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IoT-Based Air Pollution Trend Analysis: A Case Study in Residential Areas of Karawang Industrial Estate

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Abstract — Air quality degradation in industrial zones poses a significant health risk to surrounding residential communities. Karawang, as a major manufacturing hub in West Java, faces challenges in monitoring particulate matter and gas emissions due to the high cost and limited coverage of standard monitoring stations. This study aims to design a low-cost Internet of Things (IoT) system to monitor and analyze air pollution trends in the residential buffer zones of the Karawang Industrial Estate. The proposed system integrates an ESP32 microcontroller with multispectral sensors, including MQ-135 for hazardous gases, PMS5003T for particulate matter (PM2.5/PM10), and DHT22 for meteorological variables. Data is transmitted in real-time to a web-based server using a non-blocking transmission algorithm to ensure data integrity. The results demonstrate that the system reliably captures diurnal fluctuations in air quality. Trend analysis reveals a consistent pattern of increased pollutant concentration during morning (06:00–09:00) and late-night (19:00–22:00) periods, correlated with anthropogenic activities and meteorological phenomena such as temperature inversion. While the daily average Air Quality Index (AQI) predominantly falls within the "Moderate" category, episodic spikes reaching "Unhealthy for Sensitive Groups" were observed, highlighting the necessity for granular, real-time monitoring for public health mitigation.

Keywords – Air Quality Index (AQI), Internet of Things, Pollution Trend Analysis.

I. INTRODUCTION

Air pollution is defined as the introduction of chemical, physical, or biological agents into the atmosphere that modify its natural characteristics. In the context of industrial development, rapid manufacturing growth often correlates with increased emissions of hazardous pollutants, such as Particulate Matter (PM2.5, PM10), Carbon Monoxide (CO), and Nitrogen Dioxide (NO_2). According to recent environmental reports, Indonesia frequently ranks among the countries with significant air quality challenges, with numerous cities exceeding the World Health Organization (WHO) safety thresholds, creating severe health risks for vulnerable populations [1]. Current trends indicate a worrying increase in pollutant concentration levels across major industrial hubs in the country [2].

The Karawang Industrial Estate, hosting clusters of automotive, chemical, and logistics industries, is a critical economic zone that simultaneously presents environmental risks to adjacent settlements. Preliminary observations indicate that the Air Quality Index (AQI) in this region often reaches unhealthy levels, driven by dynamic industrial emissions and vehicular traffic [3]. Prolonged exposure to these pollutants is associated with acute respiratory infections (ARI) and cardiovascular diseases. However, the existing authoritative monitoring infrastructure, such as the standard Air Quality Monitoring System (AQMS), is limited in quantity and distribution due to high procurement and operational costs [4]. This creates a "blind spot" in environmental data, particularly in residential areas directly bordering industrial zones.

The advancement of the Internet of Things (IoT) offers a viable solution for scalable and cost-effective environmental monitoring. Previous studies have demonstrated the efficacy of microcontrollers like the ESP32 in acquiring and transmitting sensor data reliably for real-time analysis [5]. By integrating specific sensors for gas and particulates, it is possible to construct a granular monitoring network that provides real-time insights superior to manual sampling methods [6]. This research aims to bridge the monitoring gap by developing an integrated IoT system capable of acquiring, validating, and visualizing air quality parameters in real-time. Furthermore, this study focuses on analyzing the temporal trends (diurnal and monthly) of pollution in Karawang's residential areas to understand the correlation between industrial activity, meteorological factors, and pollutant accumulation.

This research aims to bridge the monitoring gap by developing an integrated IoT system capable of acquiring, validating, and visualizing air quality parameters in real-time. Furthermore, this study focuses on analyzing the temporal trends (diurnal and monthly) of pollution in Karawang's residential areas to understand the correlation between industrial activity, meteorological factors, and pollutant accumulation.

II. METHODOLOGY

This study employs an applied research approach following the System Development Life Cycle (SDLC), encompassing requirements engineering, prototyping, and field validation.

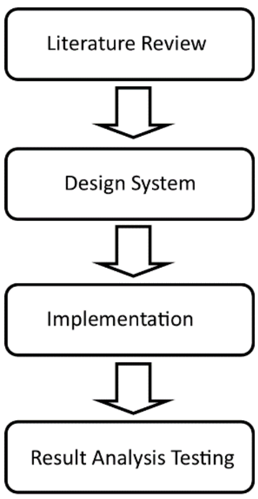

Fig.1. Research Methodology Block Diagram

A. Hardware Architecture

The system is built upon a multi-layered IoT architecture. The Perception Layer consists of the sensor array, while the Network Layer utilizes Wi-Fi for transmission.

1. Processing Unit: ESP32 DevKit V1 is selected for its dual-core processing power and built-in Wi-Fi/Bluetooth, essential for handling concurrent sensor data streams without latency.
2. Sensing Unit:
   a) PMS5003T: Utilizes laser scattering principles to quantify PM2.5 and PM10 concentrations with high precision [8].
   b) MQ-135: An electrochemical sensor sensitive to a broad range of gases including Ammonia (NH_3) and Nitrogen Oxides (NO_x).
   c) DHT22: Monitors ambient temperature and humidity to provide meteorological context for pollutant dispersion.
   d) ESP32-CAM: Captures visual evidence of site conditions to validate sensor anomalies [9].

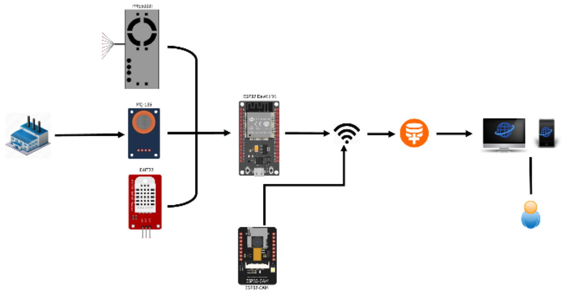

Fig.2. IoT Architecture

B. System Flowchart

The operational logic begins with system initialization. The ESP32 acquires raw analog and digital signals from the sensors. A non-blocking timer algorithm ensures continuous data sampling every few seconds. This raw data is then processed locally to filter noise before being encapsulated into JSON format and transmitted via HTTP POST requests to the web server. If the connection fails, a local buffering mechanism temporarily stores data to prevent loss.

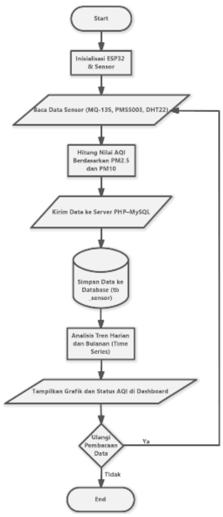

Fig.3. IoT-Based Air Quaity Monitoring Flowchart

Figure 3 delineates the sequential operational logic of the proposed air quality monitoring framework. Upon system startup, an initialization routine configures the ESP32 microcontroller and the connected sensor array. The data acquisition phase ensues, where the system retrieves real-time environmental metrics from the MQ-135, PMS5003T, and DHT22 sensors. These raw inputs are processed to compute the Air Quality Index (AQI), specifically utilizing PM2.5 and PM10 concentrations. Subsequently, the telemetry data is transmitted to a PHP-MySQL server and archived within the tb_sensor database for data persistence. The system then executes a time-series analysis to evaluate daily and monthly pollution trends. Finally, the processed insights and AQI status are visualized on the web dashboard. This data cycle operates in a continuous loop to ensure uninterrupted environmental surveillance.

C. *Use Case Diagram*

The use case diagram presented below delineates the functional interactions between the users and the IoT-based air quality monitoring system. Two distinct actors are identified in the system operations: the Field Officer (Petugas Lapangan) and the Resident (Warga).

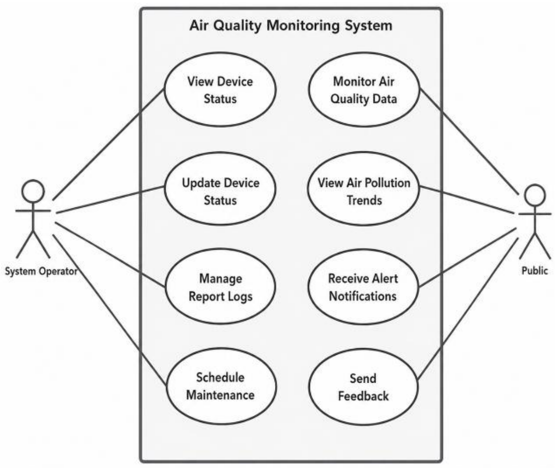

Fig. 4. Use Case Diagram of the Air Quality Monitoring System

Brief Explanation: In the use case diagram above, the system accommodates two primary actors with specific roles. The actors can perform the following actions:

1. The Field Officer is responsible for technical operations, including viewing device status and updating device status to ensure the hardware functions correctly.
2. Administrative tasks, such as managing field reports and submitting maintenance requests, are designated to the Field Officer to maintain system reliability.
3. The Resident can access the platform to monitor air quality data in real-time and view air pollution trends over specific periods.
4. The system automatically sends warning notifications to Residents whenever the air quality index reaches hazardous levels.
5. A feedback loop is established where Residents can send feedback regarding the system or environmental conditions.

The system design segregates administrative privileges from public access. While Field Officers focus on hardware integrity and reporting, Residents are provided with access to environmental insights and alert mechanisms. This structured approach grants the Field Officer full control over device maintenance, while effectively disseminating critical air quality information to the community in real-time.

D. *Circuit Prototype*

Figure 5 depicts the circuit configuration of the IoT devices designed for the residential air quality monitoring system, focusing on the integration of the ESP32 microcontroller with the MQ-135 gas sensor, PMS5003T particulate sensor, DHT22, and ESP32-CAM module.

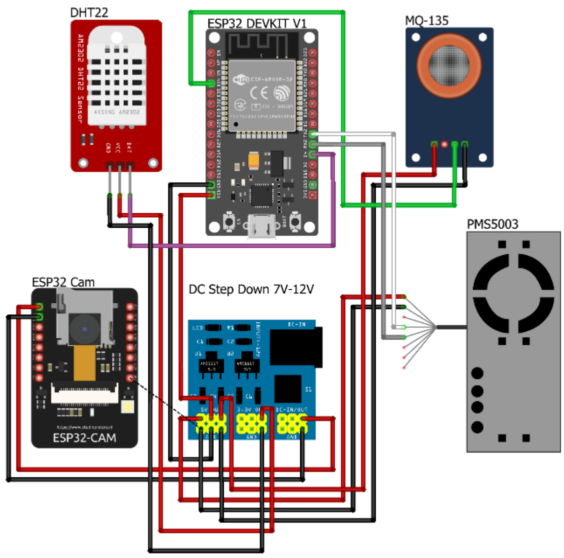

Fig. 5. IoT Device Component Circuit

E. *Implementation of the AQI Calculation Algorithm*

- *Linear Interpolation*

MethodThe core calculation is performed using the segmented linear interpolation method for each pollutant parameter (PM2.5 and PM10). This approach maps the raw concentration data into a standardized index value.Formula:

$$I = \frac{I_{hi} - I_{lo}}{BP_{hi} - BP_{lo}}(C - BP_{lo}) + I_{lo} \quad (1)$$

Where:

1) I_p: The calculated Air Quality Index for pollutant p.
2) C_p: The truncated concentration of pollutant p.

3) BP_{Hi}: The breakpoint that is greater than or equal to C_p.
4) BP_{Lo}: The breakpoint that is less than or equal to C_p.
5) I_{Hi}: The AQI value corresponding to BP_{Hi}.
6) I_{Lo}: The AQI value corresponding to BP_{Lo}.

The concentration data collected from the sensors are categorized into specific breakpoints established by environmental protection standards. The levels are defined based on $\mu g/m^3$ (micrograms per cubic meter) as follows:

Particulate Matter 2.5 (PM2.5) – PMS5003T:

1) Good: 0 - 15.0μg/m^3
2) Moderate: 15.1 - 35.0μg/m^3
3) Unhealthy: 35.1 - 65.0μg/m^3

Particulate Matter 10 (PM10) – PMS5003T:

1) Good: 0 - 50μg/m^3
2) Moderate: $51 - 100$\mu g$/m^3
3) Unhealthy: $101 - 150$\mu g$/m^3

The raw values from the sensors are processed using Equation (1) to determine the intermediate index for each pollutant type.

- *Determination of the Critical Pollutant*

The system employs a maximization logic to determine the final daily Air Quality Index (AQI) reported to the user. The overall AQI is dictated by the highest individual index calculated among the measured pollutants:

Logic:

$$AQI = \max(I_{PM2.5}, I_{PM10})$$

This ensures that the reported air quality status reflects the most hazardous condition present in the environment at any given time. For instance:

1) IF $I_{PM2.5}$ > I_{PM10} THEN Final AQI = $I_{PM2.5}$
2) IF I_{PM10} > $I_{PM2.5}$ THEN Final AQI = I_{PM10}

Each calculated AQI score corresponds to a specific health category, ranging from "Good" to "Hazardous".

Note: While the system monitors multiple parameters including gases via the MQ-135 sensor, the primary AQI calculation for regulatory compliance in this study focuses on particulate matter. The gas readings serve as supplementary data to provide a comprehensive environmental profile. This adjustment helps maintain the system's adherence to standard reporting protocols while offering detailed insights into industrial chemical exposure.

- *Status Classification Output*

The system utilizes a discrete classification method for the final output. The numerical AQI value derived from the interpolation formula is mapped to a descriptive status for the web dashboard display as follows:

1) 0 – 50: Good (Green)
2) 51 – 100: Moderate (Yellow)
3) 101 – 150: Unhealthy for Sensitive Groups (Orange)
4) 151 – 200: Unhealthy (Red)
5) 201 – 300: Very Unhealthy (Purple)
6) 300: Hazardous (Maroon)

III. RESULTS AND DISCUSSION

The developed IoT-based air quality monitoring system underwent a rigorous validation phase to assess sensor accuracy, data transmission latency, and the integration reliability between the hardware nodes and the web-based dashboard. The field deployment and testing were conducted in a residential buffer zone within the Karawang Industrial Estate, West Java, specifically at the KGV 2 Cluster. This location was selected to capture real-world pollution dynamics driven by the surrounding industrial activities and vehicular logistics.

A. Hardware Specifications

a) ESP32 Development Board Specifications

Table 1. ESP32 DevKit V1 Specifications

Specification	Value
Microcontroller	Tensilica Xtensa LX6 (Dual-Core)
Connectivity	Wi-Fi 802.11 b/g/n + Bluetooth
Operating Voltage	3.3V
Input Voltage	5V - 12V (Vin)
Clock Speed	240 MHz
Digital I/O Pins	25 Pins
Flash Memory	4 MB
ADC Resolution	12-bit

The ESP32 microcontroller functions as the primary processing unit for this research. Its dual-core architecture and integrated Wi-Fi stack are critical for managing asynchronous data streams from multiple environmental sensors while simultaneously maintaining a stable connection to the web server. The specifications outlined in Table 1 confirm that the ESP32 possesses the computational headroom required for real-time edge computing and data transmission in an outdoor environmental monitoring setup.

b) Environmental Sensor Specifications

The sensor array in table 2 comprising the MQ-135, PMS5003T, and DHT22 was selected to provide a comprehensive profile of ambient air quality.

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Table 2. Specifications of the Multispectral Sensor Array

Sensor	Specification	Value
MQ-135	Target Gas	Ammonia, Sulfide, Benzene, NO_x
	Heater Voltage	5.0V ± 0.1V (AC/DC
	Detection Range	10 – 1000 ppm
PMS5003T	Principle	Laser Scattering (Mie Theory)
	Particle Size	PM2.5 & PM10
	Response Time	< 10 Seconds
DHT22	Temp. Range	-40°C to 80°C (±0.5°C accuracy)
	Humidity Range	0% to 100% RH (±2% accuracy)
	Sampling Rate	0.5 Hz (Once every 2 seconds)

The MQ-135 targets hazardous industrial gases, while the PMS5003T utilizes laser scattering to quantify particulate matter (PM2.5 and PM10) with high precision. Additionally, the DHT22 monitors meteorological variables that influence pollutant dispersion. This multi-parameter approach ensures that the system enables data-driven decision-making regarding environmental health risks.

c) Laptop Device Specifications

Table 3. Specifications of the Development Workstation

Device	Specification
Laptop Model	Dell LATITUDE E6510
Operating System	Windows 10 64-bit Build 19045
Storage	SSD 512GB
RAM	8 GB

Table 3 shows the workstation was utilized for the entire development lifecycle, including firmware coding for the ESP32 and the full-stack development of the web dashboard. The specifications listed above were sufficient to handle the compilation of C++ code in the Arduino environment and the local deployment of the XAMPP server for database management during the testing phase.

B. Software Specification

a) Integrated Development Environment (IDE)

The Arduino IDE (table 4) served as the primary platform for firmware development, facilitating library management for the sensor modules and the ESP32 board manager.

Table 4. Arduino IDE Specifications

Specification	Value
Version	2.3.7
CLI Version	1.3.1
OS Compatibility	Windows, macOS, Linux

b) Backend and Frontend Architecture

Modern environmental monitoring requires a robust software architecture to visualize complex data streams. The system employs a LAMP stack (Linux, Apache, MySQL, PHP) adapted for Windows via XAMPP (table 5). The backend logic processes incoming JSON data from the IoT nodes, implementing the Linear Interpolation algorithm to calculate the Air Quality Index (AQI). Simultaneously, the frontend utilizes responsive design frameworks to ensure data accessibility across various devices, allowing residents to monitor pollution trends seamlessly.

Table 5. Web Application Specifications

Specification	Type
Backend Language	PHP 8.3.12
Database	MySQL (MariaDB 10.4)
Local Server	XAMPP v3.3.0
Frontend Stack	HTML5, CSS3, JavaScript (Chart.js)
Data Format	JSON (JavaScript Object Notation)

This web-based architecture ensures that the air quality data is not only stored securely for historical analysis but also presented in an intuitive format for the end-users in the Karawang residential area.

C. Testing the Multispectral Sensor Array

The functional verification phase aimed to validate the capability of the MQ-135, PMS5003T, and DHT22 sensors to accurately quantify the concentrations of hazardous gases, particulate matter (PM2.5 and PM10), and meteorological variables. The data acquisition system was evaluated using the Arduino IDE environment, with real-time telemetry displayed synchronously through the Serial Monitor and the dedicated web-based dashboard.

Fig. 6. Initiation of the Data Acquisition Process

D. Experiment on Monitoring Air Quality Status

Upon acquiring the raw concentration values from the MQ-135 (Gas), PMS5003 (Particulates), and DHT22 (Temperature/Humidity) sensors, the data were processed using the Linear Interpolation algorithm. Unlike fuzzy logic approaches, this system aligns the measured parameters with standardized health breakpoints to classify the air quality into discrete categories: Good, Moderate, Unhealthy for Sensitive Groups, Unhealthy, Very Unhealthy, and Hazardous.

Instead of fuzzy membership values, each pollutant category is defined by specific concentration ranges ($\mu g/m^3$) as established by environmental protection standards. The system computes the individual indices for both PM2.5 and PM10 to determine the specific sub-index for each parameter.

The final system output is derived using a maximization logic AQI = max ($I_{PM2.5}$, I_{PM10}) to identify the critical pollutant of the day. This calculated AQI score is then mapped to its corresponding color-coded health status. The classification results are visualized in real-time via the web dashboard and validated against the raw data stream on the Serial Monitor. Experimental results demonstrate that the system successfully correlates the detected pollutant fluctuations with the appropriate health risk categories.

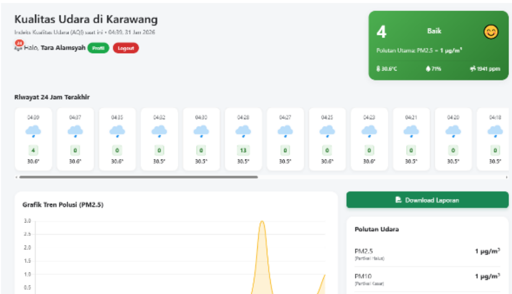

Fig. 7. Air Quality Status Visualization on the Web Dashboard

Figure 7 presents the documentation of the monitoring results, illustrating the dynamic changes in AQI status for particulate matter and gas concentrations as displayed on the user interface.

E. Experiment on Data Transmission to the Database Server

Upon acquiring the concentration values from the MQ-135, PMS5003, and DHT22 sensors, the telemetry data were transmitted to the central database server using the Arduino IDE environment supported by the HTTPClient library. The http.POST payload method was utilized to dispatch the sensor readings to the designated API endpoint. The data were successfully received and validated within the MySQL database in real-time, ensuring that all environmental parameters were securely archived for further processing and historical analysis.

Fig. 8. Successful Data Transmission to the Server Database

Figure 8 demonstrates the system's efficacy in transmitting the sensor data packets to the backend server. The logs confirm that the particulate matter (PM2.5/PM10), gas concentrations, and meteorological variables are recorded with precise timestamps, establishing a reliable foundation for the monitoring system.

F. Experiment on Real-time Visualization on the Web Dashboard

Following the successful data ingestion by the server, the system was further evaluated on its capability to visualize the information on the Web-based Dashboard. The processed values for hazardous gases, particulate matter, and ambient temperature were retrieved and rendered dynamically on the graphical user interface. This process employed asynchronous data fetching to update the Air Quality Index (AQI) status indicators and trend charts automatically. The dashboard (see Fig. 9) provides residents with immediate situational awareness regarding the pollution levels in the Karawang industrial buffer zone.

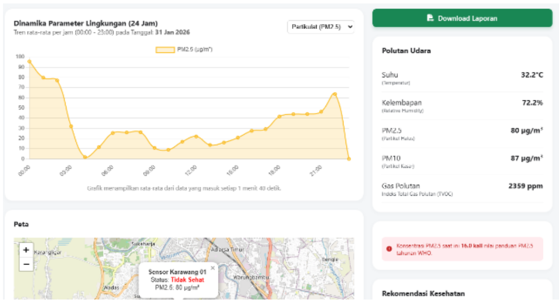

Fig. 9. Visualization of Air Quality Trends on the Web Dashboard

G. Figures and Tables Experiment on Exporting Analytical Reports

Figure 10 illustrates the functionality test of the report generation feature, which allows users to download comprehensive historical logs of the air quality parameters in PDF format.

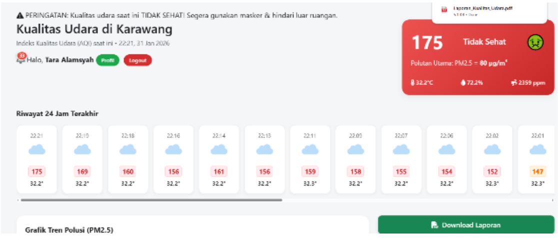

Fig. 10. Downloading Daily Air Quality Reports

H. Test Results

The testing phase was executed to validate the system's efficacy in quantifying the concentrations of Particulate Matter (PM2.5 and PM10) and hazardous gases, ensuring that the generated Air Quality Index (AQI) status aligned with the designed Linear Interpolation algorithm. Data acquisition was carried out across diverse temporal segments, capturing both baseline ambient conditions and peak pollution episodes triggered by diurnal anthropogenic activities.

LAPORAN KUALITAS UDARA

Kawasan Industri Karawang - Dicetak oleh: Tara Alamsyah

Tanggal Cetak: 10 February 2026, 05:07

Waktu	PM2.5	PM10	Gas CO	AQI	Status
2026-01-31 22:21:30	80	87	2359	174.6	Tidak Sehat
2026-01-31 22:19:49	74	83	2320	168.6	Tidak Sehat
2026-01-31 22:18:06	65	78	2363	159.6	Tidak Sehat
2026-01-31 22:16:25	61	76	2384	155.6	Tidak Sehat
2026-01-31 22:14:44	66	78	2395	160.6	Tidak Sehat
2026-01-31 22:13:01	61	75	2382	155.6	Tidak Sehat
2026-01-31 22:11:20	64	78	2339	158.6	Tidak Sehat
2026-01-31 22:09:40	63	75	2383	157.6	Tidak Sehat
2026-01-31 22:07:59	60	75	2385	154.6	Tidak Sehat
2026-01-31 22:06:19	59	72	2371	153.6	Tidak Sehat
2026-01-31 22:02:58	57	71	2366	151.6	Tidak Sehat
2026-01-31 22:01:17	54	69	2305	146.6	Tidak Sehat
2026-01-31 21:59:37	52	63	2343	141.6	Tidak Sehat
2026-01-31 21:57:53	51	62	2330	139.2	Tidak Sehat
2026-01-31 21:56:13	50	59	2325	136.7	Tidak Sehat
2026-01-31 21:54:32	47	55	2295	129.3	Tidak Sehat

Fig. 11. Comprehensive System Test Results

The telemetry data streams were visualized synchronously through the Arduino IDE Serial Monitor and the web-based dashboard interface. Furthermore, the raw concentration values from each sensor were processed by the system to determine the specific AQI category, automatically classifying the environmental status into distinct levels such as "Good," "Moderate," or "Unhealthy." The consolidated monitoring outcomes are illustrated in Figure 11.

IV. CONCLUSION

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

1. The IoT-based air quality monitoring system has been successfully developed utilizing the ESP32 microcontroller integrated with a multispectral sensor array (MQ-135, PMS5003, DHT22) to detect real-time concentrations of hazardous gases, particulate matter (PM2.5 and PM10), and meteorological variables. The system effectively provides immediate data regarding environmental parameters that exceed the standard health safety thresholds [6].
2. The visualization and alert features have been successfully implemented through a dedicated Web Dashboard. The system displays the specific status of each pollutant parameter along with a unified Air Quality Index (AQI), offering quick and practical situational awareness to residents without the need for complex manual data interpretation [9].

The Linear Interpolation method has been employed to classify pollution levels into standardized categories, ranging from Good to Hazardous. The integration of particulate and gas concentration data enables the system to provide a precise assessment of environmental health risks, maintaining alignment with established regulatory standards. Thus, the developed system proves to be an effective solution for automatically monitoring ambient air quality in industrial buffer zones, being both responsive and digitally integrated [10].

Parallel to advanced environmental decision support systems, the Linear Interpolation algorithm serves as the core logic for normalizing heterogeneous sensor data. The computational structure follows a deterministic approach, where specific concentration breakpoints trigger corresponding index values, ensuring that the reported AQI reflects the critical pollutant of the day. This data processing method allows for consistent, high-fidelity readings that operate efficiently in real-time on the ESP32 edge device. The scalability of this calculation model further demonstrates the adaptability of IoT-based sensing to various micro-climatic conditions and urban layouts. Furthermore, the system's ability to synthesize quantitative variables into a single intelligible index mirrors the analytical consistency required for public health reporting, allowing stakeholders to determine air quality trends with greater accuracy and objectivity.

In conclusion, the developed system demonstrates the capability to perform environmental surveillance automatically and responsively, supporting rapid decision-making for health mitigation in residential areas.

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