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Principal Component Analysis for Identifying Key Indoor Air Quality Factors in a Healthcare Facility

(Analisis Komponen Utama untuk Mengenal Pasti Faktor Kualiti Udara Dalaman Utama di Fasiliti Penjagaan Kesihatan)

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ABSTRACT

Effective management of indoor air quality (IAQ) is essential in healthcare settings, serving as a key element in supporting sustainability through patient comfort and staff well-being. This study aims to establish a baseline IAQ dataset as part of sustainability programs (SP) in Malaysian government healthcare facilities and determine primary contributors for IAQ variability by Principal Component Analysis (PCA). IAQ assessment was conducted in four departments at Hospital Kuala Lumpur, Endoscopy Clinic (EC), Psychiatric Clinic (PC), Cytotoxic Drug Reconstitution (CDR), and Information Technology (IT) based on the Industry Code of Practice on Indoor Air Quality (ICOP on IAQ 2010). Eleven parameters were measured, and PCA was performed using XLSTAT 2019 software to identify dominant influencing IAQ parameters. Results showed most IAQ parameters complied with acceptable ranges; however, deviations were observed in air temperature (21.43 ± 0.61 °C), air movement (0.13 ± 0.01 m/s), relative humidity (68.85 ± 5.38%), and carbon dioxide (CO_2) concentration (760.5 ± 413.63 ppm), particularly at P6-PC where CO_2 peaked at 1380 ppm. One-way ANOVA and Tukey post hoc tests showed statistically significant differences ($p < 0.001$) in CO_2 and RH across departments. PCA results identified CO_2, total bacterial count (TBC), and total fungal count (TFC) as dominant contributors, with loadings exceeding 0.75. Variations in occupancy and ventilation performance were the main contributors to IAQ differences between departments. This study underscores the importance of targeted IAQ interventions tailored to departmental functions and reinforces the role of PCA supported IAQ assessment in advancing sustainable healthcare facility management.

Keywords: Healthcare facilities; indoor air quality; sustainability management

ABSTRAK

Pengurusan kualiti udara dalaman (IAQ) yang berkesan adalah penting dalam persekitaran penjagaan kesihatan kerana ia merupakan elemen utama dalam menyokong kelestarian melalui keselesaan pesakit dan kesejahteraan kakitangan. Kajian ini bertujuan untuk mewujudkan set data asas IAQ sebagai sebahagian daripada program kelestarian (SP) di fasiliti penjagaan kesihatan kerajaan Malaysia dan menentukan penyumbang utama kepada kevariabelan IAQ menggunakan Analisis Komponen Utama (PCA). Penilaian IAQ telah dijalankan di empat jabatan di Hospital Kuala Lumpur iaitu Klinik Endoskopi (EC), Klinik Psikiatri (PC), Unit Rekonstitusi Ubat Sitotoksik (CDR) dan Teknologi Maklumat (IT) berdasarkan Kod Amalan Industri mengenai Kualiti Udara Dalaman (ICOP on IAQ 2010). Sebanyak sebelas parameter telah diukur dan PCA dijalankan menggunakan perisian XLSTAT 2019 untuk mengenal pasti parameter IAQ yang paling dominan. Hasil kajian menunjukkan kebanyakan parameter IAQ mematuhi julat dan had yang boleh diterima, namun terdapat penyimpangan pada suhu udara (21.43 ± 0.61 °C), pergerakan udara (0.13 ± 0.01 m/s), kelembapan relatif (68.85 ± 5.38%) dan kepekatan karbon dioksida (CO_2) (760.5 ± 413.63 ppm), terutamanya di P6-PC dengan CO_2 mencecah 1380 ppm. Ujian ANOVA sehala dan ujian pasca hoc Tukey menunjukkan perbezaan yang signifikan secara statistik ($p < 0.001$) bagi CO_2 dan RH antara jabatan. Keputusan PCA mengenal pasti CO_2, jumlah kiraan bakteria (TBC) dan jumlah kiraan kulat (TFC) sebagai penyumbang dominan dengan nilai pemuatan melebihi 0.75. Variasi dalam kepadatan penghuni dan prestasi pengudaraan dikenal pasti sebagai penyumbang utama kepada perbezaan IAQ antara jabatan. Kajian ini menekankan kepentingan intervensi IAQ yang disasarkan mengikut fungsi jabatan dan mengukuhkan peranan penilaian IAQ yang disokong oleh PCA dalam memajukan pengurusan fasiliti penjagaan kesihatan yang lestari.

Kata kunci: Fasiliti penjagaan kesihatan; kualiti udara dalaman; pengurusan kelestarian

INTRODUCTION

The Ministry of Health (MOH), Malaysia has embarked on a sustainability program in all healthcare facilities to adopt green and low-carbon initiatives to achieve smart and sustainable facilities (Abdullah et al. 2019). Under this program, MOH implements green building parameters which consist of three elements which are Sustainable Energy Management Program (SEMP), the Reuse, Reduce, Recycle (3R) program, and Indoor Air Quality (IAQ) management (Noor Muhammad, Lim & Ahmad 2021). Green buildings are designed and built by developed and developing countries to use less energy and resource than traditional buildings and aim to minimize their impacts on human health and the environment (Aghili et al. 2019; Pavate et al. 2024). In alignment with this framework, IAQ assessments within Malaysian healthcare facilities are conducted in accordance with the ICOP on IAQ 2010. As indoor environments directly impact occupant health, effective IAQ monitoring is essential to ensure both environmental compliance and the well-being of occupants (Chirico, Settimo & Magnavita 2023).

In healthcare settings, IAQ plays a crucial role in protecting worker health, as healthcare staff are continuously exposed to air pollutants that can affect their comfort, safety, and productivity (Gola, Settimo & Capolongo 2019). Unlike other building types, hospitals accommodate immunocompromised patients, operate 24/7, and contain a wide range of chemical, biological, and physical sources of pollution. These include emissions from sterilization procedures, medical devices, cleaning products, and even human biological activities (Ibrahim et al. 2022). Most hospital buildings rely on mechanical ventilation and air conditioning (MVAC) systems to regulate temperature, humidity, and airflow (Zainal et al. 2019). However, when these systems are inefficient or poorly maintained, they often contribute to degraded IAQ and have been directly linked to the onset of Sick Building Syndrome (SBS), a condition frequently reported among workers (Abdul Ghani et al. 2024; Božić, Ilić & Ilić 2019; Chow & Yu 2000).

According to Seppanen and Fisk (2002), the SBS is demonstrated to be influenced by the type of ventilation system. Higher SBS prevalence was found in buildings with MVAC compared to the normal ventilation system. Few kinds of research in tropical countries focus to demonstrate the age of the building and its characteristics with the prevalence of SBS symptoms, such as dizziness, skin rashes, and fatigue and other health effects (Zubir, Jalaludin & Rasdi 2022). The most severe SBS symptoms were associated with the group of physical health risk factors, such as building dampness moisture damage, lack of daylight, exposure to increased noise levels and decreased ventilation. Other than that, chemical health risk factors, especially related to poor IAQ, which involving CO_2, unpleasant odor, and volatile organic compounds (VOC), and psychosocial factors, such as workload and decreased quality of working life were also associated with the prevalence of SBS symptoms (Akova et al. 2022). Moreover, poor ventilation systems with high humidity and low temperature encourage the growth of mildew and other fungi on the building fabric and furnishings, thus can cause allergic reactions and other health problems to the occupants (Shahidah & Shukri 2017).

In Malaysia, although several studies have addressed IAQ, most have focused on episodic events such as haze, traffic emissions, or industrial activities, with limited attention given to indoor environments in healthcare settings (Ahmad et al. 2022; Anwar, Jaafar & Ramdzan 2024; Zakaria & Mahyuddin 2022). Furthermore, the lack of comprehensive national guidelines specific to healthcare IAQ highlights the need for more targeted research, particularly in the context of tropical climates and ageing infrastructure. This study addresses these gaps by evaluating IAQ parameters in Malaysian healthcare facilities, thus contributing to baseline data for future reference and supporting the development of targeted IAQ management strategies in line with national sustainability goals. However, limited data exist on IAQ baseline levels within Malaysian healthcare departments using multivariate statistical analysis like Principal Component Analysis (PCA). The research aims not only to establish a robust IAQ baseline dataset but also to investigate the influence of background operational activities in different hospital departments on IAQ parameters using PCA.

MATERIALS AND METHODS

Figure 1 illustrates the conceptual research framework adopted in this study.

SITE DESCRIPTION

Four selected departments inside Hospital Kuala Lumpur (HKL) were selected for this study, which are Endoscopy Clinic (EC), Psychiatric Clinic (PC), Cytotoxic Drug Reconstitution (CDR), and Information Technology (IT). All selected locations are served by a centralized Mechanical Ventilation and Air Conditioning (MVAC) system. Average occupancy across these departments ranged from 8 to 30 people during the sampling period, depending on specific departmental functions. The selected department represents different activities inside this healthcare facility. The EC department was for treatment procedures, the PC department was for consultation, the CDR department represents pharmacy and lastly, the IT department represents administration or office. In these selected departments, a site data collection involving a series of air monitoring has been performed and designed to obtain baseline information and facilitate the evaluation of the exposure-effects concerning indoor air pollution.

SAMPLING AND ANALYTICAL METHOD

The IAQ assessment in this healthcare facility was conducted in accordance with the ICOP on IAQ 2010 by the Department of Occupational Safety and Health (DOSH), Malaysia. Sampling was performed based on

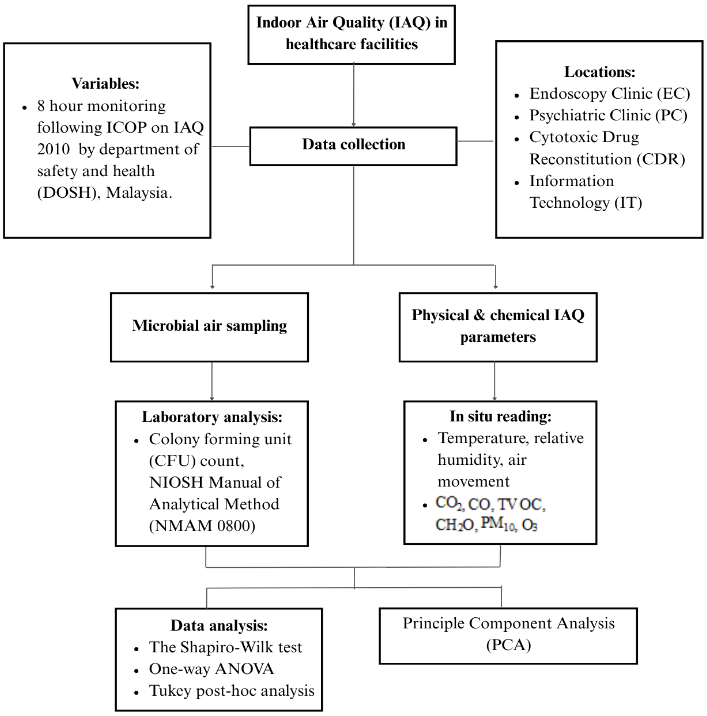

FIGURE 1. Sampling protocol

8 h of exposure representing the normal business activity in specialist clinic, Hospital Kuala Lumpur (HKL), which refers to the typical daily operating for healthcare occupants from 8:00 am to 5:00 pm. The sampling was divided into four slots, which cover two slots in the morning and two slots in the afternoon, to represent variations in occupancy and activity levels during different times of the day. The IAQ assessment followed a surrogate sampling method over a two-week duration in accordance with the Department of Occupational Safety and Health (DOSH) guidelines. In each department, five sampling points were established to provide a representative spatial assessment. Monitoring was conducted for 8 h, divided into four sampling slots. Within 30-min slot each, parameters were measured at 5-min intervals, yielding six readings per slot. These 24 daily readings per point were subsequently averaged to calculate the Total Weighted Average 8-h (TWA-8) for each parameter. Each sampling slot was conducted at designated points with an average measurement duration of approximately half-hour as specified in Table 1. This selected duration was intended to capture representative data for all IAQ parameters measured. Table 2 provides the list of instruments used to measure the concentration of each IAQ parameter in this study.

MICROBIAL SAMPLING USING AEROSOL IMPACTOR

Microbial sampling was performed using the Merck MAS-100 VF Air Sampler. At each sampling point, air was drawn at a calibrated flow rate of 50 L min^{-1} for 5 min, resulting in a total sampled volume of 250 L. Malt Extract Agar (MEA) and Tryptic Soy Agar (TSA) were used to quantify total fungal and bacterial counts, respectively. Two types of media were used which are Malt Extract Agar (MEA) to quantify fungal contamination and Tryptic Soy Agar (TSA) for detection of bacteria. The bioaerosol impactor was calibrated before each sampling using the Primary Airflow Calibrator. The method of NIOSH Manual Analytical Method (NMAM 0800) was referred to. A triplicate sample was collected for each sampling site for the IAQ assessment. The sample was sent to the accredited laboratory within 24 h to comply with the chain of custody of the microbial air sampling.

STATISTICAL ANALYSIS

Descriptive analysis was carried out to present the spatial and temporal patterns of measured indoor air parameters regarding the differences in sampling locations. Besides, all the data were summarized into a master table and graph according to the IAQ parameters and were compared with the ICOP on IAQ 2010. The Shapiro-Wilk test was used to analyze the normality of the experimental data. The results obtained for the selected IAQ parameters (air temperature, relative humidity, air movement, and CO_2 concentration) were compared by one-way analysis of variance (ANOVA) at a significance level of $p<0.001$ using PRISM GraphPad software for different sampling locations (P1-IT, P2-CDR, P3-EC, and P6-PC) operating in different conditions. Post-hoc Tukey test was performed afterwards to determine which specific location have a significant difference ($p<0.001$) between the selected IAQ parameters.

TABLE 1. Sampling period for IAQ assessment conducted in selected departments at HKL, Malaysia

Sampling slot	Time interval
Slot 1	0800 to 1000
Slot 2	1000 to 1200
Slot 3	1300 to 1500
Slot 4	1500 to 1700

Sampling was done from the 1st sampling point to the 4th sampling point (4 departments) in a four-slot sampling session

TABLE 2. Test parameters and baseline regulatory limits/equipment

Category	IAQ Parameter	Acceptable Limit (ICOP on IAQ 2010)	Unit	Equipment (Brand/ Model)	Detection Limit	Calibration Status
Physical	Air temperature	23.0 – 26.0	°C	Climomaster (Kanomax)	±0.1 °C	Calibrated (valid until Apr 2026)
	Relative humidity	40 – 70	%	Climomaster (Kanomax)	±1 %	Calibrated (valid until Apr 2026)
	Air movement	0.15 – 0.50	m/s	Climomaster (Kanomax)	0.01 m/s	Calibrated (valid until Apr 2026)
Chemical	Carbon dioxide (CO_2)	C1000	ppm	YES Air 8-Channel IAQ Monitor	1 ppm	Calibrated using certified gas
	Carbon monoxide (CO)	10	ppm	YES Air 8-Channel IAQ Monitor	0.1 ppm	Calibrated using certified gas
	Formaldehyde (CH_2O)	0.1	ppm	YES Air 8-Channel IAQ Monitor	0.001 ppm	Calibrated using certified gas
	Ozone (O_3)	0.05	ppm	YES Air 8-Channel IAQ Monitor	0.001 ppm	Calibrated using certified gas
	TVOC	3	ppm	YES Air 8-Channel IAQ Monitor	0.01 ppm	Calibrated using certified gas
	PM_{10}	0.15	mg/m³	YES Air 8-Channel IAQ Monitor	0.001 mg/m³	Factory calibrated
Biological	Total Bacterial Count (TBC)	500	cfu/m³	Merck MAS-100 VF	1 cfu/m³	Flow rate calibrated before sampling
	Total Fungal Count (TFC)	1000	cfu/m³	Merck MAS-100 VF	1 cfu/m³	Flow rate calibrated before sampling

The PCA biplot (Figure 3) served as an exploratory tool to visualize similarities and differences among the healthcare departments. Although PCA is a dimensionality-reduction technique rather than a formal classification method, the biplot shows distinct grouping tendencies among the sampling locations. The P6-PC department is positioned along the positive PC1 axis, indicating strong associations with CO_2, CO, and PM_{10}. This pattern suggests high occupancy and potentially limited ventilation efficiency, consistent with confined spaces and prolonged patient–staff interactions (Budaiwi & Mohammed 2023). In contrast, P1-IT and P2-CDR are located in the negative regions of both PC1 and PC2, reflecting comparatively lower pollutant concentrations and better ventilation conditions.

P3-EC is positioned along the positive PC2 axis and shows strong associations with TVOC, formaldehyde, total bacterial count (TBC), and total fungal count (TFC). This pattern is consistent with the intensive use of disinfectants and the potential for bioaerosol generation during endoscopic procedures (Sheng et al. 2024). Furthermore, the PCA biplot indicates a strong positive association between TFC and TVOC ($r = 0.906$), suggesting that volatile organic compounds may support microbial growth by acting as carbon sources (Jiao et al. 2023).

Subsequently, Principal Component Analysis (PCA) was performed using XLSTAT 2019 software to identify the key variables distinguishing each healthcare department. Prior to PCA, the suitability of the dataset was assessed using the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's Test of Sphericity. The KMO value exceeded the recommended threshold of 0.60, while Bartlett's Test of Sphericity was statistically significant ($p < 0.001$), confirming the appropriateness of the data for factor analysis.

RESULTS AND DISCUSSION

The results obtained with the IAQ assessment for four selected health departments and analyzed parameters are presented in Table 3. This study shows that four out of eleven IAQ parameters, which are the air temperature (Temp), air movement (AM), relative humidity (RH), and CO_2 inside the selected health departments were not complied with the referred guidelines of ICOP on IAQ 2010. The results in Table 3 show that the indoor CO_2 concentration varied between 531 ppm and 1380 ppm with average 760.5 ± 413.63 ppm, indoor air temperature range between 20.8 °C and 22.0 °C with average 21.43 ± 0.61 °C, indoor air relative humidity between 63.6% and 74.3% with average 68.85 ± 5.38%, indoor air movement readings between 0.11 m/s and 0.14 m/s with average 0.13 ± 0.01 m/s. Meanwhile, other IAQ parameters which were not mentioned were within the referred guideline based on ICOP on IAQ 2010. Slots 1 and 2 (Morning) represent peak occupancy and clinical activity hours, while Slots 3 and 4 (Afternoon) represent the stabilization period and typical decline in patient turnover toward the end of the operating day.

Based on the Figure 2(a), the concentration of CO_2 at the station P6-PC was exceed the acceptance level 1000 ppm as outlined in the ICOP on IAQ 2010. Indoor CO_2 concentrations are primarily influenced by the number of occupants in a building and the rate of CO_2 production from human activities. Therefore, CO_2 concentration is widely recognized as an indicator of ventilation performance, where elevated concentrations suggest inadequate dilution of indoor pollutants by MVAC system. P6-PC is a clinic with high occupancy compared to the other three sampling locations. High occupancy and poor MVAC system performance contribute to high CO_2 concentration at this sampling location. Occupancy could not be controlled during this study, as the clinic receives patients from across Malaysia. Given that CO_2 also serves as a proxy for airborne transmission risk, mitigation strategies such as fully opening fresh air dampers or installing additional exhaust fans are recommended to enhanced ventilation (Khan et al. 2020).

Figure 2(b) shows that air movement values were predominantly below the recommended guideline of 0.15 m/s across the sampling locations; however, compliance with the guideline was observed at certain locations during specific sampling hours. The lowest air movement was observed at P6-PC, with a recorded

TABLE 3. Summary of IAQ parameters based on Total Weighted Average 8 h (TWA_8) for four selected health departments

Points	Temp (°C)	RH (%)	AM (m/s)	CO (ppm)	CH_2O (ppm)	PM_{10} (mg/m^3)	O_3 (ppm)	CO_2 (ppm)	TVOC (ppm)	TBC (cfu/m^3)	TFC (cfu/m^3)
P1-IT	**21.9**	**72.6**	**0.13**	1.3	0.000	0.015	0.000	531	0.320	16	23
P2-CDR	**22.0**	64.9	**0.14**	1.2	0.000	0.012	0.000	546	0.875	300	278
P3-EC	**21.0**	**74.3**	**0.13**	1.4	0.044	0.015	0.000	585	0.890	280	327
P6-PC	**20.8**	63.6	**0.11**	1.7	0.000	0.022	0.000	**1380**	0.576	203	136
Reference standard: ICOP on IAQ 2010	23.0-26.0	40.0-70.0	0.15-0.50	10	0.100	0.150	0.050	C1000	3.000	500	1000

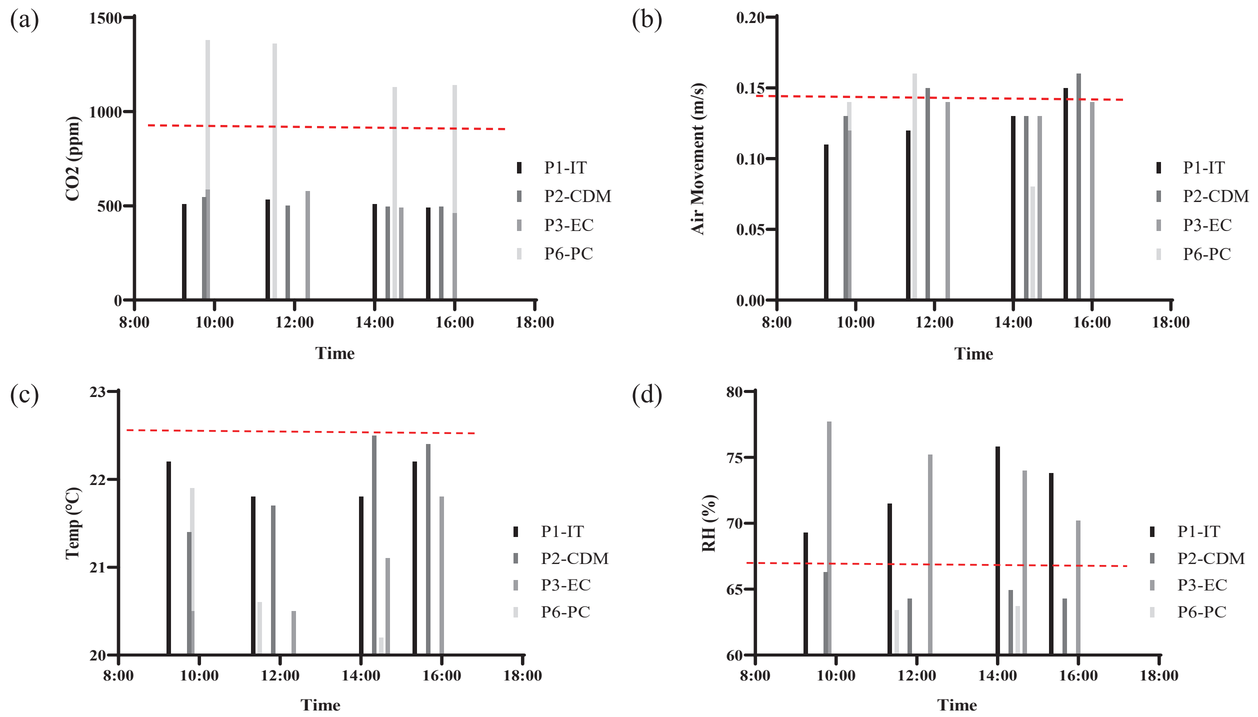

FIGURE 2. Indoor air quality (IAQ) parameters measured at selected departments: (a) CO_2 concentration, (b) air movement, (c) air temperature, and (d) relative humidity. The dotted line in each plot indicates the corresponding acceptable limit recommended by the ICOP on IAQ 2010

value of 0.11 m/s. Air movement, defined as directional airflow over time, is the value of airflow in a certain direction measured over time. Well-designed and operated ventilation and air conditioning systems are essential to provide the occupant with ventilated air sufficient to dilute contaminants to acceptable levels. Previous study has indicated that increasing air movement will improve the acceptability of air quality (Liu et al. 2018). Indoor air flow rate is influenced by factors such as air inlet and outlet positions, window size, ventilation design, occupant activity, temperature, and humidity. Inadequate airflow can cause stagnant conditions, while excessive airflow may lead to discomfort due to draftiness. Both extremes negatively impact thermal comfort and perceived air quality (Özdamar & Umaroğullari 2018). Nevertheless, the air movement reading needs to be justified by air change per hour reading to measure the risk of possible airborne transmission (Liu et al. 2018). Testing, adjusting, and balancing (TAB) are suggested to improve the air movement reading inside all sampling locations. This procedure will help in optimizing the MVAC system (Božić, Ilić & Ilić 2019).

The temperature readings for all sampling locations were below the referred guideline of 23.0-26.0 °C, with the lowest temperature observed at P6-PC (20.8 °C) (Figure 2(c)). The ICOP on IAQ 2010 and ASHRAE Standard 55 have specified temperatures of 23.0-26.0 °C as an acceptable range where most people work comfortably. Low temperatures are associated with a low set point at the air handling unit (AHU) or thermostat (Wu et al. 2017). Besides, the low air temperature may cause moisture lock if the temperature differential between air and surface is more than 5 °C and leading to potential fungal growth and poor IAQ (Galvin 2010). This study was conducted during working hours with full occupancy. However, to study the trend of temperature readings, 24-h monitoring by a data logger is needed. Adjusting the set point temperature according to referred guidelines will also help in reducing energy consumption from the AHU and chiller thus supporting a sustainable healthcare facility (Fonseca et al. 2018).

The optimum comfort range for relative humidity is 40-70% as recommended in the ICOP on IAQ 2010. Additionally, ASHRAE 55-2004 (Thermal Environmental Conditions for Human Occupancy) recommends that the relative humidity be kept below 60%. In this study, elevated RH readings were observed at P1-IT and P3-EC (Figure 2(d)), both exceeding the ICOP on IAQ 2010 guidelines. Even though P1-IT has a server room and exhibited lower temperature, the accumulation of humidity might be due to the malfunction cooling system. At P3-EC, which is a sterile room was equipped with a sterilizer machine and procedure washing that contribute to high relative humidity. Besides, relative humidity reading was also associated with cooling coil performance inside the AHU. According to the Guidelines on Occupational Safety and Health in the Office issued by DOSH (2010), low relative humidity can lead to mucosal dryness and increased static electricity shocks, whereas high humidity levels above 80% are associated with fatigue and stuffiness. Maintaining IAQ parameters, including optimal RH is essential to ensuring occupant well-being and operational efficiency. P1-IT and P3-EC were running on normal office hours operation; thus, the reading of relative humidity might be much higher after operation hours when the AHU systems were switched off at 6:00 pm. It is recommended to ensure the cooling coil inside AHU was in good condition. Besides, the installation of a data logger to analyze the trend of 24-h monitoring is important to identify the root cause of high relative humidity inside these sampling locations. Reducing the relative humidity will reduce the risk of fungal growth and thus will ensure occupants' health and safety (Shahidah & Shukri 2017).

STATISTICAL ANALYSIS

One-way ANOVA analysis was performed using GraphPad PRISM version 8.0.2 software to assess potential differences in IAQ parameters between selected health departments. The purpose of this analysis was to determine whether the location of the sampling station had a significant effect on IAQ characteristics ($p < 0.001$). The results of the one-way ANOVA test showed that there were significant differences ($p < 0.001$) for CO_2 concentration and relative humidity (Table 4). However, air movement and temperature did not show significant variation across the healthcare departments ($p > 0.001$).

Post-hoc Tukey analysis was conducted following a one-way ANOVA to determine pairwise differences between health departments and IAQ parameters. Post-hoc Tukey analysis showed statistically significant differences ($p < 0.001$) in CO_2 concentration and relative humidity between several health departments (Table 4), notably involving P6-PC. Elevated CO_2 levels at P6-PC suggest insufficient ventilation or higher occupancy rates compared to other locations. Significant variations in relative humidity, particularly between P1-IT, P3-EC, and P6-PC, are likely due to localized moisture sources (e.g., sterilization activities) and potential ventilation inefficiencies. No significant differences were observed for air movement and temperature ($p > 0.05$), indicating relatively uniform conditions across departments. However, consistently low air movement readings highlight the need for further ventilation performance assessments beyond statistical comparisons.

PRINCIPAL COMPONENT ANALYSIS (PCA)

PCA was performed to identify patterns and principal contributors among IAQ parameters and spatial variations across different hospital departments. This analysis was carried out using XLSTAT 2019 software with Varimax rotation to optimize factor loadings and reduce insignificant weights. Based on the study by Mohd Fahmi et al. (2011), factor loadings in the range of 0.5 - 0.75 are categorized as moderate, while values exceeding 0.75 are considered strong. PCA identified two PC (F1 and F2) with eigenvalues >1. Based on Table 5, it shows the first component (F1) accounted for 48.33% of the total variance and was associated with pollutant concentrations, which strongly influenced by high loadings of PM_{10} (0.993), CO_2 (0.977), and CO (0.977). Additionally, F1 exhibited strong negative associations with air movement (-0.987) and temperature (-0.763), suggesting that this component reflects the impact of inadequate mechanical ventilation and thermal conditions, which contribute to the accumulation of airborne pollutants from occupant activities and indoor sources.

The second component (F2) explained 35.78% of the variance and was mainly governed by biological contaminants and indoor chemical emissions. Strong loadings were observed for TVOC (0.999), CH_2O (0.826), TFC (0.897), and TBC (0.826), indicating that this component reflects the combined influence of volatile pollutants and bioaerosols commonly associated with cleaning agents, building materials, and microbial activity in healthcare environments.

The third component (F3), which exhibited an eigenvalue greater than 1, was characterized by a strong loading for relative humidity (RH = 0.873). This suggests that RH represents an independent environmental control factor influencing indoor air quality rather than a direct pollutant source. Although RH does not directly represent

TABLE 4. Result of the statistical tests used to compare the analyzed parameters in the healthcare facility

Health departments		CO_2	Air movement	Temperature	Relative humidity
	One-way ANOVA	<0.001	0.414	0.017	<0.001
P1-IT vs P2-CDR	Post-hoc Tukey *p*-value	>0.999	0.857	>0.999	0.001
P1-IT vs P3-EC		0.985	0.993	0.096	0.697
P1-IT vs P6-PC		**<0.001**	0.793	0.056	**<0.001**
P2-CDR vs P3-EC		0.986	0.951	0.096	**<0.001**
P2-CDR vs P6-PC		**<0.001**	0.359	0.056	0.804
P3-EC vs P6-PC		**<0.001**	0.646	0.989	**<0.001**

*In bold, *p*-value lower than 0.001

a contaminant, it plays a critical role in modulating microbial survival and proliferation, thereby indirectly affecting biological IAQ parameters in healthcare settings (Table 5). From a sustainability perspective, the strong negative correlation between air movement and CO_2 ($r = -0.931$) suggest that implementing Demand-Controlled Ventilation (DCV) could optimize energy consumption by modulating airflow based on real-time CO_2 fluctuations.

The biplot shown in Figure 3 displays the distribution of the IAQ parameters and health department projected along the first two PC which explain 84.11% of the total variance.

The PCA biplot (Figure 3) was used as an exploratory tool to visualize similarities and differences among the healthcare departments in reduced-dimensional space. Although PCA is not a clustering method, the biplot shows distinct grouping tendencies among the sampling locations based on their relative positions along the principal components.

The P6-PC department is positioned far along the positive PC1 axis, indicating strong associations with CO_2, CO, and PM_{10}. This pattern suggests the influence of high occupancy and potentially limited ventilation efficiency, consistent with confined spaces and prolonged patient–staff interactions (Budaiwi & Mohammed 2023). In contrast, P1-IT and P2-CDR are located in the negative regions of both PC1 and PC2, reflecting comparatively lower pollutant concentrations and better ventilation conditions, likely due to controlled access, regulated airflow, and reduced human activity.

The P3-EC department is positioned along the positive PC2 axis and shows strong associations with TVOC, CH_2O, total bacterial count (TBC), and total fungal count (TFC). This pattern is consistent with the intensive use of disinfectants and the potential for bioaerosol generation during endoscopic procedures (Sheng et al. 2024).

In addition, the PCA biplot indicates a strong positive association between TFC and TVOC ($r = 0.906$), suggesting

TABLE 5. Loadings of IAQ parameters at healthcare facility in Kuala Lumpur

	F1	F2	F3
Temp	**-0.763**	-0.596	-0.252
RH	-0.465	0.146	**0.873**
AM	**-0.987**	0.007	-0.158
CO	**0.977**	0.181	0.110
CH_2O	-0.212	**0.826**	0.522
PM_{10}	**0.993**	-0.008	0.115
CO_2	**0.977**	0.041	-0.210
TVOC	-0.037	**0.999**	0.006
TBC	-0.099	**0.826**	-0.556
TFC	-0.328	**0.897**	-0.296

Bold values indicate strong loadings (> 0.7)

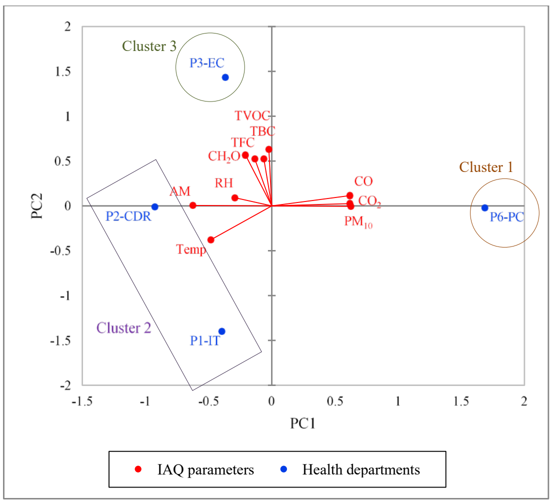

FIGURE 3. Biplot PCA for four selected health departments

that volatile organic compounds may support microbial growth by acting as carbon sources (Jiao et al. 2023). Air movement exhibited a strong negative correlation with CO_2 (r = –0.931), indicating that reduced ventilation efficiency may contribute to the accumulation of CO_2 within indoor spaces (Lazovic et al. 2015).

Overall, the PCA results confirm that variations in IAQ are significantly influenced by each department's background operational activities. Elevated CO_2 and PM_{10} levels in psychiatric clinics were associated with overcrowding and insufficient ventilation. Next, high VOCs and bioaerosols in the endoscopy unit reflected intensive sterilization routines. Moreover, better IAQ conditions observed in IT rooms and pharmacies were attributed to controlled access and well-maintained environmental systems. Although temperature and humidity were identified as secondary factors in the PCA, they were consistently well-controlled in department with better IAQ, highlighting their importance in maintaining thermal comfort and limiting microbial growth. These findings underscore the importance of customizing IAQ management based on space usage and human activity, rather than applying one-size-fits-all standards to contribute broader sustainability efforts. This study not only provides a data-driven foundation for IAQ improvement but also serves as a strategic tool for guiding future sustainable development initiatives in healthcare facilities.

CONCLUSION

This study successfully evaluated IAQ across four departments in a Malaysian hospital, achieving its aim of creating a detailed baseline that reflects how space usage and daily operations affect air quality. Most measured parameters met the ICOP 2010 standards, but the P6-PC showed elevated CO_2 concentrations, likely due to high occupancy and limited airflow. Conditions such as low temperature, high humidity, and poor air movement in some areas were also found to support microbial growth, which could pose health risks if left unaddressed. The PCA results added valuable insight by linking air quality trends to the function of each space. For example, clinical areas had more pollutants from heavy use, endoscopy units showed higher levels of chemicals and bioaerosols related to cleaning routines, while server rooms and pharmacy areas maintained cleaner air due to restricted access and stable conditions. These findings highlight the need for tailored air quality strategies that consider how each space is used. Therefore, as opportunities to improve sustainability, IAQ management in healthcare facilities should consider natural ventilation by opening fresh air dampers as a complement to mechanical ventilation systems, maintain optimal humidity and CO_2 concentration to reduce the risk of airborne infections. Besides, the installation of a data logger to analyze the trend of 24-h monitoring is important to identify the root cause of air pollution inside these health departments.

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