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SmartENose: Environmental Health Monitoring System for Cattle Sheds Using Fuzzy System Method

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Abstract — The air quality in livestock barns significantly impacts the health and productivity of animals. This study designs an air quality monitoring system based on the Internet of Things (IoT) utilizing the ESP32 microcontroller and three gas sensors: MQ-135 (ammonia), MQ-4 (methane), and MQ-7 (carbon monoxide). The collected data is processed using the Fuzzy Sugeno logic method, which involves fuzzification, rule base, and defuzzification stages to classify the air conditions into Safe, Alert, or Dangerous categories. The classification results are displayed in real-time through an I2C LCD, the Blynk application, and the SmartENose website developed with PHP and MySQL. Additionally, the system is equipped with LED indicators and a buzzer for early warning notifications. Testing results indicate that the system can detect gas concentrations responsively and accurately, providing air status classifications that align with the actual conditions in the cattle barn. This research demonstrates that the application of IoT technology, supported by Fuzzy Sugeno logic, can be effectively utilized for monitoring and early warning of air quality in agricultural environments.

Keywords – IoT, ESP32, Fuzzy Sugeno, Gas Monitoring, SmartENose

I. INTRODUCTION

The livestock industry, particularly cattle farming, plays a crucial role in supporting national food security by providing meat and milk. Data indicates that beef production in Indonesia fluctuated from 518,484 tons in 2016 to 486,319 tons in 2017, before rising again to 497,971 tons in 2018. Meanwhile, the population of beef cattle increased from 16.4 million in 2017 to 17.1 million in 2019 [1]. However, the challenges in enhancing productivity are not solely related to feed and management aspects; they also involve the air quality within livestock barns.

Hazardous gases such as ammonia (NH_3), methane (CH_4), and carbon monoxide (CO) pose significant risks to the health of both animals and humans, as well as reducing livestock productivity. Indoor Air Quality (IAQ) in residential environments has become a significant concern, considering that people spend most of their time indoors and may be exposed to various pollutants that can pose long-term health risks. In a systematic review of 23 studies, Yu et al. examined the implementation of Internet-of-Things-based Low-Cost Sensors (LCS) as an accessible approach for monitoring pollutants such as particulate matter, carbon dioxide, hazardous gases, and other environmental parameters inside homes. The review outlines sensor selection criteria, calibration procedures, data acquisition platforms, and technical challenges associated with real-world deployment. Their findings demonstrate that although low-cost devices require periodic recalibration and still have performance limitations, they remain a practical and economical option for continuous residential air monitoring, enabling occupants to make better decisions for improving indoor environmental quality [2], [3]. On the other hand, carbon monoxide binds to hemoglobin more effectively than oxygen, leading to tissue hypoxia [4]. Additionally, Nast and Sandkuhl emphasize that although the Internet of Things (IoT) has become a key driver of digital transformation across industries, many organizations still struggle to fully extract value from it due to weak integration of organizational aspects within system development.

[5].

Several studies have developed air quality monitoring systems based on the Internet of Things (IoT) [2], [6]. However, these approaches typically rely on static thresholds, making them less adaptable to the dynamic conditions in the field. To address this issue, fuzzy logic, particularly the Sugeno method, can be employed to manage uncertainty in real-time decision-making. The Sugeno fuzzy system produces either constant or linear outputs, making it well-suited for IoT-based air monitoring applications.

As a solution, this system employs the Sugeno fuzzy logic for making gas status decisions based on the PPM values from three sensors: MQ-135 (ammonia), MQ-4 (methane), and MQ-7 (carbon monoxide). Fuzzification is performed using triangular membership functions that map the PPM values into three membership degrees: Safe (*Aman*), Alert (*Waspada*), and Dangerous (*Bahaya*). For each gas, individual rule bases are utilized to associate the membership degrees with crisp output values (0.0 for Safe, 0.5 for Alert, and 1.0 for Dangerous). Additionally, the system implements a combined rule base for the gases to determine the overall danger level based on eight main rules, such as the combination of Safe NH_3 and Dangerous CO, or all three gases being Dangerous simultaneously. Defuzzification is carried out using the zero-order Sugeno method with a weighted average approach, resulting in a crisp value that represents the overall danger level (0–6). This approach allows for a more adaptive classification of air status in response to the dynamic environmental changes in the cattle barn in real-time, providing early warnings that operate automatically through fuzzy logic when gas thresholds are exceeded.

II. METHODOLOGY

In this study, the system development method employed is the prototype method. This approach is chosen because it is well-suited for developing systems that require direct and iterative interaction between users and the device. By using this method, developers can create an initial design of the device, which is then tested by users. Based on the feedback, refinements are made until the system operates according to the needs in the field.

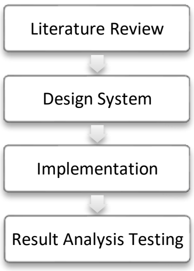


Fig.1. Research Methodology Block Diagram

A. System Diagram and IoT Architecture

The air quality monitoring system developed employs an Internet of Things (IoT) approach to integrate gas sensors, a microcontroller, and a user interface. The system architecture consists of three main layers:

1. The perception layer, which includes the MQ-135, MQ-4, and MQ-7 sensors that detect the levels of ammonia (NH_3), methane (CH_4), and carbon monoxide (CO).
2. The processing layer, which utilizes the ESP32 microcontroller to process sensor data using Sugeno fuzzy logic.
3. The application layer, which transmits data in real-time to the Blynk application and the SmartENose website built on PHP, while displaying status information through an I2C LCD, LED indicators, and a buzzer.

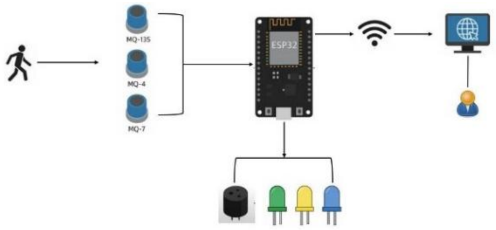


Fig.2. IoT Architecture

B. System Flowchart

The workflow of the gas monitoring system in the cattle barn is illustrated in a flowchart to facilitate understanding of its operational logic. The system begins with the initialization of the ESP32 and the reading of data from three gas sensors. This data is then processed and classified using fuzzy logic to determine the status of each gas. If a hazardous condition is detected, the system activates the LED indicators and buzzer, and subsequently transmits the data in real-time to the Blynk platform and the SmartENose website.

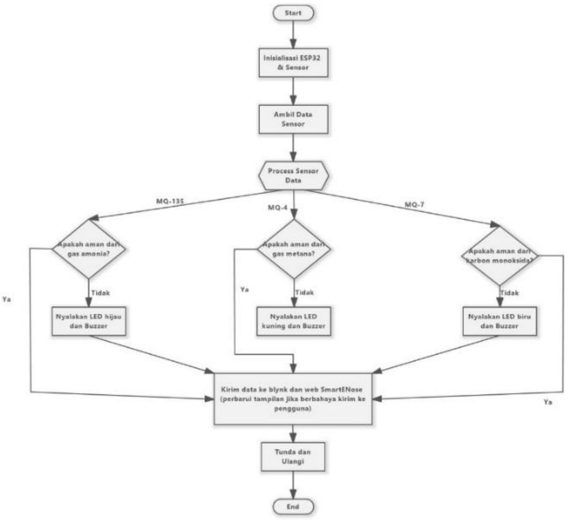


Fig.3. IoT-Based Gas Monitoring System Flowchart

Figure 3 illustrates the main processes occurring within the system. After initialization, data from the MQ-135, MQ-4, and MQ-7 sensors is read and processed. Each sensor is checked to determine if its readings fall within safe limits. If a reading exceeds these limits, a specific colored LED indicator (green for ammonia, yellow for methane, and blue for carbon monoxide) will light up, accompanied by a buzzer as a notification. All data is then transmitted to the Blynk application and the SmartENose website, and this process continues to repeat periodically.

C. *Use Case Diagram*

The use case diagram below illustrates the activities carried out by the livestock staff as actors in utilizing the IoT-based gas monitoring system in the cattle barn:

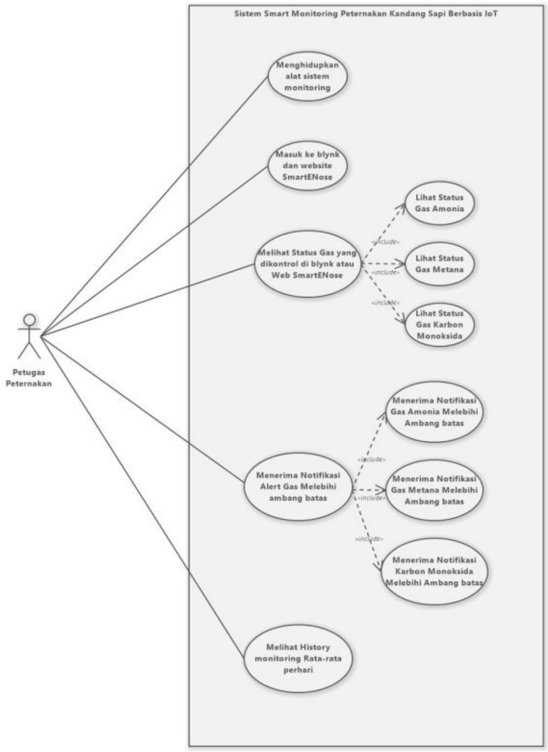


Fig.4. Use Case Diagram of the Smart Cattle Barn Monitoring System

Brief Explanation:

In the use case diagram above, the primary actor is the livestock staff who directly interacts with the system. The staff can:

1. Power on the monitoring device, which consists of the ESP32 and gas sensors.
2. Access the monitoring platform through either the Blynk application or the SmartENose website.
3. Detect gas levels and view the real-time status of each gas type.
4. Receive automatic notifications whenever the concentration of any gas exceeds the predefined threshold.
5. Review daily historical data for the monitoring of all three gases.

Several processes, such as gas detection and notifications, are divided into sub-use cases using the «include» relationship. This indicates that the system must perform detection and issue notifications for each specific gas type. This design creates a more structured system, granting the livestock staff full control to monitor and respond to the barn's air quality in real time.

D. *Circuit Prototype*

Figure 5 depicts the arrangement of the IoT devices designed for the air monitoring system in the cattle barn, focusing on the detection of ammonia, methane, and carbon monoxide gases.

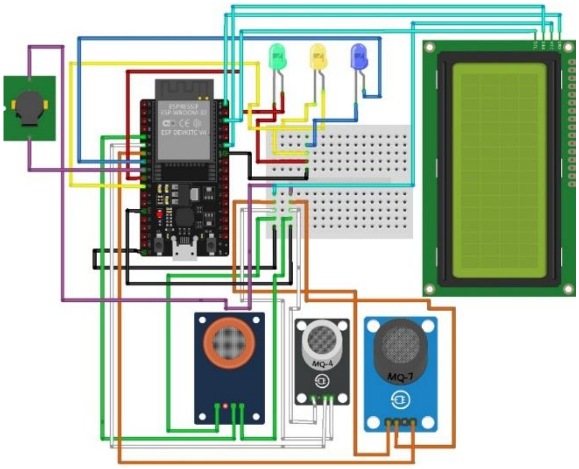


Fig.5. IoT Device Component Circuit

E. *Implementation of the Fuzzy System*

- *Triangular Fuzzification*

Fuzzification is carried out using triangular membership functions for each gas sensor.

$$\text{Formula: } \mu_A(x) = \begin{cases} 0, \; x \leq a \; atau \; x \; \geq \; c \\ \frac{(x-a)}{(b-a)}, \quad a \; < x \; \leq b \\ \frac{(c-x)}{(c-b)}, \quad b \; < x \; < c \end{cases}$$

Each gas is categorized into three membership levels: Safe (*Aman*), Alert (*Waspada*), and Dangerous (*Bahaya*), defined based on PPM (parts per million) values as follows:

Ammonia (NH_3) – MQ-135:

1) Safe (*Aman*): (0, 0, 10)
2) Alert (*Waspada*): (10, 17.5, 25)
3) Dangerous (*Bahaya*): (25, 50, 1000000)

Methane (CH_4) – MQ-4:

1) Safe (*Aman*): (0, 0, 5000)
2) Alert (*Waspada*): (5000, 7500, 10000)
3) Dangerous (*Bahaya*): (10000, 15000, 1,000,000)

Carbon Monoxide (CO) – MQ-7:

1) Safe (*Aman*): (0, 0, 30)
2) Alert (*Waspada*): (30, 40, 50)
3) Dangerous (*Bahaya*): (50, 80, 1,000,000)

The membership values are calculated using the triangular membership function formula with a linear approach.

- *Inference (Rule Base)*

The system employs two types of rule bases:

Individual Rule Base: This maps the status of a single type of gas to a numerical value:

1) Safe (*Aman*)= 0.0
2) Alert (*Waspada*) = 0.5
3) Dangerous (*Bahaya*)= 1.0

Combined Rule Base: This consists of 8 rules to generate combined fuzzy outputs, such as:

1) IF NH_3 = Aman AND CH_4 = Aman AND CO = Aman THEN Status = 0
2) IF NH_3 = Bahaya AND CH_4 = Aman AND CO = Aman THEN Status = 2
3) IF NH_3 = Bahaya OR CH_4 = Bahaya OR CO = Bahaya THEN Status = 6

Each combination of gas statuses results in a risk score ranging from danger level 0 to 6.

Note: The "Alert (*Waspada*)" status is still displayed individually for each sensor. For example, a sensor may show Safe (*Aman*), Alert (*Waspada*), or Dangerous (*Bahaya*) based on its reading. However, in the combined evaluation process (fuzzySugenoCombined() function), the "Alert (*Waspada*)" category is treated as "Safe (*Aman*)". This adjustment helps maintain the system's sensitivity without making it overly reactive to minor fluctuations. As a result, the environment is only classified as Dangerous (*Bahaya*) when the gas levels enter the actual "Dangerous" category, not merely the "Alert" state.

- *Sugeno Defuzzification*

The system utilizes the Sugeno zero-order (constant) method for defuzzification. The output from the rule base is calculated using a weighted average approach as follows:

$$z = \frac{\sum(w_i \cdot z_i)}{\sum w_i} \qquad (1)$$

III. RESULTS AND DISCUSSION

The IoT-based air quality monitoring system for cattle barns underwent a series of testing and validation stages, covering sensor functionality, system responsiveness, and integration with both the Blynk platform and the SmartENose website. The evaluation was conducted in a real-world environment at HM Cattle Farm, East Jakarta, within a semi-open barn housing an active population of approximately 27–30 cows.

A. Hardware Specifications

a) ESP-32 Specifications

Table 1. ESP32 Specifications

Specification	Value
Microcontroller	Tensilica Xtensa LX6
USB Connector	USB-Micro
I/O Voltage	3.3V
Input Voltage	5V
Max Current per I/O	40mA
Main Processor	160 – 240 MHz
Internal RAM	520KB SRAM
Flash Memory	4MB

The ESP32 serves as the central controller of the system in this project. Its ability to connect to Wi-Fi networks and interface with various sensors and actuators makes it a key component in enabling real-time air quality monitoring. The specifications listed above demonstrate that the ESP32 is highly suitable for implementing IoT-based monitoring solutions in a cattle barn environment.

b) LCD 20x4 I2C Specifications

Table 2. 20x4 I2C LCD Specifications (Blue Display, Black Characters, Backlight)

Specification	Value
Main Component	HD44780 Controller
Interface	I2C
Input Voltage	4.7V – 5V
Backlight Current	10 – 20 mA
Display Format	20 characters × 4 lines
Dimensions (W×H× D)	99mm x 60mm x (14mm)
Backlight Type	LED

The 20x4 I2C LCD functions as an on-device display, allowing users to quickly monitor the levels of Ammonia, Methane, and Carbon Monoxide without accessing the application or web interface. Utilizing the I2C communication protocol provides a convenient connection while minimizing the number of pins required on the microcontroller.

c) MQ-Series Gas Sensor Specifications

Table 3. Specifications of the MQ-Series Gas Sensors Used

Sensor	Specification	Value
MQ-135	Size	32mm x 20mm
	Main Chip	LM393
	Operating Voltage	5V (AC atau DC)
	ADC Resolution	10 bit
	I/O Voltage Level	TTL and CMOS Compatible

Sensor	Specification	Value
MQ-4	Size	32mm x 20mm
	Main Chip	LM393
	Operating Voltage	5C DC
	ADC Resolution	10 bit
	I/O Voltage Level	TTL and CMOS Compatible
MQ-7	Size	32mm x 18mm
	Main Chip	LM393
	ADC Resolution	10-12 bit
	I/O Voltage Level	TTL and CMOS Compatible

The MQ-135, MQ-4, and MQ-7 sensors are designed to detect specific gases relevant to this project: MQ-135 for Ammonia, MQ-4 for Methane, and MQ-7 for Carbon Monoxide. These sensors generate gas concentration data in parts per million (ppm), which serve as the basis for the system's decision-making process. The use of the MQ-series sensors is further supported by numerous previous research studies, reinforcing their reliability for gas monitoring applications.

d) Laptop Device Specifications

Table 4. Specifications of the Laptop Used

Device	Specification
Laptop Model	ASUS VivoBook X415EP / A416EP
Operating System	Windows 10 64-bit Build 19045
Storage	SSD 512GB
RAM	8GB

The laptop was utilized to develop both the microcontroller program and the monitoring website. Its specifications are sufficient to run the necessary software, including the Blynk application and the SmartENose web platform, for effective gas monitoring.

B. Software Specification

a) Arduino IDE Specifications

The Arduino IDE facilitated sensor configuration and firmware deployment. The use of Arduino IDE is therefore central to ensuring system functionality, scalability, and interoperability throughout the prototyping and deployment stages of the monitoring device [7].

Table 5. Specification Arduino IDE

Spesification	Value
Versi	2.3.7 -nightly-20250517
Versi CLI	1.2.0
Kompatibilitas OS	Windows, MAC, Linux

b) Backend and Frontend Specification

Hernandez and Cañas proposed an integrated IoT-based sensing device capable of monitoring key classroom environmental parameters—temperature, relative humidity, illuminance, CO_2 concentration, and noise—as a comprehensive approach to support Indoor Environmental Quality assessment in densely occupied spaces. Their system is designed to operate within large-scale networks, where each node may function as a standalone sensor, a repeater, or a hub for data aggregation. Experimental evaluations demonstrate that the device performs reliably, is replicable, and offers strong scalability potential for deployment across educational settings, office buildings, and other indoor facilities [8].

Table 6. Arduino IDE Specifications

Specification	Type
Backend Language	PHP 8.1.17
Web Server	XAMPP Control Panel v3.3.0
Frontend Languages	HTML, CSS, Java Script

This web-based monitoring system was developed using PHP on the server side and HTML, CSS, and JavaScript on the client side.

C. Testing the MQ-135, MQ-4, and MQ-7 Sensors

The testing phase aimed to verify the ability of the MQ-135, MQ-4, and MQ-7 sensors to accurately measure the concentrations of ammonia (NH_3), methane (CH_4), and carbon monoxide (CO). The system was evaluated using the Arduino IDE, with PPM readings displayed in real time through the Serial Monitor, the I2C LCD, the Blynk application, and the SmartENose website.

Fig.6. Starting the Monitoring Process

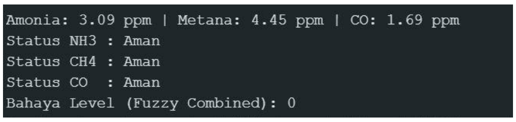
D. Experiment on Monitoring the Status of the Three Gases

After obtaining the PPM values from the MQ-135 (NH_3), MQ-4 (CH_4), and MQ-7 (CO) sensors, the data were processed using the Fuzzy Sugeno logic approach. The system applies triangular membership functions to classify the hazard level of each gas individually into three categories: Safe, Alert, and Dangerous. Each gas category is assigned a fuzzy value of 0.0 for Safe, 0.5 for Alert, and 1.0 for Dangerous.

In addition, the system implements a combined rule base to evaluate the overall status of the three gases, generating a total hazard level score ranging from 0 to 6. The final output is calculated using the Sugeno zero-order defuzzification method with a weighted average formula. The classification results are displayed in real time via the LCD, Serial Monitor, and Blynk application. Test results indicate that the system successfully reflects the appropriate hazard level according to the detected gas condition combinations.

Fig.7. Gas Status Monitoring Results Using Fuzzy Sugeno Logic on the LCD

Figure 7 shows the experimental documentation of the monitoring results for ammonia, methane, and carbon monoxide gas statuses displayed on the LCD.



```
Amonia: 3.09 ppm | Metana: 4.45 ppm | CO: 1.69 ppm
Status NH3 : Aman
Status CH4 : Aman
Status CO  : Aman
Bahaya Level (Fuzzy Combined): 0
```

Figure 8. Data Acquisition Results on the Arduino IDE Serial Monitor

Figure 8 presents the experimental documentation of the PPM readings from the ammonia, methane, and carbon monoxide gas monitoring displayed on the Arduino IDE Serial Monitor.

E. *Experiment on Sending Data to Blynk*

After obtaining the PPM values from the MQ-135, MQ-4, and MQ-7 sensors, the data were transmitted to the Blynk application using the Arduino IDE with the support of the BlynkSimpleEsp32 library. The Blynk.virtualWrite function was utilized to send the readings to virtual pins corresponding to each gas type. The data were displayed in digital format on the Blynk dashboard in real time, allowing users to monitor gas conditions directly from their mobile devices.

Status Amonia
Aman

Status Metana
Aman

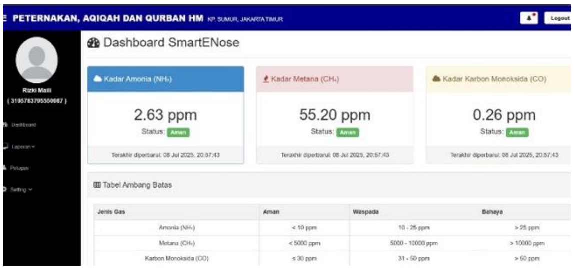
Status CO
Aman

Fig.9. Sending Data to Blynk

Figure 9 demonstrates the system's success in transmitting sensor data to the Blynk application. The ammonia, methane, and carbon monoxide readings are displayed in real time along with their classification statuses, enabling practical and efficient remote gas monitoring.

F. *Experiment on Sending Data to the SmartENose Website*

After successfully displaying the data on the Blynk application, the system was further tested to transmit the data to the SmartENose website in real time. The PPM values from each sensor ammonia (NH_3), methane (CH_4), and carbon monoxide (CO) were automatically sent via Wi-Fi using the HTTP POST method to the designated web endpoint. This process utilized the ESP32 and the HTTPClient library in the Arduino IDE to send the data to the local SmartENose server, where it was stored in the database.



Dashboard SmartENose

Kadar Amonia (NH₃)
2.63 ppm
Status: Aman
Terakhir diperbarui: 08 Jul 2025, 20:57:43

Kadar Metana (CH₄)
55.20 ppm
Status: Aman
Terakhir diperbarui: 08 Jul 2025, 20:57:43

Kadar Karbon Monoksida (CO)
0.26 ppm
Status: Aman
Terakhir diperbarui: 08 Jul 2025, 20:57:43

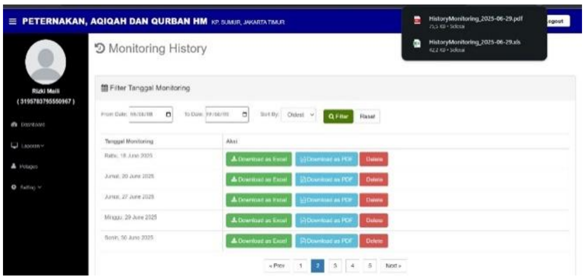
Tabel Ambang Batas

Jenis Gas	Aman	Waspada	Bahaya
Amonia (NH₃)	< 10 ppm	10 - 25 ppm	> 25 ppm
Metana (CH₄)	< 5000 ppm	5000 - 10000 ppm	> 10000 ppm
Karbon Monoksida (CO)	≤ 30 ppm	31 - 50 ppm	> 50 ppm

Fig.10. Transmitting Monitoring Data to the SmartENose Web Dashboard

G. *Experiment on Downloading Daily Monitoring Results*

Figure 11 shows the experiment of downloading the monitoring data for ammonia, methane, and carbon monoxide gases.

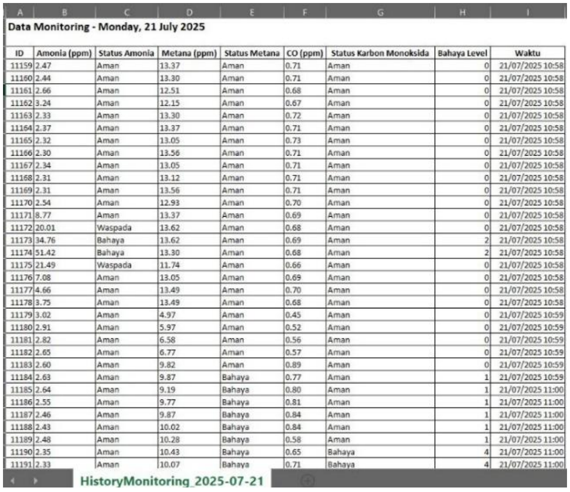


Tanggal Monitoring	Aksi
Rabu, 18 June 2025	Download as Excel · Download as PDF · Delete
Jumat, 20 June 2025	Download as Excel · Download as PDF · Delete
Jumat, 27 June 2025	Download as Excel · Download as PDF · Delete
Minggu, 29 June 2025	Download as Excel · Download as PDF · Delete
Senin, 30 June 2025	Download as Excel · Download as PDF · Delete

Fig.11. Downloading Daily Monitoring Results

H. *Test Results*

The testing was conducted to verify whether the system could accurately detect the concentrations of ammonia (NH_3), methane (CH_4), and carbon monoxide (CO) and generate statuses in accordance with the designed Fuzzy Sugeno logic. Data collection was performed under various environmental conditions, including normal conditions without gas exposure and controlled scenarios with specific gas sources.



Data Monitoring - Monday, 21 July 2025

ID	Amonia (ppm)	Status Amonia	Metana (ppm)	Status Metana	CO (ppm)	Status Karbon Monoksida	Bahaya Level	Waktu
11159	2.47	Aman	13.37	Aman	0.71	Aman	0	21/07/2025 10:58
11160	2.44	Aman	13.30	Aman	0.71	Aman	0	21/07/2025 10:58
11161	2.66	Aman	12.51	Aman	0.68	Aman	0	21/07/2025 10:58
11162	3.24	Aman	12.15	Aman	0.67	Aman	0	21/07/2025 10:58
11163	2.33	Aman	13.30	Aman	0.72	Aman	0	21/07/2025 10:58
11164	2.37	Aman	13.37	Aman	0.71	Aman	0	21/07/2025 10:58
11165	2.32	Aman	13.05	Aman	0.73	Aman	0	21/07/2025 10:58
11166	2.30	Aman	13.56	Aman	0.71	Aman	0	21/07/2025 10:58
11167	2.34	Aman	13.05	Aman	0.71	Aman	0	21/07/2025 10:58
11168	2.31	Aman	13.12	Aman	0.71	Aman	0	21/07/2025 10:58
11169	2.31	Aman	13.56	Aman	0.71	Aman	0	21/07/2025 10:58
11170	2.54	Aman	12.93	Aman	0.70	Aman	0	21/07/2025 10:58
11171	8.77	Aman	13.37	Aman	0.69	Aman	0	21/07/2025 10:58
11172	20.01	Waspada	13.62	Aman	0.68	Aman	0	21/07/2025 10:58
11173	34.76	Bahaya	13.62	Aman	0.69	Aman	2	21/07/2025 10:58
11174	51.42	Bahaya	13.30	Aman	0.68	Aman	2	21/07/2025 10:58
11175	21.49	Waspada	11.74	Aman	0.66	Aman	0	21/07/2025 10:58
11176	7.08	Aman	13.05	Aman	0.69	Aman	0	21/07/2025 10:58
11177	4.66	Aman	13.49	Aman	0.70	Aman	0	21/07/2025 10:58
11178	3.75	Aman	13.49	Aman	0.68	Aman	0	21/07/2025 10:58
11179	3.02	Aman	4.97	Aman	0.45	Aman	0	21/07/2025 10:59
11180	2.91	Aman	5.97	Aman	0.52	Aman	0	21/07/2025 10:59
11181	2.82	Aman	6.58	Aman	0.56	Aman	0	21/07/2025 10:59
11182	2.65	Aman	6.77	Aman	0.57	Aman	0	21/07/2025 10:59
11183	2.60	Aman	9.82	Aman	0.89	Aman	0	21/07/2025 10:59
11184	2.63	Aman	9.87	Bahaya	0.77	Aman	1	21/07/2025 10:59
11185	2.64	Aman	9.19	Bahaya	0.80	Aman	1	21/07/2025 11:00
11186	2.55	Aman	9.77	Bahaya	0.81	Aman	1	21/07/2025 11:00
11187	2.46	Aman	9.87	Bahaya	0.84	Aman	1	21/07/2025 11:00
11188	2.43	Aman	10.02	Bahaya	0.84	Aman	1	21/07/2025 11:00
11189	2.48	Aman	10.28	Bahaya	0.58	Aman	1	21/07/2025 11:00
11190	2.35	Aman	10.43	Bahaya	0.65	Bahaya	4	21/07/2025 11:00
11191	2.33	Aman	10.07	Bahaya	0.71	Bahaya	4	21/07/2025 11:00

Fig.12. Test Results

The sensor readings were displayed via the Serial Monitor, the I2C LCD, and the Blynk application. Additionally, the PPM values from each sensor were automatically classified by the system into one of three statuses: “Safe,” “Alert,” or “Dangerous.” The following are the monitoring show on Figure 12.

IV. CONCLUSION

Based on the design, implementation, and testing of the system, the following conclusions can be drawn:

1. The IoT-based air quality monitoring system has been successfully developed using the ESP32 and three gas sensors (MQ-135, MQ-4, MQ-7) to detect real-time concentrations of ammonia (NH_3), methane (CH_4), and carbon monoxide (CO). The system effectively provides immediate information on gas levels that exceed safe thresholds.
2. The early warning feature has been successfully implemented through LED indicators, a buzzer, the Blynk application, and the SmartENose website. The system displays the status of each gas along with a combined "Danger Level" (0–6), offering quick and practical information to users without the need for manual checks.

The Sugeno fuzzy method has been employed to classify gas conditions into Safe (*Aman*), Alert (*Waspada*), and Dangerous (*Bahaya*) statuses. The combination of individual and combined rule bases enables the system to provide a more adaptive assessment of danger levels, maintaining sensitivity to dynamic environmental conditions. Thus, the developed system proves to be an effective solution for automatically monitoring air quality in cattle barns, being responsive and digitally integrated. Case study in the *TerraGrow* system, a Sugeno-type fuzzy inference method is employed as the core decision engine for IoT-based automated irrigation. The rule base is structured following agronomic logic, where dry-hot conditions trigger longer irrigation cycles while wet soil conditions result in a complete pump shutdown. Defuzzification is performed using a standard weighted-average formulation, enabling smooth, proportional control responses that operate efficiently in real time on the ESP32 microcontroller. The tunability of rule weights further demonstrates the adaptability of Sugeno fuzzy control to multiple crop types and environmental conditions [9]. The second case presented the application of the Sugeno Integral method as a decision-making framework for evaluating oil palm varieties, integrating multiple agronomic criteria into a unified assessment model. The method enables the processing of heterogeneous attribute values across different cultivars, generating structured and objective evaluations with adjustable weighting factors. Through this approach, qualitative and quantitative variables can be synthesized into a single decision space, allowing researchers to determine superior varieties with greater accuracy and analytical consistency [10].

In conclusion, the developed system demonstrates the capability to perform air monitoring automatically, responsively, and supports rapid decision-making in cattle barn environments.

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