Indoor Air Quality Monitoring through Internet of Things System: A Case Study at UTHM-Fraunhofer IEM Innovation Lab

Shashwar Kumar Ravi[1], Ramhuzaini Abd. Rahman[1]*

[1] *Department of Mechanical Engineering, Faculty of Mechanical and Manufacturing Engineering,
Universiti Tun Hussein Onn Malaysia, Parit Raja, Batu Pahat, 86400, Johor Darul Takzim, MALAYSIA*

*Corresponding Author: huzaini@uthm.edu.my
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Abstract

Indoor Air Quality (IAQ) has a direct impact on the health, comfort, and productivity of building occupants. Traditional IAQ monitoring often relies on offline measurements that are unable to capture dynamic changes in pollutant concentrations. This study presents the development of an Internet of Things (IoT)-based system designed for real-time IAQ monitoring using an ESP32 microcontroller integrated with temperature–humidity, volatile organic compound (VOC), carbon dioxide (CO_2), and particulate matter (PM2.5) sensors. Data was collected and transmitted every 20 seconds to the ThingSpeak cloud platform for storage and MATLAB-based analysis. The system was deployed in Room G1–035 B of the UTHM-Fraunhofer IEM Innovation Laboratory. Five days of monitoring were conducted, including MVAC-active weekdays and MVAC-inactive weekends, allowing for a comparison of ventilation effects on IAQ behavior. Results show that the MVAC system significantly improves pollutant dilution, stabilizes temperature and humidity, and maintains IAQ within DOSH standards. The study confirms the reliability of low-cost IoT solutions for real-time IAQ assessment. This work contributes to the development of smart buildings, environmental monitoring, and the evaluation of ventilation performance.

1. Introduction

Indoor Air Quality (IAQ) has become a significant concern in modern built environments, given the increasing amount of time individuals spend indoors. Pollutants such as particulate matter, volatile organic compounds (VOCs), carbon dioxide (CO_2), and excessive humidity can cause respiratory illnesses, discomfort, reduced cognitive performance, and Sick Building Syndrome (SBS). These issues are particularly prevalent in enclosed or inadequately ventilated spaces, such as educational, residential, and industrial areas.

Conventional IAQ assessment techniques often involve manual, offline data collection using handheld instruments. Such practices are insufficient for continuous monitoring and provide no real-time feedback when pollutant spikes occur. Consequently, harmful exposure may remain undetected for long periods. Advances in Internet of Things (IoT) technology offer promising solutions for continuous, real-time environmental monitoring. IoT-based systems integrate low-cost sensors, wireless communication modules, and cloud platforms, enabling the acquisition of high-resolution environmental data and facilitating data-driven decision-making. Previous studies have shown that IoT technologies significantly improve the monitoring, visualization, and interpretation of IAQ data.

Despite these technological advances, limited research has investigated IAQ characteristics within university laboratories—spaces influenced by adjacent pollutant sources, such as soldering areas, laser cutters, and 3D printers. Understanding these micro-environmental pollutant dynamics is critical for ensuring occupant safety and evaluating the effectiveness of mechanical ventilation systems. This study develops and deploys an IoT-based IAQ monitoring system in UTHM-Fraunhofer IEM Innovation Laboratory, evaluates pollutant behavior across ventilated and non-ventilated conditions, and assesses MVAC performance. The findings support the adoption of smarter environmental monitoring practices and enhance the understanding of real-time IAQ fluctuations in educational laboratory environments.

The remainder of this paper is structured as follows: Section 2 reviews background studies and related work on IAQ, MVAC systems, and IoT-based environmental monitoring. Section 3 describes the system architecture, sensor integration, firmware development, and experimental procedures used in this study. Section 4 presents the results, including time-series IAQ trends, RMAC analysis, and comparisons between MVAC-active and MVAC-inactive periods. Section 5 concludes the paper by summarizing the major findings and offering recommendations for future IAQ monitoring and smart building research.

2. Background and Related Work

Indoor Air Quality research has grown substantially due to the close relationship between indoor pollutants and human health outcomes. Numerous studies highlight the importance of monitoring particulate matter (PM2.5 and PM10), carbon dioxide, VOCs, formaldehyde, and microbial contaminants to prevent respiratory illnesses, allergic reactions, and cognitive impairment (Das et al., 2024; Huang, 2023; Joshi et al., 2025; Rabbani et al., 2022; Sagai, 2019; Selvakumar et al., 2025).

In Malaysia, IAQ is governed by the Department of Occupational Safety and Health (DOSH) Industry Code of Practice on Indoor Air Quality (2010). Acceptable thresholds include VOC below 3000ppb, CO_2 levels below 1000 ppm, CO levels below 10 ppm, PM2.5 levels below 35 $\mu g/m^3$, a temperature range of 23–26 °C and humidity range of 40 to 70% (Department of Occupational Safety and Health, 2010). Maintaining these conditions can be challenging in tropical climates, where high humidity and building airtightness contribute to the accumulation of pollutants.

Mechanical Ventilation and Air Conditioning (MVAC) systems play a critical role in regulating IAQ through temperature control, pollutant dilution, and humidity management. However, poorly designed or poorly maintained systems may circulate contaminants or provide inadequate airflow distribution. Studies reveal that many educational institutions experience IAQ deviations due to insufficient MVAC operation (Ballerini et al., 2025; Du et al., 2025; Woods et al., 2025).

IoT-based IAQ monitoring has emerged as a promising solution to these challenges. Low-cost sensors such as the DHT22, SGP30, and optical dust sensors have been successfully applied in various monitoring deployments, providing continuous pollutant tracking and cloud-based analytics (Chojer et al., 2020; Hojaiji et al., 2017; Omidvarborna & Kumar, 2024). Cloud platforms like ThingSpeak support remote visualization and MATLAB-based post-processing, while microcontrollers such as ESP32 enable efficient data transmission.

Although IoT IAQ systems have been explored in residential and commercial settings, few studies have focused on university laboratory spaces that are influenced by high-emission equipment. Additionally, the ventilation performance of MVAC systems in such settings remains underreported. This study addresses these gaps by evaluating an IoT-based IAQ monitoring system in a mixed-use educational environment

3. System Architecture and Experimental Methods

3.1 System Architecture Overview

The IoT-based IAQ monitoring system, as shown in the schematic diagram of Fig. 1, was built around the ESP32 DevKit microcontroller, selected for its integrated Wi-Fi module, low power consumption, and high processing capability. Three sensors were interfaced with the ESP32: a DHT22 for measuring temperature and relative humidity, an SGP30 for detecting CO2 and total VOC levels, and a GP2Y1010AU0F optical dust sensor for PM2.5. These components were mounted on an 830-hole solderless breadboard. All wiring connections were completed using jumper wires, and the entire system was powered through a USB-C connection to a laptop. Sensor readings were collected every 20 seconds and immediately processed by the ESP32 before being transmitted wirelessly to the ThingSpeak cloud platform. The modular hardware configuration ensured robust data acquisition and reliable long-term operation.
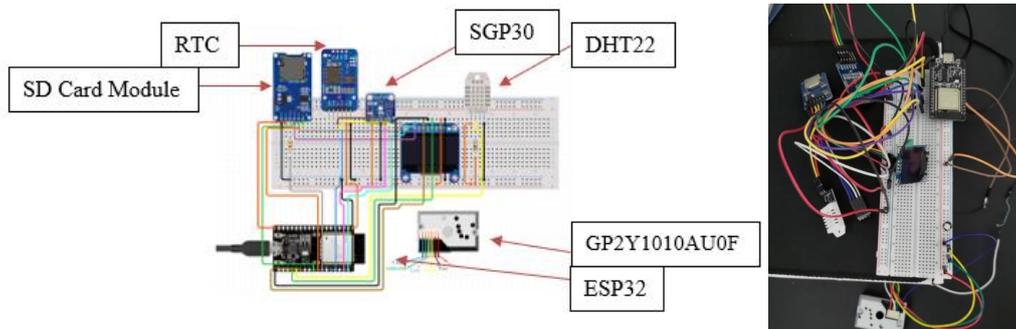
Fig. 1 *Proposed indoor air quality monitoring system*

3.2 Sofware and Firmware Development

The ESP32 was programmed using Arduino IDE. Custom firmware was developed to initialize and calibrate sensors, acquire raw measurements, convert raw outputs into calibrated IAQ parameters, assign data to ThingSpeak fields and transmit data using HTTP POST requests. On the server side, ThingSpeak automatically stored incoming data and generated real-time graphical dashboards. MATLAB Analytics was utilized for in-depth data processing, trend identification, and Root Mean Square Error (RMSE) calculations to evaluate sensor stability during both ventilated and non-ventilated periods. Fig. 2 depicts a snapshot of the Arduino IDE, and ThingSpeak used for the software and firmware development.
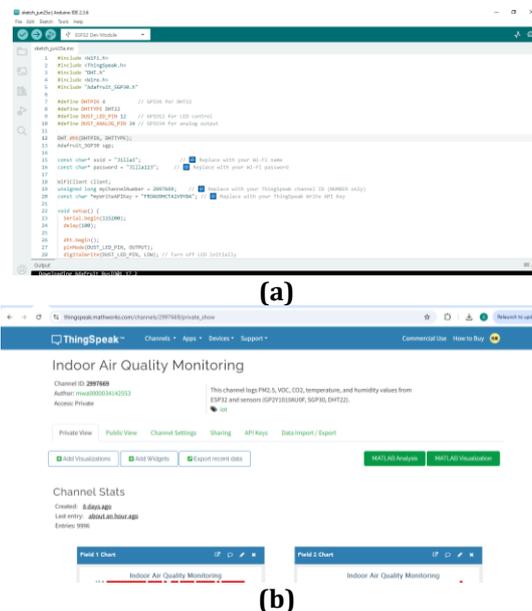

(a)

(b)

Fig. 2 *Software and hardware development: (a) Arduino IDE, (b) ThingSpeak*

3.3 Experimental Setup

The monitoring system was installed in Room G1–035B, located on the upper floor of the UTHM-Fraunhofer IEM Innovation Lab at Universiti Tun Hussein Onn Malaysia. Although this room remained inactive during measurements, it shared ventilation channels with several laboratories that generated pollutants, including soldering stations, CO_2 laser cutters, 3D printers, and computer workstations. The room measured 1305 cm × 590 cm × 288 cm, corresponding to a volume of approximately 222 m^3. It was equipped with 8 MVAC diffusers supplying conditioned air and 4 exhaust outlets extracting indoor air, as shown in Fig. 3. Note that the red box in Fig. 3 indicates the location where the developed IAQ monitoring system was set up. Measurement data were collected over five days, specifically three weekdays with MVAC turned on and two weekend days with MVAC turned off, respectively. This information provided controlled insight into the effect of ventilation on IAQ fluctuations
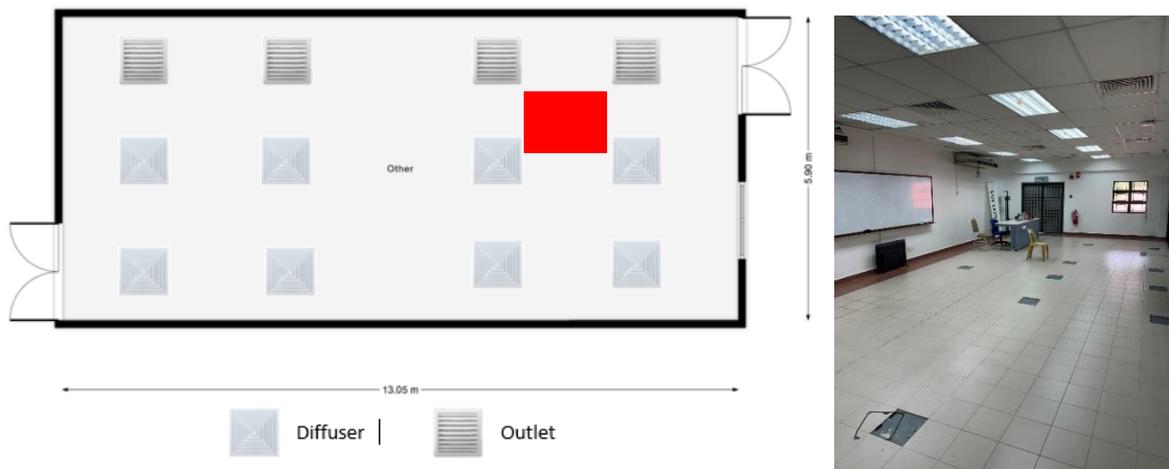
Fig. 3 *Layout of MVAC diffuser and outlet, and actual photo of the room*

3.4 Data Analysis

The dataset was analyzed using a time-series trend evaluation and compared with DOSH IAQ thresholds. The RMSE computation was then performed to assess signal stability under different ventilation conditions. Furthermore, parallel comparison with outdoor air quality data for the Parit Raja region was also conducted. This approach enabled a robust assessment of IAQ dynamics and the effectiveness of ventilation.

4. Results and Discussion

4.1 Temperature and Humidity

Temperature remained within the DOSH comfort range (23–26°C) during MVAC-active weekdays, with minor fluctuations. On weekends, the temperature increased by 1–2°C, attributable to stagnant air and the absence of conditioned airflow. Humidity also exhibited higher variability during non-ventilated periods, indicating limited moisture removal. **Table 1** presents a comparison between weekend and weekday average maximum and minimum temperature and humidity readings.

Table 1 *Average max and min temperature and humidity readings during the weekend and weekdays*

Parameters	Weekend (ave) Sat (28/6/25) to Sun (29/6/25)	Weekday (ave) Mon (30/6/25) to Wed (2/7/25)
Temperature (°C)	28 (max) / 26 (min)	24 (max) / 23 (min)
Humidity (%)	90 (max) / 70 (min)	76 (max) / 70 (min)

4.2 CO_2 and VOC Concentrations

CO_2 levels remained below the 1000 ppm standard throughout the study, though spikes were observed during afternoon periods when adjacent laboratories were in operation. VOC levels were maintained below 3000 ppb and showed similar behavior, suggesting pollutant migration through shared ventilation ducts. Weekend VOC readings displayed slower decay rates—consistent with reduced ventilation. Table 2 presents a comparison of weekend and weekday average readings of CO2 and VOC.

Table 2 *Average CO_2 and VOC readings during the weekend and weekdays*

Parameters	Weekend (ave) Sat (28/6/25) to Sun (29/6/25)	Weekday (ave) Mon (30/6/25) to Wed (2/7/25)
CO_2 (ppm)	605.00	442.67
VOC (ppb)	18.35	9.92

4.3 PM 2.5 Levels

PM2.5 concentrations remained within acceptable limits, which is below 35 µg/m³, but showed measurable elevation during times when equipment in adjacent areas was active. Time-series plots in Fig. 4indicated distinct weekday–weekend differences, with improved pollutant dilution during MVAC operation.
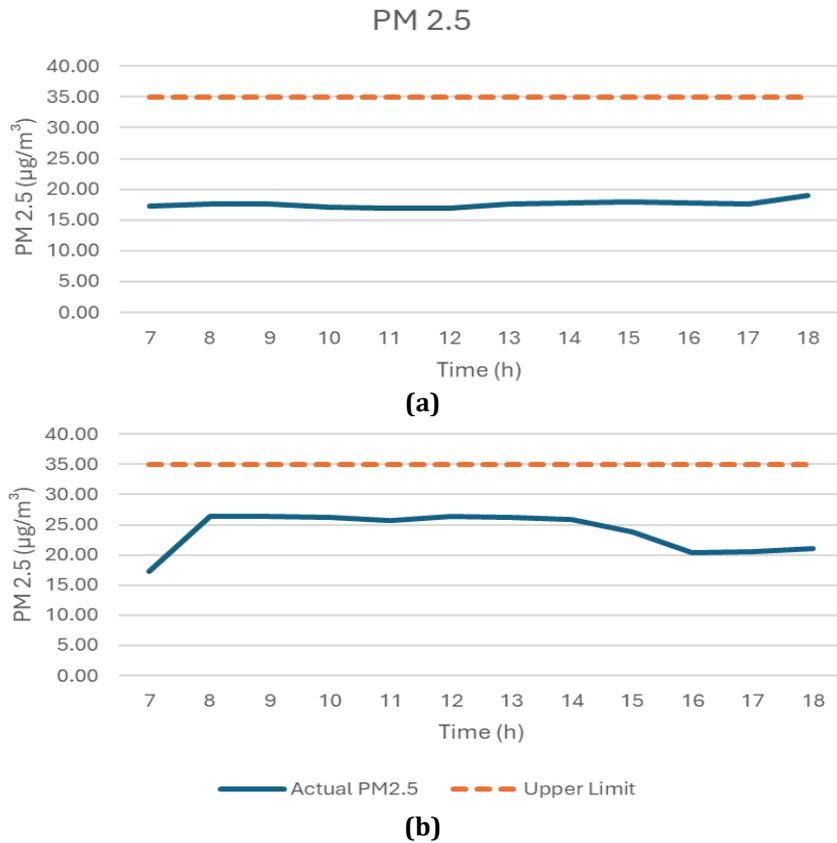

(a)

(b)

Fig. 4 *Pm2.5 reading: (a) weekend (Sunday - 29/6/25), and (b) weekday (Monday – 30/6/25)*

4.4 RMSE Analysis

RMSE calculations, as summarized in Table 3, revealed lower values during weekdays, indicating more stable sensor operation under consistent airflow conditions. A higher RMSE during weekends suggests greater variability due to stagnant air and a lack of forced circulation.

Table 3 *Average RMSE between weekend and weekdays*

Parameters	Weekend (ave) Sat (28/6/25) to Sun (29/6/25)	Weekday (ave) Mon (30/6/25) to Wed (2/7/25)
Temperature (°C)	2.67	1.13
Humidity (%)	12.26	5.39
CO_2 (ppm)	365.00	323.95
VOC (ppb)	2956.88	2947.30
PM2.5 (µg/m³)	18.11	10.96

4.5 Comparison with Outdoor Air Quality

Indoor pollutant levels generally remained below those recorded for Parit Raja in the outdoor Air Quality Index (AQI) as shown in Fig. 5, confirming that the MVAC system made a significant contribution to pollutant reduction. However, VOC transmission from adjacent fabrication rooms highlights a potential design or sealing weakness in the ventilation system.
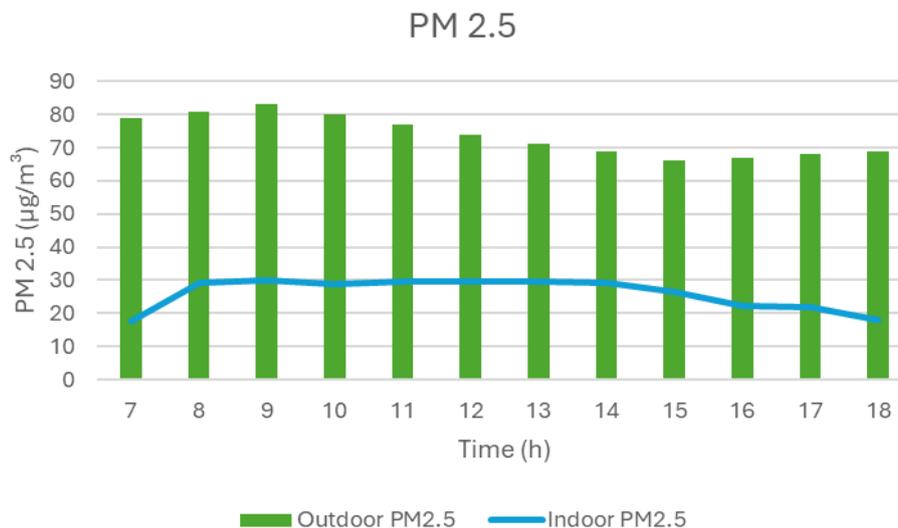
PM 2.5

Fig.5 *Outdoor AQI versus IAQ for PM2.5*

4.6 Discussion

The findings validate the reliability of the IoT system in capturing real-time IAQ fluctuations and demonstrate the significant influence of MVAC operation on pollutant dynamics. The system successfully detected ventilation-related variations and revealed pollutant migration from nearby laboratory activities. These insights support future integration of automated ventilation control based on sensor feedback.

5. Conclusion

This study demonstrates the feasibility of deploying a low-cost IoT-based IAQ monitoring system using an ESP32 and multi-sensor integration. The system captured high-resolution environmental data and successfully identified differences between MVAC-operational and non-operational periods. Results confirm that the MVAC system plays a significant role in maintaining IAQ within DOSH guidelines, highlighting the influence of adjacent pollutant-generating activities on indoor air conditions. The system offers a scalable platform for smart building applications, supporting data-driven ventilation control and continuous IAQ management.

Acknowledgement

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Shashwar Kumar Ravi, Ramhuzaini Abd Rahman; **data collection:** Shashwar Kumar Ravi; **analysis and interpretation of results:** Shashwar Kumar Ravi, Ramhuzaini Abd Rahman; **draft manuscript preparation:** Shashwar Kumar Ravi, Ramhuzaini Abd Rahman. All authors reviewed the results and approved the final version of the manuscript.*

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