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Design and Development of IoT-Enabled Portable Device for Multiparameter Air Quality Monitoring

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DERBY BRYLIAN ADINARA, AGUSTINA RACHMAWARDANI, ADI WIDIATMOKO WASTUMIRAD, BENYAMIN HERYANTO RUSANTO, DWI INDRA PRASETYO, HANIF KURNIAWAN, ABDUL MANAF MAHANI

State College of Meteorology Climatology and Geophysics, Indonesia
Email: adinara.cmpt@gmail.com

ABSTRAK

Keterbatasan infrastruktur pemantauan kualitas udara di Indonesia mendorong penelitian untuk mengembangkan perangkat pemantauan portabel berbasis Internet of Things (IoT). Sistem dirancang menggunakan ESP32 dan Arduino Uno yang terintegrasi dengan sensor MQ136 (SO2), MQ131 (NO2), MiCS-5524 (CO), TGS-2611 (CH4), Gravity-0460 (PM), dan Gravity-0321 (O3). Data dikonversi menjadi nilai AQI dan ditampilkan melalui LCD, Telegram, dan website. Perangkat dilengkapi Sistem peringatan dini berbasis buzzer, pop-up website dan pesan telegram. Hasil pengujian lapangan selama 24 jam di POS KU Cibeureum mencatat konsentrasi puncak PM2.5 (19 µg/m³), PM10 (58 µg/m³), NO_2 (1.375 ppb), CO (238 ppb), SO_2 (0,74 ppb), dan O_3 (45 ppb). Perangkat dapat beroperasi secara portabel dengan dimensi: enclosure I 20×20 cm, enclosure II 7×12 cm, box-panel 30×40 cm (pra-rakit) dan 100×180 cm (pasca-rakit). Perangkat terbukti efektif sebagai solusi pemantauan adaptif untuk pemukiman sekitar kawasan industri.
***Kata kunci**: kualitas udara, portabel, internet of things (IoT), AQI, real-time*

ABSTRACT

The limitations of Indonesia's air quality monitoring infrastructure have prompted research to develop portable Internet of Things (IoT)-based monitoring devices. The system is designed using ESP32 and Arduino Uno integrated with MQ136 (SO2), MQ131 (NO2), MiCS-5524 (CO), TGS-2611 (CH4), Gravity-0460 (PM), and Gravity-0321 (O3) sensors. Data is converted into AQI values and displayed via LCD, Telegram, and website. The device is equipped with an early warning system that includes a buzzer, a website pop-up, and Telegram messages. Field testing results over 24 hours at POS KU Cibeureum recorded peak concentrations of PM2.5 (19 µg/m³), PM10 (58 µg/m³), NO_2 (1.375 ppb), CO (238 ppb), SO_2 (0.74 ppb), and O_3 (45 ppb). The device can be operated portably with the following dimensions: enclosure I, 20×20 cm; enclosure II, 7×12 cm; control panel box, 30×40 cm (pre-assembled) and 100×180 cm (post-assembled). The device has proven effective as an adaptive monitoring solution for residential areas surrounding industrial zones.
***Keywords:** air quality, portable, internet of things (IoT), AQI, real-time*

1. INTRODUCTION

Indonesia is currently facing a serious challenge regarding the air quality emergency. According to the World Air Quality Report 2024, released by IQAir, Indonesia ranks 15th among countries with the highest PM2.5 concentrations worldwide, based on a population-weighted analysis **(IQAir, 2025).** This situation is exacerbated by rapid urbanization and increased industrial activity, which significantly contribute to the decline in air quality **(Kang et al., 2022**). Emissions from fossil fuel-powered vehicles, as well as industrial activities, are the primary sources of pollution, leading to high concentrations of pollutants in the atmosphere **(Rachmawardani et al., 2024).**

The Ministry of Environment and Forestry of Indonesia (KLHK) has initiated mitigation efforts by tightening ambient air quality standards. However, the limitations of monitoring infrastructure pose a significant challenge in obtaining accurate and representative air quality data. Currently, Indonesia has only 68 Ambient Air Quality Monitoring Stations (SPKUA) **(Fahim et al., 2024)**, a number that is very limited compared to the 514 districts and cities in Indonesia **(Harjito, 2020).** This creates a significant gap in the collection of accurate and representative data. Failures in monitoring can result in a lack of necessary information for prompt and appropriate mitigation actions **(Sirsikar & Karemore, 2015).** Furthermore, there are over 3,750 industrial facilities spread across various regions, meaning that many industrial areas, particularly those in remote locations, may be overlooked by the national air quality monitoring system **(Directorate of Air Pollution Control, 2024).** Therefore, there is a need for innovative solutions in the form of portable air quality monitoring devices based on the Internet of Things, which adhere to AQI (Air Quality Index) standards. These devices can be flexibly used in industrial areas and provide real-time data to support pollution mitigation efforts.

The Air Quality Index (AQI) is an indicator used by the Environmental Protection Agency (EPA) in the United States to communicate air quality information to the public. The AQI categorizes air quality into six levels: Good, Moderate, Unhealthy for Sensitive Groups, Unhealthy, Very Unhealthy, and Hazardous **(Benchrif et al., 2021).** Monitoring is conducted for five major pollutants: particulate matter (PM), carbon monoxide (CO), nitrogen dioxide (NO2), sulfur dioxide (SO2), and ozone (O3) **(Cromar et al., 2020).** Each AQI category offers specific recommendations for pollution mitigation tailored to the level of pollution detected **(Fino et al., 2021).**

The Internet of Things (IoT) is a network that connects sensor-equipped physical objects to Internet-based systems **(Ash-Shiddiqy et al., 2023).** This concept encompasses three main elements: physical devices with sensors to detect environmental conditions, internet connectivity for data transmission, and data centres or servers for information storage and management **(Farooq et al., 2022).** The integration of these three elements enables the automatic and real-time collection and processing of data across various applications, including disaster early warning systems **(Wu et al., 2023).** The Internet of Things (IoT) also offers 24-hour real-time monitoring systems and the capability to operate automatically without human intervention **(Rachmawardani et al., 2023).**

Portable systems are devices designed to be lightweight, easy to carry, and operable without permanent installation. In air quality monitoring, these systems offer high flexibility for direct measurements in locations lacking fixed monitoring infrastructure **(Subagiyo et al., 2021).** The main advantage of portable devices lies in their ability to perform real-time detection in dynamic areas such as remote industrial zones, pollution-prone regions, or densely populated settlements **(Oyo-Ita et al., 2023).** With the integration of IoT technology, data can be transmitted directly to cloud platforms for analysis, enabling rapid, accurate, and contextual reporting **(Zagita, 2021).** Therefore, portable systems represent a strategic alternative that can expand the coverage of air quality monitoring in Indonesia.

Previous research has developed an IoT-based air quality monitoring system utilizing multiparameter sensors and LoRaWAN networks, which features a web dashboard interface and the Virtuino application **(Jabbar et al., 2022).** Although this system is reliable for data collection, limitations such as a non-portable design, the absence of methane (CH_4) and PM10 sensors, and restricted data access to specific applications remain challenges. To address these issues, this study develops a portable IoT-based device that utilizes GSM networks capable of performing real-time AQI analysis and presenting data through a local LCD, a Telegram chatbot, and an interactive website. This innovation is designed to enhance flexibility and monitoring coverage in industrial areas, featuring an early warning system and a more interactive and user-friendly interface.

2. METHODOLOGY

2.1 Operational Principles of the System

This air quality monitoring system is designed to perform multi-parameter measurements in real-time and in a portable manner, utilizing Internet of Things (IoT) technology. The system is capable of detecting various types of air pollutants, including PM2.5, PM10, SO_2, O_3, CO, NO_2, and CH_4, and displays the measurement results through multiple interfaces, both local and online. The measurement results are processed into Air Quality Index (AQI) values and automatically provide alerts if hazardous air conditions occur. The system is also equipped with a solar panel-based power supply, enabling independent operation in various locations, including residential areas around industrial zones that fixed monitoring stations do not yet cover.

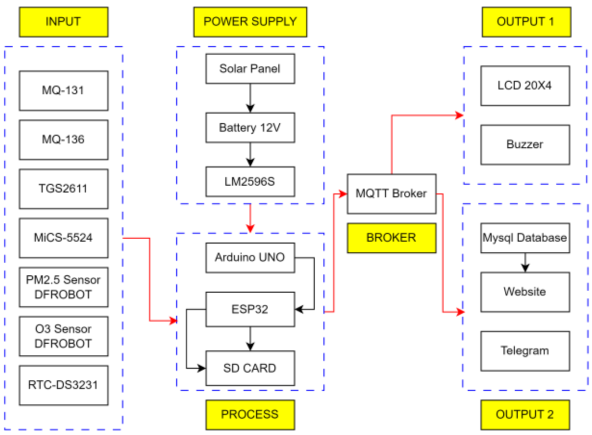

Figure 1. Block Diagram

Figure 1 illustrates the operational principle of the system, which consists of five main components: input, process, power supply, broker, and output. The input section includes sensors such as the MQ-131 (NO_2), MQ-136 (SO_2), MiCS-5524 (CO), TGS2611 (CH_4), Gravity SEN0460 (PM2.5, PM10), and Gravity SEN0321 (O_3), as well as the DS3231 RTC module for time recording. Sensor data is acquired by the Arduino Uno and forwarded to the ESP32 via serial communication. The ESP32 processes the data into JSON format, stores it on a microSD card, and sends it to the MQTT broker. The system's power supply is derived from a solar panel that charges a 12V battery, which is then stabilised using an LM2596S step-down module to power the circuit. On the output side, the system displays air quality data through a 20x4 LCD, a Telegram chatbot, and a website and provides alerts via a buzzer notification.

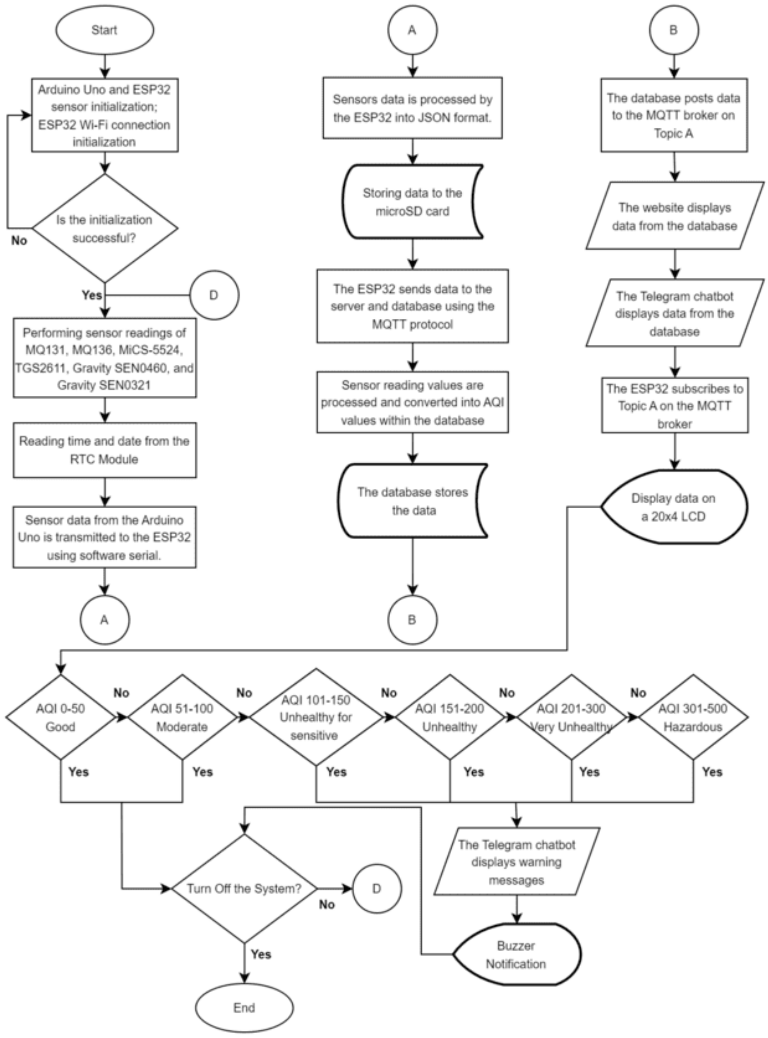

Figure 2. System Flowchart

Figure 2 illustrates the overall operational process of the system. The system begins with the initialization of sensors by the Arduino Uno and the establishment of a network connection by the ESP32. If this process fails, the system will automatically repeat the initialization until successful. After initialization, the Arduino reads data from the sensors and the time from the RTC module and then sends this information to the ESP32 via serial communication. The ESP32 converts the data into JSON format, stores it on a microSD card, and sends it to the server via MQTT (Topic A). The server processes the data to calculate the AQI value and stores it in a database, then sends the calculation results back to the MQTT broker through Topic B. A second ESP32, connected to the LCD and buzzer, subscribes to Topic B to display the AQI value in real time. If the AQI value falls within the "Good" to "Moderate" categories, the system continues monitoring as usual. However, if it enters risk categories such as "Unhealthy for Sensitive Groups" to "Hazardous," the buzzer will be activated, and automatic alerts will be sent via Telegram, along with a pop-up of mitigation steps on the website. The website also retrieves data from the database to display graphs and current air quality information. This system is designed to operate continuously and responsively, providing accurate and easily accessible information both locally and online.

2.2 AQI Calculation Method

The process of calculating the Air Quality Index (AQI) begins with the collection of data on pollutant concentrations. The parameters O_3 and CO are calculated as an 8-hour average (or

1 hour for O_3 under certain conditions), while $PM_{2.5}$ and PM_{10} are averaged over 24 hours, and SO_2 and NO_2 are averaged over 1 hour. This averaging process is designed to provide a representative measure of pollutant levels over a specific time period, reflecting the potential health impacts of these pollutants on the population. Once the data is collected, the system meticulously identifies the highest concentration from each parameter. These concentration values are then carefully adjusted: O_3 is rounded to three decimal places, $PM_{2.5}$ and CO to one decimal place, and PM_{10}, SO_2, and NO_2 to whole numbers. Next, the crucial AQI breakpoint table is used to determine two concentration limit values, namely BPLo (lower limit) and BPHi (upper limit), which bracket the actual concentration value, along with the corresponding AQI index values ILo (AQI value for BPLo) and IHi (AQI value for BPHi).

Table 1. Breakpoint AQI

AQI (Index Values)	O_3 (ppm)		PM (µg/m³)		CO [ppm]	SO_2 [ppb]	NO_2 [pbb]
	[8-hour]	[1-hour]	$PM_{2.5}$ [24hour]	PM_{10} [24hour]	[8-hour]	[1-hour]	[1-hour]
Good (up to 50)	0 - 0.054	-	0.0 – 9.0	0 - 54	0 – 4.4	0 - 35	0 - 35
Moderate (51 – 100)	0.055 – 0.070	-	9.1 – 35.4	55 - 154	4.5 – 9.4	36 - 75	54 - 100
Unhealthy for sensitive Groups (101 – 150)	0.071 – 0.085	0.125 – 0.164	35.5 - 55.4	155 - 254	9.5 – 12.4	76 - 185	101 - 360
Unhealthy (151 – 200)	0.086 – 0.105	0.165 – 0.204	55.5 - 125.4	255 - 354	12.5 – 15.4	186 - 304	361 - 649
Very Unhealthy (201 – 300)	0.106 – 0.200	0.205 – 0.404	125.5 – 225.4	355 - 424	15.5 – 30.4	305 – 604 [24-hour]	650 -1249
Hazardous (301 – 500)	0.201+	0.405+	225.5+	425+	30.5+	605+ [24-hour]	1250+

Based on these values, the AQI is calculated using the following linear equation **(EPA, 2024):**

$$I_p = \left(\frac{(IHi-ILo)(C_p-BPLo)}{BPHi-BPLo}\right) + ILo \quad (1)$$

where I_p is the AQI index and C_p is the truncated concentration of the pollutant. The resulting I_p value is then rounded to the nearest whole number to obtain the final AQI value, which represents the level of air pollution **(EPA, 2024).**

2.3 System Design

2.3.1 Hardware Design

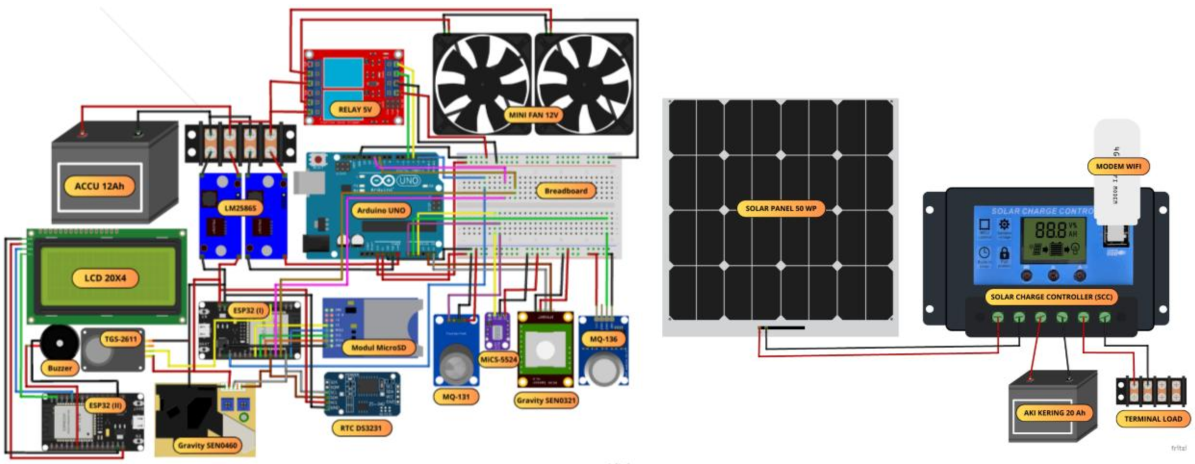

Figure 3. Schematic Diagram of the System

The schematic diagram is designed to systematically illustrate the flow of power distribution and connectivity among its components, ensuring the operational stability of the device and minimizing the risk of connection errors. In addition to serving as a technical reference during the assembly and reproduction of the device, this schematic plays a crucial role in managing energy distribution priorities, particularly in supporting power consumption efficiency to ensure optimal performance in portable operating mode.

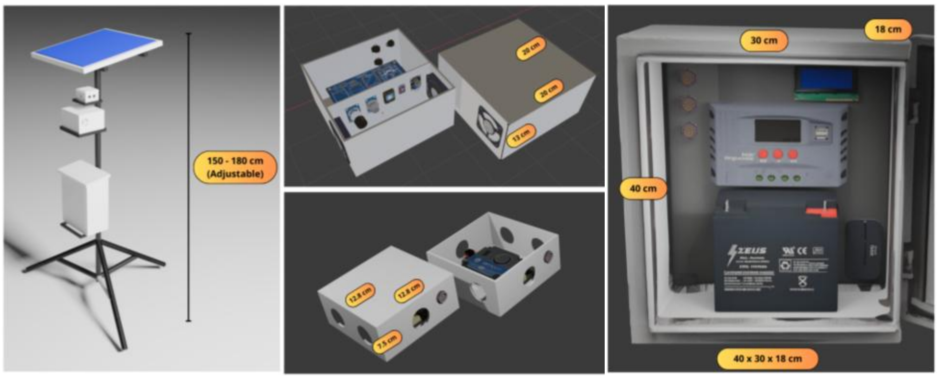

Figure 4. Physical Design of the System

The physical design of the system is created to visualize and optimize the overall arrangement of components in a comprehensive and integrated manner. This stage plays a strategic role in supporting the accurate planning of component layout, thereby minimizing the likelihood of design errors before the actual implementation phase begins. Additionally, this design is specifically tailored to support the portable characteristics of the system, taking into account space efficiency, ease of assembly, and operational stability under various environmental conditions. The physical design of the system in this research encompasses the device's physical design, the system's box enclosure design, the particulate sensor enclosure design, and the panel box design.

2.3.2 Software Design

In this research, the website will serve as the primary interface to display real-time air quality information and provide early warnings to the public. This platform will present data on the concentration of each pollutant parameter, the Air Quality Index (AQI) value, and recommendations for mitigation actions based on pollution levels. The website will also feature an interactive map to visualize data by location, hourly trend graphs to support user analysis, and a data download feature to facilitate further analysis. Additionally, the system will provide integration with a Fetch API based on the MQTT protocol, enabling connectivity with other compatible monitoring devices and thereby expanding the scope of digital and flexible air quality monitoring.

The Telegram chatbot in this research is designed as a social media-based interface, providing users with real-time air quality data. With a simple command, users can access the most up-to-date information, including the date and time, device location, concentration of each pollutant parameter, Air Quality Index (AQI) value, and air quality status. Additionally, the system is equipped with an automatic alert messaging feature that sends notifications if the AQI value exceeds certain threshold limits. This feature is designed to support the early detection of hazardous air conditions, ensuring the safety and well-being of the users.

The SD Card in this research serves as a backup storage medium to ensure data security during the transmission process from the sensor to the server, especially in cases of network unavailability, server disruptions, or inactive connection devices. The sensor readings will be automatically recorded in separate files each time a measurement is taken, using a lightweight

JSON format that is easy to read and compatible with various data processing systems. Each file will be named based on a timestamp to facilitate identification and grouping of information. This storage function not only acts as a backup but also serves as an alternative data source for manual processing or retransmission when network connectivity is restored.

3. RESULTS

3.1 Hardware Implementation

Figure 5. Overall Appearance of the Device

The Device has been successfully developed in a portable format, featuring a control system based on the ESP32 and Arduino Uno, and integrated with several air quality sensors, including the MQ131, MQ136, Gravity SEN0460, Gravity SEN0321, MiCS-5524, and TGS-2611. The data communication system is designed using a GSM-based Orbit modem connected to an ESP32 device, with a microSD module and microSD card facilitating local data storage. To support autonomous operation in the field, the system is equipped with a power supply based on solar panels, consisting of a 50WP solar panel, a 20Ah dry battery, and a 20A MPPT Solar Charge Controller (SCC).

Figure 6. Device Enclosure Appearance

All main components, including the control module, sensors, and power system, are housed in three separate enclosures: the PM sensor box, control box, and panel box, to enhance protection against direct exposure to sunlight and rain. The separation of the particulate sensors into a dedicated box is carried out considering the different sampling ecosystem requirements and the relatively large dimensions of the sensors. However, this separation does not affect the integrity of the overall system. The system is designed to maintain its integrity, ensuring that all components continue to operate within an integrated working environment, thereby maintaining the system's reliability and stability.

3.2 Software Implementation

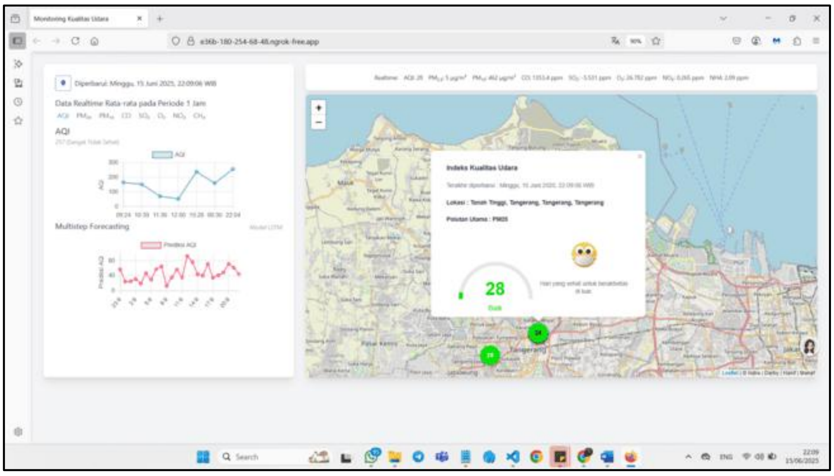

Figure 7. Website: Dashboard

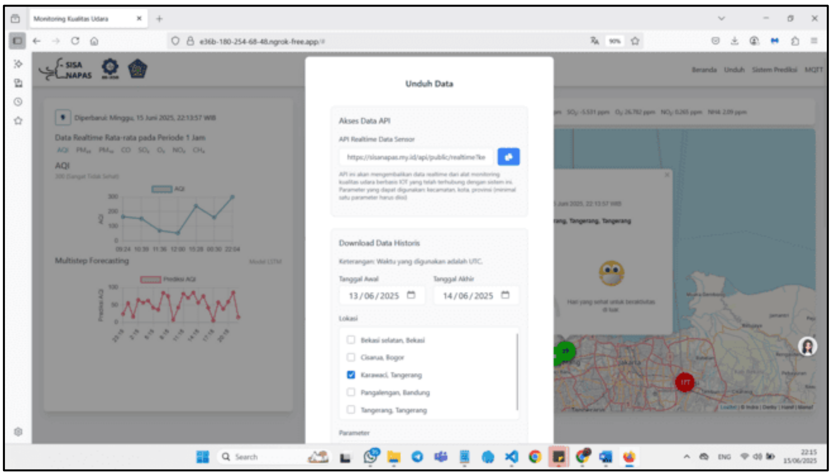

Figure 8. Website: Download Interface

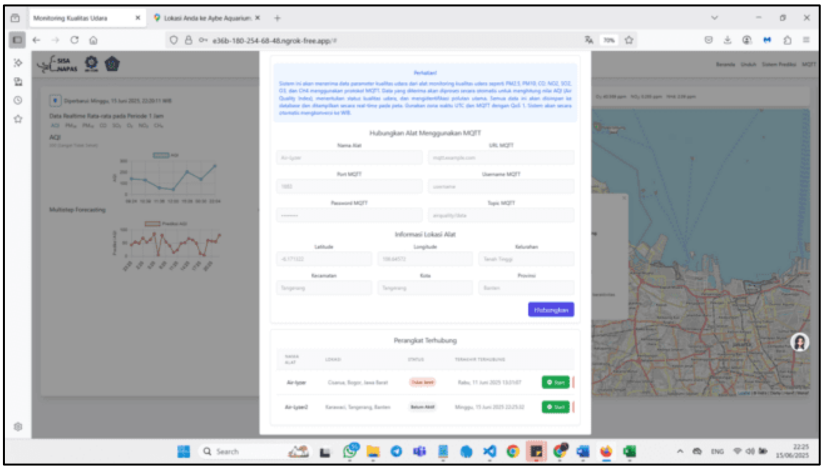

Figure 9. Website: MQTT Data Fetch Interface

The developed website demonstrates optimal performance as a responsive, informative, and real-time air quality monitoring platform. The homepage interface features integrated elements, including hourly data trend graphs, current numerical information on pollutant parameters, the Air Quality Index (AQI) value, and mitigation recommendations based on pollution levels. The inclusion of an interactive map enhances the spatial aspect of the system by displaying the geographical distribution of monitoring locations. The data download feature effectively provides historical data in a structured CSV format, which can be utilized for further analysis. Additionally, the fetch data function, based on the MQTT protocol, showcases successful bidirectional communication between the monitoring devices and the website, as indicated by the display of connectivity status and information from active devices. The system also supports the dynamic integration of new devices through the MQTT protocol, reflecting the flexibility and scalability of the monitoring infrastructure.

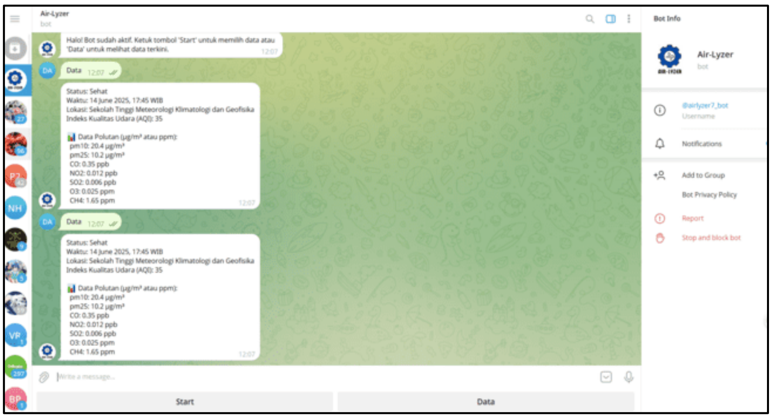

Figure 10. Chatbot Telegram: Real-Time Data Request

Figure 11. Chatbot Telegram: Specific Data Request

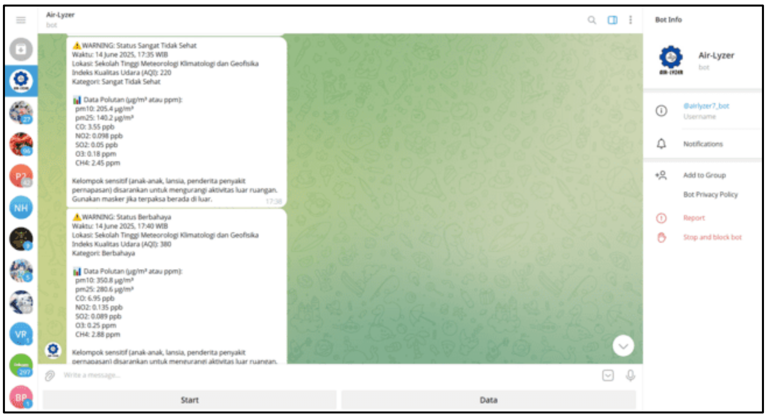

Figure 12. Chatbot Telegram: Automated Warning Message

All features implemented in the Telegram chatbot demonstrate good functional performance and align with the system design. The Data button successfully displays real-time air quality information. In contrast, the Start button serves as the primary trigger to present a menu of data options that users can select according to their needs. Additionally, the automatic early warning feature has proven capable of detecting anomalies in air quality parameters and sending notifications to users in a timely manner, thereby playing a crucial role in supporting an early detection system for potential pollution risks. The success of the integration indicates that the Telegram chatbot can provide an accessible, and responsive communication interface.

3.3 Data Storage System Testing

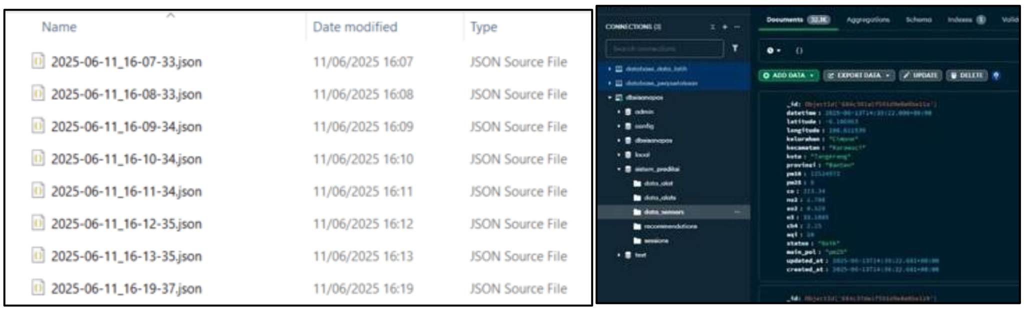

Figure 13. MicroSD and Database Storage Performance

The testing of the data storage system has shown that both local and cloud storage mechanisms have operated according to specifications and function reliably. In local storage, the device successfully records sensor data to the microSD card in a structured format (JSON), supporting compatibility with various analytical software, both manual and automated. This functionality ensures the continuity of data logging even in the event of internet connectivity disruptions. Meanwhile, in cloud-based storage, data has been successfully transmitted automatically by the ESP32 module to the server via the MQTT protocol, with transmission success verified through the system interface and the database contents.

3.5 Portability Testing


Figure 14. Pre-Assembly and Post-Assembly

The device assembly process is documented in a video, which can be accessed through the following link: https://shorturl.at/Vop1Q. Portability testing demonstrated that the developed device fulfils the criteria of mobility, ease of operation, and installation efficiency in field applications. The assembly process can be completed within a short time without the need for specialised tools or complex technical procedures, reflecting its ergonomic and modular design. Key components, including the sensor enclosure, control panel enclosure, and solar panel, can be efficiently assembled while maintaining structural stability for outdoor deployment. The compact dimensions and lightweight structure enable the device to be easily transported between locations without requiring extensive logistical support, making it well-suited for deployment in both residential and industrial environments. The dimensions of individual components before assembly are as follows: Enclosure I (20 × 20 cm), Enclosure II (7 × 12 cm), panel box (30 × 40 cm), tripod (15 × 94 cm), and solar panel (58 × 61 cm). After assembly, the overall system dimension is 100 × 180 cm. Furthermore, the intuitive installation process does not demand advanced technical expertise, enabling personnel from diverse backgrounds to operate the system effectively.

3.6 Pengujian Sistem Peringatan dini

Table 2. Video Documentation Link for Early Warning via Buzzer

Condition	AQI	Link
Unhealthy for Sensitive Group	101 - 150	https://short url.at/FmCHZ
Unhealthy	151 - 200	https://shorturl.at/5RBVQ
Very Unhealthy	201 - 300	https://shorturl.at/DFFP7
Hazardous	301 - 500	https://shorturl.at/zhBIt

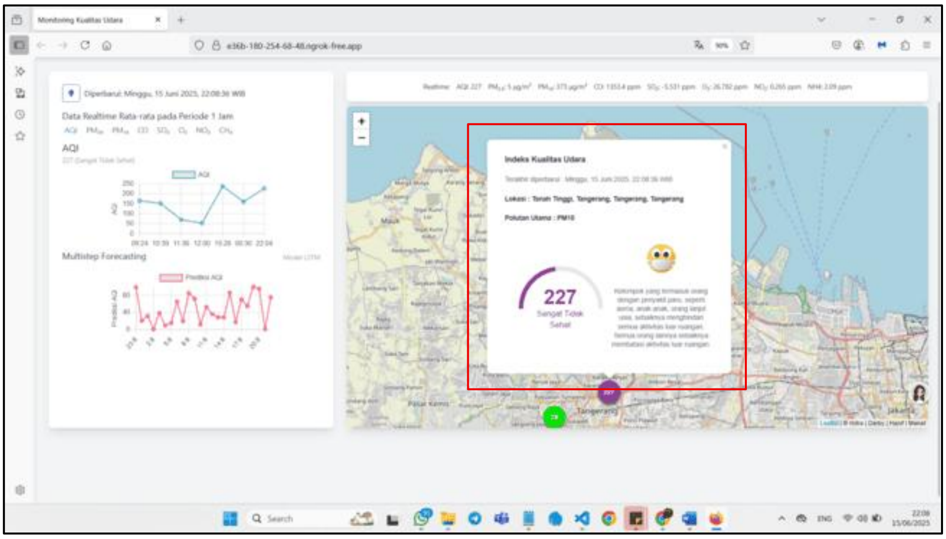

Figure 15. Early Warning Notifications via Website Pop-up

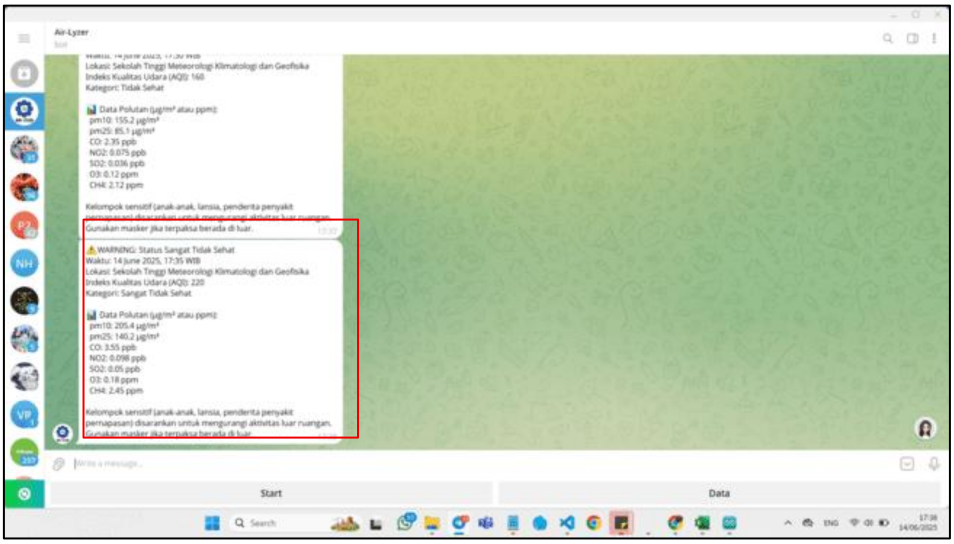

Figure 16. Automated Early Warning Message via Telegram Chatbot

The developed early warning system demonstrates real-time response capabilities to air quality conditions that exceed threshold limits through three main channels: a physical buzzer, Telegram notifications, and pop-ups on the website. The buzzer is automatically activated when air quality reaches categories such as Unhealthy for Sensitive Groups, Unhealthy, Very Unhealthy, or Hazardous, indicating the system's effectiveness in providing immediate local alerts. The Telegram channel successfully sends automated, informative, and structured notifications that include air quality status, time and location of the event, AQI values, pollutant concentrations, and mitigation recommendations, thereby supporting quick and accurate decision-making. On the other hand, the website channel displays automatic pop-up alerts with visualizations of air quality status, current AQI values, and mitigation suggestions, thereby enhancing information accessibility without requiring additional navigation.

3.7 Field Testing

Field testing was carried out at the Cibeureum Air Quality Monitoring Station over a 24-hour period to evaluate the performance of the developed system. Measurements were conducted in real time without applying artificial simulations under controlled conditions. The primary objective of this test was to examine the device's capability to continuously record and report air pollutant concentrations within a representative environment. The system was configured to collect data at one-minute intervals; however, for trend analysis and visualization, the measurements were aggregated into hourly averages. This data processing strategy was adopted to minimize short-term variability and emphasize long-term concentration dynamics, which is particularly critical for the objectives of this research.

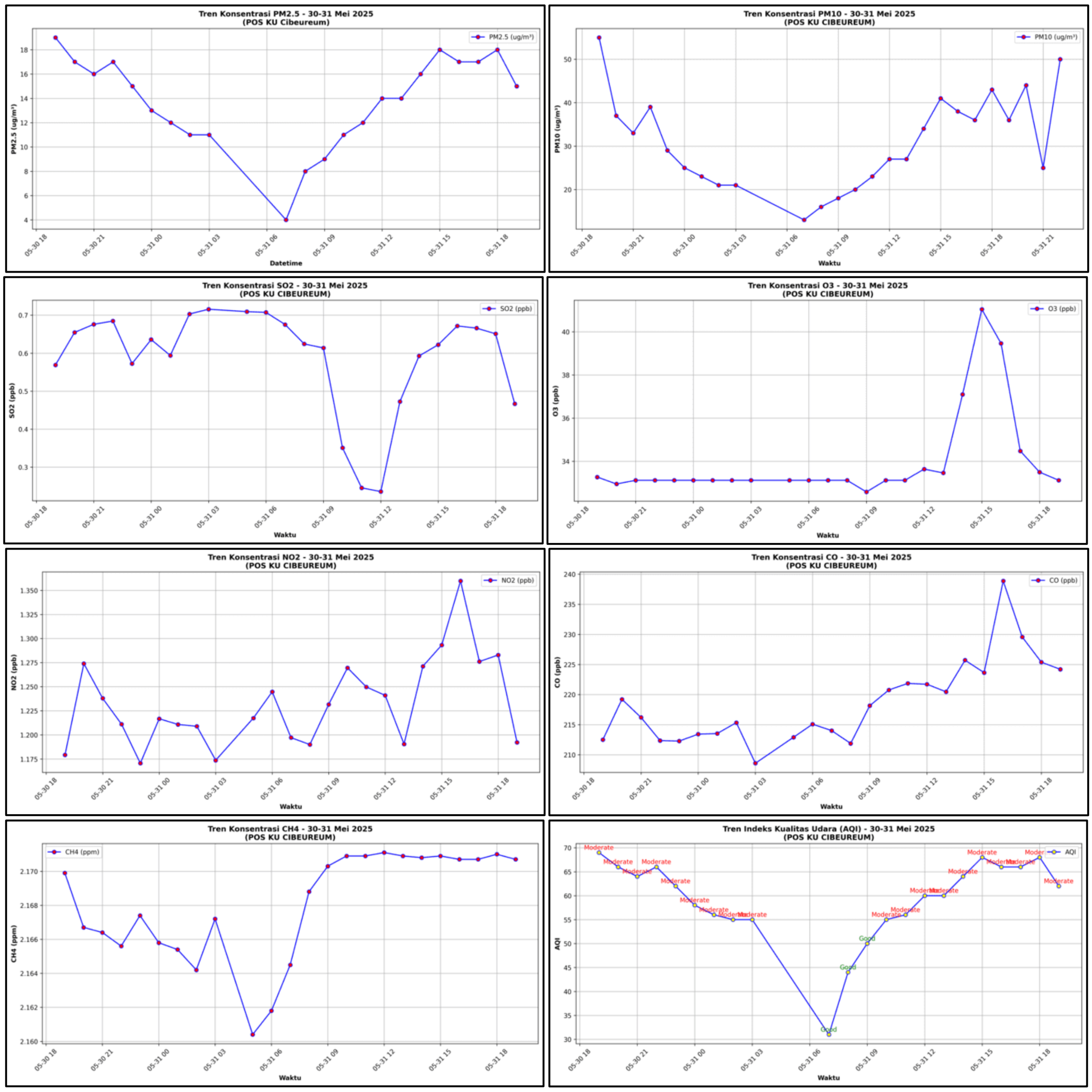

Figure 17. Field Test Results: Data Trend Visualization

Based on Figure 18, an overview of the fluctuations in the concentrations of six major air pollutants $PM_{2.5}$, PM_{10}, CO, NO_2, SO_2, CH_4, O_3 and the Air Quality Index (AQI) values during the 24-hour observation period at the Cibeureum Air Quality Monitoring Station are obtained. The data indicates that the system successfully recorded the dynamics of pollutant concentrations continuously and was able to represent the temporal trends of air quality parameters at the testing location.

$PM_{2.5}$ and PM_{10} concentrations showed significant fluctuations, with the highest peaks at 7:00 p.m., with PM2.5 (19 μg/m³) and PM10 (58 μg/m³) values. This condition is likely influenced by human activities and atmospheric conditions, such as decreased wind speed and increased humidity at night, which worsen particulate dispersion and can lead to particulate accumulation near the surface. CO and NO_2 concentrations fluctuated significantly and increased, especially during peak hours, with the highest peak occurring at 16:00, when NO_2 (1,375 ppb) and CO (238 ppb) values reflected emissions from vehicles or local combustion sources. SO_2 concentrations exhibited sharp fluctuations during the middle to end of the observation period, with the highest peak at 3:00 a.m. (0.74 ppb). This peak was likely influenced by local combustion activities, such as waste burning or small industrial emissions, as well as meteorological conditions, including nighttime temperature inversions. Meanwhile, CH_4 concentrations were relatively stable during the day and fluctuated at night, which could be attributed to consistent contributions from biological sources, such as wetland emissions, and anthropogenic sources, including livestock waste. O_3 concentrations were also relatively stable at (20 ppb) and increased at 15:00 to (45 ppb). The air quality index (AQI) shows a decline in air quality at certain times, which is consistent with increases in the concentrations of major pollutants such as PM and NO2.

4. CONCLUSION

Based on the discussion results, it can be concluded that the development of the portable air quality monitoring system has been successfully implemented comprehensively. The developed hardware, consisting of the ESP32 microcontroller and Arduino Uno, equipped with various air quality sensors, a GSM-based communication system, and a solar panel-based power supply system, demonstrates reliable performance with high mobility for field applications. The strategy of placing components in three separate enclosure units has proven to enhance protection against environmental conditions while improving operational efficiency without compromising the overall system integration. The software implementation, including the website interface and Telegram chatbot, has met technical and functional standards as an informative environmental monitoring platform. Key features, including trend data visualization, historical data download, MQTT-based data acquisition, and an early warning system via a buzzer, Telegram notifications, and website pop-ups, demonstrate the system's flexibility and scalability in real-time monitoring scenarios. Additionally, testing of data storage, both locally (microSD) and online (cloud database), has demonstrated the system's success in ensuring continuity and reliability in data recording. Field testing over 24 hours at the Cibeureum Air Quality Monitoring Station - BMKG confirmed the system's capability to continuously record and analyze the dynamics of significant pollutant concentrations such as $PM_{2.5}$, PM_{10}, CO, NO_2, SO_2, and CH_4. The fluctuations in pollutant concentrations influenced by human activities and local atmospheric conditions indicate the system's sensitivity to real-time environmental changes. Therefore, this system is deemed effective as an adaptive solution in supporting air quality evaluation and mitigation, with potential for further development in broader coverage areas and additional parameters.

ACKNOLEDGMENTS

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REFERENCES

Ash-Shiddiqy, K. M., Widiatmoko, A., Rachmawardani, A., Hariyanto, G., Ariyanto, P., Amri, S., & Pratiwi, A. (2023). Prototipe sistem monitoring tinggi muka air dan curah hujan Waduk Situ Parigi berbasis website. *Seminar Nasional Fisika (SiNaFi)*, (pp. 421–435).

Benchrif, A., Wheida, A., Tahri, M., Shubbar, R., & Biswas, B. (2021). Air quality during three COVID-19 lockdown phases: AQI, PM2.5 and NO2 assessment in cities with more than 1 million inhabitants. *Sustainable Cities and Society*, *74*, 103170. https://doi.org/10.1016/j.scs.2021.103170

Cromar, K., Ghazipura, M., Gladson, L., & Perlmutt, L. (2020). Evaluating the U.S. *Air Quality Index* as a risk communication tool: Comparing associations of index values with respiratory morbidity among adults in California. *PLOS ONE*, *15*(11), e0242031. https://doi.org/10.1371/journal.pone.0242031

Direktorat Pengendalian Pencemaran Udara. (2025, January 10). *Laporan kinerja Direktorat Pengendalian Pencemaran Udara tahun 2024*. Kementerian Lingkungan Hidup dan Kehutanan. Retrived from https://ppkl.menlhk.go.id/*website* on 21 Juni 2025

Environmental Protection Agency (EPA). (2024). *Technical Assistance Document for the Reporting of Daily Air Quality – the Air Quality Index (*AQI*)*. Retrived from https://www.airnow.gov/publications/air-quality-index/technical-assistance-document-for-reporting-the-daily-aqi/ on 21 June 2025

Fahim, K., Sholichah, S. A., Hanafi, L., Surjanto, S. D., Herisman, I., & Doctorina, W. F. (2024). Prediksi Indeks Standar Pencemar Udara (ISPU) di Kota Surabaya Menggunakan Rantai Markov Waktu Diskrit. *Jurnal Ilmiah Soulmath : Jurnal Edukasi Pendidikan Matematika*, *12*(2), 121–134. https://doi.org/10.25139/smj.v12i2.8684

Farooq, M., Riaz, S., Helou, M., Khan, F., Abid, A., & Alvi, A. (2022). *Internet of Things* in greenhouse agriculture: A survey on enabling technologies, applications, and protocols. *IEEE Access*, 10, 53374–53397. https://doi.org/10.1109/access.2022.3166634

Fino, A., Vichi, F., Leonardi, C., & Mukhopadhyay, K. (2021). An overview of experiences made and tools used to inform the public on ambient air quality. *Atmosphere, 12*(11), 1524. https://doi.org/10.3390/atmos12111524

Harjito, Y., Nugraha, P. S., & Yulianto, Y. (2020). *Analisis Kinerja Keuangan Pemerintah Kabupaten dan Kota Di Indonesia*. *Jurnal Akuntansi dan Ekonomi (JAE), 5*(1), 19–28. https://doi.org/10.29407/jae.v5i1.14061

IQAir. (2025). 2024 World Air Quality Report. Retrived from https://www.iqair.com/world-air-quality-report on 21 June 2025

Jabbar, W. A., Subramaniam, T., Ong, A. E., Shu'Ib, M. I., Wu, W., & de Oliveira, M. A. (2022). LoRaWAN-Based IoT System Implementation for Long-Range Outdoor Air Quality Monitoring. *Internet of Things, 19*, 100540. https://doi.org/10.1016/j.iot.2022.100540

Kang, Y., Aye, L., Ngo, T. D., & Zhou, J. (2022). Performance evaluation of low-cost air quality sensors: A review. *Science of The Total Environment, 818*, 151769. https://doi.org/10.1016/j.scitotenv.2021.151769

Oyo-Ita, E. U., Ekah, U. J., Ana, P., & Ewona, I. O. (2023). Development of a smart air quality monitoring system using wireless sensors. *Advances in Research, 24*(6), 50–59. https://doi.org/10.9734/air/2023/v24i6984

Rachmawardani, A., Prabowo, D., Nardi, Toruan, K. L., Abdurachman, S., & Adinara, D. B. (2024). Designing a cost-effective IoT air quality sensor for *real-time* data monitoring. *In 2024 IEEE International Conference on Computing (ICOCO)* (pp. 219–224). Kuala Lumpur, Malaysia. https://doi.org/10.1109/ICOCO62848.2024.10928212

Rachmawardani, A., Virgianto, R. H., Giarno, Prabowo, D., Nardi, Wastumirad, A. W., Rasya, M. F., & Ash-Shiddiqyi, K. M. (2023). Wireless Sensor Network (WSN) of a flood monitoring system based on the *Internet of Things* (IoT*). E3S Web of Conferences*, 464, 01004. https://doi.org/10.1051/e3sconf/202346401004

Sirsikar, S., & Karemore, P. (2015). Review paper on air pollution monitoring system. *International Journal of Advanced Research in Computer and Communication Engineering (IJARCCE), 4*(1), 218–220. https://doi.org/10.17148/ijarcce.2015.4147

Subagiyo, H., Tri Wahyuni, R., Akbar, M., & Ulfa, F. (2021). Rancang Bangun Sensor Node untuk Pemantauan Kualitas Udara. *Jurnal Sains, Teknologi dan Industri, 18*(1). https://doi.org/10.24014/sitekin.v18i1.11461

Wu, Q., Zhang, Z., Zhu, H., Fan, P., Fan, Q., Zhu, H., & Wang, J. (2023). Deep reinforcement learning-based power allocation for minimizing age of information and energy consumption in multi-input multi-output and non-orthogonal multiple access *Internet of Things* systems. *Sensors, 23*(24), 9687. https://doi.org/10.3390/s23249687

Zagita, M. F. A. B. (2021). Rancang bangun sistem pemantauan dan pengendali kualitas udara di ruang MI (Manual Insert) PT. Smart Meter. *Jurnal Teknologi Elektro, 12*(1). https://doi.org/10.22441/jte.2021.v12i1.004