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Development of an IoT-Integrated Smart Sensor System for Real-Time Outdoor Air Quality Monitoring

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ABSTRACT

Outdoor air quality plays a crucial role in ensuring public health and environmental well-being. This study aims to develop an outdoor real-time Air Quality Monitoring System (AQMS) capable of capturing reliable, real-time data without overheating when exposed to varying weather conditions. The system features a protective casing that shields the electronic components from environmental factors while maintaining high operational accuracy. The research begins by identifying the relevancy of particulate matter (PM)2.5, PM10, temperature and humidity towards urban pollution and meteorological impact. The casing design adheres to the IEC 60529 standard, which specifies the degrees of protection provided by enclosure against the intrusion of solid objects and water, thus ensuring the system's durability and reliability in outdoor conditions. Key electronic components integrated into the system include various air quality sensors, a Raspberry Pi 4 microcontroller, and a DC exhaust fan for regulating internal airflow. Computer-aided design (CAD) software is employed to develop the 3D model of the AQMS casing. The design is embedded with structural features optimized for ventilation performance and component protection. The prototype was constructed with a prefabricated Polyvinyl Chloride (PVC) protective casing and a custom aluminum roof fabricated through laser welding. The validation process was conducted by comparing the AQMS performance in both open and enclosed configurations under controlled conditions. For post-processing, data were analyzed by using Grafana and Excel, and the results indicated that the developed AQMS successfully preserved sensor accuracy with minimal error within an acceptable range. This finding confirms the effectiveness of the AQMS design, demonstrating its suitability for potential real-world applications.

Keywords: AQMS, Particulate Matter, Casing, Outdoor

1. Introduction

Outdoor air pollution has long been recognized as a critical global public health issue, contributing to millions of premature deaths annually, primarily due to chronic exposure to fine particulate matter such as PM2.5 and PM10 [1]. The health implications of air pollution are extensive, affecting multiple organ systems and all age groups. Notably, prolonged exposure has been linked to adverse reproductive outcomes, including reductions in semen volume, sperm concentration, total motility, progressive motility, and normal morphology rates. Simultaneously, a significant increase in the DNA fragmentation index (DFI) has been observed [2]. These reproductive effects are hypothesized to arise from air pollution-induced oxidative stress, genotoxicity, and the bioaccumulation of toxic substances such as heavy metals and polycyclic aromatic hydrocarbons (PAHs), which interfere with spermatogenesis and DNA integrity [2]. Children and adolescents are particularly susceptible to the harmful effects of air pollutants. Research indicates that increased levels of particulate matter ($PM_{2.5}$, PM_{10}), ozone (O_3), nitrogen dioxide (NO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and sulfur dioxide (SO_2) are associated with reduced lung function, with the most pronounced impacts occurring within three to four days of exposure [3]. Moreover, children with pre-existing conditions such as asthma are even more vulnerable. A growing body of evidence also links air pollution to the progression of myopia in children aged 6 to 12 years, with pollutants such as $PM_{2.5}$, CO, and O_3 demonstrating a clear dose-response relationship [4]. The proposed mechanisms include disruption of dopamine pathways, allergic inflammation, tissue hypoxia, and direct remodeling of the scleral tissue. In addition to these condition-specific health outcomes, atmospheric particulate matter containing heavy metals (HMs) has been associated with an increased risk of respiratory and cardiovascular diseases, neurological disorders, and various cancers. Children are at elevated risk for both carcinogenic and non-carcinogenic health effects due to their higher respiratory rates, hand-to-mouth behaviors, and developing biological systems [5].

Given these widespread and severe health consequences, air pollution is now regarded as a significant global public health emergency. The World Health Organization (WHO) underscores the urgency of this issue, reporting that a substantial majority of the global pediatric population breathes air that exceeds WHO guideline limits. As such, accurate assessment of personal air pollution exposure is essential for epidemiological studies and public health policymaking. However, fixed-site ambient monitoring stations often fail to account for individual variability in mobility and microenvironments, leading to significant exposure misclassification [6]. Furthermore, indoor air quality (IAQ) has emerged as an equally critical concern, particularly as individuals spend approximately 80–90% of their time indoors. Indoor pollutant concentrations often exceed outdoor levels, especially in poorly ventilated or urban households, even in areas that meet ambient air quality standards [7]. These factors highlight the necessity of improving exposure assessments by incorporating both indoor and outdoor environments into monitoring strategies.

To address this challenge, Air Quality Monitoring Systems (AQMS) have become vital tools for tracking and understanding pollution exposure. However, the performance, accuracy, and reliability of AQMS are highly dependent on the resilience of their components to environmental stressors. In regions such as Malaysia, which features a tropical climate characterized by high humidity, elevated temperatures, and frequent rainfall, maintaining sensor functionality becomes increasingly difficult. These climatic conditions accelerate degradation processes in sensitive electronic components, leading to issues such as corrosion, electrochemical migration, and conductive anodic filament (CAF) formation, which ultimately compromise system accuracy and lifespan [8]. Existing AQMS solutions often rely on 3D-printed enclosures made from materials such as polylactic acid (PLA). While PLA offers ease of fabrication, it is relatively expensive and exhibits poor durability under UV radiation and high-moisture conditions common environmental stressors in Malaysia's climate [9]. This underscores a critical gap: the need for a cost-effective, robust, and weather-resistant protective casing that can safeguard internal electronics while preserving at least 90% of the system's operational accuracy.

This study aims to develop an IoT-based AQMS integrated with a DC exhaust fan to regulate internal airflow and maintain optimal sensor operating temperatures. The primary objective is to design a casing that preserves at least 90% of the system's operational accuracy under various environmental conditions.

2. Air Quality Monitoring System (AQMS)

An AQMS is a system that combines different sensors and technologies to evaluate, track and monitor air quality. The AQMS is generally categorized into manual and automated systems. The manual monitoring systems mainly involve laboratory-based systems. As for automated monitoring systems, they encompass fixed monitoring stations, mobile monitoring systems, aerial monitoring systems, and satellite systems that are designed to measure pollutants with specific functions[10]. These systems are pivotal in protecting public health and the environment by delivering precise and prompt information on air pollution rates.

The manual approach is proven to be the most precise technique. However, the manual AQMS approach is incapable of providing users with real-time data and it is highly relying on laboratory-based methods for capturing outdoor air quality parameters[10, 11]. These characteristics have made this method less favorable in modern applications, and there is a significant need to shift towards automated AQMS to achieve real-time monitoring and provide continuous data. According to the United States Environmental Protection Agency (USEPA), various pollutants such as particulate matter (PM), ground-level ozone (O_3), carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen dioxide (NO_2) have to be consistently monitored and measured to protect public health [12]. The automated AQMS employs Internet of Things (IoT) like wireless technology, Wi-Fi and Bluetooth. These features aid the instant transfer of collected data to computers, thus allowing the establishment of a monitoring network [13]. This approach is relatively economical as it could be constructed by utilizing inexpensive sensors, known as low-cost sensors (LCS) [14]. The automated AQMS could be classified into various types, distinguished by their operational features and deployment strategies. Some of the most common AQMS types including station-based, satellite-based, mobile-based, and aerial platform-based.

Fixed monitoring stations are the most extensively used in air quality assessment due to their simplicity and high level of precision. With reference to the study conducted by E. Collado [15], the systems would collect data on pollutants like PM, NO_2, SO_2, PM2.5, PM10 and O_3 and usually placed in areas with high pollution where regular monitoring is necessary[16]. In the present study by E. Collado, a fixed monitoring station was developed to measure ambient temperature, humidity, and the pollutants mentioned above, along with meteorological data such as wind speed, direction and precipitation. Two microcontrollers are used to manage multiple sensors to optimize the functionality and precise data acquisition. The ethernet cable allows data transmission while ensuring a stable and high-speed connection. The collected data is then transmitted through the Internet and displayed on a user-friendly interface. To validate the system accuracy, sensor measurements were compared with a commercial-grade device known as the Aeroqual Series 500. It was found out that the device showed a minimal error, which further strengthened that the fixed monitoring station could offer reliable data collection. With the combination of comprehensive engineering theories, validated simulation methods and smart environmental sensing, the AQMS developed able to provide a scalable and sustainable solution to address air pollution monitoring challenges in urban and industrial regions.

3. Methodology

This study primarily focuses on the development of an IoT-Integrated Smart Sensor System for Real-Time Air Quality Monitoring. Figure 1 illustrates a systematic procedure to develop an IoT-Integrated Smart Sensor System for Real-Time Air Quality Monitoring.

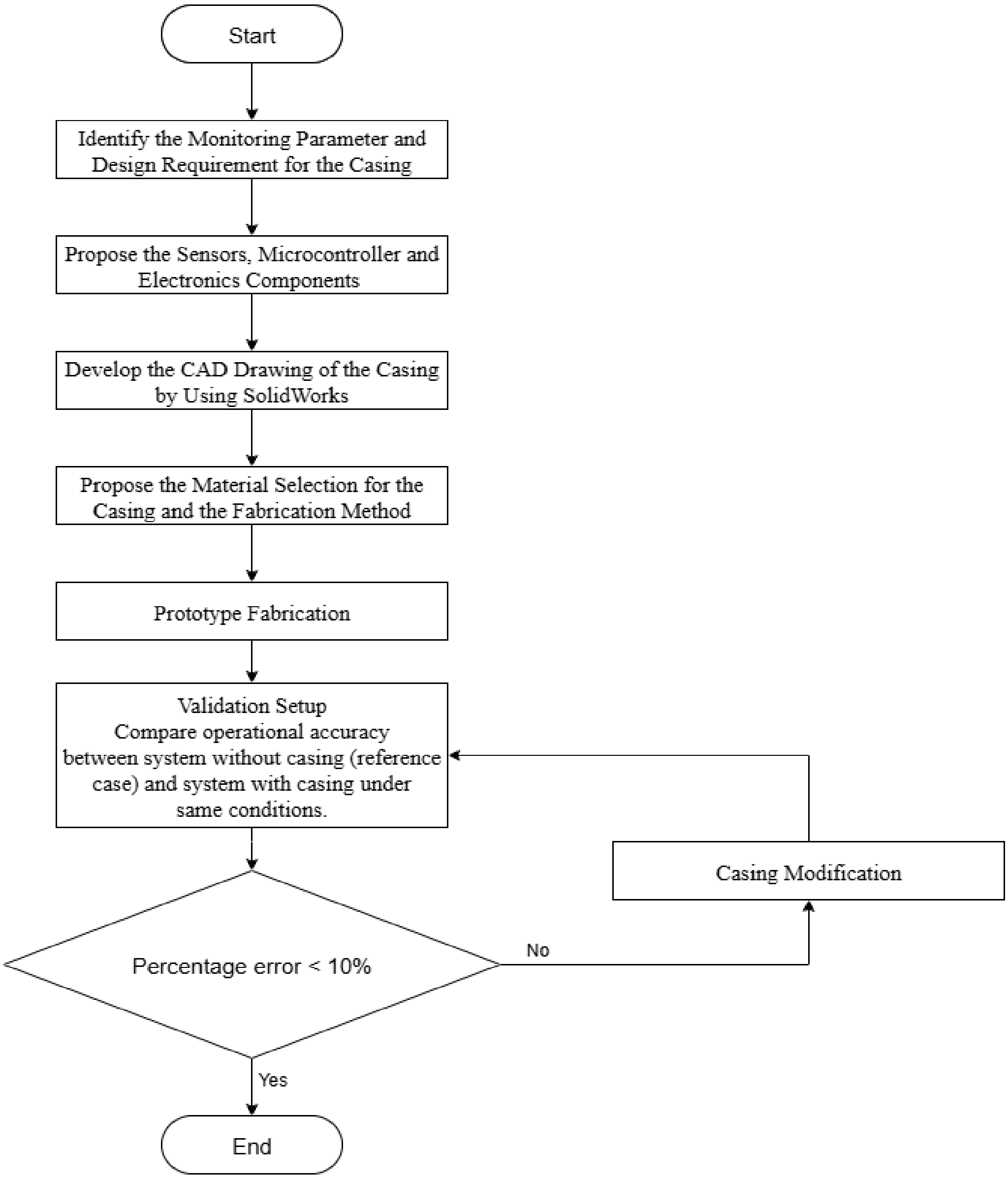


Figure 1. Flowchart of designing and developing a physical casing for outdoor air quality monitoring system

The AQMS could be developed based on the following steps:

i) Identify the monitoring parameters and design requirements
ii) Selection of the sensors, microcontroller and electronic components
iii) Using CAD software to design the casing
iv) Material selection and fabrication
v) Validation on the operational accuracy of the system

3.1 Design and Development of an AQMS

The design and development of the AQMS enclosure focused on creating a robust, weather-resistant casing that could protect internal components from environmental exposure while ensuring accurate sensor functionality. The development process began by identifying the essential air quality monitoring parameters: PM2.5, PM10, temperature, and relative humidity, which were critical for assessing outdoor air pollution levels, especially in urban and industrial regions [17]. To meet these performance criteria, the casing was designed in compliance with the International Electrotechnical Commission (IEC) 60529 standard. This standard provides guidelines for classifying the degrees of protection provided by enclosures for electrical equipment. By adhering to this standard, the AQMS enclosure achieved an appropriate ingress protection (IP) rating, which enhanced its durability and system reliability [18].

The enclosure was conceptualized and modeled using commercial computer-aided design (CAD) software, which facilitated the integration of key structural and functional elements. These elements included dedicated slots for mounting sensors and electronic modules, well-defined pathways for air circulation, and strategically placed access points to simplify wiring, calibration, and maintenance tasks. The final design featured two primary sections: a protective main casing and a detachable roof that provided easy access to internal components. The protective casing had dimensions of 142 mm (W) × 226 mm (L) × 304 mm (H), and the roof had dimensions of 202 mm (W) × 295 mm (L) × 25 mm (H).

To maintain an optimal thermal environment within the enclosure and support accurate sensor readings, multiple air inlet vents were designed at the lower section of the casing. An exhaust outlet was positioned at the upper section and was paired with a direct current (DC) cooling fan. This configuration promoted continuous airflow through the enclosure and helped dissipate heat generated by electronic components [15]. Within the casing, careful attention was given to the spatial arrangement of internal modules. The particulate matter sensors were positioned near the air inlets to allow immediate exposure to ambient air, thereby enhancing response time and data accuracy. Meanwhile, temperature and humidity sensors were placed away from heat-generating components such as the Raspberry Pi to minimize thermal distortion and preserve measurement reliability. This overall design approach ensured both the physical protection of the internal hardware and the operational precision of the AQMS. It enabled the system to perform consistently in diverse outdoor environments, making it suitable for long-term environmental monitoring applications across various geographic and climatic contexts.

3.2 Selection of Sensors and Components

The selection and arrangement of electronic components were essential for developing an accurate and reliable AQMS. The selected sensors effectively measured the targeted pollutants and operated under extreme conditions, including the high temperatures and humidity typical in tropical rainforest environments. To ensure stable system performance in such challenging conditions, integrating robust power supplies and microcontrollers was crucial. Additionally, a DC exhaust fan was incorporated into the system to enhance internal air circulation, mitigate heat accumulation, and maintain sensor functionality within the optimal operating temperature range [15]. By strategically selecting components suited for these environmental challenges, the AQMS achieved reliable long-term data collection and operational stability. Figure 2 shows the schematic diagram of the IoT smart sensors, Raspberry Pi, related components, and database linkage. Table 1 presents the key electronic components utilized in this study.

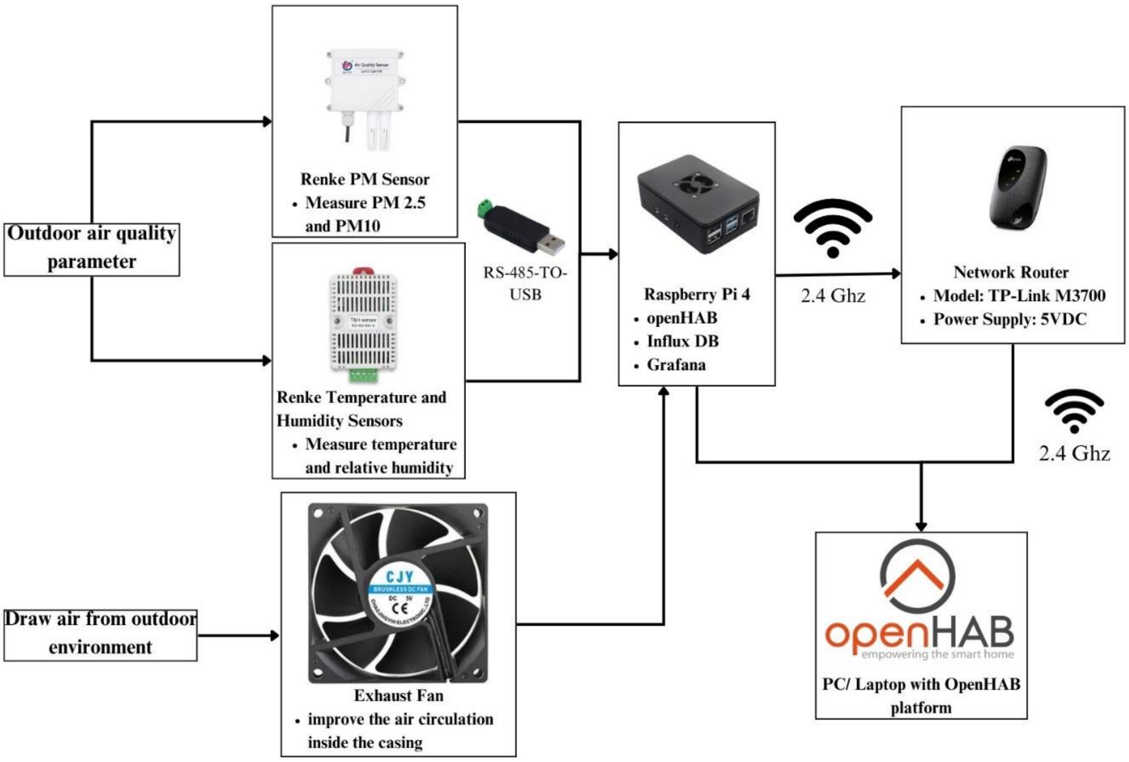


Figure 2. The schematic diagram of the IoT smart sensors, raspberry pi, related components and database linkage

Table 1. Electronic component

No	Components	Brand	Model	Parameter	Response time	Output signal	References
1	Renke pm2.5 air quality sensor	Renke	RS-PM-*−2	PM2.5 and PM10	≤90s	RS485/0-5V/0-10V/4-20mA	https://www.renkeer.com/product/pm-sensor/
2	RS-WS-N01-8-EX	Renke	RS-WS-N01-8	Temperature	≤25s	RS485	https://www.renkeer.com/product/modbus-rtu-temperature-sensor/
			RS-WS-N01-8	Humidity	≤8s	RS485	
3	Microcontroller	Raspberry pi	4 Model B	-	Instant	-	https://www.raspberrypi.com/products/raspberry-pi-4-model-b/
4	DC 5V exhaust fan	-	8025-12-HX2.54 2pin	Exhaust fan	Instant	12V (XH2.54 2pin)/ (0.2-0.3) A +/-10%	https://shopee.com.my/DC-5V-USB-12V-2-Pin-4010-5010-6025-8025-12025-CPU-PC-Desktop-High-Speed-Heatsink-Brushless-Cooling-Fan-40-60-80-120mm-i.33091591.1796940602

3.3 Fabrication and Assembly

The fabrication and assembly of the AQMS enclosure focused on creating a durable, weather-resistant enclosure optimized for outdoor use. The protective casing was constructed using a pre-fabricated PVC junction box due to its excellent resistance to water, corrosion, and dust accumulation [12], while the roof was fabricated from aluminum alloy 1100 to provide additional protection against direct sunlight and rain [12, 19]. The material properties of the aluminum alloy are summarized in Table 2.

Table 2. Material properties of aluminum alloy 1100

Aluminium alloy	Density	Melting Range	Thermal Conductivity	Specific Heat Capacity	Electrical Resistivity
1100	2.71 g/cm^3	643–657 °C	~222 W/m·K	~900 J/kg·K	~2.99×10^{-8} Ω·m

Air inlet vents were strategically placed at the bottom of the casing to allow ambient air intake, and a DC exhaust fan was installed at the top to facilitate continuous airflow and prevent heat accumulation. The internal layout was carefully planned to position the PM sensors near the air inlets for accurate pollutant detection, while temperature and humidity sensors were placed away from heat sources to minimize interference.

The roof was supported using C-shaped brackets formed from combined stainless-steel L-brackets with dimensions of 16 mm (W) × 50 mm (L) × 50 mm (H) which provide strong mechanical stability. All components, including the Raspberry Pi 4, sensors, and fan were mounted securely and cables were organized to maintain unobstructed airflow. The complete system underwent a functionality check and outdoor test to ensure structural integrity, proper airflow, and operational reliability before validation testing. Figure 3 illustrates the developed prototype of the AQMS. Figure 4 shows the AQMS with dimension and the location of the sensors and electronics components.

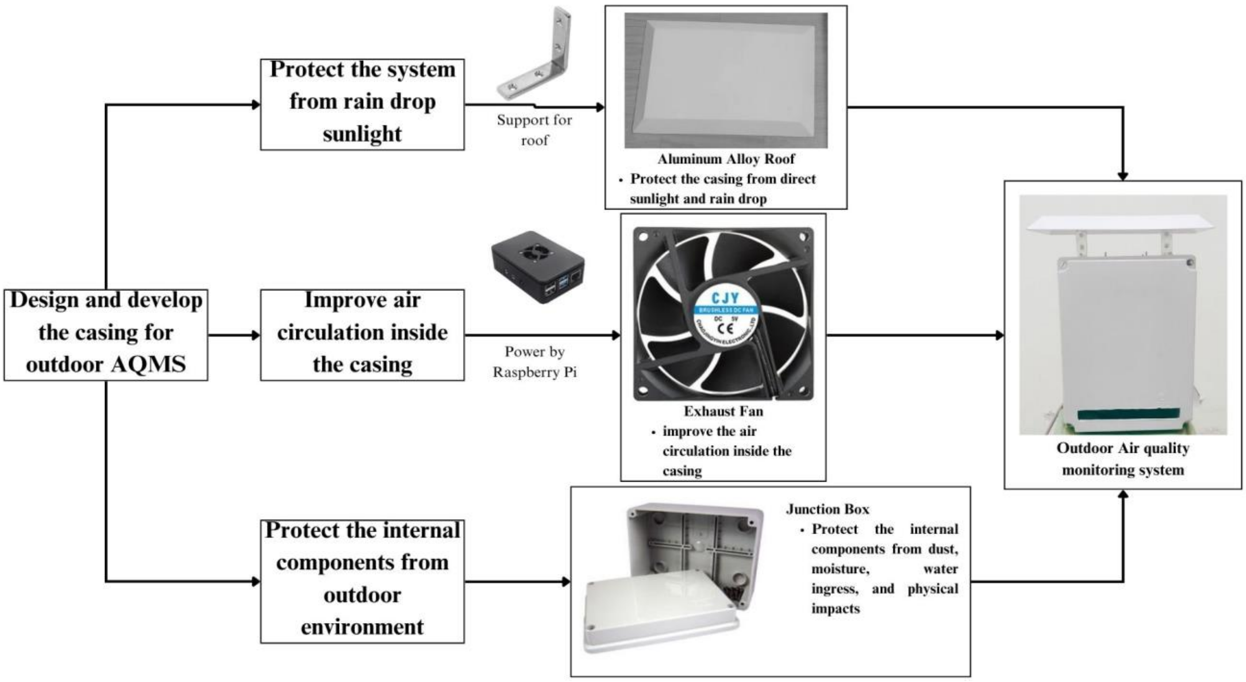


Figure 3. Development prototype of AQMS

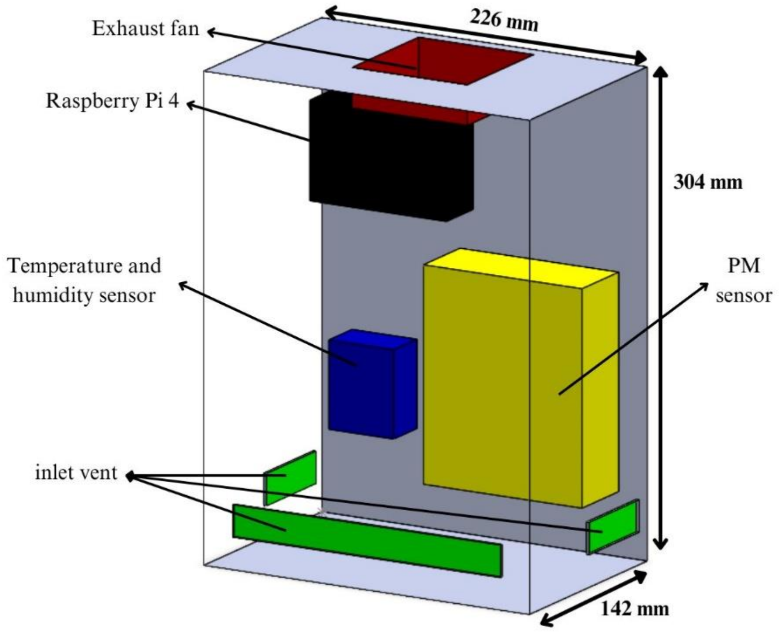
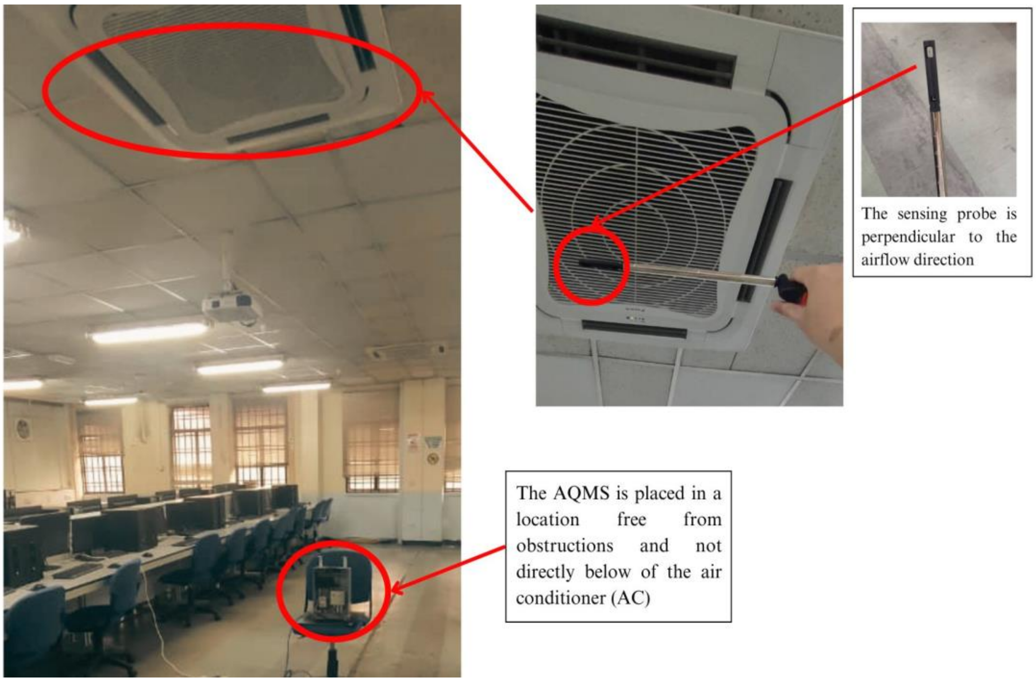


Figure 4. AQMS with dimension and the location of the electronics component and sensors

3.4 Validation Testing

To ensure that the incorporation of the protective casing did not adversely affect the performance and accuracy of the AQMS, a systematic validation procedure was implemented. This validation aimed to compare the performance of the system under two distinct configurations: one in which the sensors and electronic components were fully exposed (without casing configuration), and another where all components were securely housed within the custom-fabricated protective casing.

The validation experiments were conducted in a controlled indoor environment maintained at a stable temperature and airflow velocity. An anemometer was used to measure both the temperature and airflow velocity at the air outlet of the room's air conditioning system as shown in Figure 5. Based on the readings, the AC settings were fine-tuned to achieve a stable environment before commencing the data collection process. The environmental conditions during the validation were maintained at a temperature of 18.1 °C and airflow velocity of 0.3 m/s. These controlled conditions were selected to minimize environmental variability and ensure consistency in the evaluation process. Figure 5 illustrates the setup for the validation test.



The sensing probe is perpendicular to the airflow direction

The AQMS is placed in a location free from obstructions and not directly below of the air conditioner (AC)

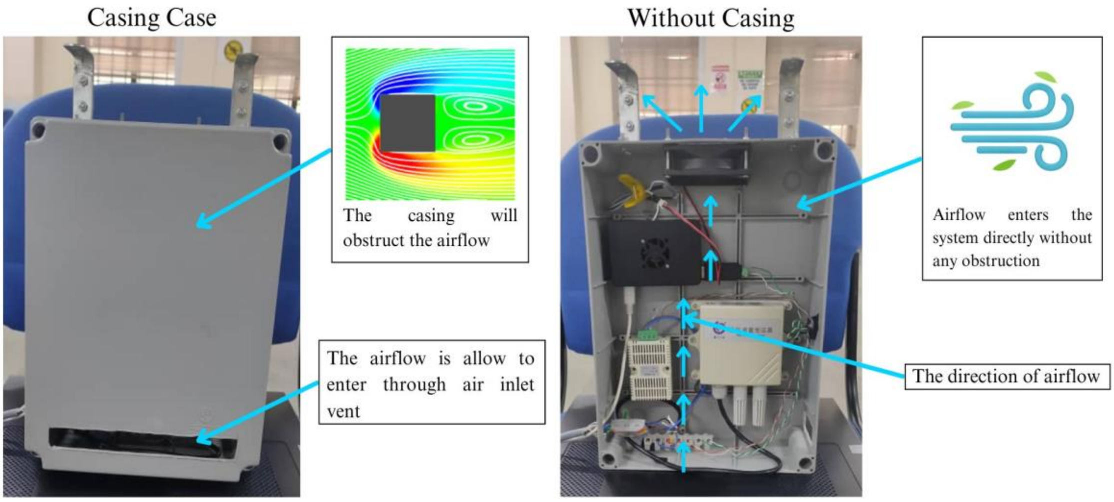
Figure 5. The setup for the validation test.

To guarantee the accuracy of the result, several precautionary measures were implemented prior to the commencement of the experiment. These precautions were specifically designed to minimize any interference from external factors, such as ambient temperature fluctuations, heat accumulated inside the casing, airflow fluctuations and heat generated by the Raspberry Pi.

To ensure the data collection accurately reflected the system operational performance, several systematics steps were taken as outlined at below:

1. During the validation process, the control room was kept closed to prevent human movement and the entry of outdoor air, which could affect the room’s temperature and airflow.
2. The AQMS was allowed to pre-cool to room temperature before each validation test to avoid residual heat affecting sensor readings.
3. After each test, the Raspberry Pi and internal components were allowed to cool down before proceeding to the next test.
4. A thermal gun was used to confirm that no heat had accumulated inside the casing before data collection.
5. The AQMS was placed in a clean location, free from obstructions, to avoid airflow disturbances.

The configuration without the casing served as the reference case, representing an ideal scenario in which sensors are fully exposed to ambient air without any obstructions [17]. This provided a baseline against which the performance of the enclosed system could be evaluated. Figure 6 illustrates the without casing configuration and the casing configuration setup used in the validation process.



Casing Case

The casing will obstruct the airflow

The airflow is allow to enter through air inlet vent

Without Casing

Airflow enters the system directly without any obstruction

The direction of airflow

(a) (b)

Figure 6. AQMS setup for validation process (a) casing case (b) without casing case

During the validation process, temperature and relative humidity, were continuously recorded and transmitted to an online visualization and analytics platform, Grafana. Following real-time monitoring, the data were exported in Comma-Separated Values (CSV) format for detailed analysis. To quantify any discrepancies betweenthe two configurations, the percentage error between the datasets was calculated for each parameter using Equation 1 [20].This analysis was crucial in determining whether the thermal and airflow characteristics of the protective casing influenced the sensor outputs, thereby validating the integrity and operational reliability of the enclosure design for outdoor deployment.

$$Percentage\ error = \frac{(|Result_{with\ casing} - Result_{without\ casing}|)}{Result_{without\ casing}} \times 100\% \qquad (1)$$

4. Results and Discussion

To evaluate the operational accuracy of the developed AQMS, a validation test was conducted by comparing the sensor readings from two configurations: (i) an open setup with sensors directly exposed to environment, and (ii) a protected setup with the sensors housed within the fabricated casing. The objective of this validation was to determine whether the casing influenced the accuracy of temperature and relative humidity measurements. Given the test was conducted in a control room with potential environmental disturbances such as door openings and human movement the data collection interval was reduced to 6 minutes instead of the standard 30 minutes. This shorter interval was implemented to minimize the impact of rapid environmental fluctuations and to enhance the reliability of the comparison.

The sensor data for both configurations were visualized in real-time using Grafana, a web-based platform that enables continuous monitoring and live tracking of sensor performance. After each six-minute sampling interval, all readings were exported in CSV format and analyzed using Microsoft Excel to calculate the percentage error between the open and enclosed configurations. Table 3 presents the recorded values for temperature and relative humidity across both setups, along with the computed percentage errors.

Table 3. Comparison of temperature and relative humidity measurements with and without protective casing for validation purposes

	Temperature (°C)			Relative humidity (%)		
	Without Casing	Casing Case	Percentage error	Without Casing	Casing Case	Percentage error
	21.68	21.80	0.57	64.46	63.77	1.07
	21.60	21.80	0.95	64.71	64.63	0.11
	21.59	21.73	0.66	64.25	62.93	2.05
	21.55	21.62	0.31	63.87	61.82	3.22
	21.49	21.45	0.18	63.41	60.87	4.01
	21.45	21.30	0.69	62.80	60.57	3.55
Average Percentage error (%)			0.56			2.34

The results show that the average percentage error for temperature was only 0.56%, while that for relative humidity was 2.34%. These values suggest that the protective casing has a minimal impact on sensor accuracy, particularly for temperature measurements. Slightly higher deviations observed in humidity readings are likely due to minor variations in airflow patterns within the enclosure.

5. Conclusions

In summary, the present study successfully developed a real-time IoT-based AQMS equipped with a protective casing for outdoor applications. The casing is specifically designed to safeguard electronic components, such as microcontrollers and sensors from adverse weather conditions including inadequate heat dissipation, high humidity, and direct exposure to rain. To support efficient internal ventilation, a DC exhaust fan was incorporated to improve airflow distribution, thereby maintaining optimal system performance. Validation tests confirmed that the casing had minimal effect on temperature and humidity sensor accuracy. The observed average errors (0.56% for temperature) and (2.34% for relative humidity) fell within acceptable ranges, demonstrating the system’s reliability and suitability for real-world outdoor deployment. The prototype strikes an effective balance between performance and cost, delivering a durable and economical solution for real-time outdoor air quality monitoring. For future work, it is recommended that researchers explore improvements in airflow design, integration of additional pollutant sensors, and the use of advanced materials to enhance the system's durability and expand its application scope. Such developments will contribute to broader efforts in mitigating the impacts of air pollution in diverse environmental settings.

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