



Design, Implementation, and Performance Evaluation of a Real-time Industrial Air Quality Monitoring System using ESP32 and Multi-gas Sensors

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ABSTRACT

Abstract— Industrial air pollution poses significant risks to human health and environmental sustainability, particularly in regions affected by mining and other industrial activities. Pollutants such as ozone (O₃), carbon monoxide (CO), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and particulate matter, as observed in Ikpeshe and Iloke due to mining operations in Edo State, Nigeria, contribute to both acute and chronic health conditions, including cardiovascular diseases, lung cancer, and respiratory infections. Conventional air-quality monitoring systems are often expensive, difficult to deploy, and limited in their ability to provide continuous, remotely accessible data. This study presents the design, implementation, and performance evaluation of a cost-effective, real-time industrial air-quality monitoring system based on the Internet of Things (IoT). The system utilizes an ESP32 Wi-Fi microcontroller integrated with MQ-135 and MQ-2 gas sensors to detect variations in air pollutants and combustible gases. An OLED display and the Blynk IoT platform facilitate both local and remote access to monitoring data. The system was designed and simulated in Proteus and implemented in a compact 3D-printed enclosure. Experimental evaluation examined sensor responses to different gas-source proximities, carbon monoxide generated during wood combustion, and changes in the air quality index (AQI). Results demonstrated a direct correlation between pollutant-source proximity and sensor response: sensor resistance decreased, and output voltage increased as the gas source approached the sensing elements. In the carbon monoxide experiment, measured concentrations increased from 10 ppm as smoke accumulated in an enclosed environment, confirming the system's ability to detect declining air quality. Similarly, the AQI rose from 24 under baseline conditions to hazardous levels after petroleum exposure, then decreased after the pollutant source was removed. The complete system consumed approximately 3.33 W, with an estimated battery operating time of 5.3 hours. These findings suggest that the proposed IoT-enabled system provides a compact, low-power, and remotely accessible solution for real-time air-quality monitoring and early pollution alerts in industrial environments. The system offers potential for affordable environmental monitoring and could be further enhanced through sensor calibration, expanded pollutant detection, and integration with advanced data analytics.

ARTICLE INFO

Article History

Received: February, 2026

Received in revised form: March, 2026

Accepted: May, 2026

Published online: June, 2026

KEYWORDS

Air Quality Monitoring; Internet Of Things; ESP32; Gas Sensors; MQ-135; MQ-2; Real-Time Monitoring; Environmental Monitoring; Industrial Pollution

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INTRODUCTION

Air pollution introduces unpleasant odours, particulate matter, and harmful gases into the environment. The impact of these pollutants depends on their type and concentration, potentially causing adverse health effects for individuals residing or working near affected areas over time (Seesaard, Kamjornkittikoon, & Wongchoosuk, 2024). Industrialisation, deforestation, and rapid expansion of transportation are primary contributors to pollution in developing countries, yet awareness and control measures remain insufficient. This has led to a significant increase in respiratory illnesses among populations (Rentschler & Leonova, 2023). The financial burden on governments may become substantial if air quality continues to decline.

Conventional air quality monitoring equipment, often considered essential, typically relies on manual handheld devices, which are inefficient and labour-intensive, or on wired systems that are difficult to scale, bulky, and costly. These traditional systems frequently fail to account for industry-specific and environmental adaptability, space limitations, and operator expertise, restricting broader implementation (Paithankar *et al.*, 2023). As the detrimental effects of various pollutants become more evident amid economic and technological advancement, there is an increasing demand for effective and affordable indoor air quality monitoring solutions. This demand is fostering the development of innovative wireless systems capable of addressing these challenges. Accordingly, this study developed an improved air quality monitoring system that provides real-time monitoring of carbon monoxide (CO) and liquefied petroleum gas, with instant alerts for users.

LITERATURE REVIEW

Extensive research has addressed air quality monitoring and management. Venkata Sudhakar & Reddy (2023) critically evaluated the environmental impact of air pollutants from the cement industry. Paithankar *et al.* (2023) developed a low-power wireless area network for effective air quality monitoring, leveraging the

Internet of Things to measure air quality changes. Ionascu (2024) proposed calibration methods for nitric oxide, sulfur dioxide, and particulate matter to improve air pollution detection. Goh *et al.* (2025) examined factors influencing the adoption of artificial intelligence (AI) in air quality monitoring systems using the UTAUT model, highlighting the roles of performance expectations, effort, and social influence in technology uptake.

Rahaman (2025) discussed Smart Environmental Monitoring Systems (SEMS) that utilise IoT, AI, and blockchain to enhance air and water quality management, emphasising their effectiveness in real-time pollution tracking, regulatory compliance, and public engagement, while also noting challenges to broader adoption. Garcia *et al.* (2025) reviewed AI applications in air quality monitoring, identifying challenges related to data availability and algorithm effectiveness, and underscoring the need for standardised evaluation procedures. Aini *et al.* (2025) investigated factors influencing Behavioural Intention to Use (BIU) Air Quality Monitoring Solutions (AQMS), emphasising Technology Readiness (TR) and Hedonic Motivation (HM), and identifying HM as a key determinant for adoption. Wahyudi *et al.* (2025) presented an IoT-based air quality monitoring system for indoor environments, featuring real-time data processing and user-friendly reporting to ensure timely alerts and promote healthier conditions.

Öncü *et al.* (2025) investigated potentially toxic elements (PTEs) in street dust in Istanbul, revealing significant contamination from industrial runoff, traffic emissions, and natural sources, and highlighting the need for pollution management strategies. Nor *et al.* (2025) discussed a real-time air quality monitoring system for ducted air-conditioning systems to enhance filtration efficiency and indoor air quality, emphasising the importance of air filters and the impact of clogged filters on energy consumption and air quality. Khaleefah (2025) presented a low-cost IoT weather and air-quality monitoring node based on the ESP8266/ESP32 and various sensors, detailing its design, implementation, and evaluation, and providing a blueprint for replication and future enhancements.

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Air Quality Index

The air quality index (AQI) (Paithankar, 2023) is a widely accepted scale used to evaluate air quality in a region by measuring levels of pollutants such as particulate matter, ozone, nitrogen dioxide, sulfur dioxide, and carbon monoxide. Each pollutant is assigned a numerical value, which is then categorized into a specific level of air quality, ranging from 'Good' to 'Hazardous'. These categories are represented by distinct colours, indicating the degree of health risk associated with air quality and providing a clear,

concise way to communicate air quality information to the public. An AQI value of 100 corresponds to the national standard for protecting public health, and values at or below 100 are considered satisfactory. However, when AQI values exceed 100, air quality becomes unhealthy, initially posing risks to sensitive groups and eventually to everyone as the values continue to rise. The AQI provides valuable information for public awareness, policymaking, and implementing measures to protect public health during periods of poor air quality.

Table 1: Air Quality Index Scale for Ozone and Particles Pollution (Odubanjo, 2024)

AQI Color	Color Level	Index Values	Description of Air Quality
Green	Good	0 - 50	Air quality is satisfactory, and air pollution poses little or no risk.
Yellow	Moderate	51 - 100	Air quality is acceptable. However, there may be a risk for some people, particularly those who are unusually sensitive to air pollution.
Orange	Unhealthy for Sensitive Groups	101 - 150	Members of sensitive groups may experience health effects. The general public is less likely to be affected.
Red	Unhealthy	151 - 200	Some members of the general public may experience health effects; members of sensitive groups may experience more serious health effects.
Purple	Very Unhealthy	201 - 300	Health alert: The risk of health effects is increased for everyone.
Maroon	Hazardous	301 - higher	Health warning of emergency conditions: everyone is more likely to be affected.

Internet of Things (IoT)

The Internet of Things is a transformative technology that simplifies human tasks by seamlessly integrating various devices and communication technologies (Li, Wang, Wang, & Zhang, 2024). It connects physical (sensors, communication devices wired/wireless) and virtual objects (virtual machines, web applications), allowing for the collection and analysis of various data types from diverse applications through the Internet. Increasingly, organisations in a variety of industries are using IoT to deliver enhanced customer service, operate more efficiently, improve decision-making and increase the value of the business (Gills & Alexander 2021). Overall, IoT technology is the foundation of modern pollution monitoring,

allowing for efficient and effective environmental management (Ayele & Mehta, 2018).

Sensors

A sensor is a device designed to detect changes in its surroundings and produce a response in another system. It converts physical phenomena into a measurable signal, either as a digital signal or an analogue voltage, which is displayed for further processing or human interpretation (Idakwo *et al.*, 2018). Sensors are widely found in everyday devices, such as lamps that adjust brightness via touch, touch-sensitive elevator buttons, and numerous other applications often unnoticed by users. Sensors are available in various types, like those that detect gases, particulate matter, temperature, and sound. These

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sensors provide essential real-time data, supporting informed decision-making and effective pollution control strategies, thereby safeguarding public health and the environment (Abutu *et al.*, 2018)

Environmental Health and Air pollution

Air pollution refers to the contamination of the air by harmful substances, known as pollutants. The pollutant can negatively impact the environment, human health, and other living organisms (Seesaard, Kamjornkittikoon, & Wongchoosuk, 2024). It has remained a significant environmental issue, posing a major challenge in modern societies. The adverse effects of air pollution extend to natural ecosystems, human health, man-made structures, and wildlife. Furthermore, it contributes to climate change by intensifying the greenhouse effect, depleting the ozone layer, and causing acid rain, which are global environmental problems of paramount concern. Air pollution can occur both outdoors and indoors, resulting from natural processes and human activities.

While the deterioration of air quality poses a worldwide threat to human wellbeing, it is closely linked to environmental inequality. Differences in air pollution exposure and its effects are evident across countries, with developing nations facing more severe indoor air pollution. In these regions, organic fuels like wood and coal are commonly used for cooking and heating, and their

combustion releases harmful pollutants, especially particulate matter, into homes.

Developed System

The proposed smart pollution monitoring system comprises hardware and software components. The hardware segment consists of various components like:

1. Microcontrollers that process and analyse data
2. A lithium battery that provides backup power
3. An OLED display that shows real-time data
4. A power module that ensures a reliable energy supply
5. Sensors that detect and measure pollutant levels.

These hardware components work together to collect and transmit data.

Arduino UNO

The Arduino Uno R3 Microcontroller was adopted as the brain of the smart walking stick. The different sensors were attached to the board as it has fourteen (14) digital input and output (I/O) pins attached to the board. This eases scalability by allowing more sensors to be added. Furthermore, it has six (6) analogue inputs, a USB connection, an ICSP reset button, and a power jack as shown in Figure 1 (Sabado, 2024)

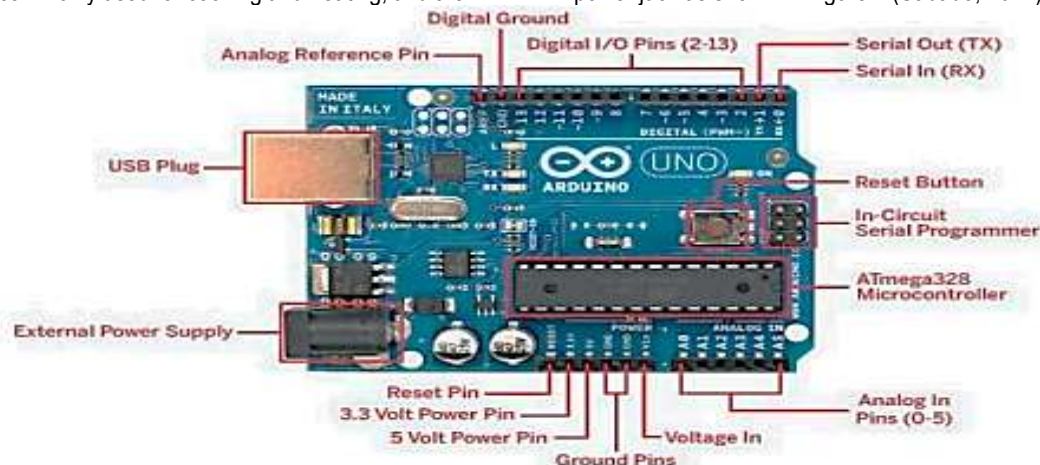


Figure 1: Arduino Uno R3

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The Arduino Uno processes inputs from different sensors and uses programmed logic to make decisions before sending signals to actuators like buzzers and LEDs as feedback to the user.

NodeMCU ESP8266

The NodeMCU ESP8266 shown in Figure 2 is an affordable and popular development board widely used for IoT projects (Lezcano Sirre, 2024). It features a built-in Wi-Fi-enabled ESP8266 microcontroller, making it ideal for connecting to devices and networks. Its compact size and versatility allow it to interface with sensors, actuators, and peripherals through GPIO pins. Supporting multiple programming languages, including Lua, Arduino IDE, and MicroPython, it caters to developers of varying skill levels. Its strong community support and powerful features make it a top choice for this research.

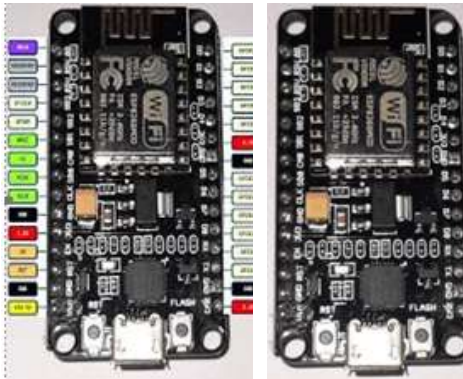


Figure 2: ESP8266 Node MCU 1st generation Development Board and Pin

MQ-135, MQ-7, and MQ-2 sensors

The MQ-135, MQ-7, and MQ-2 sensors shown in Figure 3 are essential components in this research as they play a critical role in detecting harmful gases. The MQ-135 sensor is a versatile air quality monitoring tool, capable of detecting a wide range of gases, including benzene, nitrogen oxides, and ammonia, for both outdoor and indoor environments. It provides valuable insights into pollution levels and enables measures to maintain healthy living conditions and environmental

sustainability. The MQ-7 sensor, on the other hand, is specifically designed for carbon monoxide detection. The MQ-2 sensor offers versatility by detecting combustible gases such as propane, methane, and hydrogen. Their unique ability to detect various gases makes them ideal for detecting leaks and pollutants.



Figure 3: MQ2 and MQ135 Sensor (Easterline, 2024)

These sensors detect gases by measuring changes in resistance, which directly correlate with the gas concentration. When connected to electronic devices or microcontrollers, they can monitor gas levels, automate control, and trigger alarms.

Lithium Battery

A lithium battery, as shown in Figure 4, provides a reliable backup power source, offering consistent and efficient energy during outages or critical situations. Its key features, including high energy density, long shelf life, and low self-discharge rates, make it an ideal choice for the developed system.

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Figure 4: Lithium Battery

OLED Portable Display Unit

Organic Light Emitting Diode (OLED) screens (Ashraf et al., 2024), as shown in Figure 5, offer a visual experience characterised by wide viewing angles, high contrast, and rich colours. It belongs to the class of display technologies that use organic compounds to generate light when electrically stimulated. In contrast to conventional liquid crystal displays, OLEDs do not require a backlight, thus enabling more flexible, thinner, and energy-efficient designs. These unique features make OLEDs a popular choice for various applications, including wearable devices, TVs, and smartphones, where exceptional image quality and versatility are essential.



Figure 5: Organic Light Emitting-diode Display

The Software segment, on the other hand, comprises programming tools like Arduino IDE and the Blynk IoT application that facilitates remote monitoring and analysis of real-time data.

Arduino IDE

The Arduino Integrated Development Environment (IDE) is a user-friendly software tool for programming Arduino microcontroller boards, as shown in Figure 6. It simplifies development by allowing users to easily write, compile, and upload code. Featuring C/C++-based syntax, the IDE includes helpful tools like syntax highlighting, code auto-completion, and error checking to support efficient, error-free coding.



Figure 6: Arduino IDE

Proteus

Proteus (Arif et al., 2024) is a powerful software suite designed for electronic circuit design, simulation, and PCB layout, offering a comprehensive platform for creating, testing, and refining circuits in a virtual environment. By enabling digital design and simulation, it helps users save time and resources by reducing the need for physical prototypes and minimising errors. Furthermore, it has an extensive library of components and an intuitive interface, as shown in Figure 7.

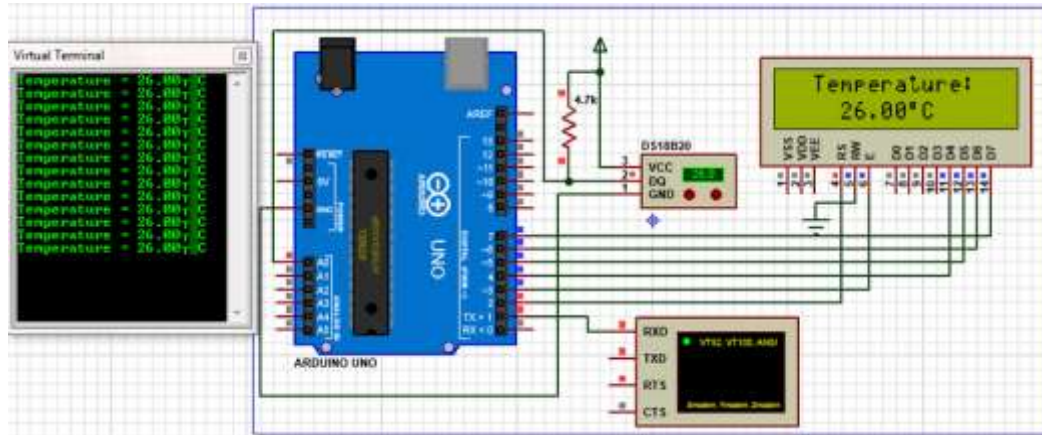


Figure 7: Circuit Simulation in Proteus

Blynk IoT

Blynk IoT is an innovative platform designed to simplify the creation of Internet of Things projects and accommodate users of all skill levels (Suhaidi & Yunus, 2021). Its user-friendly drag-and-drop interface, as shown in Figure 8, allows for easy development of custom control panels, while its cloud-based system enables real-

time data monitoring, analysis, and visualisation. Blynk seamlessly integrates with popular hardware like Arduino and Raspberry Pi, offering compatibility with a wide range of IoT devices. With features such as remote device management, data analytics, and alert systems, Blynk empowers users to develop advanced IoT applications with ease, making it ideal for this research.



Figure 8: Blynk IoT Interface

Power Consumption by the Developed System

The system was designed with a dual power source, from an AC-DC adapter and a battery bank. Each works independently and simultaneously, providing the system with all-

around-the-clock operation. The supply voltage is selected to be above the system operating voltage; hence, it can be sufficient to power the system. The power demand for the proposed system is shown in Table 2.

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Table 2: Power Demand by the Proposed System

Sn	Component	Voltage	Current	Power	Source
1	Esp 32 Wi-fi Module	5	0.206	1.03	Mouser Electronics
2	Mq 135	5	0.15	0.75	Elveta
3	Mq 2	5	0.15	0.75	Elveta
4	IC2 Backpack	5	0.05	0.25	Addicore
5	LCD 16x2	5	0.102	0.51	Addicore
6	LED	2	0.02	0.04	Stream light
Total			0.678	3.33	

The total current and power drawn by the system is 0.678A and 3.33w respectively. Two lithium battery of 3.6v each were connected to meet the voltage supply requirement using equation (1) (Bustos, R. et. al., 2022) during the system design.

$$\text{BatteryVoltage} = E_s > D_v \quad (1)$$

Where V_s is the Supply Voltage
 D_v is the Device Operating Voltage
 $D_v = 5V$

The electromagnetic force in series was evaluated using equation (2)

$$E_s = \sum_{k=1}^n E \quad (2)$$

$$E_s = 3.6 + 3.6 = 7.8_v$$

To evaluate the backup-time by the lithium battery (3.6v, and 3.6A from the lithium battery description) equation (3) was adopted.

Given:

Battery Current = 3.6A

Load Current = 0.678 A

$$B_r = \frac{B_c(\text{AmpsHour})}{I(\text{Amps})} \quad (3)$$

Where B_r is the Battery Backup-Time

B_c is the Battery capacity

I is the current Load

∴

$$B_r = 3.6(A) / 0.678(A) = 5.3\text{hours}$$

Therefore, the estimated operating time of the system is 5.3hours provided all physical condition remain constant. Recall that the circuit demand 3.33W of power. Hence, it is expedient to

select an effective transformer for the ac-dc conversion. The transformer is the center hub of power for any AC-DC conversion circuit power reliance system. Using a tolerance of 20% to account for heat and other physical conditions, the transformer required was evaluated using equation (4).

$$P_{\text{Transformer}} = P_{\text{circuit}}(1 + T) \quad (4)$$

Given:

$P_{\text{circuit}} = 3.33w$

$T = 0.20$

Therefore:

$$P_{\text{transformer}} = 3.33 \times (1 + 0.20) = 3.996w.$$

A transformer with a power rating greater than 3.995w is required. The voltage selection of the transformer is determined by the battery voltage. The transformer voltage must exceed the battery voltage to ensure efficient charging. Given the battery bank voltage of 7.6V and considering market availability, a step-down transformer from 220VAC to 12VAC was selected. Considering factors such as size, cost, availability, and reliability, a transformer rated at 12W, which exceeded the required 3.995W was chosen.

Selecting Voltage Regulator

Given the required voltage of the regulator:

$$V_s = 5v$$

The current requirement is calculated using the mathematical expression given by equation (5)

$$I = \frac{P_{\text{transformer}}}{V_r} \quad (5)$$

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Given :

$$P_{\text{transformer}} = 3.995\text{w}$$

Therefore:

$$I = \frac{3.995}{5} = 0.799$$

The available regulator in the market is rated at 1A, which is greater than 0.799A, and thus, it was selected for the design.

Selection of Smoothing Capacitor

To select the smoothing capacitor for the AC-DC converter, equation (6) was used.

$$C = \frac{I}{2 \times f \times V_{pp}} \quad (6)$$

Where: I = load current in amperes.

F is the frequency = 100Hz (Full wave rectifier)

V_r is the maximum ripple voltage in volts = 1v.

$$I_{\text{load}} = \frac{3.995}{12} \approx 0.33\text{A}$$

$$C = \frac{0.33}{2 \times 100 \times 1} = 0.00165\text{F}$$

$$C = 1650\mu\text{F}$$

The nearest to this in the market is 2200uf thus it was chosen for the work. From the values obtain from equation(1) to (5) the matching components value where select from the proteus library to design the circuit prototype as shown in Figure 9.

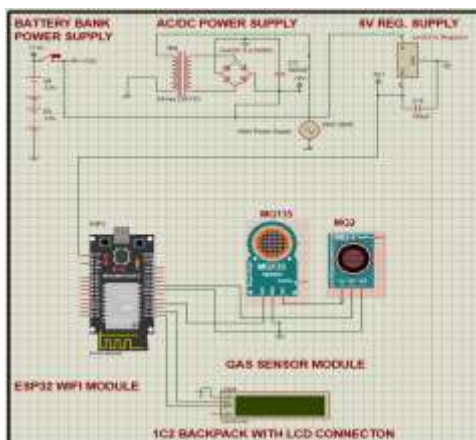


Figure 9: Circuit Design Using Proteus Software

Packaging

To ensure that the developed circuits fit well into a portable package, the casing dimensions were first designed before printing using a 3D printer. The step-by-step design showing the detailed isometric view (left, right, back, front, south-west and north-east) is presented in Figure 10

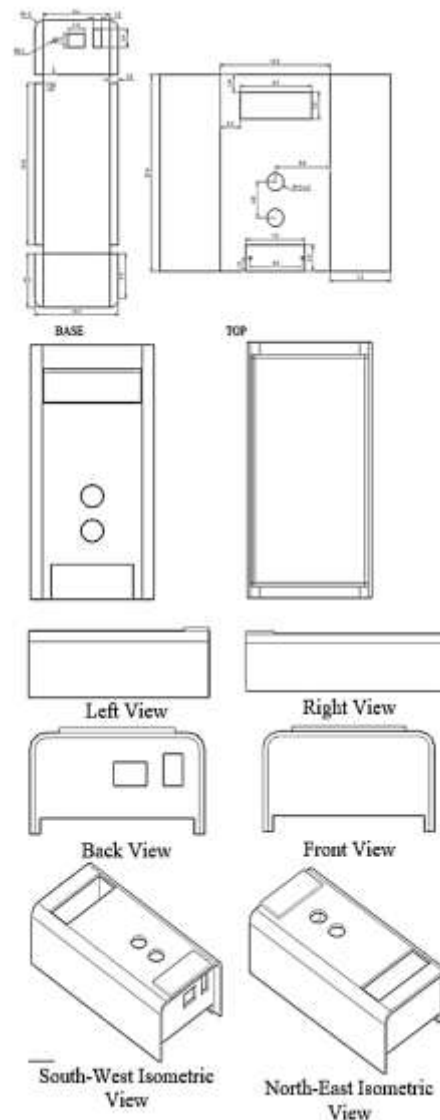


Figure 10: Orthographical Projection

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RESULTS AND DISCUSSION

The designed circuit was neatly enclosed within the 3D-printed casing, as illustrated in Figure 11.

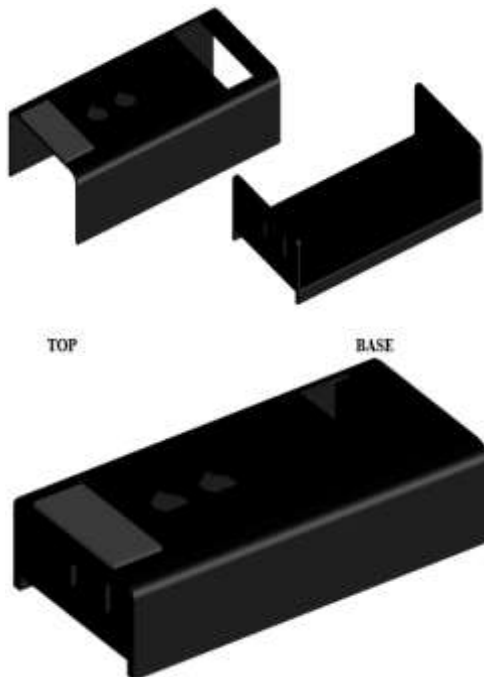


Figure 11: Developed System Casing

Figure 11 demonstrates that the developed system casing is compact and portable, providing a convenient solution for housing the circuit. This design enables straightforward deployment in industrial areas and supports remote access to environmental pollutant readings, thereby ensuring both practicality and efficiency.

Proximity Sensor Evaluation

To ascertain the developed system's sensitivity to pollutants, the distance between the MQ135 and MQ2 sensors and the LNG pollutant sources was varied. The results obtained from the variation of the MQ135 and MQ2 sensors in response to LNG pollutant sources are presented in Tables 3 and 4, respectively.

Table 3: MQ135 Sensor Proximity to Gas Pollutant

Gas Proximity (cm)	Resistance (r)	Voltage (v)
1	2.1	3.1
5	3.8	1.2
10	4.19	0.88
20	4.29	0.67
30	4.47	0.58

Table 4: MQ2 sensor distance variation with LNG

Gas Proximity (cm)	Resistance (r)	Voltage (v)
1	1.8	4.3
5	5	2.6
10	6.25	2
20	6.6	1.7
30	7	1.5

Table 3 and Table 4 indicate that as the LNG source approaches the sensing element, increasing the gas concentration, the sensor's resistance decreases. This inverse relationship leads to an increase in voltage, consistent with Ohm's Law, which states that the voltage across a conductor is directly proportional to the current at constant resistance. Consequently, lower resistance yields higher voltage for a given current. This behaviour confirms the sensors' effectiveness in detecting gas concentrations. Therefore, the proximity of the pollutant source to the sensor significantly reduces the sensor's resistance, enhancing its accuracy in detecting and responding to the presence of gas.

Cabon Monoxide Detection

The developed system was further subjected to the fluctuations in carbon monoxide (CO) levels over a 40-minute period during wood combustion. The system response, with measurements taken at 5-minute intervals, is shown in Figure 12.

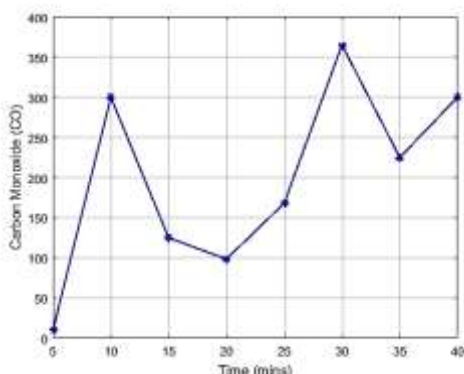


Figure 12: Carbon monoxide detection

Figure 12 shows that at the 5-minute mark, the CO concentration is 10 ppm, measured just before wood was placed in an enclosed space, allowing smoke to accumulate. Following enclosure, CO levels gradually increase, eventually reaching hazardous levels, which indicates elevated pollutant concentrations and unsafe air quality. The data also suggest a temporary reduction in smoke density, followed by a subsequent increase due to continued combustion.

Air Quality Index

To ensure adequate air-quality measurements, the sensor was placed in an enclosed space and exposed to a container of petroleum. The observation from the experimental setup is shown in Figure 13.

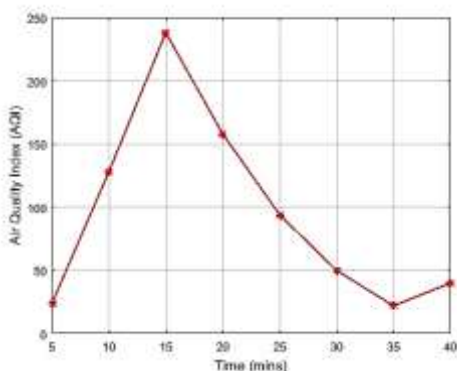


Figure 13: Air quality index measurement

Figure 13 illustrates changes in the Air Quality Index (AQI) over a 40-minute period, with measurements taken at 5-minute intervals. At the 5-minute mark, the AQI is 24, indicating good air quality. After the sensor is exposed to a container of petroleum in an enclosed space, the AQI rises steadily, eventually reaching hazardous levels, which signal increased pollutant concentrations and unsafe air. Once the petroleum container is closed, the AQI decreases consistently, reflecting pollutant dispersion and subsequent improvement in air quality.

Developed System Graphical User Interface

The developed improved air-quality measurement graphical user interface allows users to monitor air quality remotely, as shown in Figure 14.



Figure 14: Developed Graphical User Interface

The system includes an intuitive interface that supports real-time monitoring of environmental pollutants. The developed module is remotely accessible and controllable through a user-friendly frontend, which integrates with the ESP32-WiFi module to enable continuous real-time data transmission. This design offers a reliable and robust solution for efficient environmental management.

CONCLUSION

This study presents an enhanced air-quality measurement system with a user-friendly interface. The proposed system delivers high efficiency in precise measurement, real-time data collection, and energy optimization. It accurately monitors pollutants and noise levels, facilitating timely responses to environmental changes. Designed for low power consumption and cost-



effective operation, the system maximizes resource utilization while ensuring compliance with regulatory standards.

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