

IoT-Based Low-Cost Indoor Air Quality Monitoring and Data Logging System: Comparative Analysis with Standard Devices

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Abstract. Air pollution is one of the crucial environmental and public health issues. Traditional air quality monitoring systems provide accurate data but are expensive and are fixed in certain areas, limiting access to rural settings. This paper develops a low-cost, portable, and real-time air quality monitoring system using an ESP-32-WROOM-32 microcontroller and three sensors, PMS5003, MQ-7B, and DHT11, to measure particulate matter, carbon monoxide, temperature, and humidity, respectively, and tests it for analysis. The system was tested with Aerocet 831 for particulate matter and Aeroqual Series 500 for carbon monoxide in a controlled environment with no airflow. The experiment showed major deviations for PMS5003 and acceptable deviations for carbon monoxide, with temperatures ranging from 20°C to 30°C and humidity ranging from 40% to 60%. The results demonstrate the scope of the low-cost air quality monitoring system for improved accuracy through sensor calibration.

Keywords: IoT; AQM; IAP meter; CO; PM; Biomass

1. Introduction

Air pollution is the presence of harmful substances in the air, including particulate matter, nitrogen oxides, sulfur dioxide, carbon monoxide, volatile organic compounds, and ozone, that can affect health and the environment [1]. These substances originate from various sources, such as industrial emissions, vehicular exhaust, burning fossil fuels, wildfires, and biomass combustion.

In 2019, 99% of the world's population was exposed to air pollution above the WHO's safety limits [2]. The safe levels as per WHO for PM_{2.5} are 15 µg/m³, and PM₁₀ is 45 µg/m³ over 24 hours, yet many countries report concentrations far above these thresholds [3]. There are 6.7 million premature deaths due to air pollution annually [4]. Alarmingly, by March 2025, only 7 countries met the WHO's PM_{2.5} air quality guideline [5].

In the context of Nepal, significant air pollution occurs due to its reliance on traditional biomass for cooking, rapid urbanization, and unregulated industrial activities. Approximately 69% of the population still uses biomass fuels for cooking, leading to severe indoor air pollution in rural areas [6]. This has caused cardiovascular disease and respiratory diseases like Chronic Obstructive Pulmonary Disease (COPD) and pneumonia, affecting women and

children. Outdoor air quality is also a matter of concern, as Kathmandu Valley, **capital of Nepal**, is often ranked among the most polluted cities globally [7]. On April 10, 2024, the recorded PM_{2.5} levels were 510 µg/m³, 34 times higher than WHO's recommended annual limit [7,8]. Such extreme pollution levels emphasize the immediate need for mitigation strategies.

However, air quality management is hindered by the lack of reliable, real-time monitoring data and the high cost of mitigation technologies. Although traditional air quality measurement instruments are highly accurate, they are expensive and require continuous maintenance. Therefore, this paper addresses this gap by developing a portable, cost-effective, and real-time Indoor Air Pollution meter for CO, PM₁, PM_{2.5}, PM₁₀, temperature, and humidity. The system was built with an ESP32 microcontroller with CO, PM, and temperature/humidity sensors. Sensor data is collected by ESP32 and transferred to the MySQL database with the use of Python API. For real-time data visualization, the mobile application was developed, and this entire system was powered by a USB. This paper presents a comparison of the two sensors, PMS5003 and MQ-7, with standard devices and explains the feasibility of using low-cost sensors for Indoor Air Pollution (IAP) meters.

2. Component Selection and System Design

During biomass combustion, emitted particulate matter, especially PM_{2.5}, can penetrate deep into the lungs, causing severe health issues, whereas carbon monoxide reduces oxygen transport in the bloodstream. The system is focused on detecting these two pollutants [9]. The choice of sensors was based on cost effectiveness, low power consumption, and their compatibility with the microcontroller, whereas the microcontroller was chosen for its built-in Wi-Fi, which makes it easier for real-time data transmission. The Air Quality Monitoring (AQM) system consists of the following components:

1. Particulate Matter Sensor (PMS5003): It measures PM₁, PM_{2.5} and PM₁₀ concentrations using laser scattering technology. For the PM_{2.5} standard, it can measure from (0-500) µg/m³, and beyond 1000 µg/m³, the readings are extrapolated. The lifespan is around 2 years [10].
2. Carbon Monoxide Sensor (MQ-7B): It detects CO levels based on changes in the resistance of a metal oxide semiconductor material. It can detect from 10-500 ppm. The lifespan of this sensor ranges from 3 to 5 years [11].
3. Temperature and Humidity Sensor (DHT11): It measures temperature (0°C to 50°C) and humidity (20% to 90%) with high accuracy. It has a lifespan of about 2 years [12].
4. Microcontroller (ESP32-WROOM-32): It collects data from the sensors, processes it, and transmits it to the database via built-in Wi-Fi with a lifespan of 10+ years [13].

System Architecture:

Figure 1 illustrates that the system initializes when the power is on, collects data from PMS5003, MQ-7B, and DHT11 sensors, processes it on the ESP32, and transmits it via Wi-Fi. The data is then stored in a database through an Application Programming Interface (API) and visualized in real time.

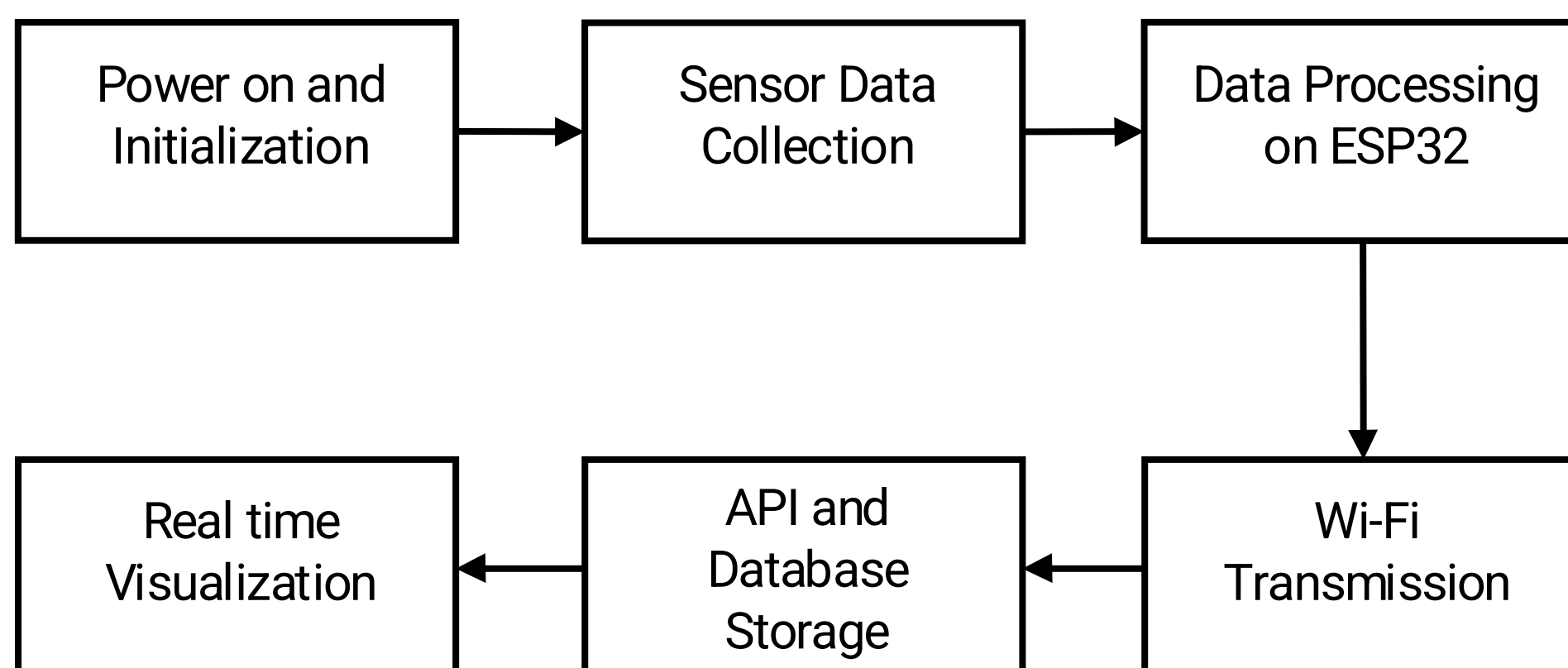


Figure 1. Block Diagram of Data Flow Process

3. Design and Calculations

3.1 Electrical Circuit and Printed Circuit Board Design

As shown in the **Figure 2**, the PMS5003 sensor was connected to the ESP32's UART pins for stable serial communication. The MQ-7B sensor requires an analog input, so it was connected to one of ESP32's ADC pins, and the DHT11 sensor was connected to a digital GPIO pin for communication. For the custom Printed Circuit Board design, the ESP32 was placed at the center to minimize wiring complexity. With this design, proper voltage supply to all components and efficient data transfer are ensured. Also, voltage regulators are not needed as the USB power directly meets the ESP32's requirements.

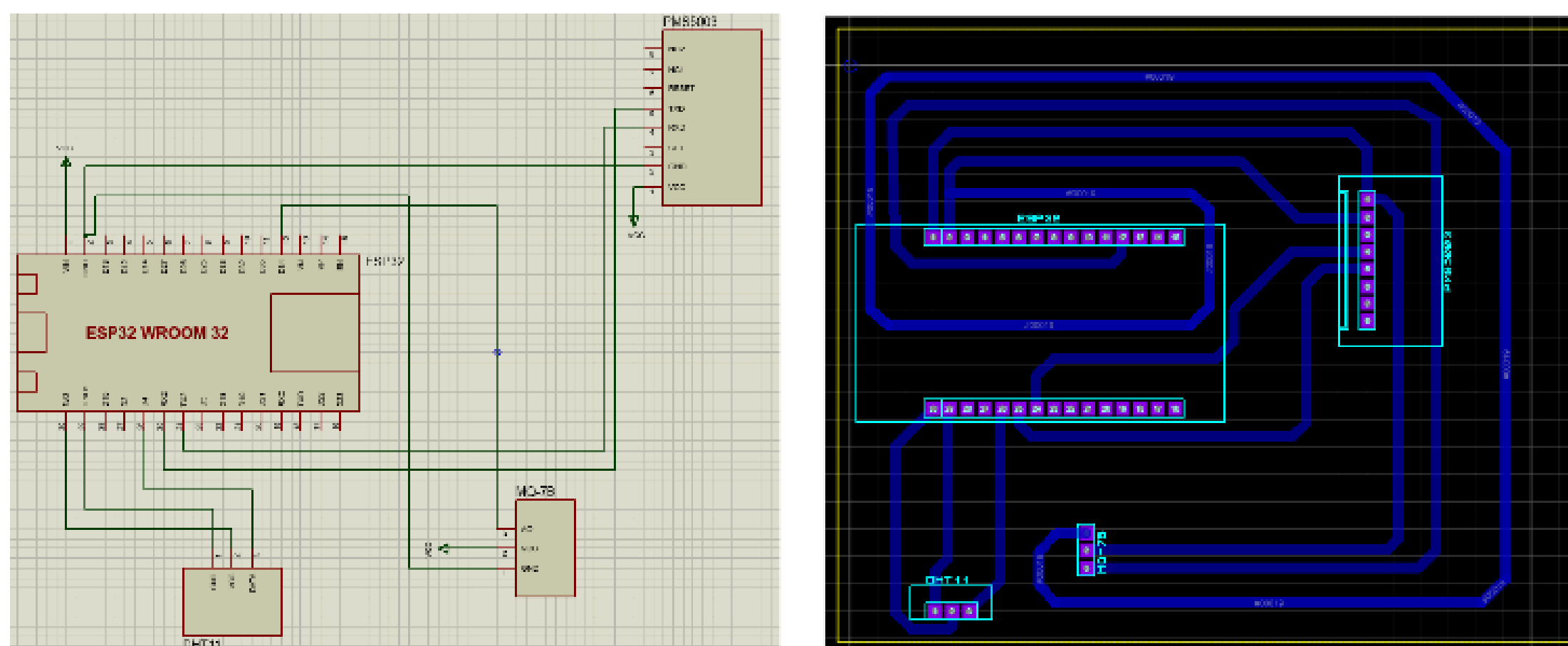


Figure 2. Circuit diagram and Printed Circuit Board design

3.2 CAD Model and Final Product

Figure 3 illustrates the CAD model developed using SolidWorks provides a designated space for flat placement of PCB, mounting points for securing sensors, and access to USB. The ESP-32 was placed at the center, and the sensors were kept close to their respective pins for efficient connections, and overheating was minimized by adding ventilation. To ensure portability and electrical insulation, polylactic acid was used for 3D printing the CAD model.

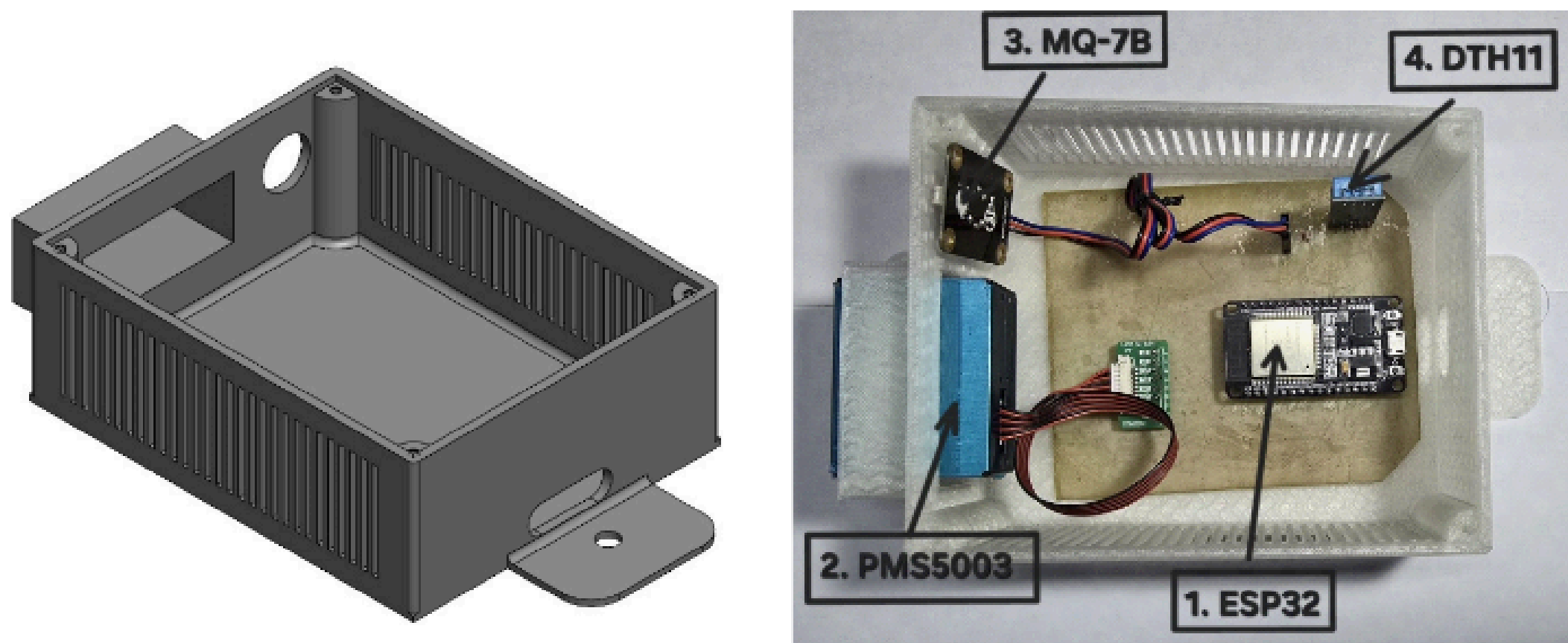


Figure 3. CAD and Final Product

3.3 Power Calculation

For each component, both the current draw and the power consumption were calculated by using the following formula:

$$P = V \times I$$

where P is power, V is operating voltage, and I is current draw. This calculation provides an accurate estimate of the total power demand, which is essential for selecting an appropriate power supply.

Table 1. Calculation Data

Table 1 summarizes the operating voltage, current, and power consumption of the components used in the AQM system.

Components	Operating Voltage (V)	Current Consumption (mA)	Power Consumption (W)
ESP32-Wroom-32	5	160	0.8
PMS5003	5	40	0.2
DHT11	3-5	2.5	0.0125
MQ-7B	5	150	0.75

Total Current Draw: $I = 160 \text{ mA} + 40 \text{ mA} + 150 \text{ mA} + 2.5 \text{ mA} = 352.5 \text{ mA}$

Total Power Consumption: $P = 0.8 \text{ W} + 0.2 \text{ W} + 0.7 \text{ W} + 0.0125 \text{ W} = 1.76 \text{ W}$

The calculations suggest that the system requires 5V at 352.5 mA to function, which can be provided by the USB 3.0 port with 5V at 900 mA, even with an extra load from the Wi-Fi of ESP32.

3.4 Software Design

The software is intended for data collection, processing, storage, and real-time monitoring. Sensor data was processed by a Python-based API, which has extensive libraries and is efficient for real-time data handling [14]. MySQL has been used for structured data storage

and retrieval of data [15]. A Flutter-based mobile app has been developed to support real-time tracking based on its compatibility to run on both IOS and Android [16].

3.5 Experimental Setup

The AQM system was tested in an enclosed room with a volume of 26 m³ to ensure controlled environmental conditions. A traditional cooking stove served as the pollution source, producing particulate matter (PM) and carbon monoxide (CO). Sensors were positioned 1 meter away from the stove and 1.5 meters above the floor surface, approximating typical human breathing height. The PMS5003 and MQ-7B sensors measured PM and CO concentrations, respectively, alongside temperature and humidity sensors. Reference instruments (Met One Aerocet 831s and Aeroqual Series 500) were used for comparative validation. Figure 4 presents the schematic and actual experimental setup.

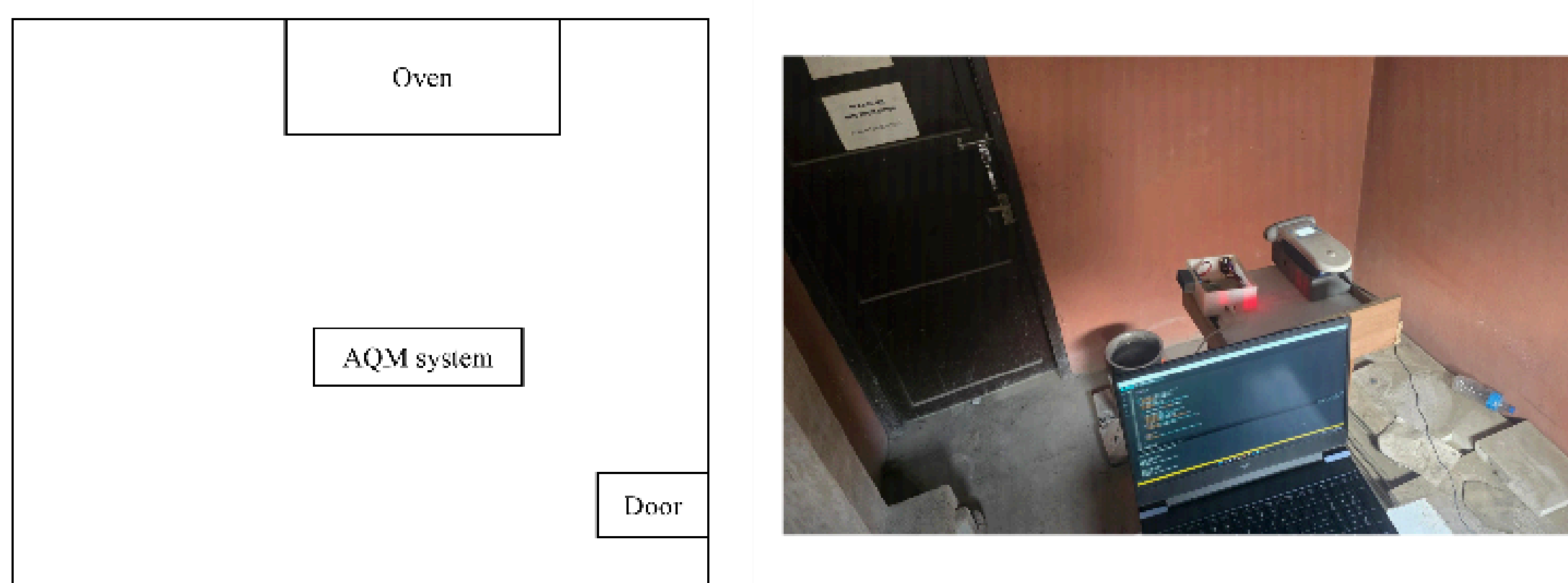


Figure 4. Schematic and Actual Experimental Setup

4. Results and Discussion

To check the performance of our IAP meter, a water-boiling test **version 4.2. 4 was performed under no wind condition using biomass having moisture content range between 7-10% in wet basis**, focusing on the cold-start of the one-pot cooking stove at the Air Pollution and Health Research lab of Kathmandu University. The experiment was conducted for 4 hours in a room volume of 26 m³, and the results are as shown.

As shown in Figure 5, the MQ-7B captured the overall trend of CO concentration, increasing during combustion. However, it consistently overestimated values compared to the Aeroqual Series 500. This indicates the sensor's sensitivity and the necessity for calibration for accurate use.

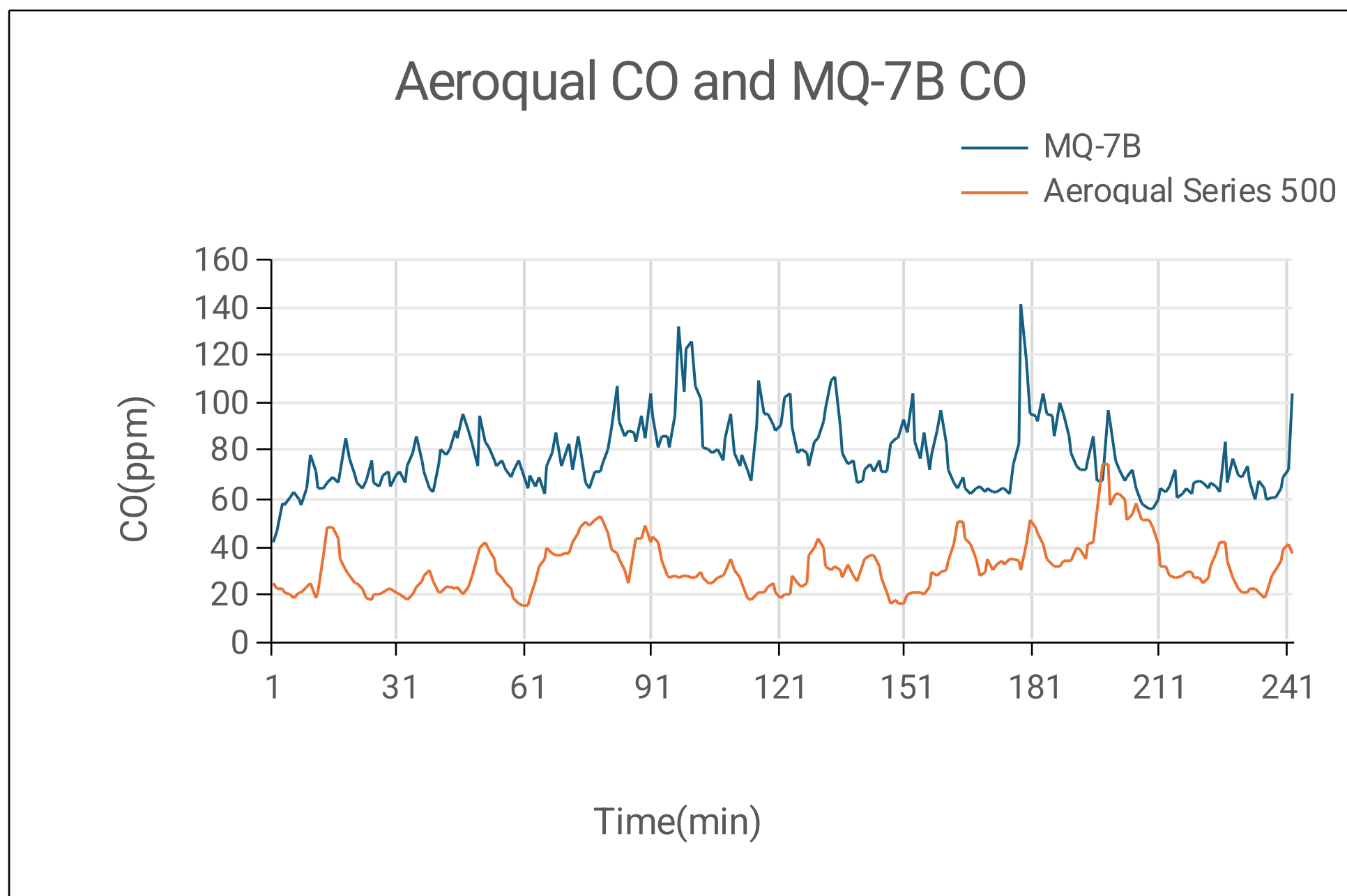


Figure 5. Aeroqual CO and MQ-7B CO

Figure 6 illustrates that the PMS5003 reflected the increasing PM₁ levels during biomass combustion, with fluctuations corresponding to combustion phases. It recorded higher values than the Aerocet 831s, requiring correction.

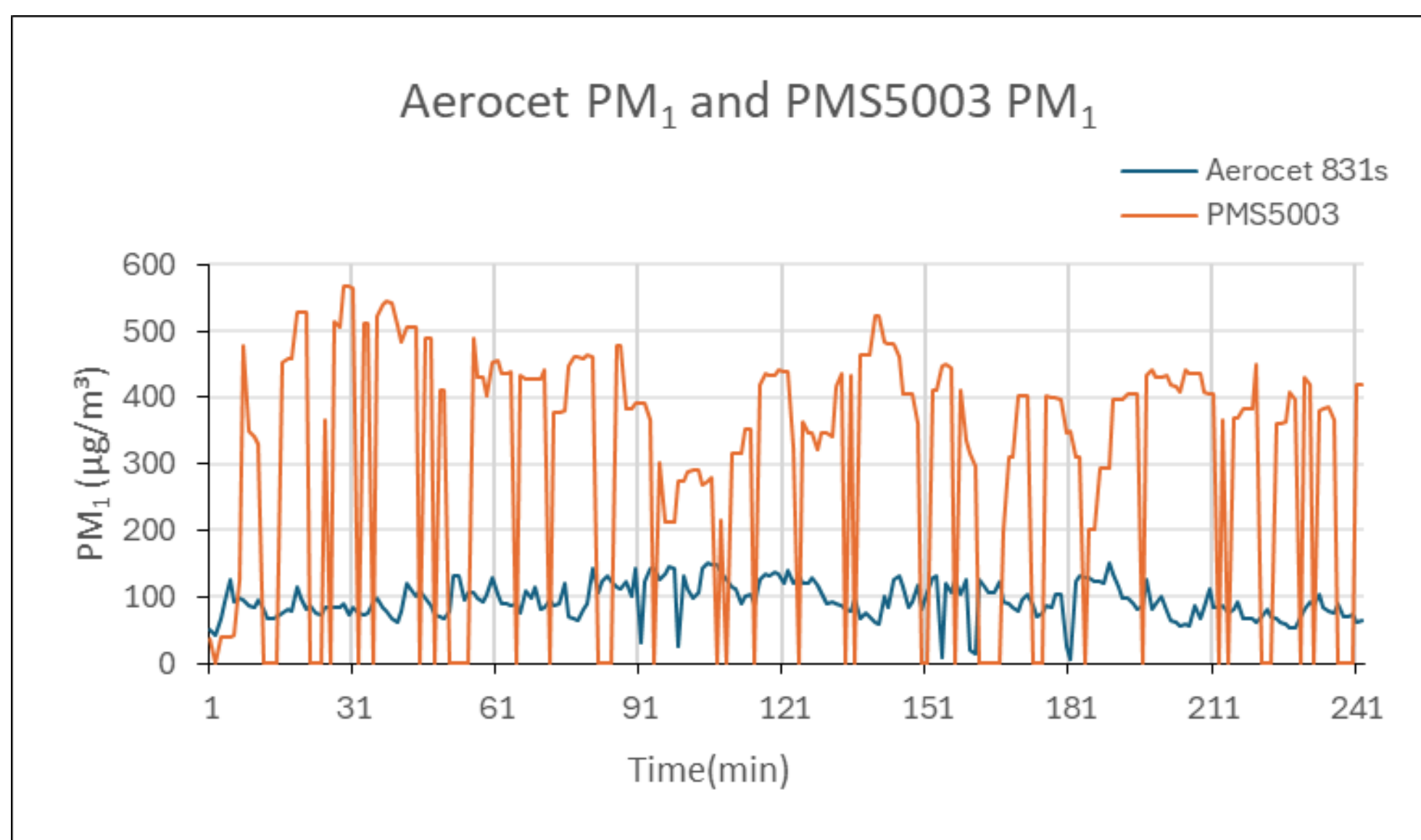


Figure 6. Aerocet PM₁ and PMS5003 PM₁

Figure 7 shows that the PM_{2.5} levels increased with combustion, with PMS5003 displaying a similar pattern to Aerocet 831 but with greater fluctuation and higher readings. This reflects its responsiveness but also highlights the need for calibration.

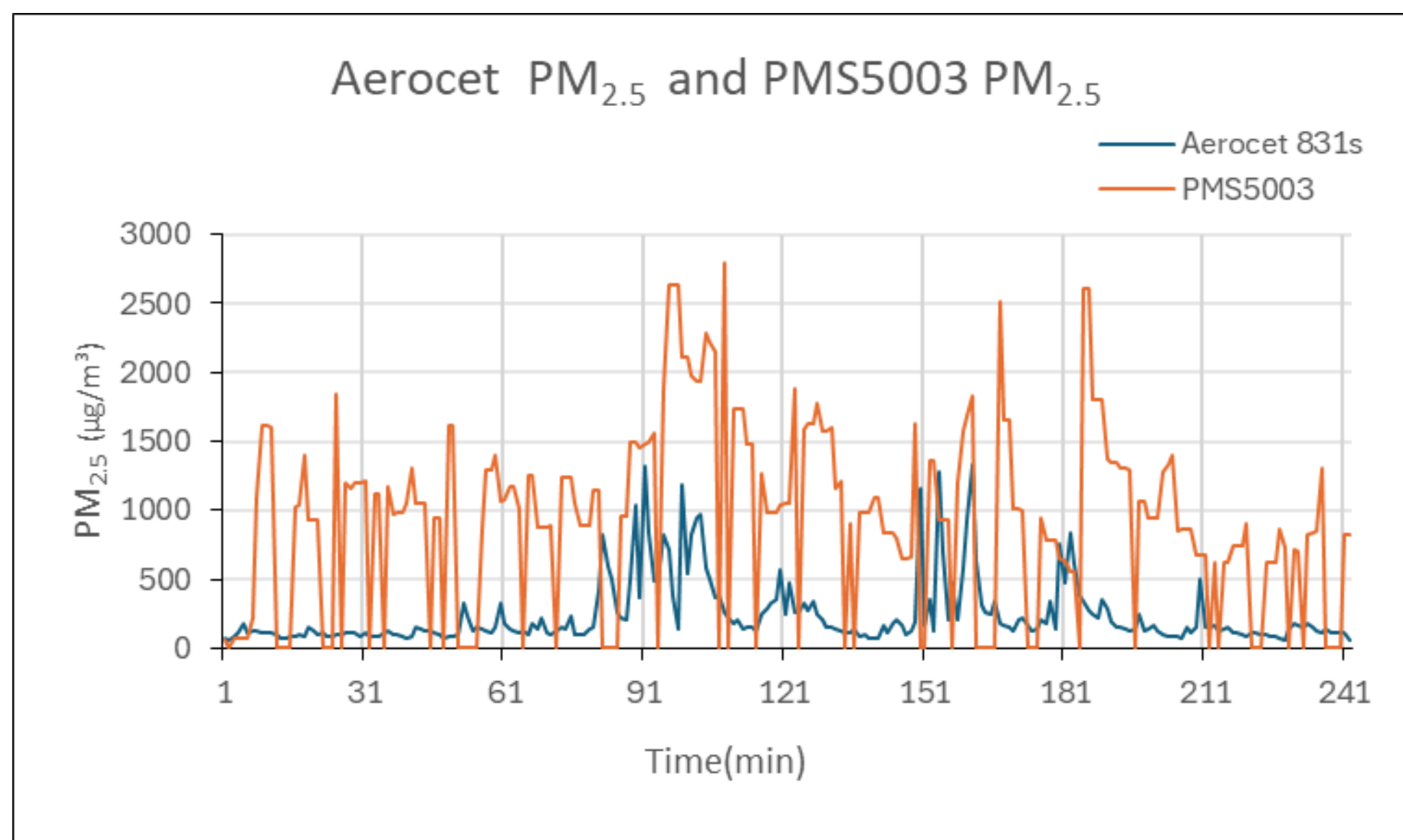


Figure 7. Aerocet PM_{2.5} and PMS5003 PM_{2.5}

Figure 8 suggests that the PM₁₀ levels rose steadily during the experiment. PMS5003 followed this trend but consistently overestimated concentrations, indicating lower accuracy for larger particles under uncalibrated conditions.

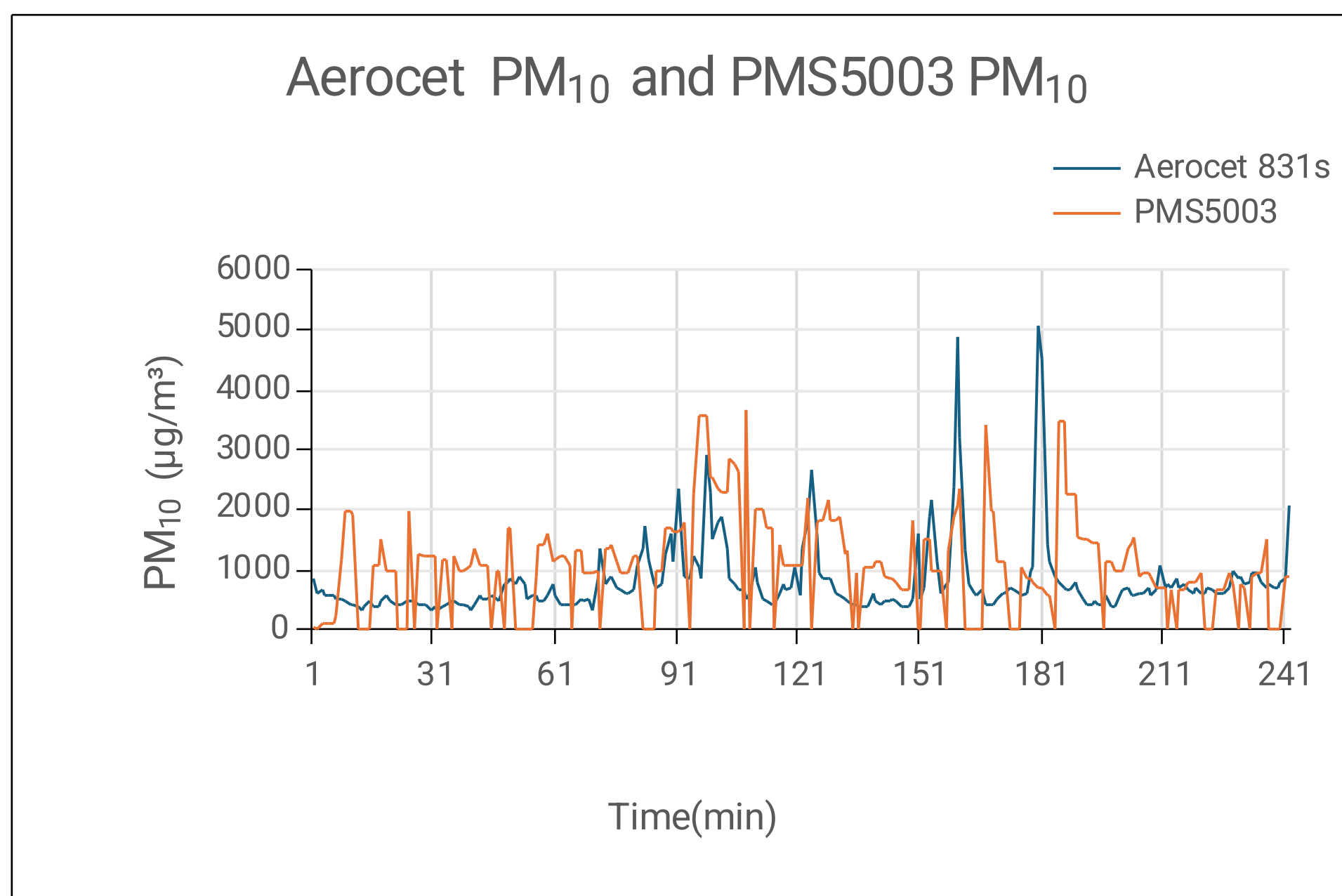


Figure 8. Aerocet PM₁₀ and PMS5003 PM₁₀

5. Conclusion

This study shows that low-cost sensors like the PMS5003 and MQ-7B can effectively measure air quality when properly calibrated. The system consumes about 1.76 W of power at 5 V, making it suitable for portable and battery-powered use. Although low-cost sensors have higher variability than professional devices, this research demonstrates that their performance can be optimized to provide reliable data for monitoring particulate matter and carbon

monoxide. These results support the use of affordable sensors for widespread air quality monitoring, especially in areas where expensive equipment is not feasible. Future work should focus on improving calibration techniques, adding sensors for more pollutants, and developing real-time correction methods. These steps will help create more accurate and scalable air quality monitoring systems, benefiting environmental management and public health.

References

- [1] Shaffer R M, Blanco M N, Li G, Adar S D, Carone M, Szpiro A A, Kaufman J D, Larson T V., Larson E B, Crane P K and Sheppard L 2021 Fine particulate matter and dementia incidence in the adult changes in thought study Environ Health Perspect 129
- [2] World Health Organization. (October 24 2024). Ambient (outdoor) air pollution
- [3] WHO European Centre for Environment and Health 2021 WHO global air quality guidelines: Particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide, and carbon monoxide
- [4] Wang W, Zhang L, Zhao J, Qi M and Chen F 2020 The effect of socioeconomic factors on spatiotemporal patterns of pm_{2.5} concentration in Beijing-Tianjin-Hebei region and surrounding areas Int J Environ Res Public Health 17
- [5] World Health Organization W 2024 2024 World Air Quality Report: Region & City PM_{2.5} Ranking
- [6] Paudel D, Jeuland M and Lohani S P 2021 Cooking-energy transition in Nepal: Trend review Clean Energy 5 1–9
- [7] The Kathmandu Post 2024 Kathmandu world's most polluted city, again
- [8] IQAir 2024 Nepal Air Quality Index (AQI) and Air Pollution information
- [9] Suriyawong P, Chuetor S, Samae H, Piriyaakarnsakul S, Amin M, Furuuchi M, Hata M, Inerb M and Phairuang W 2023 Airborne particulate matter from biomass burning in Thailand: Recent issues, challenges, and options Heliyon 9 e14261
- [10] Plantower Product Specification Product: Laser Particle Sensor Product model
- [11] Jain M and Ramesh S 2023 *Accuracy analysis of MQ-7B sensor in low-cost air monitoring systems* **Int. J. Eng. Adv. Technol.** 12(3) 45–49.
- [12] Divyashree J, V V A, Arkasali V N, B R K and Haller M 2024 DHT11 Sensor: A Comprehensive Study on Temperature and Humidity Sensor International Journal of Scientific Research in Engineering and Management
- [13] Maier A, Sharp A and Vagapov Y 2017 Comparative analysis and practical implementation of the ESP32 microcontroller module for the internet of things 2017 Internet Technologies and Applications, ITA 2017 - Proceedings of the 7th International Conference (Institute of Electrical and Electronics Engineers Inc.) pp 143–8
- [14] Hillar G C 2016 Building RESTful Python Web Services Create web services that are lightweight, maintainable, scalable, and secure using the best tools and techniques designed for Python
- [15] Farnham B, Tokyo S, Boston B, Sebastopol F and Beijing T Efficient MySQL Performance Best Practices and Techniques
- [16] Zaccagnino C Programming Flutter Native, Cross-Platform Apps the Easy Way