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# Volatile Threats in Hospital Indoor Air: Exceeding TVOC Thresholds and The Role of Ventilation Strategy

**ERMIE ABDULL HAMID[1], SUBKI AHMAD[1], NURUL FARAHANA KAMALUDIN[1,2]*, ANUAR ITHNIN[3] and NORMAH AWANG[1,2]**

[1]Center for Toxicology and Health Risk Studies, Faculty of Health Sciences, Universiti Kebangsaan Malaysia, Jalan Raja Muda Abdul Aziz, 50300 Kuala Lumpur, Malaysia.
[2*]Environmental Health and Industrial Safety Program, Faculty of Health Sciences, Universiti Kebangsaan Malaysia, Jalan Raja Muda Abdul Aziz, 50300 Kuala Lumpur, Malaysia.
[3]Center for Community Health Studies (ReaCH), Faculty of Health Sciences, Universiti Kebangsaan Malaysia, Jalan Raja Muda Abdul Aziz, 50300 Kuala Lumpur, Malaysia.

*Corresponding author E-mail: nurulfarahana@ukm.edu.my

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**ABSTRACT**

Healthcare workers and patients are increasingly exposed to total volatile organic compounds (TVOC), an often-overlooked hazard that threatens hospital air quality, occupational health, and clinical safety. Total volatile organic compounds (TVOC), originate from disinfectants, cleaning products, and medical procedures, contributing to cumulative chemical exposure in healthcare settings. This study investigated TVOC concentrations and their temporal and ventilation-related variability across eleven hospital wards in Klang Valley, Malaysia. Real-time monitoring was performed under natural and mechanical ventilation during morning and evening sessions. Data were analyzed using Kruskal–Wallis, Mann–Whitney, and multiple regression methods. TVOC concentrations ranged from 24.8–545.0 ppm, exceeding the ICOP (IAQ) 2010 limit (3 ppm). Emergency and surgical wards with mechanical ventilation demonstrated the highest pollutant burdens, while wards with natural ventilation exhibited significant dilution between morning and evening measurements. Regression analysis revealed temperature as a negative predictor ($\beta = -15.57$, $p = 0.048$) and carbon monoxide as a positive predictor ($\beta = 50.10$, $p = 0.026$). These findings present critical evidence that the type of ventilation and diurnal airflow dynamics have a pervasive impact on VOC accumulation, simultaneously indicating an urgent need for ongoing IAQ surveillance, improved HVAC design, and targeted ventilation strategies to ensure the safety of hospital occupants.

**Keywords:** Total volatile organic compounds (TVOC); Indoor air quality (IAQ); ventilation type; occupational exposure

## INTRODUCTION

The impact poor of indoor air quality (IAQ) in hospitals extends far beyond individual health outcomes. It is a broader public health challenge which profoundly affect patient safety, healthcare workers and overall healthcare outcomes. In recent years, poor IAQ has been increasingly correlated to healthcare-associated infections (HCAIs), which are a major issue related to internal and external factors that compromise hospital air quality.

HCAIs continue to post a significant threat to patient safety and a persistent challenge for healthcare systems.[1] Among the various transmission routes, airborne contaminants are a notable factor in increasing the risk of HCAI.[2,3] The ongoing battle against invisible pathogenic microorganisms demonstrates the vital importance of infection prevention and control (IPC) measures, which must remain a top priority for healthcare workers, patients, and healthcare stakeholders. Lemiech-Mirowska et al. (2021) have asserted that the implementation of disinfection, strict hygiene, and aseptic procedure represents a critical line of defence in the prevention of HCAIs.[2] Haque et al. (2020) emphasized that the CDC's 2011 Infection Prevention Guidelines recommend routine, and thorough cleaning of all inpatient and outpatient areas as a key measure to reduce the transmission of communicable diseases.[4]

However, infection prevention strategies that rely heavily on chemical disinfectants may reduce biological risks, but simultaneously elevate total volatile organic compounds (TVOC) concentrations, thereby compromising IAQ as well as the safety of healthcare workers and patients—an issue that remains comparatively under explored. In addition to disinfectants and sterilants, routine clinical, maintenance, and support activities can emit TVOCs from sources such as anaesthetic gases and laboratory or pharmaceutical agents, placing both healthcare workers and patients at risk of exposure.[5] Numerous studies have substantiated that hospitals constitute complex TVOC environments, with emissions originating from cleaning agents, decorative finishes, medical devices, and personal care products used by healthcare workers and patients.[6,7] Given the multiplicity of sources and the temporal and spatial variability of volatile organic compounds (VOC) emissions within hospital wards, Hori (2020), noted that TVOCs are commonly used in IAQ assessment as a simplified and comprehensive indicator of overall VOC levels.[8] This approach is consistent with recommendations from the World Health Organization (WHO), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the Department of Occupational Safety and Health Malaysia (DOSH). TVOCs have negative health effects when they are breathed in or absorbed through the skin.[9] The World Health Organization (WHO), the U.S. Environmental Protection Agency (EPA), and Public Health England (PHE) have reported that exposure to TVOCs can cause a number of problems, such as irritation of the eyes and respiratory tract, allergic reactions and asthma attacks, central nervous system effects, liver and kidney damage, and an increased risk of cancer.[10] In recognition of these risks, the United Kingdom has established short and long-term limits for TVOC exposure in the workplace to protect workers from these risks through the Health and Safety Executive (HSE).[11] The UK Health Security Agency (UKHSA) has also recently released guidelines for IAQ that list 11 priority compounds contributing to TVOCs as being of particular concern due to significant adverse health effects.[12]

The Industry Code of Practice on Indoor Air Quality (ICOP (IAQ) 2010) in Malaysia stipulates that the acceptable level of TVOC in mechanically ventilated environments including hospital is 3 ppm.[13] Similarly, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62.1 specifies minimum outdoor air ventilation requirements to lower TVOC levels in indoor environments.[14] In Europe, Directive 2008/50/EC and EN 13779 establish air quality targets for non-residential buildings, though hospital-specific TVOC thresholds remain limited.[15,16] The absence of harmonized international standards for TVOC exposure in healthcare facilities highlights a critical regulatory gap.

Historically, several investigations have demonstrated that hospitals are particularly prone to elevated TVOC concentrations. For instance, mean TVOC levels at Leicester Royal Infirmary (UK) were significantly higher than those reported at Glenfield General Hospital.[9] Moldovan & Moldovan (2024) recently reported that TVOC levels were higher during cleaning and disinfection cycles, occasionally exceeding occupational benchmarks.[17] Haleem

(2019) also found very high levels of TVOC in operating rooms across three hospitals in Baghdad, Iraq, with the highest levels observed in a private hospital, followed by a public teaching hospital, and a public specialized hospital — each substantially exceeding the WHO reference limit.[18] These international findings underscore a persistence global issue in the management of TVOC pollution within healthcare facilities.

Despite growing evidence, the effects of ventilation type (natural versus mechanical) and diurnal timing (morning versus evening) on TVOC variability in hospital wards, where patient safety is at stake, remain poorly understood. Addressing this gap is critical, given the heightened vulnerability of hospital populations to indoor air pollution and a lack of unified global standards. This study therefore aims to investigate diurnal variations in TVOC concentrations within hospital wards by comparing measurement taken in the morning and evening, in order to identify exceedances in relation to international IAQ thresholds standards, and to evaluate how the impact of ventilation type on these concentrations.

## MATERIALS AND METHODS

### Study Design and Setting

This study was conducted in a hospital located in Klang Valley, Malaysia, involving eleven wards across four clinical departments - Medical, Surgical, Orthopaedic, and Emergency - representing different clinical functions. The selected wards accommodated high patient and healthcare worker densities and were ventilated either through natural airflow systems or centralized heating, ventilation, and air conditioning (HVAC) mechanisms. In total, eleven sampling sites (one per ward) were designated in accordance with the area-based requirements outlined in the ICOP (IAQ) 2010.[13]

### Sampling Points

Sampling at each monitoring station was performed in triplicate, with measurements recorded at five-minute intervals over a total duration of 15 minutes per session. Two sessions were conducted in the morning and two in the evening to capture time-of-day variability. In each ward, instruments were placed at breathing zone height (1.2–1.5 m above floor level) and located at least one metre away from windows, doors, and HVAC outlets to minimise airflow interference.[13]

### Measurement of Parameters

A suite of calibrated instruments by National Institutes of Safety and Health (NIOSH) Malaysia was employed to capture chemical and physical IAQ parameters. Both parameters were measured by direct-reading method, and details are given below.

### A) Chemical Parameters

The chemical parameters, including CO2 were:

- Total Volatile Organic Compounds (TVOC): Assessed with Aeroqual Series 500.
- Ozone ($O_3$): Assessed with Aeroqual Series 500.
- Carbon Monoxide (CO): Measured with the Tetra 3 Crowcon.
- Carbon Dioxide ($CO_2$): Measured with the Tetra 3 Crowcon.
- Particulate Matter ($PM_{10}$): Measured with the Tetra 3 Crowcon.
- Formaldehyde ($CH_2O$): Measured with the Formaldemeter.

### B) Physical Parameters

The physical parameters were:

- Temperature: Ambient air temperature was recorded.
- Relative Humidity (Rh): Hygrometer was used to measure the moisture content in the air.
- Air Movement: To evaluate ventilation effectiveness, air velocity in every ward was measured.

### Statistical Analysis

All data were statistically analysed using IBM SPSS Statistics 26.0 software. Data analysis involved descriptive statistics to summarise the mean, standard deviation, and range of pollutant concentrations. Non-parametric tests, such as the Kruskal–Wallis test, were used to compare TVOC levels between departments and wards, and the Mann–Whitney test to assess the differences based on ventilation type throughout the day. Multiple linear regression analysis was performed to discover environmental factors of that affect TVOC variability.

The results were subsequently evaluated against the ICOP (IAQ) 2010 threshold of 3 ppm to determine exceedances and assess any potential risks.

## RESULTS

### TVOC Concentrations Across Hospital Departments and Wards

Analysis of TVOC concentrations across departments revealed consistent exceedances of the ICOP (IAQ) 2010 threshold of 3 ppm, surprisingly with values ranging from 24.8 ppm to 545.0 ppm (Table 1). Strong departmental variability was evident. The Emergency Department experienced the most pollution, while the Orthopaedic Department recorded the least pollution. The Surgical and Medical Departments showed moderate yet consistently high concentrations, particularly with certain mechanically ventilated ward. The Kruskal–Wallis analysis confirmed significant inter-departmental differences ($\chi^2(3) = 14.91$, $p = 0.002$) with the Emergency Department (mean rank = 56.25) recording significantly higher concentrations than the Surgical (36.89), Medical (28.44) and Orthopaedic (25.50) Department (Table 2). There was also greater heterogeneity within wards ($\chi^2(10) = 27.53$, $p = 0.002$), demonstrating how important ward-level activity patterns and ventilation design. In this case, mechanically ventilated wards - Ward H (59.75), Ward R3 (54.25), Ward R2 (53.50), Ward G (52.75) and Ward R1 (46.00) - had the greatest amount of pollutant. Ward A (27.75), Ward B (24.50), Ward C (31.88), Ward D (25.00), Ward E (22.88) and Ward F (28.13) were naturally ventilated wards, and their levels were much lower.

### Ventilation-Related Differences in Morning and Evening TVOC Concentrations

Clear variations were observed between morning and evening TVOC measurements across hospital wards. Morning values were generally exceeding evening levels in most wards. Naturally ventilated wards exhibited consistent reductions from morning to evening. Mean TVOC concentrations in Ward A decreased from 138.1 ± 44.2 ppm in the morning to 58.8 ± 47.5 ppm in the evening, while Ward B dropped from 147.7 ± 87.0 ppm to 38.6 ± 6.4 ppm. Similar reductions were observed in Medical Department (Ward C: 138.1 ± 106.9 ppm to 72.1 ± 20.0 ppm; Ward D: 141.5 ± 78.6 ppm to 38.7 ± 20.8 ppm and the Orthopaedic Department (Ward E: 283.4 ± 288.3 ppm to 24.8 ± 5.6 ppm; Ward F: 104.6 ± 88.9 ppm to 83.0 ± 34.9 ppm). Ward E (Orthopaedic Department), was the most obvious example of this, as it showed a huge drop from morning to evening. The Mann–Whitney test confirmed significantly higher morning levels (mean rank = 41.29) compared with evening concentrations (27.71) ($Z = -2.833$, $p = 0.005$), (Table 2). Conversely, mechanically ventilated wards showed persistent or worsening concentrations in the evening. For example, in the Surgical Department (Ward R1–R3), the levels in the morning were between 235.5–385.4 ppm, while the levels in the evening remained high (188.3–275.8 ppm). The Emergency Department showed a very strong accumulation effect. Ward G went from 196.2 ± 3.4 ppm to 318.8 ± 35.6 ppm, and Ward H increasing sharply from 237.8 ± 29.3 ppm to 545.0 ± 137.1 ppm, which was the highest value ever recorded (Table 1).

**Table 1: Mean TVOC concentrations grouped by hospital departments, wards, ventilation type and time of day**

| Department | Ward | Ventilation Type | Morning TVOC (Mean ± SD) | Evening TVOC (Mean ± SD) |
|---|---|---|---|---|
| Surgical | A | Natural | 138.1 ± 44.2 | 58.8 ± 47.5 |
| | B | Natural | 147.7 ± 87.0 | 38.6 ± 6.4 |
| | R1 | Mechanical (AC) | 235.5 ± 167.8 | 188.3 ± 167.9 |
| | R2 | Mechanical (AC) | 240.0 ± 6.4 | 275.8 ± 89.2 |
| | R3 | Mechanical (AC) | 385.4 ± 255.2 | 246.2 ± 2.3 |
| Medical | C | Natural | 138.1 ± 106.9 | 72.1 ± 20.0 |
| | D | Natural | 141.5 ± 78.6 | 38.7 ± 20.8 |
| Orthopaedic | E | Natural | 283.4 ± 288.3 | 24.8 ± 5.6 |
| | F | Natural | 104.6 ± 88.9 | 83.0 ± 34.9 |
| Emergency | G | Mechanical (AC) | 196.2 ± 3.4 | 318.8 ± 35.6 |
| | H | Mechanical (AC) | 237.8 ± 29.3 | 545.0 ± 137.1 |

*TVOC standard, 3.0 ppm (ICOP IAQ (2010)); AC, Air-conditioned*

### Influence of Ventilation Strategy (Natural vs Mechanical Ventilation)

TVOC concentrations differed significantly between naturally and mechanically ventilated wards. All naturally ventilated wards (e.g., Wards A, B, C, D, E, F) showed consistent reductions, with pollutant clearance facilitated by daytime airflow. By contrast, mechanically ventilated wards frequently exhibited pollutant persistence or evening accumulation. For instance, Surgical Department and Emergency Department demonstrated a particularly strong accumulation effect in the evening (Table 1). The Mann–Whitney test further confirmed the significant influence of ventilation type, namely that mechanically ventilated wards recorded substantially higher pollutant burdens (mean rank = 53.25) compared to naturally ventilated wards (26.69) ($Z = -5.047$, $p < 0.001$).

Table 2: Statistical Comparison of TVOC Concentrations Across Departments, Wards, Ventilation Types, and Time of Day Using Kruskal–Wallis and Mann–Whitney Tests

| Test | Comparison | Test Statistic | df | *p* | Mean Ranks |
|---|---|---|---|---|---|
| Kruskal–Wallis | Department | $\chi^2$ = 14.908 | 3 | 0.002 | Medical 28.44<br>Surgical 36.89<br>Orthopaedic 25.50<br>Emergency 56.25 |
| | Ward | $\chi^2$ = 27.528 | 10 | 0.002 | Ward C 31.88<br>Ward D 25.00<br>Ward A 27.75<br>Ward B 24.50<br>Ward E 22.88<br>Ward F 28.13<br>Ward H 59.75<br>Ward G 52.75<br>Ward R1 46.00<br>Ward R2 53.50<br>Ward R3 54.25 |
| Mann–Whitney | Ventilation Type (Natural vs Mechanical) | Z = –5.047 | – | 0.000 | Natural 26.69<br>Mechanical 53.25 |
| | Time of Day (Morning vs Evening) | Z = –2.833 | – | 0.005 | Morning 41.29<br>Evening 27.71 |

*p* < *0.01 indicates statistical significance*

## Environmental Predictors of TVOC Variability

To further identify environmental drivers of TVOC levels, a multiple regression model was applied (Table 3). The model was significant, explaining 53.4% of the variation in TVOC concentrations ($R^2$ = 0.534, F(8,59) = 8.457, p < 0.001). The temperature and carbon monoxide (CO) levels were the two most significant factors of the eight predictors. Temperature was discovered to be a significant negative predictor (β = –15.57, p = 0.048), indicating that a 1°C rise in temperature was correlated to a drop in TVOC concentrations approximately 15 ppm. Conversely, CO was a positive predictor (β = 50.10, p = 0.026), with each 1 ppm increase in CO linked to an approximate 50 ppm increase in TVOC levels. Other parameters, such as Rh, AM, CO2, O3, CH2O, and PM10, were not statistically significant, which likely indicates that they do not have a direct or primary effect on TVOC dynamics (Figure 1).

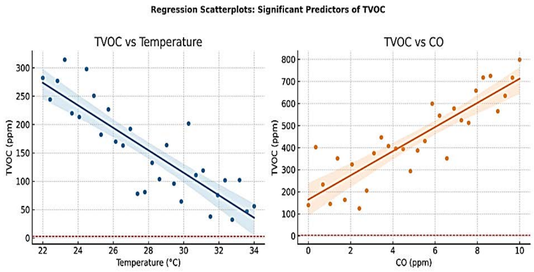


**Fig. 1: Regression scatterplots of significant predictors of TVOC in hospital wards**

Table 3: Multiple Linear Regression Analysis of Environmental Predictors of TVOC concentrations in hospital wards

TVOC scores: $R^2$ = 0.534, F(8,59) = 8.457, p < 0.001

| Model | Unstandardized Coefficients | | Standardized Coefficients | *t* | *p* | 95% CI | |
|---|---|---|---|---|---|---|---|
| | β | Std Error | Beta | | | Lower bound | Upper bound |
| (Constant) | 412.68 | 503.36 | | 0.820 | 0.416 | -594.540 | 1419.893 |
| Temperature | -15.570 | 7.707 | -0.444 | -2.020 | 0.048 | -30.991 | -0.148 |
| Relative Humidity (Rh) | 3.008 | 4.842 | 0.089 | 0.621 | 0.537 | -6.680 | 12.696 |
| Air Movement (AM) | -147.167 | 191.863 | -0.105 | -0.767 | 0.446 | -531.083 | 236.750 |
| $CO_2$ | 0.116 | 0.154 | 0.137 | 0.756 | 0.453 | -0.191 | 0.424 |
| CO | 50.103 | 21.937 | 0.265 | 2.284 | 0.026 | 6.207 | 93.999 |
| $O_3$ | 6.126 | 20.653 | 0.034 | 0.297 | 0.768 | -35.202 | 47.453 |
| $CH_2O$ | 379.203 | 396.813 | 0.122 | 0.956 | 0.343 | -414.818 | 1173.224 |
| $PM_{10}$ | -801.758 | 617.886 | -0.191 | -1.298 | 0.199 | -2038.145 | 434.630 |

## DISCUSSION

The study found that the TVOC concentrations in different departments and wards of the hospital consistently exceeded the ICOP (IAQ) 2010 standard, indicating persistent and clinically significant as TVOC exposures has been associated with various significant health risks,[10,19] including deficits in lung function, respiratory irritation, lung cancer, heart disease and damage to the brain, nervous system, liver or kidneys.[5] Importantly, all TVOC measurements were taken while ward activities were ongoing, and we observed that concentrations were particularly high, which maybe attributable to ongoing medical procedure, occupancy, and cleaning-related emissions. These substantial exceedances are consistent with recent reports from other healthcare environments for example Riveron et al. (2023) discovered average TVOC levels surpassing the standard in European hospitals9, whereas Zaman et al. (2021) reported elevated TVOCs in Bangladeshi healthcare facilities, with TVOC concentrations observed ranging from 81.0 to 441.7 ppm, significantly exceeding the ASHRAE threshold of 3 ppm.[19] Within the present study, the Emergency Department demonstrated the highest pollutant burden, which is consistent with Moldovan et al. (2024), who reported that the emergency care environments tend to represent persistent TVOC hotspot compared with outpatient rooms and wards.[17] However, further investigations are required to validate the potential causal influence of disinfection protocols and clinical workload on the increase of TVOC levels in this setting. By contrast, Orthopedic wards recorded the lowest concentrations, however, ward-level variability also observed in this study, as confirmed by the Kruskal–Wallis tests. These variabilities suggest that TVOC levels build up in hospitals is highly localized and may depend on the department's function, the activity in the ward, the time of day, and ventilation design. These findings corroborate previous reports indicating that chemical pollution in hospitals is influenced by both structural and operational factors.[9,20]

In line with this, clear differences between morning and evening measurements were observed in our study, with TVOC concentrations generally higher in the morning across most wards. Naturally ventilated wards exhibited marked reduction by evening, suggesting effective daytime dilution of accumulated pollutants, aligning with evidence that open airflow enhances pollutant dispersion in tropical hospital settings.[21] Elevated daytime TVOC levels are likely associated with heavy human occupancy, various medical treatments, and the frequent use of cleaning products, as reported in other studies.[9,22,23] However, the opposite trend by mechanically ventilated wards which showed an elevated TVOCs during the evening period, which may reflect both inadequate ventilation and intensive evening cleaning cycles, with extensive use of disinfectants and detergents, as has been previously reported.[17] Seasonal evidence also supports this observations: studies by Riveron et al. (2023), Lee et al. (2020), and Baurès et al. (2018) indicates that TVOC concentrations are generally elevated in winter compared to summer.[9,20,24] Riveron et al. (2023) elucidated that this seasonal variation is partially attributable to reduced emissions from alcohol-based products in warmer conditions.[9] Similarly, cooler conditions in the evening may lead to higher TVOC levels in the Emergency Department, even while occupancy and medical activity decrease. This effect is made worse by the heavy use of alcohol-based products in the Emergency Department, such as hand sanitizers, surface disinfectants for beds, trolleys, and instruments, as well as skin antiseptics used during resuscitation and wound care, combined with frequent cleaning cycles, all of which contribute to elevated TVOC levels in the indoor environment. These various results, highlight how vital it is to design ventilation systems in hospitals for controlling TVOC levels low over time. Reflecting this statement, statistical analysis, the Mann–Whitney test in this study revealed that mechanically ventilated (HVAC) wards had higher mean ranks than naturally ventilated wards. These results align with what Baudet et al. (2022) described, in that high TVOC levels are indicative of poor ventilation sign.[25] Overall, these findings suggest that ventilation strategy employed throughout the operating day are critical factors influencing TVOC exposure in hospital settings.[22] From a clinical standpoint, naturally ventilated wards despite their variability, may offer an intrinsic advantage for pollutant removal, in contrast to mechanically ventilated wards deficient in sufficient fresh-air exchange or effective control of TVOC levels, thereby reducing exposure risks for both patients and healthcare personnel.

This pattern is further supported by the regression analysis in this study, which showed that environmental conditions particularly temperature had a negative correlation while carbon monoxide demonstrated a positive correlation with TVOC levels. Although higher temperatures usually enhance volatilization of organic compounds, which could lead to more emissions,[26] in the hospital setting examined, the ventilation effect of elevated temperature appears to surpassed the emission impact. Elevated temperature prompted greater outdoor intake and increase the air exchange rates through HVAC cooling operations, which may facilitate effective indoor pollutants dilution. Conversely, during cooler conditions, HVAC systems tend to reduce intake of cold outdoor air to conserve energy, leading to the accumulation of indoor-generated TVOC concentrations. The same principle applies to naturally ventilated wards, where the stack (or buoyancy) effect, as WHO (2009) explains, increases convective airflow under warmer conditions.[27] This increased air movement facilitates pollutant dispersion, which lowers the levels of indoor TVOC concentrations. On the other hand, buoyancy-driven airflow becomes weaker when the temperature drops. This implies that pollutants stay in the air longer and are less diluted. These dynamics help explain the correlation between elevated temperatures and diminished measured TVOC concentrations in this study, despite the presence of continuous emission sources. Meanwhile, a positive correlation between CO with TVOC concentrations suggest a direct relationship - as CO concentration increases, TVOC levels also increase in indoor air. CO, a toxic by-product of incomplete combustion, is largely introduced from external sources such as heavy traffic and vehicle exhausts[28] near the hospital. When such pollutants infiltrate indoor spaces, especially under conditions of insufficient ventilation, they may co-occur with elevated TVOC levels arising from indoor activities such as disinfection, cleaning, or medical procedures. This co-accumulation elucidates the positive correlation identified between CO and TVOCs in the regression model. From a clinical perspective, the TVOC concentrations observed in this study - frequently 100-fold higher exceeding regulatory standards – raises serious concerns regarding potential adverse respiratory, cardiovascular, and systemic health outcomes[5,19,29]. From an infection-control standpoint, these exposures may compromise respiratory defences, increasing vulnerability to HCAIs.

From a policy standpoint, these results indicate the need for hospitals to start monitoring IAQ by time, optimizing ventilation cycles, and taking action against specific contaminants immediately. To stop pollutants from piling up in wards with naturally ventilation, enhanced ventilation management and operational controls may be required. Meanwhile mechanically ventilated wards would benefit from filtration upgrades, pollutant extraction mechanisms, and rigorous HVAC maintenance to prevent airborne from recirculating. For the safety of patients and healthcare worker from the dual hazards of chemical exposure and infectious risk, it is strongly recommended to incorporate integrated monitoring of CO and TVOC levels into infection-prevention and occupational-health frameworks.

## CONCLUSION

Hospital indoor environments in this tropical urban study were observed to consistently exceed ICOP (IAQ) 2010 TVOC limit. The levels of pollutants were found to be associated with departmental function, activity patterns, and ventilation mode throughout the day. Emergency wards, particularly those with mechanical ventilation, were more frequently characterised by higher TVOC burdens, while naturally ventilated wards generally demonstrated patterns consistent with more effective daytime dilution. Given the potential threats to patient and staff respiratory health, these findings suggest the importance of tailored IAQ management, continuous monitoring, optimized ventilation strategies and regulatory reinforcement in hospital settings.

## LIMITATION

A significant limitation must be acknowledged when interpreting these findings. TVOC concentrations in this study were measured as an aggregate parameter using monitoring equipment designed for total VOC assessment, rather than for compound-specific VOC identification. This screening-level approach, is useful for figuring out overall pollutant burden across hospital wards and ventilation types, but however it limits the ability to identify specific chemical compounds, determine their distinct emission sources, or assess their differential toxicity profiles. Since different VOC species have very different impacts on health, reactivity, and behaviour in indoor environments, using total TVOC values may hide compound-specific risks that are important for both health and the environment.

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**Conflict of Interest**

The author(s) do not have any conflict of interest.

**Data Availability Statement**

This statement does not apply to this article.

**Ethics Approval**

The study was conducted following ethical guidelines, securing approval from the National Uni-versity of Malaysia (Reference No: JEP-2020-131). This included adherence to ethical standards in research involving human environments and the collection of environmental data.

**Informed Consent Statement**

This study did not involve human participants, and therefore, informed consent was not required.

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