INTERNATIONAL JOURNAL OF SUSTAINABLE CONSTRUCTION ENGINEERING AND TECHNOLOGY
ISSN: 2180-3242 e-ISSN: 2600-7959

IJSCET

Vol. 16 No. 2 (2025) 333-348
https://publisher.uthm.edu.my/ojs/index.php/ijscet

A Comprehensive Assessment of HVAC Preventive Maintenance Effectiveness in Controlling Indoor Air Quality in Hospital Buildings

Muhamad Shahril Mohd Abdullah[1], Mohd Arif Rosli[1]*, Mohd Syafiq Syazwan Mustafa[1], Azian Hariri[2], Amir Abdullah Muhamad Damanhuri[3]

[1] *Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Batu Pahat, Johor, MALAYSIA*
[2] *Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Batu Pahat, Johor, MALAYSIA*
[3] *Faculty of Mechanical Technology and Engineering, Universiti Teknikal Malaysia Melaka (UTeM), 76100, Durian Tunggal, Melaka, MALAYSIA*

*Corresponding Author: mohdarif@uthm.edu.my
DOI: https://doi.org/10.30880/ijscet.2025.16.02.020

Article Info

Received: 16 February 2025
Accepted: 4 November 2025
Available online: 31 December 2025

Keywords

Intervention, indoor air quality, parameter, sick building syndrome

Abstract

Indoor Air Quality (IAQIndoor Air Quality (IAQ) is critical in hospital environments due to the increased vulnerability of patients and healthcare workers to airborne contaminants. Maintaining optimal IAQ is essential for protecting health and ensuring a safe clinical environment. This study evaluates the effectiveness of HVAC Planned Preventive Maintenance (PPM) in improving IAQ within hospital wards, following guidelines from the Department of Occupational Safety and Health (DOSH) and the Ministry of Health (MOH) under ICOP 2010. A case study approach was applied in two hospital wards with centralized HVAC systems. IAQ measurements were taken before and after PPM interventions. Ethical approval was obtained, and monitoring was conducted in collaboration with hospital management and the National Institute for Occupational Safety and Health (NIOSH) Malaysia. The Wilcoxon signed-rank test revealed significant improvements ($p < 0.05$) in case study 1 for temperature, air movement, TVOC, CO_2, CO, CH_2O, O_3, and PM2.5. In case study 2, significant changes were noted for RH, PM10, CO_2, O_3, and $PM_{2.5}$. However, parameters such as microbial counts, PM10 (CS1), and temperature (CS2) showed no significant change. These findings highlight the positive impact of PPM on IAQ while identifying areas that require targeted improvements, supporting the development of more effective HVAC maintenance strategies in healthcare settings.

1. Introduction

Indoor Air Quality (IAQ) plays a critical role in safeguarding the health and comfort of hospital occupants, including patients, healthcare personnel, and visitors, who are particularly vulnerable to airborne pollutants. Effective IAQ management depends heavily on systematic maintenance practices, with Planned Preventive Maintenance (PPM) of HVAC systems being a key strategy. Despite its importance, hospital administrators often lack evidence on whether PPM activities result in measurable improvements in IAQ parameters. Therefore, this study aims to evaluate the impact of HVAC PPM on IAQ by comparing parameter measurements taken before and after maintenance. The analysis, conducted using the Wilcoxon signed-rank test, is guided by the standards outlined in the Industry Code of Practice on Indoor Air Quality (ICOP 2010) and the Ministry of Health (MOH) IAQ guidelines for hospitals.

This study addresses a significant research gap: the lack of access to IAQ data from hospital wards, which are often highly restricted areas. Previous studies either monitored IAQ parameters before or after PPM interventions or relied on secondary data from hospital support services, limiting the scope of analysis. In contrast, this research obtained direct measurements under ethical approval from the National Medical Research Register (NMRR), the Universiti Tun Hussein Onn Malaysia (UTHM) Ethics Committee, and the Malaysian Research Ethics Committee (MREC). This study received ethical approval from the Human Research Ethics Committee of UTHM (approval code: UTHM/RMC/100-9/139 Jld. 3(04), dated 16th August 2023) and the Medical Research & Ethics Committee, NMRR (approval code: NMRR ID-23-02808-KFP [IIR]). All participants were thoroughly informed about the study's objectives, procedures, and anticipated results. The researchers hold absolute confidentiality for individual participants and organizational information throughout the research process. With the assistance of hospital administration and NIOSH Malaysia, this study effectively conducted IAQ monitoring in hospital wards, offering useful insights into the effects of PPM HVAC on IAQ levels in healthcare settings.

1.1 Indoor Air Quality

IAQ is a critical component of Indoor Environmental Quality (IEQ), encompassing the air condition within buildings and its impact on the health, comfort, and well-being of occupants. The World Health Organization (WHO) [1] defined IAQ as "the quality of indoor air inside buildings and structures, especially as it relates to the health and comfort of building occupants." Similarly, in Malaysia, the Department of Occupational Safety and Health (DOSH) [2] emphasized IAQ's role in safeguarding the health and comfort of individuals in indoor environments [3], [4].

Indoor air pollutants are divided into two categories: pollutants produced by indoor activities and characteristics and ambient pollutants that enter indoor areas from the outside [5]. Historically, research on air quality has been concentrated on outside habitats, leaving interior air quality and its implications relatively unexplored until the last decade [6]. The significance of IAQ becomes clear when contemplating its far-reaching consequences. Notably, poor ventilation in air-conditioned areas, such as hotel rooms, can result in the buildup of pollutants and temperature discomfort. This produces an atmosphere conducive to virus transmission, posing severe dangers to inhabitants' bodily and mental health [7]. For instance, symptoms associated with Sick Building Syndrome (SBS) such as headaches, dizziness, fatigue, and respiratory issues are known to reduce work performance and overall life satisfaction, particularly in environments where people spend extended periods indoors [8]. Accordingly, these challenges highlight the need to prioritize IAQ as a public health issue [9] [10]. Hence, public awareness and education about IAQ's impact on health are equally crucial. Furthermore, enhancing compliance with IAQ standards can significantly improve public health outcomes [11]. Addressing IAQ comprehensively requires an integrated approach, combining mechanical systems for heating, cooling, and ventilation, as well as strategies for reducing pollutant sources and improving air circulation [12]. In summary, maintaining appropriate IAQ is critical for occupant health, comfort, and productivity. As research highlights its significance, incorporating IAQ management into building design and maintenance methods will play a critical role in improving the quality of indoor spaces.

IAQ is influenced by various contaminants, as indicated by organizations such as WHO and Malaysia's DOSH. DOSH defined 11 essential characteristics for this study, which focuses on IAQ in Malaysia, and divided them into three categories: physical, chemical, and microbiological. The physical parameters include temperature, Relative Humidity (RH), and air movement, which collectively impact thermal comfort and air distribution within indoor spaces. The chemical parameters encompass Carbon Dioxide (CO_2), Carbon Monoxide (CO), respirable particulate matter (PM_{10}), Total Volatile Organic Compounds (TVOC), Formaldehyde (CH_2O), and Ozone (O_3). All of these factors significantly influence air quality and occupant health by contributing to both short- and long-term exposure risks. Lastly, the microbiological parameters are represented by Total Bacterial Count (TBC) and Total Fungal Count (TFC), critical indicators of microbial contamination that can affect respiratory health and overall well-being. These classifications align with international IAQ standards and provide a comprehensive framework for assessing and managing IAQ in Malaysian buildings. Table 1 summarizes the regulations on IAQ specifically for Malaysia introduced by the DOSH in 2010. The DOSH guidelines provide standards to protect the health of workers and other building occupants.

Table 1 *The guidelines for an acceptable limit of IAQ parameters*

No.	Parameter	Unit	Acc. Limit Malaysia
1	Temperature	°C	23-26
2	Relative humidity	%	40-70
3	Air movement	m/s	0.15-0.50
4	Carbon dioxide	ppm	C1000
5	Carbon monoxide	ppm	10
6	Respirable particulate	mg/m^3	0.15
7	TVOC	ppm	3
8	Formaldehyde	ppm	0.1
9	Ozone	ppm	0.05
10	Total bacteria count	cfu/m^3	500
11	Total fungal count	cfu/m^3	1000

Fonseca [13] highlighted a growing research interest in IAQ in healthcare facilities, driven by the prolonged time healthcare providers, staff, and patients spend in these environments. IAQ in such settings is influenced by various factors, including outdoor air quality, occupant density, ventilation practices, indoor activities, and emissions from equipment, furniture, and coatings. Moreover, vulnerable individuals and the nature of healthcare activities underscore the need for effective IAQ management in these facilities [14]. Various sources of IAQ contaminants from the hospital ward condition were recorded from the walkthrough inspection before the physical measurement at the case study location. This includes the function of spaces in hospital buildings, finishes and furnishings in hospital buildings, building equipment (machines and appliances) in hospital buildings, occupants and occupant activities in hospital buildings and maintenance in hospital buildings.

2. Method

For the physical measurements conducted in this study, data collection was divided into two phases: before and after the PPM of the HVAC system. This division allowed for a comparative analysis of the indoor environmental conditions resulting from the PPM HVAC intervention. Both types of monitoring followed guidelines from DOSH 2010 and the 'Guideline on IAQ for Hospital Support Services' from MOH, Malaysia [15].

Based on the eleven parameters outlined in the guidelines, this study selected all of these parameters for IAQ sampling, including temperature, RH, air movement, TVOC, CO_2, CO, PM_{10}, $PM_{2.5}$, O_3, CH_2O, and TBC and TFC. Sampling points are determined based on the size of the building, specifically the total area of the hospital ward at the case study location. This study employed real-time monitoring techniques to detect contaminant sources and assess the temporal variation of indoor air quality (IAQ) parameters throughout the day. In accordance with the guideline [15], when continuous 8-hour sampling is impractical, an intermittent or surrogate measurement strategy is permissible. This involves averaging half-hour measurements taken during four distinct time slots. Time slots were selected based on the building's operational schedule, ensuring even distribution across typical office hours. Accordingly, sampling was conducted at 9:00 am, 11:00 am, 1:00 pm, and 5:00 pm. The number and distribution of sampling points were determined based on the total floor area, following ICOP 2010 guidelines. For buildings under 3,000 m^2, one sampling point per 500 m^2 is required. For larger buildings, the number of fixed sampling points is scaled accordingly: 8 for 3,000–4,999 m^2, 12 for 5,000–9,999 m^2, 15 for 10,000–14,999 m^2, 18 for 15,000–19,999 m^2, and 21 for 20,000–29,999 m^2. For facilities exceeding 30,000 m^2, one sampling point should be provided for every 1,200 m^2. In this study with estimated 1,011.03 square meters as the layout shown in Figure 1, eight sampling points were identified by a qualified IAQ assessor from the National Institute of Occupational Safety and Health (NIOSH) Malaysia, who was engaged to conduct all physical measurements. The locations for physical measurements were selected from two wards in a public hospital in Johor, Malaysia, referred to as case study 1 and case study 2. These wards were chosen based on their comparable characteristics, including the use of a centralized HVAC system, identical building layout, and similar HVAC system specifications such as the Air Handling Unit (AHU) configuration, system components, ducting layout, and the Planned Preventive Maintenance (PPM) procedures. These similarities make the locations suitable for comparative analysis. Additionally, the ward environment involves healthcare staff working in shifts of approximately eight hours per day, resulting in prolonged exposure to indoor air contaminants. This exposure has the potential to influence Indoor Air Quality (IAQ) parameters and contribute to Sick Building Syndrome (SBS) symptoms among the staff.

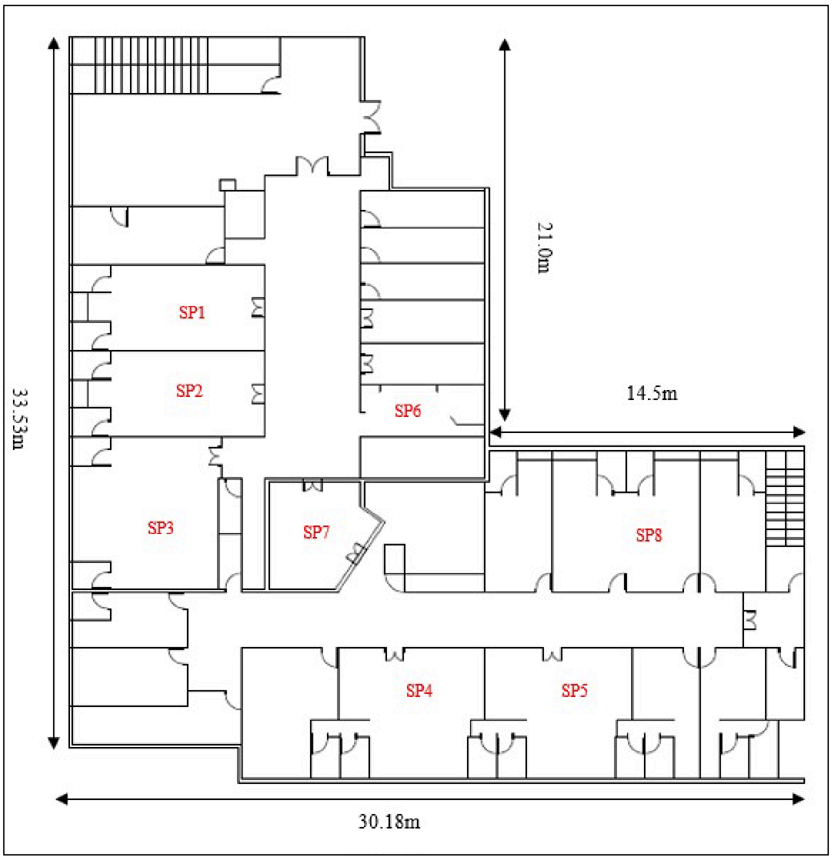

Fig. 1 *Case study layout*

Monitors should be placed at appropriate sampling points according to the ICOP-IAQ criteria [2]. A building map and duct arrangement might help inpoint specific places to monitor. Workstations should be properly placed to reduce disturbances, avoiding corners, windows, walls, air supply sources, direct sunlight, and localized pollution sources such as printers. In addition, workstations should also have sufficient clearances at least 3 meters from elevators, 2 meters from doors, and 0.5 meters from vertical surfaces and not hinder occupant movement. Meanwhile, sampling inlets should be mounted at a height of 75-120 cm, preferably 110 cm above the floor. Notably, specific calibrated equipment was used for sampling various IAQ parameters: A portable TSI IAQ Meter and YES AIR Monitor for temperature, humidity, air velocity, TVOC, CO_2, and CO; a CH_2O meter for CH_2O; a TSI Dust-Trak for particulate matter; and an AEROQUAL Ozone Monitor for O_3. Microbial sampling utilized the SKC Biostage Bioaerosol Impactor with Malt Extract Agar(MEA) for fungi andTryptic Soy Agar (TSA) for mold and bacteria, calibrated per NIOSH guidelines. Samples were analyzed at the NIOSH Industrial Hygiene Laboratory. All equipment was operated according to the manufacturers' guidelines and standard operating procedures to ensure the accuracy and reliability of the collected data. The data collected during IAQ monitoring were subjected to statistical analysis using IBM SPSS Statistics software. Descriptive statistics, including the mean (average), minimum, and maximum values, were computed for each IAQ parameter to characterize the environmental conditions across different time slots and sampling locations. This approach provided a comprehensive overview of the variation and distribution of indoor air quality indicators within the monitored buildings.

Besides, The PPM activities were carried out according to a standard PPM checklist, which included inspecting the interior of the air handler and performing cleaning as necessary, checking the condition of belts, adjusting tension, or replacing them if required, inspecting the cooling coil and heating coil for any signs of damage or leakage, examining the heat pipe or electric heater (if available) for damage, checking the drain pan for leaks and clearing any blockages, and assessing the condition of the primary filter. Washable filters were cleaned if needed, while non-washable filters were replaced only when necessary or on an annual basis, as stipulated in the maintenance protocol. General cleaning and housekeeping were also performed on the equipment, control panel, and the surrounding mechanical room to maintain cleanliness and ensure proper operation of the system.

3. Analysis and Discussion

3.1 Physical Parameter

The data sampling for IAQ parameters was conducted before and after the PPM for HVAC was conducted. Technically, the data sampling collected before the PPM maintenance has been influenced by contaminants. The physical parameters of IAQ include temperature, RH, and air movement, which play a crucial role in determining indoor environmental comfort and air quality. These parameters are measured to assess whether the indoor environment meets recommended ranges for health and comfort [16] [17]. Figure 2 illustrates the recorded trends of temperature over a three-day monitoring period in Case Studies 1 and 2. The data reflects continuous measurements conducted across the three days to assess these IAQ parameters. This analysis provides a clear understanding of physical conditions over time and their alignment with acceptable thresholds. Temperature is a critical parameter in assessing thermal comfort and indoor air quality (IAQ) in hospital wards. According to the ICOP (2010)[2] guidelines, the acceptable temperature range for indoor environments is between 23°C and 26°C. Measurements were taken over six consecutive days three days before and three days after the PPM HVAC at four intervals daily (9:00 am, 11:00 am, 1:00 pm, and 5:00 pm) in two case study wards.

Before the PPM intervention, temperatures in both CS1 and CS2 consistently remained within the acceptable limits. However, slightly higher temperatures were observed, particularly during midday readings, where CS1 recorded values up to 24.99°C and CS2 up to 24.09°C as illustrated in Figure 2. Post-PPM, a noticeable improvement in temperature regulation was observed. In CS1, temperatures stabilized closer to the lower limit of the acceptable range, with values ranging from 23.03°C to 23.40°C. Similarly, CS2 showed a trend towards lower and more consistent temperature readings, ranging from 22.20°C to 24.57°C, indicating enhanced cooling efficiency.

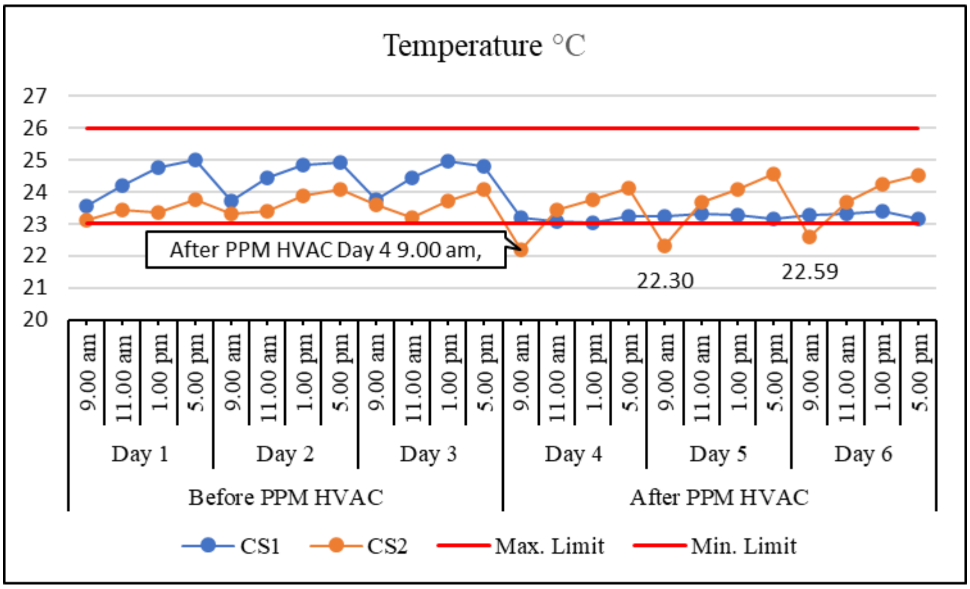

Fig. 2 *Temperature record*

Relative humidity (RH) plays a vital role in maintaining thermal comfort, controlling microbial growth, and ensuring the overall IAQ in hospital settings. The acceptable RH range as prescribed by the ICOP (2010)[2] is between 40% and 70%. Prior to the PPM intervention, RH levels in CS1 consistently exceeded the maximum allowable limit of 70%, with values ranging from 73.09% to 75.23% as presented in Figure 3. This indicates an over-humid environment, which can increase the risk of microbial growth and reduce occupant comfort. In contrast, CS2 recorded relatively lower RH levels during the same period, with some values falling within the acceptable range (e.g., 62.33%–71.13%), though still approaching or slightly exceeding the upper limit. Following the PPM, CS1 showed a notable reduction in RH levels, with values decreasing to a range of 71.40%–75.11%. While some readings remained slightly above the recommended limit, the overall trend indicates improved humidity control. CS2, on the other hand, demonstrated further improvements, with RH readings stabilizing within or near the acceptable range (67.34%–70.93%), and a more consistent pattern of humidity regulation was observed post-maintenance. These findings suggest that the PPM activity positively impacted the performance of the HVAC system in moderating indoor humidity levels, particularly in CS2. Improved RH control contributes to better occupant comfort and reduces the potential for microbial proliferation in critical indoor environments such as hospital wards.

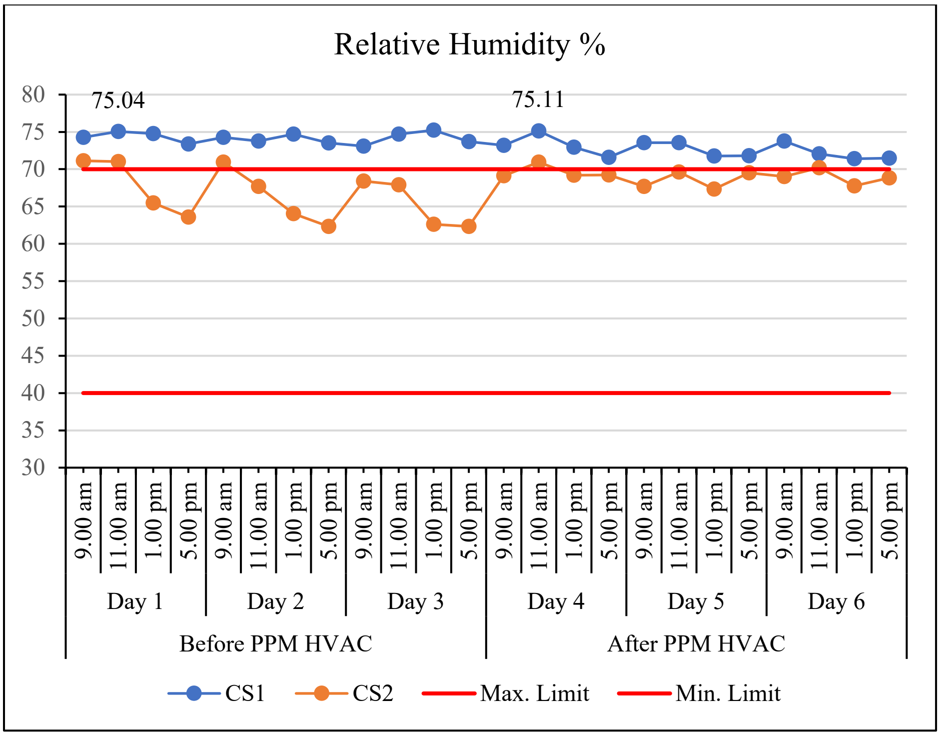

Fig. 3 *Relative humidity record*

Air movement is a key parameter in IAQ assessment, particularly in hospital environments where effective ventilation supports occupant comfort and reduces airborne contaminant levels. According to ICOP (2010)[2], the acceptable air velocity range is between 0.15 m/s and 0.50 m/s. Prior to maintenance, most air movement readings in both wards were below the minimum threshold as shown in Figure 4. CS1 recorded values ranging from 0.11 m/s to 0.15 m/s, while CS2 showed even lower velocities, with some measurements as low as 0.04 m/s. This indicates poor ventilation performance, particularly in CS2. Following HVAC maintenance, slight improvements were observed. CS2 achieved its highest post-PPM value of 0.129 m/s, but overall, both wards still recorded values below the recommended limit. In CS1, post-maintenance air movement ranged between 0.054 m/s and 0.089 m/s, showing minimal improvement.

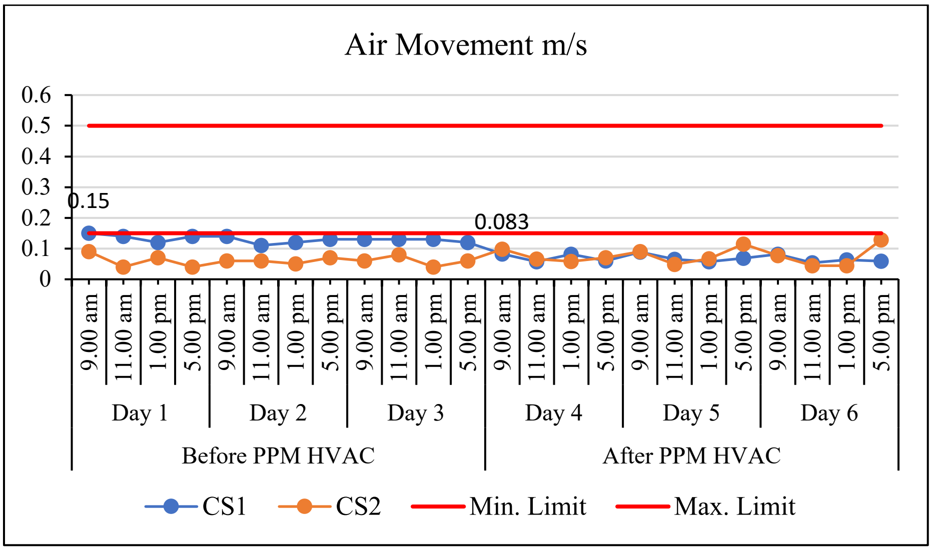

Fig. 4 *Air movement record*

The chemical parameters of IAQ include a set of seven critical metrics that indicate the presence of pollutants and the overall air quality. The chemical IAQ parameters consisting of PM_{10}, $PM_{2.5}$, TVOCs, CO_2, CO, CH_2O, and O_3 were measured before and after maintenance to assess the effectiveness of interventions. The changes in these chemical parameters for both case studies over three days are analyzed and visualized using a line chart in Figure 5, highlighting trends and shifts pre- and post-maintenance. These parameters were observed in hospital wards, primarily due to human occupancy and inadequate ventilation [18]. Across three days of monitoring in CS1, PM_{10} concentrations prior to PPM consistently remained well below the acceptable limit of 0.15 mg/m^3 set by ICOP (2010)[2]. Specifically, PM_{10} levels ranged from 0.015 to 0.022 mg/m^3 on Day 1, 0.015 to 0.026 mg/m^3 on Day 2, and 0.022 to 0.038 mg/m^3 on Day 3, with the peak value recorded during day 3 at 1.00 pm.

Following PPM, while PM_{10} concentrations showed some fluctuations, they remained within permissible limits. On Day 1 post-maintenance, concentrations increased slightly to a range of 0.016 to 0.042 mg/m^3, with the highest value observed during day 4, 9.00 am. On Day 5, the range narrowed to 0.015 to 0.027 mg/m^3, and on Day 6, values ranged from 0.016 to 0.026 mg/m^3. The observed fluctuations, particularly the spike on Day 4, which first day of post-PPM, may be attributed to increased human activity or mechanical disturbance immediately following maintenance. This is supported by Palmisani et al. [18], who noted that particulate matter concentrations in hospital environments can be influenced by resuspension of settled particles due to staff or patient movement, as well as cleaning activities. Such factors could temporarily elevate PM_{10} levels, even in well-maintained indoor environments.

In CS2, PM_{10} levels both before and after PPM were markedly below the ICOP (2010)[2] permissible limit of 0.15 mg/m^3. Before maintenance, concentrations ranged from 0.023 to 0.037 mg/m^3, with the highest value observed on Day 1 during 11.00 am. After PPM, a general reduction in PM_{10} levels was noted, with concentrations falling between 0.017 and 0.031 mg/m^3, and the peak again occurring on Day 4 (9.00 am). The consistently low levels of PM_{10} in CS2, both before and after maintenance, suggest effective existing control measures and a relatively stable indoor air environment.

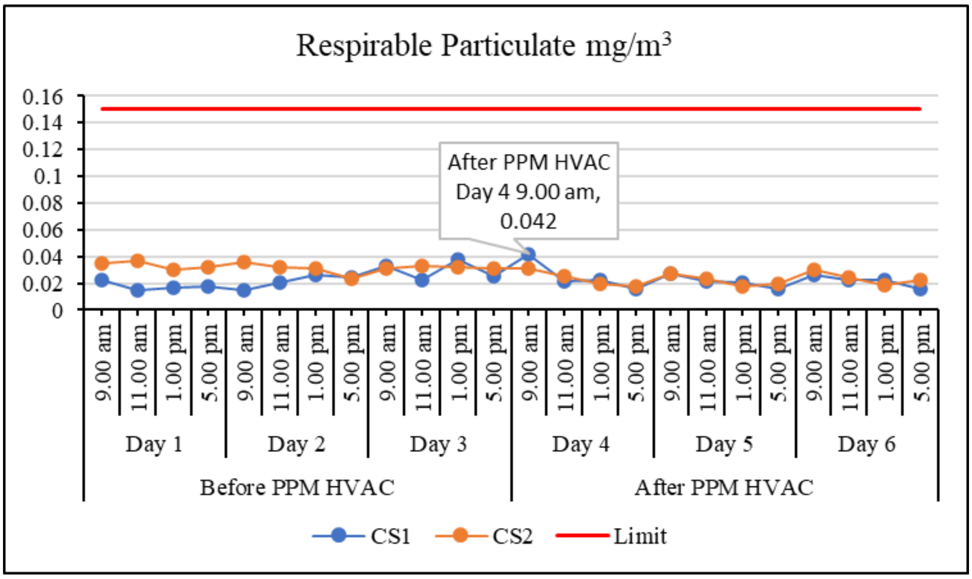

Fig. 5 *Respirable particulate (PM_{10})concentrations*

For case study 1, TVOC concentrations were consistently well below the acceptable limit of 3.0 ppm as stipulated by the ICOP (2010)[2]. Prior to the HVAC maintenance, TVOC levels ranged from 0.395 to 1.159 ppm, with the peak value observed on Day 3 at 11.00 am as shown in Figure 6. Following the PPM, there was a notable reduction in TVOC levels across all sampling slots, with concentrations ranging from 0.22875 to 0.570 ppm. The highest post-maintenance value was again recorded on Day 6, on 11.00 am, but at a significantly lower concentration of 0.570 ppm. This consistent decline in TVOC levels after PPM illustrates the effectiveness of HVAC maintenance in enhancing indoor air quality. Importantly, all measured values remained well within the permissible exposure limits throughout the monitoring period, ensuring compliance with national IAQ standards and contributing to a safer indoor environment for hospital staff.

In contrast, for CS2, although all TVOC readings remained below the 3.0 ppm threshold, the trend observed after maintenance differed from CS1. Pre-maintenance TVOC concentrations ranged from 0.106 to 0.371 ppm, with the highest value recorded on Day 2 at 1.00 pm. Interestingly, after the PPM intervention, TVOC levels increased in several sampling slots, ranging from 0.081 to 1.002 ppm. The maximum post-maintenance concentration was recorded on Day 4 at 9.00 am. Despite this increase, all values still fell within the acceptable range defined by ICOP (2010)[2]. The unexpected rise in TVOC levels post-maintenance may suggest external influencing factors, such as occupant activities, use of cleaning agents, or material off-gassing, which warrant further investigation. This contrasting outcome between CS1 and CS2 highlights the importance of contextual factors in assessing IAQ improvements and emphasizes that while PPM plays a critical role, it must be complemented by other IAQ management practices to achieve consistent results across different settings.

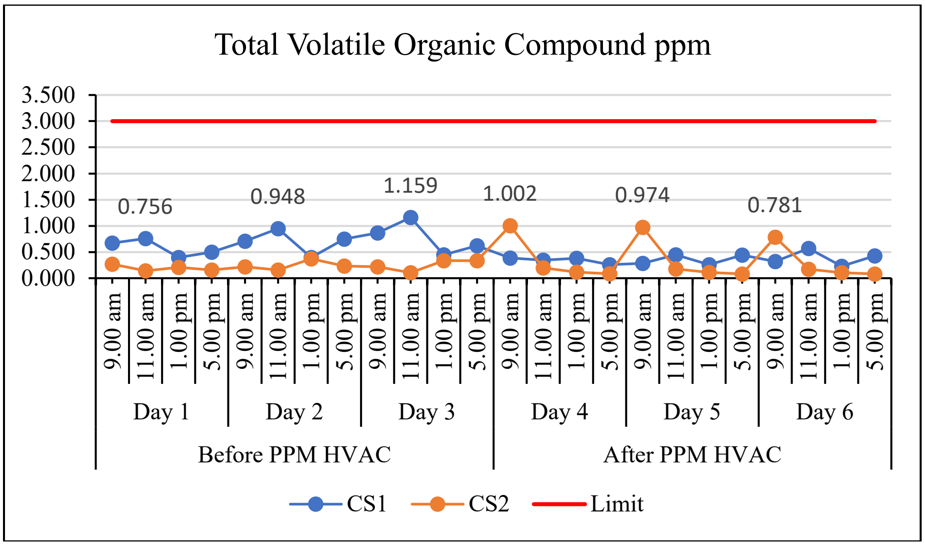

Fig. 6 *Total volatile organic compound concentration (TVOC) concentrations*

For both CS1 and CS2, CO_2 concentrations measured before and after the PPM intervention remained consistently below the recommended limit of 1000 ppm, as set by both the ICOP (2010)[2] and the ASHRAE standard. This indicates that the ventilation systems in both hospital wards were functioning within acceptable parameters to support indoor air quality and occupant comfort. In CS1, pre-maintenance CO_2 levels ranged from 445 to 533 ppm, with the highest value recorded on Day 3 at 9.00 as illustrated in Figure 7. Following HVAC maintenance, CO_2 concentrations increased noticeably, ranging from 562 to 627 ppm, with the peak level observed on Day 4 at the evening 5.00 pm. Despite the increase, all values remained well within the permissible exposure limit, reflecting sufficient ventilation and compliance with IAQ guidelines. The observed rise in CO_2 levels after maintenance may be attributed to changes in occupancy patterns, increased staff activity, or the reintroduction of enclosed spaces post-servicing. Palmisani et al. [18] noted that CO_2 concentrations tend to rise during peak occupancy hours (typically between 08:00 and 15:00) due to elevated metabolic emissions from occupants, supporting the possibility that human presence and activity levels may have influenced these results.

Similarly, in CS2, CO_2 concentrations before PPM ranged from 534 to 606 ppm, with the highest level occurring on Day 3 at 5.00 pm. The lowest concentration was recorded on Day 2 at 11.00 am (556 ppm). After maintenance, CO_2 levels showed a modest increase, ranging from 552 to 696 ppm. The highest post-maintenance concentration was measured on Day 6 at 9.00 am, while the lowest was observed on the evening at the same day. Although a slight rise was evident post-intervention, all readings remained significantly below the 1000 ppm threshold, indicating sustained air quality and effective ventilation throughout the monitoring period. These findings suggest that while CO_2 concentrations increased slightly in both case studies following HVAC maintenance, they did not exceed safety thresholds and thus did not compromise indoor environmental quality. The results highlight the dynamic nature of indoor CO_2 levels and reinforce the need to consider contextual factors such as occupancy density, activity levels, and operational schedules when interpreting IAQ data. Overall, the PPM intervention-maintained compliance with established standards, contributing to a safe and healthy indoor environment in both healthcare settings.

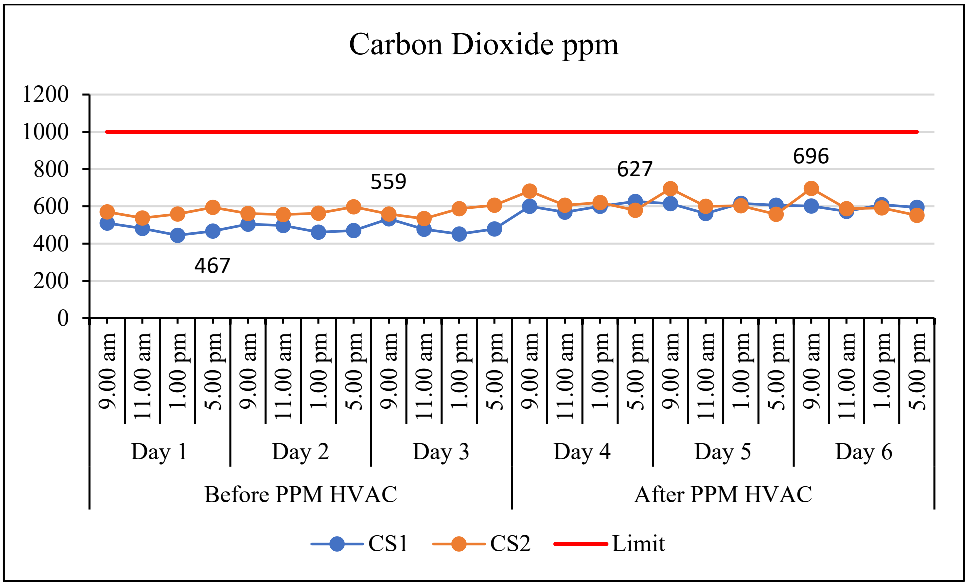

Fig. 7 *Carbon dioxide (CO_2) concentrations*

In both CS1 and CS2, CO concentrations measured before and after the PPM of the HVAC system remained well within the permissible limit of 10 ppm, as stipulated by ICOP (2010)[2]. This indicates that the indoor environments in both settings maintained safe CO levels throughout the monitoring period, regardless of fluctuations observed pre- and post-intervention. At CS1, CO concentrations prior to HVAC maintenance ranged from 2.9 to 3.5 ppm, with the highest value recorded on Day 3 at 11.00 am as illustrated in Figure 8. Following the PPM intervention, CO levels increased noticeably, ranging from 3.9 to 5.6 ppm, with the maximum value detected on Day 4 evening at 5.00 pm. Although the post-maintenance levels were higher, they remained well below the regulatory limit, indicating continued compliance with IAQ standards and no immediate health concerns for occupants. The observed rise could be linked to temporary operational changes, external infiltration, or increased mechanical activity during or shortly after the maintenance process.

While in CS2, the pattern of CO concentrations was more stable. Before maintenance, levels ranged from 1.9 to 3.0 ppm, with the highest concentration observed at 5.00 pm day 2, and the lowest in slot day 1 at 1.00 pm. After the maintenance, CO levels fluctuated only slightly, between 1.8 and 3.1 ppm. The highest post-maintenance values were recorded in Day 5 at 5.00 pm and Day 6 at 9.00 am (3.1 ppm), while the lowest occurred on Day 6, 1.00 pm with 1.8 ppm. These modest fluctuations indicate minimal impact of the HVAC PPM on CO concentrations in this case, possibly due to more consistent indoor conditions and ventilation patterns.

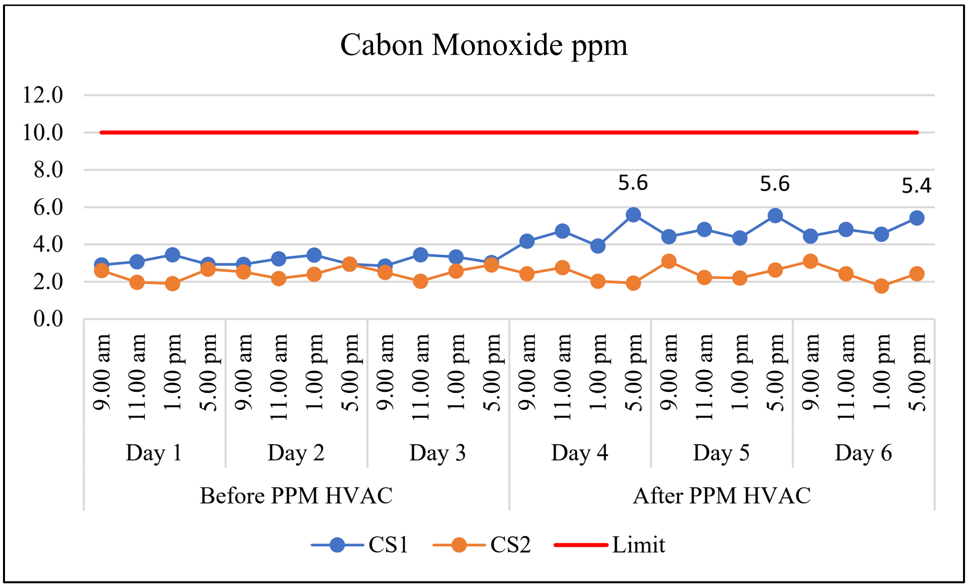

Fig. 8 *Carbon monoxide (CO) concentrations*

The CH_2O concentration trends before and after the PPM of the HVAC system are illustrated in the corresponding figure, showing fluctuations that largely remained within the acceptable limit of 0.1 ppm set by ICOP (2010)[2]. In CS1, pre-maintenance CH_2O concentrations ranged from 0.030 to 0.075 ppm, with the highest value recorded on Day 1 at 1.00 pm and the lowest on Day 3 at 5.00 pm as shown in Figure 9. Following maintenance, CH_2O levels increased slightly, ranging from 0.049 to 0.103 ppm. The peak value, observed on Day 5 at 1.00 pm, slightly exceeded the regulatory limit. This marginal exceedance may be attributed to short-term emissions released during or after HVAC servicing, highlighting the importance of ongoing monitoring to ensure consistent compliance with IAQ standards.

In CS2, CH_2O levels remained well within the permissible limit throughout the monitoring period. Before maintenance, concentrations varied modestly between 0.020 and 0.040 ppm, with the highest value found in Day 2 at 1.00 pm and the lowest at Day 3 at 11.00 am. After PPM, concentrations ranged from 0.010 to 0.079 ppm, peaking in Day 4 early morning at 9.00 am and reaching the minimum in day 3 at 5.00 pm. The post-maintenance values demonstrated slight fluctuations but remained within safe levels.

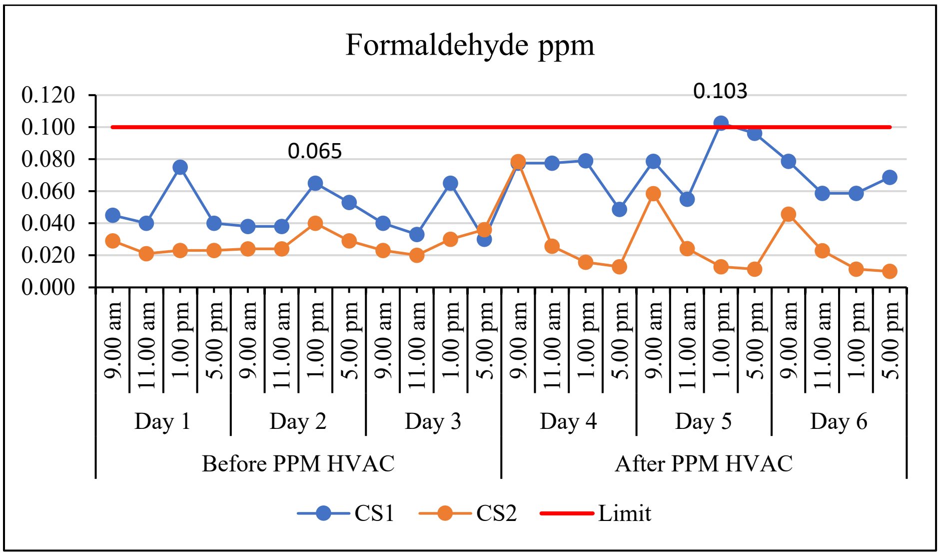

Fig. 9 *Formaldehyde (CH_2O) concentrations*

In both CS1 and CS2, O_3 levels remained well below the ICOP (2010)[2] limit of 0.05 ppm before and after the PPM HVAC. At CS1, most pre-maintenance readings were 0.010 ppm, with some slots showing no detectable O_3 as shown in Figure 10. After maintenance, levels dropped further to between 0.000 and 0.008 ppm, suggesting improved air quality. While in CS2, O_3 was undetectable (0.000 ppm) before maintenance. After PPM, there was a slight increase to between 0.003 and 0.006 ppm, but still far below the allowable limit. These results show that O_3 levels were well controlled in both cases and that HVAC maintenance contributed to maintaining a safe indoor environment.

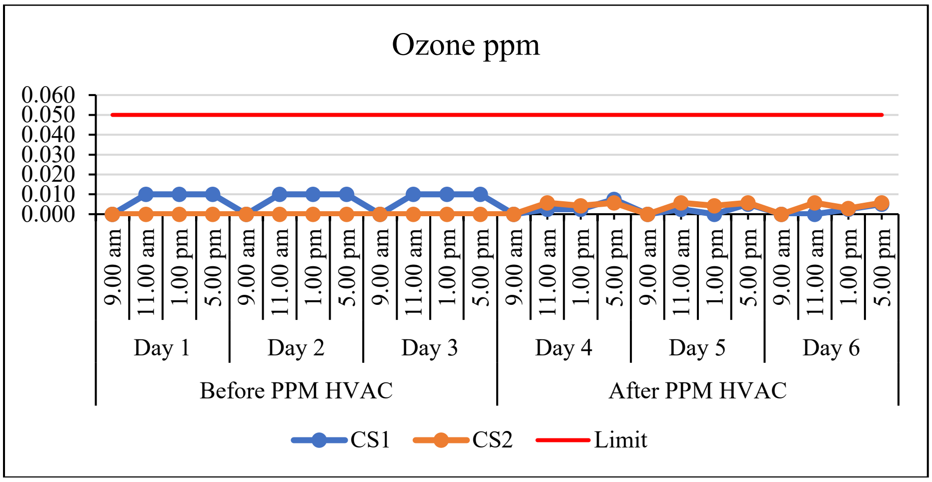

Fig. 10 *Ozone (O_3) concentrations*

In both CS1 and CS2, $PM_{2.5}$ concentrations remained below the WHO (2010) 24-hour guideline of 0.025 mg/m^3, indicating safe indoor air quality throughout the study. At CS1, $PM_{2.5}$ levels ranged from 0.0044 to 0.0072 mg/m^3 before maintenance and increased slightly after PPM to between 0.0064 and 0.0114 mg/m^3 as shown in Figure 11. Despite the rise, values remained within safe limits. At CS2, $PM_{2.5}$ levels ranged from 0.0097 to 0.0172 mg/m^3 before PPM and showed a slight decline post-maintenance, falling between 0.0079 and 0.0162 mg/m^3. Although ICOP (2010)[2] does not set $PM_{2.5}$ limits, all values complied with WHO standards, confirming that HVAC PPM helped maintain good air quality in both hospital settings

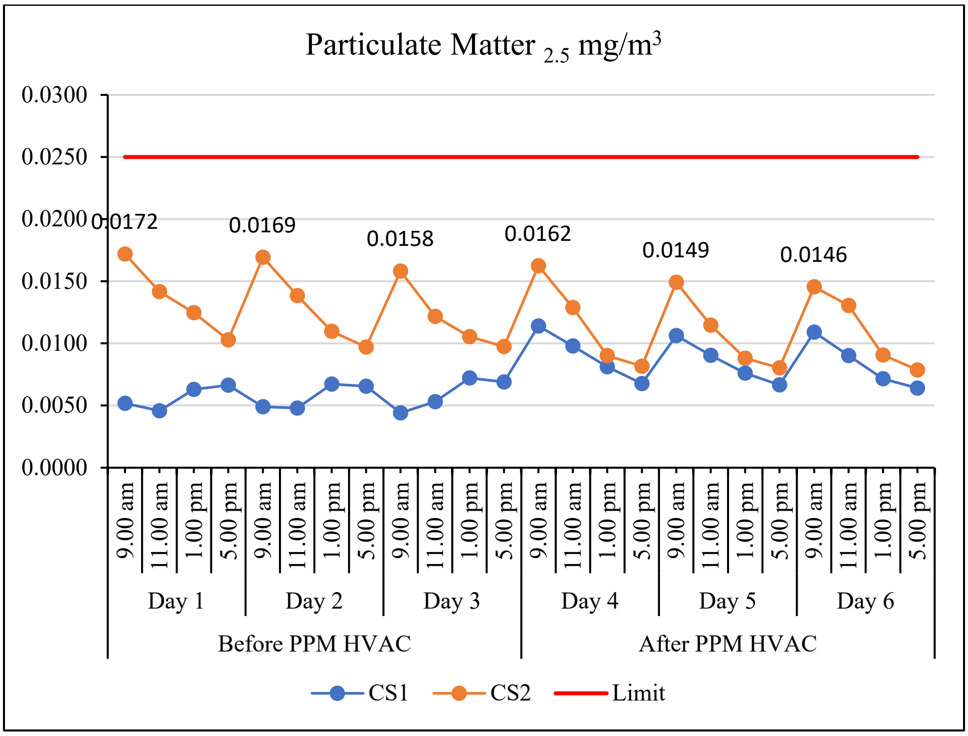

Fig. 11 *Particulate matter ($PM_{2.5}$) concentrations*

The microbiological parameters of IAQ focus on the presence and concentration of TBC and TFC, which are crucial for assessing the microbial contamination of indoor environments. The measurement of bacteria and fungi is vital as they are linked to respiratory disorders and thrive in nutrient-enriched microclimates [19][20][21]. Accordingly, microbiological parameters, including TBC and TFC, were collected for a single day and are presented in the table with their mean, maximum, and minimum values. Unlike other parameters, microbiological data require laboratory analysis, making them more complex to evaluate. Figure 12 compares the levels of TBC with the acceptable limits, highlighting any deviations from the recommended standards.

In CS1, TBC peaked around midday before PPM-HVAC at 11.00am and declined thereafter. A similar trend was observed in Phase 2, with slightly lower readings, suggesting improved conditions post-PPM. TBC levels consistently remained below the ASHRAE and ICOP limit of 500 cfu/m^3. In CS2, TBC levels were higher before the PPM-HVAC compared to after the PPM-HVAC, reinforcing the positive impact of HVAC maintenance. Both phases showed a consistent diurnal trend, with TBC rising during midday breaks and falling toward the evening. At all times, values remained well within the acceptable limits, supporting the role of PPM in maintaining microbiological air quality.

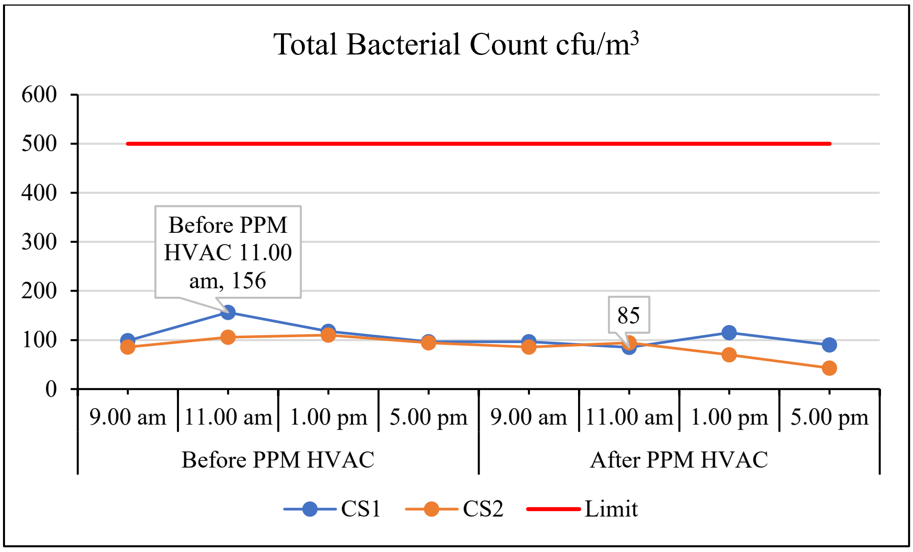

Fig. 12 *Total bacterial count concentrations*

In case study 1, TFC patterns before and after HVAC maintenance were largely consistent, with post-PPM readings showing slight reductions as shown in Figure 13. This suggests that PPM contributed to better fungal control within the ward environment. Similarly, in Case Study 2, TFC levels declined after the PPM intervention and remained well below the ICOP (2010)[2] and ASHRAE limit of 1000 cfu/m^3. These findings highlight the effectiveness of routine HVAC maintenance in reducing airborne fungal contamination in hospital settings.

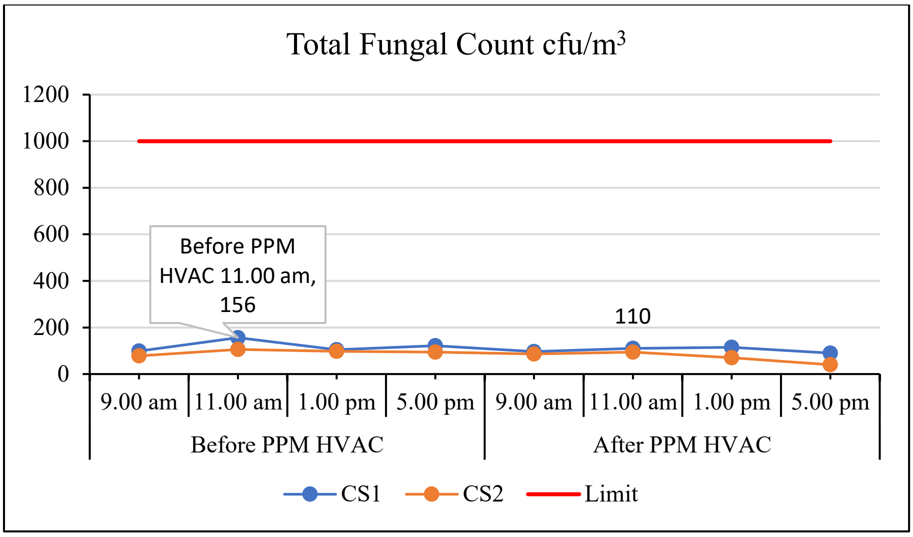

Fig. 13 *Total fungal count concentrations*

4. The Significance of PPM Toward IAQ Parameters

The Wilcoxon Signed-Rank Test is a nonparametric test that compares paired data, making it appropriate for determining changes in IAQ parameters before and after maintenance. The Wilcoxon Signed-Rank test for the intervention of PPM HVAC on the level of IAQ parameters was investigated using the previous work [22]. Prior to conducting statistical comparisons, the normality of IAQ parameter data collected before and after PPM HVAC was assessed using the Kolmogorov-Smirnov and Shapiro-Wilk tests. Normality tests were performed for the data in Case Study 1 and case study 2 prior to conducting the Wilcoxon signed-rank test. The results indicated that the data did not meet the assumption of normality, warranting the application of the non-parametric Wilcoxon signed-rank test. This test was employed to rigorously evaluate the significance of changes in IAQ parameters attributable to PPM interventions. The preliminary normality assessment is critical for selecting suitable analytical techniques, ensuring the robustness and validity of the study's findings.

The author defined this method as a nonparametric method employed in engineering to compare measurements before and after maintenance. It successfully detects changes in performance or quality without assuming a certain distribution of the data. Additionally, it determines whether the median ranks of two linked datasets differ significantly without requiring that the data be regularly distributed. Moreover, this test is especially useful for assessing IAQ parameters, which frequently exhibit outliers or non-normal distributions. Comparing matched observations, such as CO_2 levels or PM_{10} concentrations, can reveal if maintenance actions resulted in statistically significant changes, offering useful insights into their effectiveness. Table 2 summarizes the Wilcoxon Signed Ranks Test results, indicating significant changes in most IAQ parameters after the intervention compared to before, as suggested by p-values (Asymp. Sig. 2-Tailed) less than 0.05. The Z values reflected the magnitude and direction of the differences as follows; A negative Z value indicated that the parameter level after PPM was significantly lower than before PPM and a positive rank highlighted improvements where the parameter level after intervention increased significantly. Note that key parameters like temperature, air movement, TVOC, CO_2, CO, CH_2O, O_3, and $PM_{2.5}$ exhibit statistically significant improvements, suggesting effective intervention. However, parameters such as PM_{10}, TBC, and TFC did not demonstrate significant changes, with p-values of 0.336, 0.234, and 0.493, respectively, indicating these may require further investigation or targeted measures.

Table 2 *The intervention level of parameters for case study 1*

IAQ Parameter Tested	Z	Asymp. Sig. (2-Tailed)
Temp after-Temp before	-6.581[b]	.000
Rh after-Rh before	-2.479[b]	.013
Air M. after-Air M. before	-5.425[b]	.000
PM10 after-PM10 before	-.963[c]	.336
TVOC after-TVOC before	-4.807[b]	.000
CO_2 after-CO_2 before	-6.064[c]	.000
CO after-CO before	-5.153[c]	.000
CH_2O after-CH_2O before	-6.435[c]	.000
O_3 after-O_3 before	-4.158[b]	.000
TBC after-TBC before	-1.191[b]	.234
TFC after-TFC before	-.685[b]	.493
PM2.5 after-PM2.5 before	-6.005[c]	.000

a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

c. Based on negative ranks.

The results were further analyzed by separating the parameters into positive and negative ranks based on the direction of the observed changes. The test results indicated positive ranks for parameters, where their values recorded after the intervention were significantly higher than before the intervention. Notable examples included temperature, which had asymp. sig. (2-tailed) value of 0.000 and Z value of -6.581, as well as air movement, TVOC, and O_3, with respective Z values of -5.425, -4.807, and -4.158. These findings highlighted improvements in these parameters post-intervention. Conversely, negative ranks were observed for parameters whose values were significantly lower after the intervention. These included relative humidity with Z value of -2.479 and asymp. sig. (2-tailed) value of 0.013, as well as CO_2, CO, CH_2O, and PM_2.5, which all recorded highly significant asymp. sig. (2-tailed) values of 0.000. The respective Z values for these parameters were -6.064, -5.153, -6.435, and -6.005, indicating substantial reductions in their levels after intervention. The Z values across all parameters reflected the magnitude and direction of the differences observed. A negative Z value suggested that the parameter level after the PPM intervention was significantly lower than before, indicating improved parameters benefiting from reduction (e.g., pollutants such as CO_2, CO, and PM2.5). On the other hand, parameters with significant positive ranks implied that the intervention increased desirable levels, such as air movement and temperature stability.

For case study 2, the Wilcoxon Signed Ranks Test results indicate significant changes in specific IAQ parameters after intervention. RH, PM_{10}, CO_2, O_3, and $PM_{2.5}$ presented statistically significant differences ($p < 0.05$), suggesting improvements due to the intervention. However, parameters like temperature, air movement, TVOC, CO, CH_2O, TBC, and TFC, as indicated in Table 3, did not reveal significant changes ($p > 0.05$). This indicates no notable effect, and further measures may be required to address these.

Table 3 *The intervention level of parameters for case study 2*

IAQ Parameter Tested	Z	Asymp. Sig. (2-Tailed)
Temp after-Temp before	-1.006[b]	.314
Rh after-Rh before	-4.235[b]	.000
Air M. after-Air M. before	-1.222[b]	.222
PM10 after-PM10 before	-5.076[c]	.000
TVOC after-TVOC before	-.261[b]	.794
CO2 after-CO2 before	-4.969[b]	.000
CO after-CO before	-1.515[c]	.130
CH2O after-CH2O before	-.634[c]	.526
O3 after-O3 before	-5.657[b]	.000
TBC after-TBC before	-1.813[c]	.070
TFC after-TFC before	-1.447[c]	.148
PM2.5 after-PM2.5 before	-5.049[c]	.000

a. Wilcoxon Signed Ranks Test
b. Based on negative ranks.
c. Based on positive ranks.

The results were further differentiated by positive and negative ranks, highlighting the observed changes direction. For parameters with negative ranks, where post-intervention levels were significantly lower than pre-intervention levels, three parameters which are relative humidity, CO_2, and O_3 recorded highly significant differences, with asymp. sig. (2-tailed) values of 0.000 and corresponding Z values of -4.235, -4.969, and -5.657, respectively. These reductions in parameter levels indicated successful mitigation of pollutants and undesirable conditions, particularly for CO_2 and O_3, which are critical to maintaining a healthy indoor environment. Conversely, for parameters with positive ranks, where post-intervention levels were significantly higher than pre-intervention levels, two parameters such as PM10 and PM2.5 also recorded asymp. sig. (2-tailed) values of 0.000, and the corresponding Z values of -5.076 and -5.049 indicated substantial improvements in particulate matter levels after PPM intervention. These positive outcomes reflected the system's capacity to filter and reduce airborne particles, improving air quality effectively. The statistical analysis highlighted the Z values as measures of the magnitude and direction of changes, with negative Z values signalling reductions in parameter levels and positive ranks showing beneficial increases. Parameters such as relative humidity, PM10, PM2.5, CO_2, and O_3, with significant asymp. sig. (2-tailed) values, validated the PPM's ability to enhance IAQ by addressing critical pollutants and maintaining favorable environmental conditions. On the other hand, CO, TBC, and TFC, while not statistically significant, demonstrated values near the 0.05 threshold, suggesting that the intervention may partially influence these parameters.

Hassan et al. [23] underscored the significance of PPM and the essential function of HVAC systems in hospital settings for regulating thermal conditions, humidity levels, and air cleanliness as an factors critical to ensuring patient safety and comfort. Their findings advocate for the integration of regular IAQ monitoring within HVAC maintenance protocols, emphasizing controlled ventilation and routine cleaning practices as key strategies to minimize the risk of hospital-acquired infections (HAIs) and to promote a safer indoor environment for both patients and healthcare personnel.

Conclusion

This study highlights the critical role of PPM in optimizing hospital IAQ, addressing a key challenge faced by administrators in assessing the effectiveness of HVAC interventions. Using the Wilcoxon Signed Ranks Test, the findings demonstrate significant improvements in specific IAQ parameters, such as temperature, air movement, TVOC, CO_2, CO, CH_2O, O_3, and $PM_{2.5}$, in case study 1, and RH, PM_{10}, CO_2, O_3, and $PM_{2.5}$ in case study 2. These findings imply that, when properly applied, PPM interventions can effectively improve important IAQ parameters. However, the lack of significant changes in microbiological counts and several physical indicators suggests that targeted strategies or increased measures are required in these areas. Therefore, by explicitly comparing IAQ data before and after PPM in limited hospital conditions, this study fills a significant gap in the literature and provides practical insights into the nuanced effectiveness of PPM interventions. Furthermore, the findings highlight the necessity of frequent, data-driven maintenance to protect hospital occupants' health and comfort, as well as the need for continual improvement of IAQ management systems. This study presents a significant opportunity for future research, particularly in the development of a comprehensive risk assessment tool to evaluate and rank indoor air quality (IAQ) in hospital environments. The data collected are valuable not only for understanding current IAQ conditions but also for informing the design of practical, evidence-based assessment tools tailored to healthcare settings. Such tools could support hospital management and occupational health professionals in identifying high-risk areas, prioritizing interventions, and ensuring a safer indoor environment for patients, staff, and visitors.

Acknowledgement

This research was supported by the Ministry of Higher Education (MOHE) through the Fundamental Research Grant Scheme (FRGS/1/2022/SS02/UTHM/03/1).

Conflict of Interest

The authors declare that there is no conflict of interest regarding the paper's publication.

Author Contributions

The authors confirm their contribution to the paper as follows: ***study conception and design:*** *Author 1, Author 2, Author 4, Author 5;* ***data collection:*** *Author 1 and Author 2;* ***analysis and interpretation of results:*** *Author 1, Author 2, Author 3;* ***draft manuscript preparation:*** *Author 1, Author 2. All authors reviewed the results and approved the final version of the manuscript.*

Reference

[1] World Health Organization. WHO guidelines for indoor air quality: household fuel combustion. World Health Organization, 2014.

[2] Department of Occupational Safety and Health (DOSH). "Industry Code of Practice on Indoor Air Quality 2010." *Department of Occupational Safety and Health* (2010).

[3] Rosli, M. A., Abdullah, M. S. M., Hariri, A., Damanhuri, A. A. M., Tamtama, B. F., & Noraini, N. M. R. (2024). Comprehensive Review on the Relationship between Duct Cleanliness and Airborne Contaminants. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *115*(2), 61-69. DOI: https://doi.org/10.37934/arfmts.115.2.6169.

[4] Abdullah, M. S. M., Rosli, M. A., Hariri, A., Damanhuri, A. A. M., Tamtama, B. F., Ebas, N. A., & Noraini, N. M. R. (2025). Evaluation of Sick Building Syndrome (SBS) Symptoms and Measurement of Indoor Air Quality (IAQ) Parameter in One of Hospital Building in Johor. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, *52*(2), 139-147. DOI: https://doi.org/10.37934/araset.52.2.139147.

[5] Goudarzi, G., & Reshadatian, N. (2024). The study of effective factors in sick building syndrome related to fungi and its control methods. *Results in Engineering*, 102703. https://doi.org/10.1016/j.rineng.2024.102703.

[6] Mannan, M., & Al-Ghamdi, S. G. (2021). Indoor air quality in buildings: a comprehensive review on the factors influencing air pollution in residential and commercial structure. *International Journal of Environmental Research and Public Health*, *18*(6), 3276. https://doi.org/10.3390/ijerph18063276.

[7] Wang, H., & Pan, W. (2024). Multi-Domain Environmental Quality of Indoor Mixed-Use Open Spaces and Insights into Healthy Living—A Quarantine Hotel Case Study. *Buildings*, *14*(11), 3443. https://doi.org/10.3390/buildings14113443.

[8] Jung, C., & Alshamasi, S. M. (2024). Indoor Air Quality Management in Dubai: Assessing the Efficacy of Air Purifiers, Photocatalysts, and Window Ventilation in Reducing HCHO. *Buildings*, *14*(9), 2815. https://doi.org/10.3390/buildings14092815.

[9] Sherzad, M., & Jung, C. (2022). Evaluating the emission of VOCs and HCHO from furniture based on the surface finish methods and retention periods. *Frontiers in Built Environment*, *8*, 1062255. DOI: 10.3389/fbuil.2022.1062255.

[10] Niza, I. L., de Souza, M. P., da Luz, I. M., & Broday, E. E. (2024). Sick building syndrome and its impacts on health, well-being and productivity: A systematic literature review. *Indoor and Built Environment*, *33*(2), 218-236. https://doi.org/10.1177/1420326X231191079.

[11] Sadrizadeh, S., Yao, R., Yuan, F., Awbi, H., Bahnfleth, W., Bi, Y., ... & Li, B. (2022). Indoor air quality and health in schools: A critical review for developing the roadmap for the future school environment. *Journal of Building Engineering*, *57*, 104908. https://doi.org/10.1016/j.jobe.2022.104908.

[12] Ganesh, G. A., Sinha, S. L., Verma, T. N., & Dewangan, S. K. (2021). Investigation of indoor environment quality and factors affecting human comfort: A critical review. *Building and Environment*, *204*, 108146. https://doi.org/10.1016/j.buildenv.2021.108146.

[13] Fonseca, A., Abreu, I., Guerreiro, M. J., & Barros, N. (2022). Indoor air quality in healthcare units—a systematic literature review focusing recent research. *Sustainability*, *14*(2), 967. https://doi.org/10.3390/su14020967.

[14] Settimo, G., Gola, M., & Capolongo, S. (2020). The relevance of indoor air quality in hospital settings: From an exclusively biological issue to a global approach in the Italian context. *Atmosphere*, *11*(4), 361. https://doi.org/10.3390/atmos11040361.

[15] Ministry of Health "Guideline on Indoor Air Quality for Hospital Support Service 2015" *Engineering Service Division* (2010).

[16] Baloch, R. M., Maesano, C. N., Christoffersen, J., Banerjee, S., Gabriel, M., Csobod, É., ... & Dewolf, M. C. (2020). Indoor air pollution, physical and comfort parameters related to schoolchildren's health: Data from the European SINPHONIE study. *Science of the Total Environment*, *739*, 139870. https://doi.org/10.1016/j.scitotenv.2020.139870.

[17] Andualem, Z., Gizaw, Z., Bogale, L., & Dagne, H. (2019). Indoor bacterial load and its correlation to physical indoor air quality parameters in public primary schools. *Multidisciplinary respiratory medicine*, *14*, 1-7. https://doi.org/10.1186/s40248-018-0167-y.

[18] Palmisani, J., Di Gilio, A., Viana, M., de Gennaro, G., & Ferro, A. (2021). Indoor air quality evaluation in oncology units at two European hospitals: Low-cost sensors for TVOCs, PM2. 5 and CO2 real-time monitoring. *Building and Environment*, *205*, 108237. https://doi.org/10.1016/j.buildenv.2021.108237.

[19] Basińska, M., Michałkiewicz, M., & Ratajczak, K. (2019). Impact of physical and microbiological parameters on proper indoor air quality in nursery. *Environment international*, *132*, 105098. https://doi.org/10.1016/j.envint.2019.105098.

[20] Yogeswaran, K., Azmi, L., Bhassu, S., Isa, H. N., & Aziz, M. A. (2023). Physical parameters influence the microbial quality of indoor air in research laboratories: A report from Malaysia. *Kuwait Journal of Science*, *50*(4), 665-673. https://doi.org/10.1016/j.kjs.2023.04.009.

[21] Ahmed, F., Ramana, A. S., Chemmal Swami Durai, C., & Dhamodharan, P. (2024). Microbial analysis of a built environment with disinfection based balanced ventilation system. *International Journal of Environmental Science and Technology*, 1-14. https://doi.org/10.1007/s13762-024-05715-4.

[22] Petcharat, K., & Sukparungsee, S. (2023). Development of a new MEWMA-Wilcoxon sign rank chart for detection of change in mean parameter. *Appl. Sci. Eng. Prog*, *16*, 5892. DOI: 10.14416/j.asep.2022.05.005.

[23] Hassan, A., & Zeeshan, M. (2022). Microbiological indoor air quality of hospital buildings with different ventilation systems, cleaning frequencies and occupancy levels. Atmospheric Pollution Research, 13(4), 101382.