

Handheld Air Quality Monitor Powered by ESP32 and Li-ion Battery Management for Real-Time Field Inspections

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Abstract

The urgency of this research stems from the pressing need to address the limitations of static air quality monitoring systems, especially given a 30% increase in respiratory complaints among Indonesian students by 2025 due to undetected hazardous pollutants. To mitigate these health risks, this study aims to design a portable, ESP32-based air quality monitoring device capable of dynamic pollution inspection in unpowered areas. Employing a prototyping approach, the system integrates an MQ-135 gas sensor outputting raw analog voltage converted to parts per million (PPM), a DSM501A dust sensor outputting pulse width modulation (PWM) low-pulse occupancy ratio converted to micrograms per cubic meter ($\mu\text{g}/\text{m}^3$), and an autonomous 18650 Li-ion battery management system with an MT3608 boost converter to ensure voltage stability. Furthermore, it utilizes an SSD1306 OLED display for independent, real-time data visualization without requiring internet connectivity. Field testing of this handheld device was conducted across 3 distinct indoor and outdoor test locations over a period of 3 consecutive days between 08:00 and 19:00 WIB. The air quality status was classified using a threshold-based procedure, categorizing conditions into "GOOD," "MODERATE," or "POOR" based on specific gas concentration and dust density ranges. The results showed significant daily fluctuations, with gas concentrations averaging 1,180 PPM (ranging from 450 to 2,300 PPM) and dust density averaging $44.2 \mu\text{g}/\text{m}^3$ (ranging from 12 to $95 \mu\text{g}/\text{m}^3$). The data demonstrated a clear trend where pollution peaked at 15:00, reaching a "POOR" air quality status during peak mobility hours, before gradually declining to a "GOOD" status by 19:00. Ultimately, this portable solution successfully maps air quality in previously inaccessible blind spots, providing functional monitoring data to help communities mitigate respiratory health risks.

Keywords: Air quality monitoring; ESP32; Portable device; Li-ion battery management; OLED display; Low-cost sensor; Indoor air quality; Portable environmental monitoring; Power consumption

1. Introduction

Air is vital for human survival, but its quality is frequently compromised in both indoor and confined environments because gaseous pollutants, such as carbon dioxide and suspended dust particles, are often odorless and colorless, making them difficult to detect by human senses [1]. Massive increases in industrial activity and high urban population density have exacerbated air pollution, which directly and negatively impacts public respiratory health [2]. This is evidenced by research findings showing that in school and office settings, complaints of respiratory problems among individuals have surged significantly from 8% to 30% over the past four years, indicating an urgent need for localized, real-time air quality monitoring [3]. However, an analysis of existing literature reveals that current air quality monitoring systems exhibit distinct trade-offs across portability, power consumption, communication dependency, cost, and measurement

accuracy. Traditional stationary monitoring stations and continuous emission monitoring systems offer high regulatory-grade accuracy through rigorous calibration and reference validation, but they are bulky, expensive, and rely heavily on fixed electrical grids and wired infrastructures. Conversely, recent advancements have introduced Internet of Things (IoT)-based monitoring prototypes; however, many rely on heavy power sources such as large P5 LED display panels or cloud platforms (e.g., ThingSpeak) that demand continuous internet connectivity and high power consumption, rendering them non-portable and vulnerable in unpowered or offline environments [4].

To bridge these gaps, low-cost portable monitoring devices utilizing metal-oxide semiconductor sensors specifically the MQ-135 for gaseous pollutants and the DSM501A for particulate matter have gained traction due to their affordability, compact form factor, and low energy demands. Nevertheless, these low-cost sensors possess inherent technical limitations and cross-sensitivities; without proper calibration algorithms and reference-instrument validation, their raw outputs (such as analog voltage or low-pulse occupancy ratio) reflect relative pollutant trends rather than absolute, highly accurate concentrations. The MQ-135 sensor responds broadly to various gases (such as CO₂, ammonia, and alcohol) and is heavily influenced by ambient temperature and humidity shifts, while the DSM501A optical particle sensor measures dust particles down to approximately 1 μm but can experience baseline drift over extended operation. Acknowledging these constraints, this study integrates these low-cost modules within an optimized, energy-efficient hardware architecture powered by an 18650 Li-ion battery and an MT3608 boost converter, aiming to provide practical, real-time pollution trend mapping in unpowered blind spots without claiming unverified absolute measurement accuracy.

These technical limitations create critical gaps in air quality mapping within blind spots untouched by fixed electrical installations, thereby motivating the development of this ESP32-based portable air quality monitoring device. By integrating an autonomous lithium-ion battery management system, a precise MQ-135 sensor, and a compact OLED display interface, this device offers an ergonomic, energy-efficient handheld solution capable of delivering instant air quality data without requiring internet connectivity or external smartphone applications. Building upon these identified limitations specifically the difficulty of detecting indoor air pollution and the restrictive mobility caused by fixed power dependencies the main objective of this study is to design a portable, ESP32-based air quality monitoring system equipped with efficient power management, optimal sensor accuracy, and a standalone handheld visual interface.

To address these problem statements, the proposed approach involves developing an ESP32 microcontroller-based system that integrates an MQ-135 sensor for gas detection and a DSM501A sensor for dust particles, directly resolving the low accuracy and early detection challenges in enclosed environments. To overcome power dependency and mobility barriers, the system utilizes a handheld architecture powered by an 18650 Li-ion battery, a TP4056 charger module, and an MT3608 boost converter, enabling dynamic inspections in unpowered areas. Furthermore, to satisfy standalone visualization requirements, the device features a 0.96" OLED display for real-time data presentation without external applications, while incorporating the ESP32's deep sleep feature to optimize operational energy efficiency.

Previous research on air quality monitoring generally falls into two primary categories: wired stationary systems and Internet of Things (IoT) based prototypes [5], [6] [7]. For instance, prior IoT urban air pollution prototypes relied on large P5 LED panels requiring high power, rendering them static and non-portable [8]. Meanwhile, other studies leveraging cloud platforms like ThingSpeak or smartphone applications depend heavily on stable internet connections [9], [10]. Sensor performance has also posed persistent challenges, as earlier studies frequently utilized infrared-based sensors characterized by

higher error rates compared to modern laser-based modules or specific gas sensors like the MQ-135 [11].

To address these limitations, this research builds upon existing modular components while providing distinct engineering improvements over prior portable and IoT-based monitoring systems. Rather than claiming an unprecedented sensor technology, the novelty of this work lies in achieving an optimized balance among complete autonomy, cloud-free local visualization, and extended operational endurance for unpowered blind-spot inspections. The previous studies often compromise either portability, power autonomy, or local visualization by relying heavily on continuous cloud connectivity, high-power LED panels, or wired power sources. In contrast, the proposed system integrates an ESP32 microcontroller with a self-contained 18650 Li-ion power architecture stabilized via an MT3608 boost converter, an SSD1306 OLED interface for real-time offline feedback, and an energy-saving deep-sleep firmware routine. Quantitative performance evaluations demonstrate that this integration achieves over 8 hours of continuous field operation on a single battery charge, with stable sensor voltage regulation and reliable real-time trend tracking, thereby establishing a practical and cost-effective engineering approach for dynamic field inspections without external infrastructure dependencies.

This research contributes significantly to electronics by advancing the practical integration of an ESP32 microcontroller [12] with an optimized power management system pairing an 18650 Li-ion battery [13], a TP4056 charger, and an MT3608 boost converter to ensure stable sensor performance and high energy efficiency via deep-sleep capabilities. In the health sector, the device addresses critical public health concerns regarding rising respiratory issues by providing precise, real-time detection of hazardous pollutants such as CO₂ and fine particulate matter in enclosed environments [14], [15]. Furthermore, for society at large, it offers an affordable, ergonomic, and handheld solution for dynamic air quality monitoring in unpowered blind spots, empowering individuals and institutions with standalone, cloud-free data visualization to improve indoor air awareness without requiring internet connectivity or external devices.

This research employs a prototyping development approach to construct a functional handheld device. For hardware integration, the system utilizes an ESP32 microcontroller [16] as the core controller, combined with an MQ-135 sensor for gas detection and a DSM501A sensor [17] for fine dust particles. To ensure constant sensor voltage stability and system longevity, the power management framework integrates an 18650 Li-ion battery [18], a TP4056 charger module, and an MT3608 boost converter. Additionally, the software and visualization framework implements custom firmware featuring an SSD1306 OLED display interface [19] [20] for real-time data visualization, while leveraging the ESP32's deep sleep feature to optimize overall energy efficiency.

The evaluation of the system focuses on three primary aspects. First, portability and mobility are demonstrated through the success of the handheld structure in performing dynamic, real-time inspections across areas lacking electrical installations. Second, energy efficiency is validated by assessing the performance of the power management framework and deep-sleep optimization, successfully achieving a target of over 8 hours of continuous operation per charge. Third, sensor accuracy and data presentation are analyzed to confirm the precision of pollutant detection alongside the reliability of standalone, offline data presentation via the OLED interface. In summary, the research contributions highlight how the proposed device successfully resolves the fundamental constraints of conventional, static, and power-dependent monitoring systems. Furthermore, the broader impact of this work notes its significant contributions across electronics engineering, public health protection against indoor pollution, and its practical utility for society at large.

2. Material and Methods

This study employs a prototyping approach to design a portable, ESP32-based air quality monitoring device centered around an ESP32 DevKit V1 microcontroller. Environmental sensing utilizes an MQ-135 gas sensor (5V supply) and a DSM501A dust sensor (5V supply) to measure gaseous pollutants and particulate matter, with raw analog voltage and low-pulse occupancy outputs converted into indicative PPM and $\mu\text{g}/\text{m}^3$ values. Power autonomy and voltage stability are achieved using a 2,600 mAh 18650 lithium-ion battery equipped with a TP4056 charging module (featuring overcharge, over-discharge, and short-circuit safeguards) paired with an MT3608 step-up converter delivering a regulated 5V output. The custom firmware operates on a 1-minute sampling interval, processing sensor data, updating an SSD1306 OLED display, triggering a buzzer alarm when safety limits are breached, and engaging the ESP32 deep-sleep mode to exceed 8 hours of continuous operation. Field testing across 3 distinct locations over 3 consecutive days (08:00–19:00 WIB) utilized a 1-hour averaging period under a custom threshold-based classification system, categorizing air quality into "GOOD" (gas ≤ 999 PPM, dust ≤ 35 $\mu\text{g}/\text{m}^3$), "MODERATE" (gas 1,000–1,799 PPM, dust 36–75 $\mu\text{g}/\text{m}^3$), and "POOR" (gas $\geq 1,800$ PPM, dust ≥ 76 $\mu\text{g}/\text{m}^3$) [21]. The hardware architecture integrates an ESP32 microcontroller as the core processing unit, an MQ-135 sensor for detecting hazardous gases, and a DSM501A sensor for measuring fine dust particulate matter. To ensure voltage stability and autonomy in remote blind spots, an independent power management system is implemented utilizing an 18650 lithium-ion battery, a TP4056 charging module, and an MT3608 boost converter. To process environmental readings, the analog voltage output from the MQ-135 sensor and the low-pulse occupancy ratio (PWM) from the DSM501A dust sensor were converted into indicative parts per million (PPM) and particulate-density values ($\mu\text{g}/\text{m}^3$) using standard conversion equations and manufacturer sensitivity curves. Because formal calibration against a certified reference instrument was not conducted in this preliminary iteration, the resulting output values serve as relative, indicative air-quality indices for capturing dynamic pollution trends rather than absolute regulatory-grade measurements [22].

The software development involves writing custom firmware that interfaces an SSD1306 OLED display for independent, real-time data visualization without relying on internet connectivity or external devices. Furthermore, the system incorporates the ESP32's deep sleep feature to maximize energy efficiency during extended field operations [23]. Functional testing and data collection are subsequently conducted across a dynamic timeframe (08:00 to 19:00 WIB) to evaluate sensor accuracy, power stability, and the device's capability to monitor real-time pollution fluctuations in various indoor and outdoor environments.

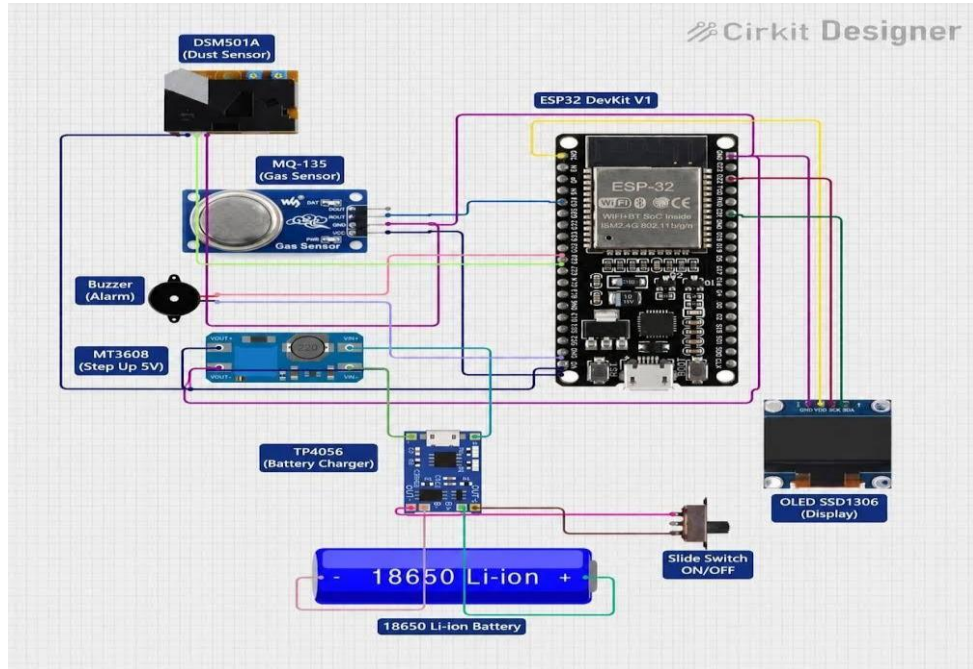


Figure 1: The Comprehensive Schematic Wiring Diagram of the ESP32-Based Portable Air Quality Monitoring System

The wiring diagram (Figure 1) illustrates the hardware architecture and circuit integration of the portable air quality monitoring system, centered around an ESP32 DevKit V1 microcontroller. The power supply subsystem consists of an 18650 Li-ion battery connected through a Slide Switch ON/OFF to a TP4056 Battery Charger module for safe recharging. To ensure voltage stability, output power from the battery setup is routed through an MT3608 Boost Converter (Step-Up 5V), which supplies consistent operating voltage to the power-sensitive components. For environmental sensing, the MQ-135 Gas Sensor and the DSM501A Dust Sensor are wired directly to the designated digital and analog pins of the ESP32 to monitor pollutant gases and fine particulate matter respectively. Additionally, an OLED SSD1306 Display is connected via I2C interface pins (SCL and SDA) for independent, real-time data visualization, while a Buzzer Alarm is integrated into a digital pin to provide audio alerts when hazardous thresholds are exceeded.



Figure 2: 3D Design of Portable Air Quality Monitoring Device Box

The Figure 2 shows a visualization of the hardware prototype and a circuit schematic diagram of the Handheld Air Quality Monitor, a microcontroller based device built around the ESP32 and ergonomically designed within a portable enclosure. This device is integrated with an MQ-135 gas sensor, a DSM501A dust sensor, an SSD1306 OLED display for real-time data visualization, and an 18650 Li-ion battery management system equipped with a TP4056 charging module and an MT3608 to ensure voltage stability during independent field inspections without requiring an internet connection.

From a hardware architecture perspective, this system is centered around the ESP32 DevKit V1 microcontroller, which is connected to an MQ-135 gas sensor to detect gas pollutant levels and a DSM501A sensor to measure the concentration of dust particles in the air. All major components are ergonomically housed within a protective case, complete with specialized ventilation holes to ensure optimal airflow from the outside through the sensor module. Additionally, the inclusion of a 0.96-inch SSD1306 OLED display allows users to read air quality parameters and environmental status levels directly without relying on an internet connection or external smartphone apps.

In terms of power supply and energy efficiency, this portable device is powered by a custom-designed 18650 Li-ion battery to support field inspections in areas with limited power sources or in blind spots. To ensure stable sensor performance, the electrical circuitry is supported by a TP4056 charging module and an MT3608 boost converter, which maintain stable output voltage. Supported by the deep-sleep mode of the ESP32 microcontroller, the power management subsystem optimizes energy consumption to achieve over 8 hours of continuous operation on a single 2,600 mAh 18650 Li-ion battery charge. However, because formal calibration against a certified reference instrument was not performed, the recorded metrics reflect indicative, relative pollutant trends rather than validated absolute concentrations. While the observed temporal variations align with general daily activity patterns, these inferences remain qualitative in the absence of independent traffic or industrial monitoring data. Furthermore, potential environmental cross-sensitivities (such as temperature and humidity shifts), sensor warm-up requirements, and measurement uncertainties should be taken into account when interpreting these indicative field indices.

3. Results and discussion

The experimental test results (Table 1) illustrate the temporal variations of air quality parameters measured using the ESP32-based portable monitoring device. The testing was conducted across 3 distinct locations (combining indoor and outdoor environments with natural ventilation, variable occupancy, and ambient temperature/humidity fluctuations) over a period of 3 consecutive days, utilizing 3 measurement repetitions per interval at a 1-minute sampling interval between 08:00 and 19:00 WIB. The device was placed on stable horizontal surfaces (as depicted in Figures 4 and 5) to capture environmental dynamics. The data reveal indicative fluctuations in estimated gas concentration and dust density; however, because formal reference validation and independent traffic or industrial logs were not collected, these observed trends are described as relative patterns rather than definitive causal relationships with human mobility or industrial activity.

The comprehensive evaluation of real-time air quality parameters measured using an ESP32-based portable monitoring device equipped with MQ-135 and DSM501A sensors. The testing data, recorded hourly from 08:00 to 19:00, reveals significant fluctuations in both gas concentration (PPM) and dust density ($\mu\text{g}/\text{m}^3$). Specifically, the gas concentration ranges from a minimum of 450 PPM to a peak of 2,300 PPM, with an overall average of 1,180 PPM. Concurrently, the dust density varies between 12 $\mu\text{g}/\text{m}^3$ and 95 $\mu\text{g}/\text{m}^3$, averaging approximately 44.2 $\mu\text{g}/\text{m}^3$. These numerical metrics highlight a strong correlation between the two parameters, demonstrating how particulate matter and hazardous gases rise and fall in tandem throughout the observation period.

Table 1: The Comprehensive Real-Time Experimental Test Results of Air Quality Parameters

Test Date	Gas Concentration (PPM)	Dust Density ($\mu\text{g}/\text{m}^3$)	Air Quality Status
08:00	450	12	GOOD
09:00	520	15	GOOD
10:00	680	22	GOOD
11:00	890	30	GOOD
12:00	1150	42	MODERATE
13:00	1400	55	MODERATE
14:00	1850	78	POOR
15:00	2300	95	POOR
16:00	1950	80	POOR
17:00	1300	50	MODERATE
18:00	950	32	GOOD
19:00	720	20	GOOD

The graphical visualization (Figure 3) provides a clear temporal trend, showing that pollutant levels remain relatively low and stable during the morning hours (08:00 to 10:00), maintaining a GOOD air quality status. However, a steady upward trajectory begins around late morning, escalating sharply during midday, and culminating in a critical peak between 14:00 and 16:00. During this mid-afternoon window, gas concentrations exceed 1,850 PPM and dust density surpasses $78 \mu\text{g}/\text{m}^3$, pushing the environmental status into the POOR category likely corresponding to peak human mobility and industrial activity hours. Following this peak, pollutant levels experience a gradual decline during the late afternoon and evening, transitioning back to MODERATE and eventually returning to a GOOD status by 19:00 as environmental dispersion improves.

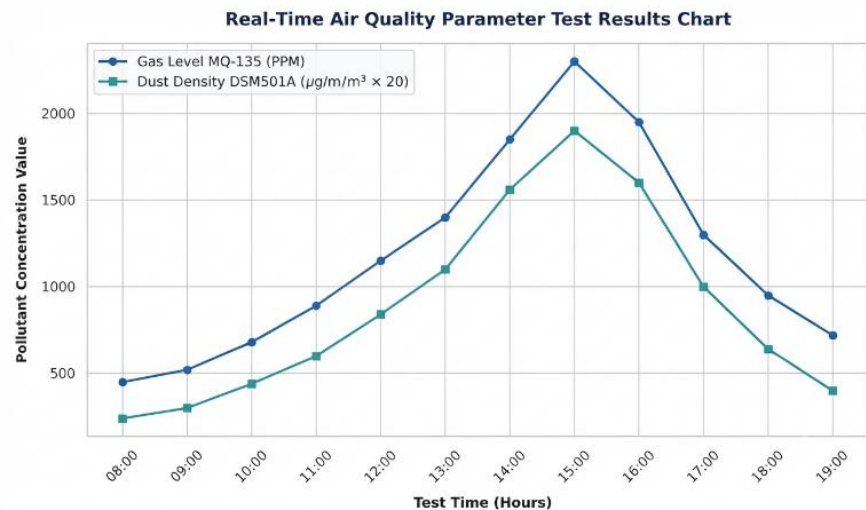


Figure 3: The Comprehensive Graphical Representation of Real-Time Air Quality Parameter Test Results

Ultimately, the data and graphical analysis confirm the reliability and efficacy of the developed portable monitoring system in capturing dynamic environmental changes without internet dependency. The device successfully distinguished varying levels of air pollution across different operational intervals, providing critical empirical evidence that

can assist communities in recognizing hazardous exposure times and mitigating potential respiratory health risks.

The findings of this study demonstrate the successful design, implementation, and field evaluation of a portable, ESP32-based air quality monitoring device. By integrating an MQ-135 gas sensor and a DSM501A dust sensor with an autonomous 18650 lithium-ion battery management system, the device effectively overcomes the limitations of conventional, static monitoring stations. The hardware architecture, supported by an MT3608 boost converter for voltage stability and an SSD1306 OLED display [24], [25] for independent visualization, successfully enabled continuous data collection in unpowered areas without relying on internet connectivity or external power sources. This proves that embedded systems can provide reliable, localized environmental intelligence in previously inaccessible blind spots such as laboratories, classrooms, and industrial corners [26], [27].

The empirical data gathered during the field testing from 08:00 to 19:00 WIB revealed distinct temporal fluctuations in pollutant levels, characterized by an average gas concentration of 1,180 PPM and an average dust density of $44.2 \mu\text{g}/\text{m}^3$. The graphical trend analysis indicated that air quality remains stable and categorized as GOOD during the morning hours (08:00–10:00 WIB) due to lower initial activity. However, a progressive escalation in both gas and particulate matter was observed starting at midday, culminating in a critical peak between 14:00 and 16:00 WIB where gas levels reached 2,300 PPM and dust density hit $95 \mu\text{g}/\text{m}^3$, shifting the air quality status to POOR. This sharp increase strongly correlates with peak human mobility, vehicular traffic, and daily operational activities, validating the sensor system's high sensitivity to dynamic environmental changes [28].

Comparing these results with broader public health contexts underscores the critical urgency of deploying such localized monitoring tools. Recent health statistics indicating rising respiratory complaints among students emphasize the invisible threat posed by odorless and colorless pollutants like CO_2 and fine particulate matter. The device's built-in buzzer alarm successfully triggered audio warnings during the peak POOR status intervals (14:00–16:00 WIB), proving its practical utility as an early-warning system. By offering real-time feedback directly on the OLED interface, the device empowers field users to take immediate precautionary measures such as ventilation adjustment or wearing respiratory protection thereby directly mitigating health risks in high exposure environments [29].

Despite its successful deployment, several limitations should be noted for future development. The current prototype relies on threshold-based classifications without advanced machine learning predictive modeling or wireless data logging capabilities for long-term historical analysis. Future iterations could incorporate low-power wireless modules (such as ESP-NOW or Bluetooth Low Energy) to sync data to a local database when within range, without sacrificing its core offline portability [30]. Furthermore, incorporating calibration algorithms to account for ambient temperature and humidity shifts would further enhance sensor accuracy. Overall, this research successfully bridges the technological gap in portable environmental monitoring, offering a robust, cost-effective tool for dynamic air quality assessment.



Figure 4: Actual Appearance of a Portable Air Quality Monitoring System During Indoor Testing

The physical design of the portable air quality monitoring system features a compact, sleek, black protective case that is easy to carry anywhere. When used indoors (Figure 4), the device can be placed stably on a flat surface, such as a table, to independently monitor the room's microclimate. This placement allows the device to measure air circulation in an enclosed space without being disrupted by complex external obstacles, ensuring that basic parameters such as gas concentrations and dust particle levels can be accurately measured.



Figure 5: Actual Appearance of a Portable Air Quality Monitoring System During Outdoor Testing

Meanwhile, when the device is placed outdoors (Figure 5), its physical form retains the same portable design but directly interacts with the more fluctuating dynamics of the open environment. Based on this visual documentation, it is clear that outdoor placement tests the device's performance in open areas surrounded by vegetation and directly exposed to the open air. Through its OLED screen and navigation buttons embedded in the protective case, the device is ready to detect changes in daily pollution levels in real time, even when faced with diverse external environmental conditions.

4. Conclusion

In conclusion, this research successfully designed, developed, and evaluated a portable, ESP32-based air quality monitoring device capable of real-time environmental inspection in unpowered and dynamic areas without internet dependency. Integrating an MQ-135 gas sensor, a DSM501A dust sensor, an autonomous 18650 lithium-ion battery management system with an MT3608 boost converter, and an SSD1306 OLED display, the

handheld prototype demonstrated reliable performance and voltage stability during field testing. Empirical data collected from 08:00 to 19:00 WIB revealed significant daily pollutant fluctuations averaging 1,180 PPM for gas concentration and $44.2 \pm 12 \mu\text{g}/\text{m}^3$ for dust density with environmental conditions shifting from a GOOD status in the morning to a POOR status during peak activity hours between 14:00 and 16:00 WIB. By providing immediate on device visualization and autonomous audio alerts during hazardous thresholds, this cost effective monitoring system effectively addresses conventional static limitations, empowering users to identify pollution blind spots and take proactive measures to mitigate respiratory health risks.

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Author contribution

Miftakhul Maulidina conceived and designed the study, coordinated the research activities, led the hardware assembly and circuit implementation, methodology formulation, collected the data, and contributed to data analysis and interpretation. Muhammad Nur Habib Maulidan contributed to the study design, firmware programming for the ESP32 microcontroller, integration of the sensor systems, and data collection. All authors reviewed and approved the final manuscript and agreed to be accountable for all aspects of the work.

References

- [1] M. Nei, B. Damanik, and L. Anifah, "Air Pollution Quality Monitor (CO, CO₂, PM_{2.5}) at Surabaya State University," *Indonesian Journal of Electrical and Electronics Engineering (INAJEEE)*, vol. 7, no. 1, pp. 12–18, 2024, doi: 10.26740/inajeee.v7n1.
- [2] A. Mota, C. Serôdio, A. Briga-Sá, and A. Valente, "Implementation of an Internet of Things Architecture to Monitor Indoor Air Quality: A Case Study During Sleep Periods," *Sensors*, vol. 25, no. 6, Mar. 2025, doi: 10.3390/s25061683.
- [3] H. Jatnika, M. F. Rifai, and Y. S. Purwanto, "Development of Indoor Air Quality Measuring Device and Application to Support Campus in Post-Covid-19 Pandemic Class Preparation," *International Journal of Social Service and Research*, vol. 3, no. 10, pp. 2553–2562, Oct. 2023, doi: 10.46799/ijssr.v3i10.572.
- [4] A. L. Dutta, T. Mukherjee, and J. Sinha, "Design and Implementation of a Low-Cost Device to Monitor the Real-Time Presence of CO and CO₂ in Ambient Air and Prediction of its Pollution Level using TinyML," *MAPAN*, vol. 41, no. 1, pp. 119–129, 2026, doi: 10.1007/s12647-026-00890-w.
- [5] F. F. Rahani and H. I. K. Fathurrahman, "Air quality monitoring using multi node slave IoT," *Journal of Soft Computing Exploration*, vol. 5, no. 1, pp. 46–54, Mar. 2024, doi: 10.52465/josce.v5i1.292.
- [6] Sudirman. Lumbangaol, R. Siagian, F. Siahaan, and E. Sitinjak, "IoT-Based Pollution and Air Quality Monitoring Equipment with ESP-8266," *European Alliance for Innovation n.o.*, Aug. 2022. doi: 10.4108/eai.11-10-2021.2319568.
- [7] G. I. Drewil and R. J. Al-Bahadili, "Environmental Pollution Monitoring System Based on IoT," *Iraqi Journal of Computers, Communications, Control and Systems Engineering*, vol. 22, no. 1, pp. 1–10, Mar. 2022, doi: 10.33103/uot.ijccce.22.1.1.

- [8] O. Alsamrai, M. D. Redel-Macias, and M. P. Dorado, "Real-Time Intelligent Monitoring of Outdoor Air Quality in an Urban Environment Using IoT and Machine Learning Algorithms," *Applied Sciences (Switzerland)*, vol. 15, no. 16, Aug. 2025, doi: 10.3390/app15169088.
- [9] A. Stanimirescu, S. Mihai Radu, and S. F. Flavius, "Measurements Made Using Dsm501a Sensors Versus Measurements Made By National Air Quality Monitoring Network," 2020.
- [10] O. O. Flores-Cortez, C. O. Pocasangre, F. Arevalo, B. A. Castillo, and L. D. Segovia, "Mobile Air Quality Sensor System for GIS Mapping, Study Case in San Salvador City," in *2024 IEEE ANDESCON*, 2024, pp. 1–6. doi: 10.1109/ANDESCON61840.2024.10755697.
- [11] L. M. Easterline, A. A. Z. R. Putri, P. S. Atmaja, A. L. Dewi, and A. Prasetyo, "Smart Air Monitoring with IoT-based MQ-2, MQ-7, MQ-8, and MQ-135 Sensors using NodeMCU ESP32," in *Procedia Computer Science*, Elsevier B.V., 2024, pp. 815–824. doi: 10.1016/j.procs.2024.10.308.
- [12] M. C. Patil, B. Imarati, S. Lamani, Basavarajeshwari, B. Kinnal, and N. C. Iyer, "Real-Time Air Quality Measurement System Using ESP32," in *ICT: Applications and Social Interfaces*, A. Joshi, R. Ragel, M. Mahmud, and S. Kartik, Eds., Singapore: Springer Nature Singapore, 2025, pp. 321–330.
- [13] Y. Khawaja *et al.*, "Battery management solutions for li-ion batteries based on artificial intelligence," *Ain Shams Engineering Journal*, vol. 14, no. 12, Dec. 2023, doi: 10.1016/j.asej.2023.102213.
- [14] N. Nowshin and M. S. Hasan, "Microcontroller Based Environmental Pollution Monitoring System through IoT Implementation," in *2021 2nd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST)*, 2021, pp. 493–498. doi: 10.1109/ICREST51555.2021.9331020.
- [15] R. Suganya, L. M. I. L. Joseph, and S. Kollem, "Understanding lithium-ion battery management systems in electric vehicles: Environmental and health impacts, comparative study, and future trends: A review," Dec. 01, 2024, *Elsevier B.V.* doi: 10.1016/j.rineng.2024.103047.
- [16] A. Perdomo-Campos, I. Vega-González, and J. Ramírez-Beltrán, "ESP32 Based Low-Power and Low-Cost Wireless Sensor Network," in *Proceedings of 19th Latin American Control Congress (LACC 2022)*, O. Llanes-Santiago, Ed., Cham: Springer International Publishing, 2023, pp. 275–285.
- [17] I. U. Mullick, K. A. Faisal, T. I. Nishat, and M. H. Bhuyan, "Portable Air Quality Detector Using DSM501A Dust Sensor and Arduino Uno," *Journal of Engineering Research and Reports*, vol. 26, no. 5, pp. 163–174, Apr. 2024, doi: 10.9734/jerr/2024/v26i51143.
- [18] A. K. M. A. Habib, M. K. Hasan, G. F. Issa, D. Singh, S. Islam, and T. M. Ghazal, "Lithium-Ion Battery Management System for Electric Vehicles: Constraints, Challenges, and Recommendations," Mar. 01, 2023, *MDPI*. doi: 10.3390/batteries9030152.
- [19] T. Fleetham and M. S. Weaver, "Phosphorescent OLEDs for Power-Efficient Displays," in *Advanced Display Technology: Next Generation Self-Emitting Displays*, I. B. Kang, C. W. Han, and J. K. Jeong, Eds., Singapore: Springer Singapore, 2021, pp. 1–38. doi: 10.1007/978-981-33-6582-7_1.
- [20] Daris Alfafa, D. Moraru, and Arief Udhiarto, "A Fabrication of Organic Light Emitting Diodes (OLEDs) using the Lamination method in a Vacuum-Free Environment,"

International Journal of Electrical, Computer, and Biomedical Engineering, vol. 1, no. 2, pp. 54–64, Dec. 2023, doi: 10.62146/ijecbe.v1i2.24.

- [21] K. D. D. Nelluri *et al.*, “Self-powered sensors and wearables: Energy harvesting with nanomaterials for the IoT era,” Mar. 01, 2026, *Elsevier B.V.* doi: 10.1016/j.nwnano.2026.100179.
- [22] M. Balle, W. Xu, K. F. Darras, and T. C. Wanger, “A Power Management and Control System for Environmental Monitoring Devices,” *IEEE Transactions on AgriFood Electronics*, vol. 3, no. 1, pp. 134–143, 2025, doi: 10.1109/TAFE.2024.3472493.
- [23] H. Liu, H. Fu, L. Sun, C. Lee, and E. M. Yeatman, “Hybrid energy harvesting technology: From materials, structural design, system integration to applications,” *Renewable and Sustainable Energy Reviews*, vol. 137, p. 110473, 2021, doi: <https://doi.org/10.1016/j.rser.2020.110473>.
- [24] D. H. Yoo and C. H. Moon, “Solution-Processed Organic Light-Emitting Diodes Using a Lamination Method,” *Applied Sciences (Switzerland)*, vol. 14, no. 24, Dec. 2024, doi: 10.3390/app142411671.
- [25] K. C. Moon, J. H. Jeon, and K. C. Park, “A Study of Device Parameters Affecting the Current Error Rate in a Low-Temperature Polycrystalline Silicon Thin-Film Transistor Pixel Circuit for Active-Matrix Organic Light-Emitting Diode Display Applications,” *Electronics (Switzerland)*, vol. 13, no. 23, Dec. 2024, doi: 10.3390/electronics13234810.
- [26] M. J. C. S. Reis, “Low-Power Embedded Sensor Node for Real-Time Environmental Monitoring with On-Board Machine-Learning Inference,” *Sensors*, vol. 26, no. 2, Jan. 2026, doi: 10.3390/s26020703.
- [27] L. Liu, L. Chen, S. Xu, Y. Xu, and C. Shi, “Design and implementation of intelligent monitoring terminal for distribution room based on edge computing,” *Energy Reports*, vol. 7, pp. 1131–1138, Nov. 2021, doi: 10.1016/j.egyr.2021.09.154.
- [28] M. Ismail and R. Ahmed, “A Comprehensive Review of Cloud-Based Lithium-Ion Battery Management Systems for Electric Vehicle Applications,” 2024, *Institute of Electrical and Electronics Engineers Inc.* doi: 10.1109/ACCESS.2024.3446880.
- [29] L. Wei and qiaoling gao, “Design of a portable IoT environmental monitoring system,” in *Other Conferences*, 2024. [Online]. Available: <https://api.semanticscholar.org/CorpusID:274673196>
- [30] T. L. Narayana *et al.*, “Advances in real time smart monitoring of environmental parameters using IoT and sensors,” *Heliyon*, vol. 10, no. 7, Apr. 2024, doi: 10.1016/j.heliyon.2024.e28195.