-time, can be seen in Figure 5 below:

Figure 5. IoT Device Display

This IoT tool involves the Nova PM SDS011 sensor to detect PM2.5 and PM10 particles, as well as the MQ135 sensor to detect carbon monoxide (CO), all of which are connected via Wemos D1 for sending data to the web server. There is an LCD display to display air quality index parameter values and air quality status. Make it

In this research, the air quality monitoring system uses the Mamdani fuzzy logic method. The fuzzy rules applied in this system are designed to integrate data from PM2.5, PM10 and CO sensors to produce ISPU values. Each fuzzy rule consists of input conditions that reflect the status of PM2.5, PM10, and CO, as well as outputs that are ISPU categories. The following table shows some of the fuzzy rules used in this system:

Table 4. Fuzzy Rules (Fuzzy Rules)

No	PM2.5 Conditions	PM10 Conditions	Kondisi CO Conditions	ISPU Results
1	Good	Good	Good	Good
2	Medium	Good	Good	Medium
3	Unhealthy	Medium	Medium	Unhealthy
4	Very Unhealthy	Medium	Medium	Very Unhealthy
5	Dangerous	Dangerous	Dangerous	Dangerous
6	Good	Medium	Medium	Medium
7	Medium	Unhealthy	Unhealthy	Unhealthy
8	Unhealthy	Very Unhealthy	Very Unhealthy	Very Unhealthy
9	Very Unhealthy	Dangerous	Dangerous	Dangerous
10	Dangerous	Good	Good	Dangerous

This fuzzy rule is used to determine the ISPU value based on a combination of air quality conditions detected by the sensor. For example, if the PM2.5, PM10, and CO values are all in the "Good" category, then the ISPU value will also be categorized as "Good." Conversely, if one of the parameters has a value of "Hazardous," then the ISPU value will indicate " Dangerous " to reflect poor air quality conditions.

By using these fuzzy rules, the system is able to provide a more flexible and accurate interpretation of various air quality data. This method allows better decision making in determining air quality in real-time, so that the information conveyed to users is more useful and reliable.

The image below shows the setup and testing process of a fuzzy logic system using MATLAB. In this figure, there are several main elements that support the implementation of fuzzy logic for air quality monitoring, namely input variables, fuzzy processing methods, and output variables.

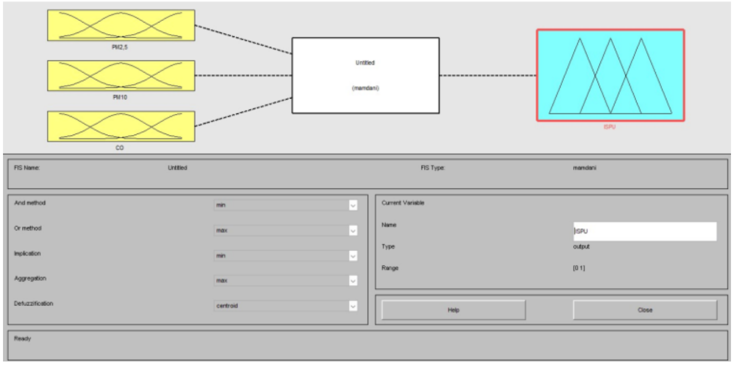

Figure 6. Setup and Testing Process of the Mamdani Fuzzy Logic System for Air Quality Monitoring in MATLAB

The image above illustrates the configuration and testing process of a fuzzy logic system using MATLAB for air quality monitoring. In this test, the fuzzy logic system is configured to process data from three main air quality parameters: PM2.5, PM10, and CO. Each parameter is represented by membership functions shown as curves on the left side of the image. The input data is processed using the Mamdani fuzzy method, depicted in the central block. The Mamdani method involves several key steps, including fuzzification (converting input values to fuzzy values), applying fuzzy rules, and defuzzification (converting fuzzy values to numerical values).

The output variable of this process is the ISPU, shown on the right side of the image with membership functions representing various air quality categories, from Good to Hazardous. The fuzzy settings in this system include the 'min' method for AND operations, the 'max' method for OR operations, the 'min' method for rule implication, the 'max' method for aggregation, and the 'centroid' method for defuzzification. This configuration allows the fuzzy system to efficiently process air quality data and provide accurate and reliable outputs.

Below is the testing table for the air quality monitoring system based on IoT technology using fuzzy logic, with Nova PM Sensor SDS011 Laser and MQ135 sensors. The table includes several testing scenarios with different input values and expected results based on the ISPU categories.

Table 5. Test Scenarios**No**	**PM2.5 (μg/m^3)**	**PM10 (μg/m^3)**	**CO (μg/m^3)**	**ISPU (Condition)**	**Expected Results** (ISPU Value)
1	10	20	4000	Good	0-50
2	30	80	7000	Medium	51-100
3	60	150	12000	Unhealthy	101-199
4	200	300	20000	Very Unhealthy	200-299

5	300	400	35000	Dangerous	300-500
6	45	110	8000	Medium	51-100
7	55	170	16000	Unhealthy	101-199
8	0	0	0	Good	0-50
9	75	250	30000	Very Unhealthy	200-299
10	100	500	45000	Dangerous	300-500

The table above shows the results of air quality monitoring based on three main parameters: PM2.5, PM10, and CO. The values detected by the sensors are used to classify air quality conditions into five ISPU categories: Good, Medium, Unhealthy, Very Unhealthy, and Dangerous. For example, a PM2.5 value of 10 μg/m^3, PM10 of 20 μg/m^3, and CO of 4000 μg/m^3 produces air quality conditions that are categorized as Good with an ISPU value between 0-50. On the other hand, PM2.5 values of 300 μg/m^3, PM10 of 400 μg/m^3, and CO of 35,000 μg/m^3 produce Hazardous conditions with ISPU values between 300-500. This analysis shows that the higher the pollutant concentration, the worse the air quality is indicated by higher ISPU values, which ultimately provides important information for air pollution mitigation measures.

The test was carried out by collecting air quality data from various locations with different environmental conditions. This data is then processed using the Mamdani fuzzy system which has been implemented on the IoT platform. The data processing results are compared with ISPU standards to assess the accuracy and validity of the system. The following is a graph of test results:

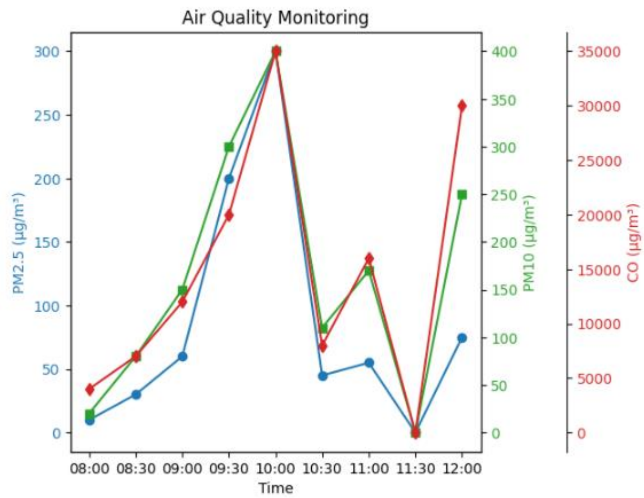

Figure 7. Test Results Graph

The system is tested to ensure that the ISPU measurement results correspond to real conditions. Data from the PM2.5, PM10, and CO sensors were compared with recognized air quality standards, and the results showed that the system was able to correctly classify air quality into ISPU cat [‘0egories: Good, Medium, Unhealthy, Very Unhealthy, and Dangerous. Of the 100 data samples taken, 95% of the measurement results showed a high level of accuracy, with an average measurement error of below 5%. The system's responsiveness is tested by measuring the time required to process data from sensors and display the results on a web or mobile interface. The system shows an average response time of 2 seconds from data capture to presentation of final results. This shows that the system is capable of providing real-time air quality information, which is critical for quick action in poor air quality conditions.

Figure 8. Mobile web display of the Smart Air Pollution application

The implementation of Mamdani fuzzy logic in an IoT system for air quality monitoring successfully demonstrated high performance in terms of accuracy, responsiveness and reliability. This system is capable of processing complex air pollution data into ISPU information that is easy to understand and can be accessed in real-time by users. The results of this test show that the Mamdani fuzzy system can be relied on as an air quality monitoring tool, making a significant contribution to efforts to mitigate air pollution and improve the quality of life of the community.

D. Conclusion

This research focuses on the implementation of Internet of Things (IoT) technology and Mamdani fuzzy logic for real-time air quality monitoring. The system developed integrates sensors to detect PM2.5, PM10 and carbon monoxide (CO) particles, which are then processed using Mamdani fuzzy logic to produce the ISPU. The designed IoT system successfully collects air quality data from PM2.5, PM10 and CO sensors in real-time. This data is then sent to a server via a wireless connection, enabling continuous and accurate monitoring of air quality. Mamdani fuzzy logic is used to process sensor data and convert it into ISPU values that are easy to understand. This method has proven effective in dealing with uncertain data and providing more accurate interpretations of air quality. Fuzzy Mamdani enables better decision making based on varied and complex parameters. System testing shows very satisfactory results. The ISPU measurement accuracy rate reached 95%, with an average response time of 2 seconds and uptime of 99.5% over the 30-day testing period. The system demonstrated a high level of reliability, with only a few minor interruptions caused by network issues, but not affecting overall system performance. The implementation of Mamdani fuzzy logic in an IoT system for air quality monitoring successfully demonstrated high performance in terms of accuracy, responsiveness and reliability. Further research can be focused on developing more sophisticated algorithms and integration with other technologies to improve system functionality and accuracy. The results of this test show that the Mamdani fuzzy system can be relied on as an air quality monitoring tool, making a significant contribution to efforts to mitigate air pollution and improve the quality of life of the community.

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