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Design of a Fuzzy Logic-Based Intelligent Hybrid Air Purifier Using Pollutant-Absorbing Plants

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ABSTRAK

Penelitian ini mengimplementasikan sistem cerdas berbasis logika fuzzy Mamdani pada alat air purifier hybrid yang menggunakan tanaman Sansevieria sebagai media penyaring polutan. Sistem dirancang untuk memantau kualitas udara dalam ruangan dengan mendeteksi konsentrasi partikel debu (PM2.5 dan PM10) menggunakan Dust Sensor dan gas berbahaya menggunakan sensor MQ-2. Data sensor diolah menggunakan mikrokontroler Arduino Uno dengan metode fuzzy logic untuk mengatur kecepatan motor DC fan secara otomatis. Dengan penerapan ini, diharapkan sistem mampu meningkatkan efisiensi penyaringan udara secara adaptif berdasarkan tingkat polutan yang terdeteksi, sehingga menciptakan lingkungan dalam ruangan yang lebih sehat dan nyaman dengan solusi yang ramah lingkungan.

Keywords:

Fuzzy Logic
Air Quality
Hybrid Air Purifier

ABSTRACT

This research implements an intelligent system based on Mamdani fuzzy logic on a hybrid air purifier device utilizing Sansevieria plants as pollutant filtering media. The system is designed to monitor indoor air quality by detecting dust particle concentrations (PM2.5 and PM10) using a Dust Sensor and hazardous gases using an MQ-2 sensor. Sensor data are processed by an Arduino Uno microcontroller employing fuzzy logic methods to automatically regulate the speed of a DC fan motor. This implementation is expected to enhance air filtration efficiency adaptively based on detected pollutant levels, creating a healthier and more comfortable indoor environment with an environmentally friendly solution.

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1. INTRODUCTION

Indoor air quality in Indonesia remains a critical concern due to elevated exposure to pollutants such as fine particulate matter (PM2.5) and hazardous gases arising from anthropogenic activities and the country's tropical, humid environment. Studies indicate that indoor PM2.5 concentrations in major Indonesian cities frequently exceed World Health Organization (WHO) recommended limits, posing increased risks of respiratory diseases and other

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health complications [1]. Hence, developing effective and adaptive air purification systems is essential to improve indoor air quality and safeguard occupant health.

The utilization of sensor technologies, including the Sharp GP2Y1010AU0F for particulate matter detection and the MQ-2 sensor for hazardous gas monitoring, offers real-time air quality assessment that can be integrated with automated control systems based on fuzzy logic [2]. The Mamdani fuzzy inference method is widely preferred due to its capability to handle sensor data uncertainty and provide adaptive fan speed control based on pollution levels [3].

In addition to electronic technologies, the application of pollutant-absorbing plants such as Sansevieria enhances the purification efficiency in hybrid systems that combine mechanical and biological filtration methods [4]. While numerous studies have implemented fuzzy logic for air quality control, there is a paucity of research integrating plant-based filtration with fuzzy logic control specifically tailored for Indonesia's indoor environments [5]. Therefore, this study aims to design and implement a Mamdani fuzzy logic-based hybrid air purifier optimized for the indoor air quality conditions prevalent in Indonesia.

As an advancement in indoor air purification technology, this study designs a hybrid air purifier system that integrates Sansevieria plants as natural pollutant absorbers with electronic sensors and an adaptive control mechanism based on Mamdani fuzzy logic. The system dynamically adjusts the speed of a DC fan based on real-time particulate matter (PM2.5) and hazardous gas concentrations detected by the Dust GP2Y1010AU0F and MQ-2 sensors. The fuzzy logic controller processes sensor inputs through IF-THEN rules, applying membership functions and inference to produce smooth and responsive fan speed control. This approach enables efficient and adaptive air purification by continuously responding to changes in indoor air quality, optimizing energy consumption and filtration performance. The integration of biological and electronic components with fuzzy control provides a novel, environmentally friendly solution tailored for the dynamic air quality conditions commonly found in Indonesian indoor environments.

2. RESEARCH METHODS

This research presents the design and analysis of a hybrid air purifier system controlled by fuzzy logic. An experimental methodology was adopted for this work, and the key stages of the development process are shown in Figure 1.

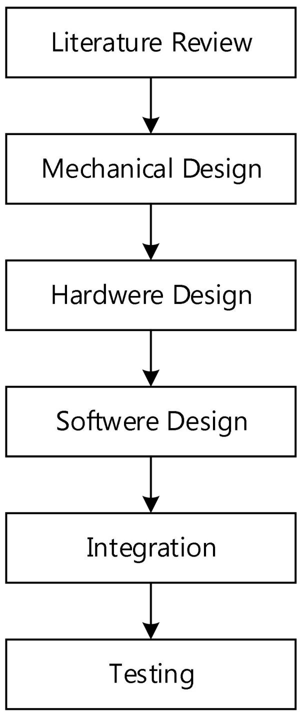

Figure 1. Flowchart of Research Method

The Flowchart shows the main stages in sequence:

1. Literature Review: Collecting supporting information and theories relevant to fuzzy logic and air purification.
2. Mechanical Design: Planning and designing the physical structure and mechanical framework of the system, including the placement of Sansevieria plants as filters.
3. Hardware Design: Designing and assembling the physical electronic components such as sensor (Dust Sensor and MQ-2), Arduino Uno, and DC fan motor, and DC fan motor.
4. Software Design: Developing the system logic and programming fuzzy logic control to process sensor data and control fan speed.
5. Integration: Combining all hardware and software components into a function system.
6. Testing: Ensuring the system operates correctly according to predetermined by monitoring its performance in real-time air quality control.

2.1 LITERATUR REVIEW

Indoor air quality management has become increasingly important due to rising levels of pollutants affecting human health. Various air purifier technologies have been developed to address this issue. Among natural solutions, Sansevieria plants have shown effective pollutant absorption capabilities, making them a promising candidate for hybrid air purifiers. Concurrently, electronic sensors such as Dust Sensor GP2Y1010AU0F and MQ-2 gas sensors are widely used for real-time air quality monitoring. Additionally, fuzzy logic Mamdani has proven to be an effective control method for dynamic environmental systems, including air purifiers. Previous studies have applied fuzzy logic in fan speed control and air quality monitoring, yet integration of natural plant filtration with sensor-based fuzzy control remains limited. This research aims to develop a hybrid air purifier that combines these elements to achieve efficient and adaptive indoor air purification.

2.2 MECHANICAL DESIGN

Mechanical design was carried out using Autodesk Inventor software to create a 3D model of the hybrid air purifier system. The main structure consists of a cylindrical pot-like container designed to house Sansevieria plants, which act as natural pollutant filters. The container features ventilation holes at the top and a triangular-patterned base frame that supports the structure while facilitating optimal airflow. The materials selected provide durability and allow sufficient air passage to maximize the plant's filtering effectiveness. The mechanical design is illustrated in Figure 2.

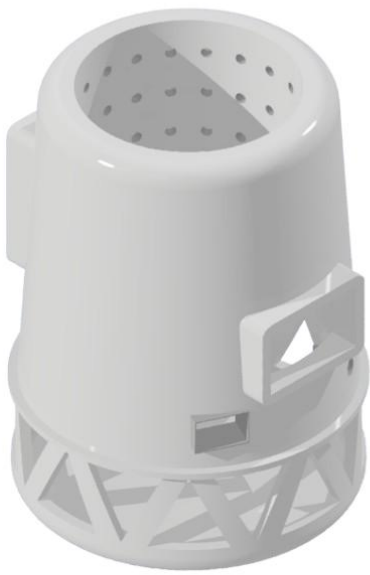

Figure 2 Mechanical Design

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2.3 HARDWARE DESIGN

The hardware design of the hybrid air purifier system is illustrated in Figure 3. This system integrates several critical components designed to monitor air quality and control airflow effectively.

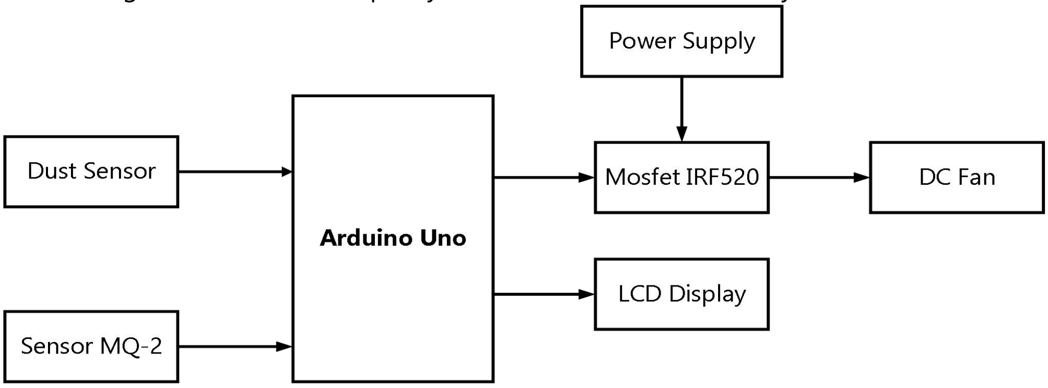

Figure 3 Hardware Design

Figure 2 is explained in the following section.

- Arduino Uno is an open-source microcontroller platform widely used in electronic projects. It features a microchip that can be programmed to read inputs from various sensors and control outputs such as motors, relays, and displays based on user-defined instructions. The design files for the Arduino board, including the printed circuit board (PCB) layout and schematic diagrams, are publicly available, allowing anyone to manufacture and customize their own Arduino devices. Arduino boards provide multiple input/output pins for interfacing with external components and include built-in power management, analog inputs, and digital communication interfaces, making them versatile for embedded system applications.[6]
- The Sharp GP2Y1010AU0F sensor is a cost-effective particulate matter sensor designed to detect PM10 particles, that is, airborne particles with a diameter of 10 micrometers or less. As the first generation of Sharp's particulate matter sensors, it utilizes an optical sensing principle to measure dust concentrations in the environment. Unlike later sensor models, this version does not feature an integrated airflow regulator; instead, airflow is managed externally using a DC brushless fan to ensure proper air circulation through the sensing chamber. This sensor is widely adopted in low-cost air quality monitoring systems due to its affordability and reliable detection capabilities for indoor and outdoor environments.[7]
- The system utilizes the MQ-2 sensor specifically for detecting cigarette smoke within the indoor environment. This sensor outputs an analog signal corresponding to the concentration of smoke particles, which is transmitted to an Arduino microcontroller (Arduino Robotdyn) for processing. Alongside the MQ-7 sensor for carbon monoxide detection, the MQ-2 sensor readings are input to a Mamdani fuzzy logic control algorithm implemented in the microcontroller. The resulting output modulates the speed of a fan motor responsible for air purification. When the detected levels of carbon monoxide and cigarette smoke are low, the fan operates at a moderate speed to cleanse the ambient air. Conversely, higher concentrations prompt an increase in fan speed to more effectively reduce pollutant levels. The system also features user feedback components including a buzzer and LCD display, with an Android application interface for real-time monitoring.[8]
- The LCD 20x4 module is interfaced with the Arduino Uno using the I2C communication protocol, which only requires two pins (A4 for SDA and A5 for SCL). This reduces pin usage and allows multiple I2C devices to share the same bus, enabling efficient expansion of peripherals.[9]
- A MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor), specifically the IRF520 model, serves as an electronic switch to regulate the flow of current within electrical circuits. It operates by controlling the conduction channel via voltage applied to its gate terminal, which in this system is driven by an Arduino microcontroller. This enables precise modulation of current supplied to devices such as pumps, allowing effective control of their operation. The integration of the Arduino board with the MOSFET driver forms the

core of the system's control mechanism, which actuates various output devices including pumps, relays, and solenoid valves.[10]

- DC motors are widely utilized in industrial applications because of their variable speed capabilities, which can be tailored to suit specific process requirements. They offer favorable speed-torque characteristics, high reliability, and straightforward control mechanisms. In this context, the system employs a DC motor-driven water pump, where the motor speed directly regulates the flow rate of water into a tank. Compared to AC motor drives, DC motor systems are generally simpler in design and more cost-effective.[10]
- A 12V power supply converts AC to stable 12V DC output using rectification and filtering. High-frequency switching devices like MOSFETs generate signals to drive a transformer for isolation and voltage adjustment. The transformer's secondary output is rectified and filtered to maintain DC voltage. Feedback circuits regulate switching to keep output voltage constant under varying conditions.[11]

2.4 SOFTWARE DESIGN

The software design encompasses the configuration of system control and data processing to operate the hybrid air purifier efficiently. The flowchart of the software process is presented in Figure 4.

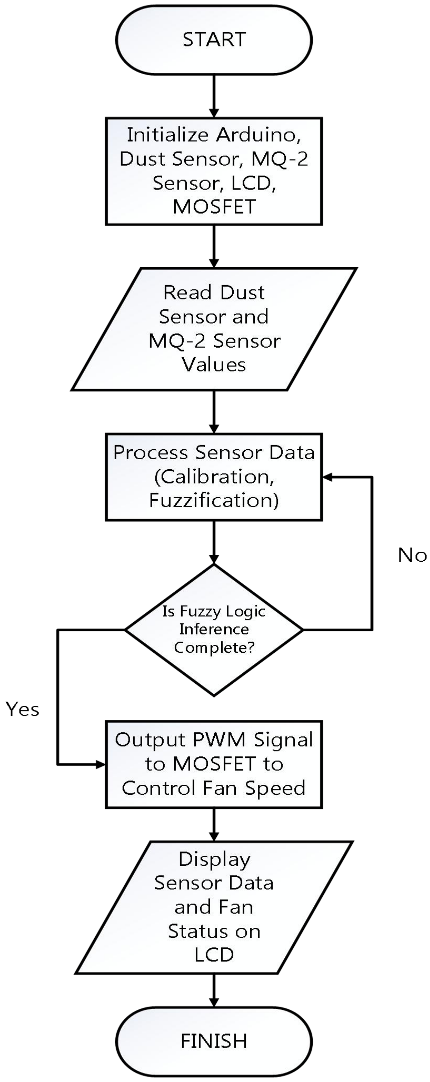

Figure 4 Software Design

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Explanation of Figure 4:

1. The system starts when the Arduino board is powered on and initializes all input sensors (Dust Sensor and MQ-2 gas sensor) and output devices (DC fan via MOSFET and LCD display).
2. Arduino continuously reads analog signals from the Dust Sensor and MQ-2 sensor to monitor particulate matter and gas concentrations in real-time.
3. Sensor data are processed using a Mamdani fuzzy logic algorithm to evaluate air quality and determine the appropriate fan speed.
4. The fuzzy logic output is converted to a PWM signal to control the speed of the DC fan through the MOSFET driver.
5. Real-time sensor readings and fan speed status are displayed on the LCD for user monitoring.
6. The system continuously loops to update sensor data, process fuzzy logic, and adjust fan speed accordingly, ensuring adaptive air purification based on environmental conditions.

2.5 FUZZY LOGIC

The Mamdani Fuzzy Inference System (FIS) is widely applied as a decision support method, such as determining eligibility criteria. The Mamdani method involves four primary stages to obtain the output: fuzzification, rule formation, application of implication functions, and defuzzification. Introduced by Ebrahim Mamdani in 1975, this approach is also known as the max-min method. It derives fuzzy output sets by taking the maximum value of each rule's activation, which is then used to modify the fuzzy region and apply it to the output using the union (OR) operator.[12]

2.5.1 FUZZIFICATION

In the fuzzification stage, the crisp analog sensor readings from the Dust GP2Y1010AU0F and MQ-2 gas sensors are converted into fuzzy values using membership functions. The system defines linguistic variables such as dust concentration and gas level, each categorized into fuzzy sets like Low, Medium, and High. Corresponding membership functions are designed for these inputs to map the sensor data into degrees of membership.[12]

2.5.2 INFERENCE

In the Mamdani Fuzzy Inference System (FIS), the inference stage is a critical decision-making process that applies predefined fuzzy rules to the fuzzified inputs from the Dust GP2Y1010AU0F and MQ-2 gas sensors. Each fuzzy rule generates an output fuzzy set by applying an implication function, typically the minimum operator, to the membership degrees of the inputs. The resulting fuzzy outputs from all rules are then aggregated using the maximum (union) operator to form the final fuzzy output set. This output guides the control signal for the DC fan speed through the MOSFET driver in the hybrid air purifier system.[12]

2.5.3 DEFFUZIFICATION

Defuzzification is the final step in the Fuzzy Inference System (FIS), where the aggregated fuzzy output is transformed into a crisp numerical value that can be used as a precise control signal. The most commonly used defuzzification method is the centroid method (also known as the weighted average method).

The crisp output value z is calculated by the weighted average of the output fuzzy sets, considering their activation degrees:

$$z = \frac{\sum_{i=1}^{n} (\alpha_i \times z_i)}{\sum_{i=1}^{n} \alpha_i} \quad (1)$$

Where:

- z is crisp output value,
- α_i is the degree of activation (firing strength) of the iii-th fuzzy rule,
- z_i is the representative output value (usually the centroid) of the fuzzy set for the iii-th rule,
- n is the total number of activated rules.

In your hybrid air purifier system, the crisp output z determines the PWM signal sent to the MOSFET driver controlling the DC fan speed, allowing adaptive airflow based on air quality sensor inputs.

3. RESULTS AND ANALYSIS

Fuzzification converts crisp analog readings from the Dust GP2Y1010AU0F and MQ-2 sensors into fuzzy values using membership functions. These functions classify pollutant levels into linguistic categories such as low, medium, and high. This process enables the system to manage uncertainty and prepares data for fuzzy inference on the Arduino Uno.

3.1 FUZZY LOGIC RESULT

3.1.1 FUZZIFICATION RESULT

The membership functions corresponding to each fuzzy variable are defined as follows:

- PM2.5 Variable

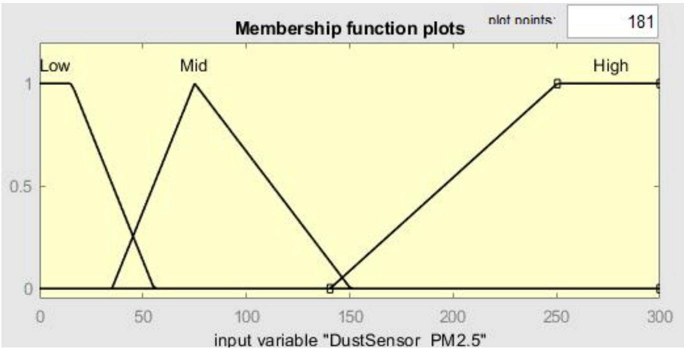

Figure 5 Membership Function PM2.5

$$\text{Low }(x) = \begin{cases} 1 & \text{jika } x \leq 15.5 \\ \frac{55.4-x}{55.4-15.5} & \text{jika } 15.5 < x < 55.5 \\ 0 & \text{jika } x \geq 55.4 \end{cases} \quad (2)$$

$$\text{Mid }(x) = \begin{cases} 0 \text{ jika } x \leq 35 \text{ atau } x \geq 150.4 \\ \frac{x-35}{75-35} \text{ jika } 35 < x < 75 \\ \frac{150.4-x}{150.4-75} \text{ jika } 75 \leq x < 150.4 \end{cases} \quad (3)$$

$$\text{High }(x) \begin{cases} 0 & \text{jika } x \leq 140.5 \\ \frac{x-140.5}{250.4-140.5} & \text{jika } 140.5 < x < 250.4 \\ 1 & \text{jika } x \geq 250.4 \end{cases} \quad (4)$$

- Butana Variable

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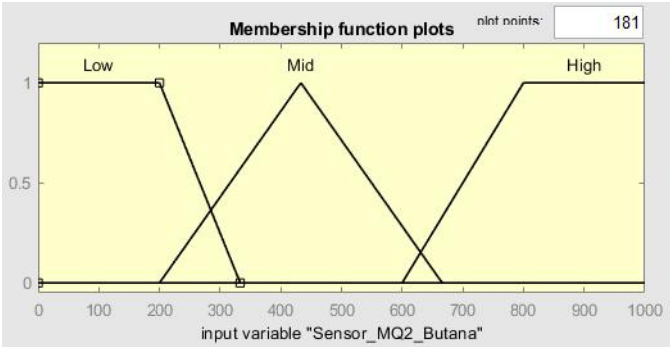

Figure 6 Membership Function Butana

$$\text{Low}\ (x) = \begin{cases} 1 & \text{jika } x \leq 200 \\ \frac{333-x}{333-200} & \text{jika } 200 < x < 333 \\ 0 & \text{jika } x \geq 333 \end{cases} \tag{5}$$

$$\text{Mid}\ (x) \begin{cases} 0 & \text{jika } x \leq 200 \text{ atau } x \geq 666 \\ \frac{x-200}{433-200} & \text{jika } 200 < x < 433 \\ \frac{666-x}{666-433} & \text{jika } 433 \leq x < 666 \end{cases} \tag{6}$$

$$\text{High}\ (x) \begin{cases} 0 & \text{jika } x \leq 600 \\ \frac{x-600}{800-600} & \text{jika } 600 < x < 800 \\ 1 & \text{jika } x \geq 800 \end{cases} \tag{7}$$

Information on the fuzzy variables can be found in Table 1

Table 1 Variables Fuzzy

Input	Variables Fuzzy	
	PM2.5	**Butana**
Low	0 – 50	0 – 300
Mid	35 – 150.4	200 – 666
High	140.5 – 250.4	600 – 800

3.1.2 INFERENCE RESULT

In the inference stage, the fuzzified inputs from the dust and gas sensors are evaluated using a set of predefined fuzzy rules. These rules encapsulate expert knowledge by linking various combinations of input linguistic terms to corresponding output fan speed levels. Each rule's activation strength is computed using fuzzy logical operators, typically the minimum operator for the antecedent conditions. Subsequently, the fuzzy outputs from all activated rules are aggregated using the maximum operator to form a comprehensive fuzzy output set. The rule base applied in this system is summarized in the following Table 2.

Table 2 Rules Fuzzy

No	Rules Base Fuzzy Logic		
	DustSensor	**MQ2**	**Fan Speed**
1	Low	Low	Low
2	Low	Mid	Mid
3	Low	High	Mid

4	Mid	Low	Mid
5	Mid	Mid	Mid
6	Mid	High	High
7	High	Low	Mid
8	High	Mid	High
9	High	High	High

3.1.3 DEFUZZIFICATION RESULT

Defuzzification is the final step in the Mamdani fuzzy inference process. It converts the aggregated fuzzy output into a crisp numerical value. This value serves as the control input for the pulse width modulation (PWM) signal that regulates the DC fan speed. The most common defuzzification method is the centroid, or weighted average, method, which is mathematically expressed as follows:

$$z = \frac{(0.8\times255)+(0.5\times170)+(0.3\times85)}{0.8+0.5+0.3} = \frac{204+85+25.5}{1.6} = 196.56 \quad (8)$$

This crisp value of approximately 196.56 corresponds to a medium-high pulse width modulation (PWM) signal that controls the fan speed. It reflects the weighted contribution of each fuzzy rule's activation degree and output value, providing an adaptive airflow response based on real-time air quality. The calculated pulse width modulation (PWM) signal ensures the fan speed is optimal for filtering airborne pollutants, neither too low to be ineffective nor too high to waste energy.

The system uses three membership functions Low, Medium, and High following the Mamdani fuzzy method. The Low function decreases linearly, Medium is a symmetrical triangle, and the High function increases linearly. The defuzzified PWM output of about 196.56 is near the upper medium range, which indicates that the fan is operating at a relatively high speed. The smooth transition between Medium and High allows for gradual adjustment of the fan speed, thus improving system stability amid varying air quality. Figure 7 illustrates this membership function.

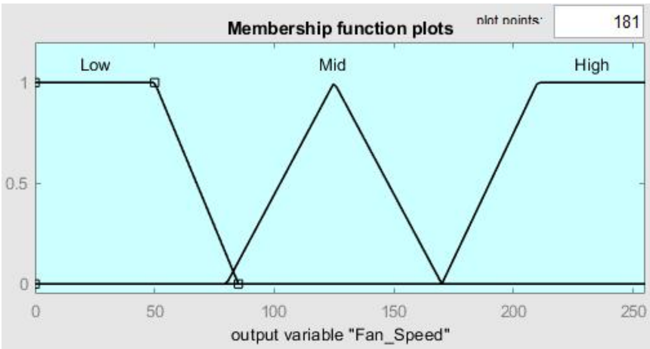

Figure 7 Defuzzification Result

3.2 SYSTEM TESTING RESULT

This test evaluated the system’s response to variations in input values from the Dust GP2Y1010AU0F and MQ-2 gas sensors. Each sensor reading was processed through fuzzification and fuzzy inference using the Mamdani method. Then, defuzzification was applied to produce pulse width modulation (PWM) signals that control the speed of the DC fan via the MOSFET driver.

Table 3 System Testing Result

No	PM2.5 ($\mu g/m^3$)	MQ2 (PPM)	Rule	PWM
1	12	150	R1 (Low-Low)	Low (40)
2	30	280	R3 (Low-Med)	Low-Medium (80)

3	60	350	R5 (Med-Med)	Medium (130)
4	90	450	R6 (Med-High)	Medium-High (170)
5	120	550	R7 (High-Med)	High-Medium (200)
6	160	700	R9 (High-High)	High (240)
7	50	400	R5 (Med-Med)	Medium (125)
8	20	600	R4 (Low-High)	Medium (150)
9	80	100	R2 (Med-Low)	Medium-Low (110)
10	200	850	R9 (High-High)	High (255)
11	15	320	R2 (Low-Med)	Low-Medium (75)
12	70	480	R6 (Med-High)	Medium-High (180)
13	130	610	R8 (High-Med)	High-Medium (220)
14	180	900	R9 (High-High)	High (255)

Based on the test results in Table X, the system produced stable pulse width modulation (PWM) outputs that were proportional to variations in the dust and gas sensor inputs. The fuzzy Mamdani controller was sensitive to changes in air pollutant levels and adjusted the fan speed smoothly, without any abrupt spikes. These results confirm that fuzzy logic control effectively manages air quality by dynamically regulating fan speed according to sensor data.

4. CONCLUSION

This research project successfully developed and implemented a hybrid air purifier system integrating Sansevieria plants, which naturally absorb pollutants, with electronic sensors and Mamdani fuzzy logic control. The Dust GP2Y1010AU0F and MQ-2 sensors provide real-time air quality data. This data is processed by the Arduino Uno microcontroller using the Mamdani fuzzy inference method, which dynamically adjusts the DC fan speed through the MOSFET driver.

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