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The Silent Threat to Patient Safety: Combating Airborne Pathogens by Investigating Natural Ventilation's Impact on Indoor Air Quality in Hospital Wards

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ABSTRACT

Indoor air quality within hospitals is a critical factor in patient safety and infection prevention, since airborne microbial contaminant scan spread rapidly in poorly-ventilated environments. The type of ventilation system, whether natural or mechanical, has a significant impact in air dilution efficiency, pollutant dispersion, and microbial distribution. This is particularly important in tropical hospital settings, in which temperature and humidity are highly variable. This study aimed to investigate the impact of natural ventilation versus mechanical ventilation on IAQ and airborne microbial contaminants concentrations in eleven hospital wards encompassing medical, surgical, orthopaedic, and emergency disciplines in Klang Valley, Malaysia. Standard instruments were used to measure physical (temperature, humidity, air movement), chemical (CO, O_3, TVOC, CH_2O, PM_{10}), including CO_2, and biological (bacterial and fungal CFU/m³) parameters in the morning and evening. We used Kruskal–Wallis, Mann–Whitney, and multiple linear regression tests to identify significant differences and predictors influencing microbial variability. There were significant differences ($p<0.01$) observed in IAQ parameters between ventilation types. Naturally ventilated wards experienced higher airflow (0.13–0.37 m/s) and slightly elevated temperatures (30.2–33.1°C), enhancing pollutant dilution. In contrast, mechanically ventilated wards accumulated higher CO_2 (476–918 ppm) and TVOC (up to 545 ppm) levels. Regression analysis identified temperature ($\beta = 2.823$, $p = 0.019$) and formaldehyde ($\beta = -154.249$, $p = 0.041$) as significant predictors of fungal variability ($R^2 = 0.162$, $p = 0.0047$). All microbial concentrations remained within the ICOP IAQ (2010) standard limits. In the context of emerging and unidentified respiratory diseases, this study confirms that natural ventilation enhances indoor air renewal, reduces pollutant buildup, and limits microbial growth. It is a long-term strategy to combat airborne microbial contaminants in tropical hospitals, which will help with stronger infection control and healthier indoor air environments. Natural ventilation should be combined with hybrid systems to strengthen resilience against future indoor air threats.

Keywords: Indoor air quality, Health clinics, Physical parameters, Chemical parameters, Biological parameters.

INTRODUCTION

Indoor air pollution has become a significant global concern issue, with the World Health Organization (WHO) stating in 2018 that approximately 3.8 million premature deaths per year result from exposure to hazardous pollutants in indoor environments.[1] Numerous studies have shown that airborne microbial contaminants in hospital environments are major contributors to infections, allergies, and immunotoxic disorders.[2] A growing concern in healthcare settings is the prevalence of healthcare-associated infections (HCAIs), which primarily result from the transmission of pathogens between patients and healthcare workers via airborne routes and contaminated surfaces.[3] Chernet (2020) reported that in developed countries, over 50% of patients in intensive care units (ICUs) and 5% to 15% of hospitalized patients are affected by healthcare-associated infections (HCAIs).[4] Data from the WHO (2011) reveal that 7–10% of hospitalized patients get at least one healthcare-associated infection (HCAI).[5] This scenario therefore leading to longer hospital stays, long-term disabilities, and increased costs for both patients and healthcare systems. In this context, enhancing IAQ and ventilation systems is now considered as a key strategy for reducing pathogen transmission.[6] A study conducted by Basinska *et al.,* (2019) similarly emphasized that ventilation in healthcare facilities is crucial for providing protection against the variability of indoor air contaminants, including physical, chemical, and microbiological factor.[7] Inadequate ventilation can lead to the accumulation of elevated indoor microbial loads and other pollutants.[8-9]

Hospitals use three main types of ventilation, namely natural ventilation, mechanical ventilation, and hybrid systems. Each has its own advantages and challenges that need to be carefully evaluated for optimal implementation. Among them, mechanical systems are still the main focus of ventilation strategies in healthcare facilities[10]; however, challenges persist in preventing airborne microbial contaminants infections and maintaining optimal indoor air quality. This is supported by the findings of Rautiainen *et al.*, (2019), which found that total volatile organic compound (TVOC) levels in hospitals ranged from 10 to 5660 μg/m³, which is extremely high and much greater than acceptable standards, even with the implementation of HVAC systems.[11] Specifically, xylene levels in pathology wards were measured at approximately 3400 μg/m³, indicating that materials utilised in these settings release VOCs at potentially hazardous concentrations.[11] Liu *et al.,* (2018) have describe the inherent limitations of mechanical ventilation, stating that HVAC systems create conditions that conducive for microbial growth including optimal temperature, humidity, and nutrient availability within components like air ducts, filters, and heat exchangers.[12] The multiplication of microorganisms under these conditions leads to the accumulation of microbial contaminants, that is then dispersed into indoor spaces through the supply airflow. This makes indoor air even more polluted and poses risks to occupant health. Even more concerning is a study by Chezganova *et al.,* (2021), which revealed that ventilation-associated particulate matter (Vent-PM) can act as a reservoir for multidrug-resistant organisms (MDROs) and healthcare-associated infection (HCAI) pathogens.[13] Their research revealed that more than 70% of Vent-PM samples were contaminated, with 60% hosting multidrug-resistant bacteria and 48% hosting biofilm-producing strains.[13] These results underscore the critical need for comprehensive air quality management plans which integrate humidity control and optimized ventilation dynamics to reduce airborne microbial contaminants in hospitals.

The study by Monge-Barrio (2022) corroborated that the use of natural ventilation systems significantly enhanced indoor air quality (IAQ) and diminished the risk of airborne microbial contaminants infections, including respiratory illnesses such as COVID-19.[14] Onmek *et al.,* (2020) discovered that hospital wards that used natural ventilation maintained the levels of microbes below the acceptable limits sets by the National Institute for Occupational Safety and Health (NIOSH) and the World Health Organization (WHO).[15] Specifically, bacterial concentrations were less than 500 CFU/m³, while fungal levels were less than 1000 CFU/m³, indicating effective air quality control. This also aligns with the findings by Morawska *et al.,* (2020), who highlighted that natural ventilation can significantly improve indoor air quality by lowering the concentration of airborne microbial contaminants in the air.[16] This is because natural ventilation allows fresh air to enter indoor spaces, which helps to disseminate and dilute airborne microbial contaminants, a crucial factor in for stopping the spread of respiratory infections.

Furthermore, Liu (2018) emphasized that HVAC systems are associated with a significant increase in Sick Building Syndrome (SBS) morbidity, ranging from 30% to 200%, compared to natural ventilation. This increase is compounded by the association of HVAC systems with multi-chemical sensitivity and building-related illnesses (BRI).[17] Building on these findings, the present study aims to evaluate the impact of natural ventilation on the concentration of airborne microbial contaminants, alongside its effect on indoor air quality (IAQ) in various hospital wards with various medical disciplines. Hospital wards differ in activities and environmental conditions depending on their medical specialties. Consequently, the microbial load in these wards is expected to vary significantly, as observed by Kayta *et al.,* (2022).[18] Liu & Dickter (2020) also discovered the variations pattern of microbial load, reporting that ICUs and surgical wards have the most cases of nosocomial infections due to their distinct clinical functions.[19] In ICUs, aggressive interventional treatments including invasive catheters, and frequent antibiotic usage lead to higher levels of microbes, particularly multidrug-resistant organisms (MDROs). Surgical wards, on the other hand, suffer from elevated microbial concentrations due to surgical site infections (SSIs), which are affected by the type of procedure performed and the condition of patient's overall health. These discrepancies indicate how specialized medical activities influence the levels of microbes, which in turn affects indoor air quality (IAQ) and the risk of infection in hospital environments.

MATERIALS AND METHODS

Study Design and Setting

This study was conducted at a hospital located in Klang Valley, Malaysia, and included the Medical Ward (MW), Surgery Ward (SW), Orthopaedic Ward (OW) and Emergency Ward (EW). The selected wards accommodated high patient and healthcare worker densities, belonged to different medical disciplines and were ventilated either through natural airflow systems or centralized heating, ventilation, and air conditioning (HVAC) mechanisms.

Sampling Points

A total of eleven sampling sites (one for each ward) were selected in accordance with the total area specified by ICOP IAQ (2010) standard.[20]

Measurement of Parameters

Physical and chemical parameters were measured by direct-reading method, whereas biological parameters were collected using active sampling method. Details are given below.

Physical Parameters

The physical parameters were:

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

Chemical Parameters

The chemical parameters, including CO_2 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.

Both physical and chemical parameters were measured in the morning and evening. To enhance measurement reliability, at each sampling point, data were collected three times, with readings taken every five minutes over a 15-min sampling period.

Biological Parameters

Biological parameters including total fungal counts (TFC) and total bacterial counts (TBC) were carried out using the Quick Take 30 sampler. Duplicate Trypticase Soy Agar (TSA) media which served to culture fungal and bacterial were used. The colony of fungal and bacterial that determined in the plate were counted by the software integrated from WIGGENS GmbH which is Galaxy 230 Colony Counter.

Statistical Analysis

All data were analysed using IBM SPSS Statistics version 26.0 software. Non-parametric tests were used, including the Mann–Whitney test, to look for differences based on ventilation type. A multiple linear regression analysis was conducted to identify the environmental predictors that significantly influenced microbial counts across hospital wards. This statistical approach is used to assess how ventilation type, especially natural ventilation, affects environmental parameters and airborne microbial contaminants levels within hospital wards.

RESULTS

We investigated a total of eleven hospital wards, including surgical, medical, orthopaedic, and emergency department, to discover how different ventilation systems impact indoor air quality (IAQ). Six wards (WA, WB, WC, WD, WE, WF) used natural ventilation, while five (WR1, WR2, WR3, WH, WG) used mechanical air-conditioning systems. The measurements were carried out in the morning and evening, and all of parameter values were compared to the standard set by the ICOP IAQ (2010). Tables 1 and 2 show the mean value and standard deviations for physical (temperature, relative humidity, and air movement), chemical (carbon monoxide, ozone, formaldehyde and total volatile organic compounds and particulate matter [PM_{10}]), including carbon dioxide, and biological (TFC and TBC) parameters.

The physical parameters indicated significant variations in airflow pattern and thermal conditions between naturally and mechanically ventilated wards. Significant differences were found in temperature parameters within wards and the type of ventilation used. In wards with natural ventilation, the morning temperatures were between 30.2±1.0°C to 32.3±0.57°C, with a slight increase in the evening to 32.7±0.86°C–33.1±0.67°C, which is higher than the ICOP IAQ (2010) comfort range of 23–26°C. Ward WC had the highest mean temperature (33.1±0.67°C), while Ward WD had the lowest temperature (30.2±1.02°C). In contrast, mechanically ventilated wards remained cooler, with morning temperatures ranging from 22.1±0.02°C to 24.8±0.28°C, while evening value were from 21.9±0.19°C to 25.2±0.42°C, well within the acceptable comfort range. Although wards with air-conditioned environments offered superior thermal comfort, the higher temperatures in naturally ventilated wards allowed buoyancy-driven airflow, promoting vertical mixing and dilution of airborne microbial contaminants. This was evidenced by the Mann–Whitney test showing a significant difference ($Z = -6.462$, $p< 0.000$), with naturally ventilated wards had higher mean ranks (44.50 vs 10.50).This indicates that natural ventilation made the air warmer but also improved convective flow (Table 3).

Table 1: IAQ parameters reading across hospital wards in the morning

Parameter	ICOP IAQ (2010) Standard	WA Natural	WB Natural	Surgical WR1 Mechanical	WR2 Mechanical	WR3 Mechanical	Medical WC Natural	WD Natural	Orthopedic WE Natural	WF Natural	Emergency WH Mechanical	WG Mechanical
Temperature	23.0-26.0°C	31.6±1.06	32.3±0.57	24.8±0.28	24.0±1.08	23.8±0.09	31.9±0.99	30.2±1.02	30.6±1.02	31.1±1.12	22.1±0.02	23.1±0.87
Relative humidity	40-70 %	65.6±4.66	62.1±2.17	62.6±0.02	62.2±0.42	62.0±0.52	61.6±2.09	70.4±1.72	73.4±2.40	69.4±2.11	67.7±0.19	64.7±3.30
Air movement	0.15-0.50 m/s	0.20±0.08	0.31±0.05	0.06±0.02	0.06±0.01	0.15±0.10	0.21±0.04	0.24±0.06	0.13±0.05	0.24±0.08	0.10±0.03	0.07±0.01
CO_2	1000ppm	369±34.69	340±17.75	619±61.99	918±89.57	867±90.98	322±19.69	383±44.95	365±70.53	341±17.11	520±68.83	476±15.32
CO	10ppm	0.43±0.55	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	0.03±0.03	2.28±1.83	1.23±1.38	0.22±0.16	0.00±0.00	0.00±0.00
O_3	0.05ppm	0.12±0.14	0.19±0.06	0.01±0.00	0.00±0.00	0.00±0.00	0.06±0.05	0.09±0.09	0.07±0.06	0.11±0.03	0.01±0.01	0.02±0.00
TVOC	3ppm	138.1±44.17	145.18±90.22	235.5±167.82	240.0±86.55	385.4±255.22	151.8±106.91	141.5±78.57	283.4±288.27	104.6±88.95	237.8±29.34	196.2±3.42
CH_2O	0.1ppm	0.08±0.01	0.14±0.01	0.02±0.00	0.06±0.00	0.04±0.00	0.06±0.00	0.07±0.00	0.06±0.01	0.16±0.05	0.02±0.00	0.04±0.00
PM_{10}	0.15mg/m³	0.07±0.009	0.07±0.010	0.04±0.007	0.04±0.03	0.03±0.01	0.02±0.002	0.09±0.006	0.08±0.006	0.11±0.027	0.01±0.000	0.01±0.002
Bacterial count	500 CFU/m³	163.1±1.73	54.9±1.42	143.4±1.00	54.5±3.25	45.0±3.96	45.0±6.58	34.5±3.24	82.8±6.10	44.5±8.40	18.9±0.71	19.5±1.48
Fungal count	1000 CFU/m³	96.2±0.69	14.2±0.86	18.9±0.71	11.7±0.78	7.60±0.71	14.3±1.88	30.2±1.02	15.6±7.56	11.7±1.34	8.6±0.71	8.6±0.71

Table 2: IAQ parameters reading across hospital wards in the evening

Parameter	ICOP IAQ (2010) Standard	WA Natural	WB Natural	Surgical WR1 Mechanical	WR2 Mechanical	WR3 Mechanical	Medical WC Natural	WD Natural	Orthopedic WE Natural	WF Natural	Emergency WH Mechanical	WG Mechanical
Temperature	23.0-26.0°C	33.0±1.03	33.0±1.06	25.2±0.42	23.4±0.07	23.8±0.19	33.1±0.67	33.1±0.42	32.7±0.86	33.0±0.71	22.4±0.31	21.9±0.19
Relative humidity	40-70%	61.4±4.20	60.2±2.22	62.0±0.09	61.1±0.40	60.9±0.12	59.7±2.07	62.6±1.52	66.7±2.57	63.4±2.12	67.2±0.26	67.3±0.33
Air movement	0.15-0.50 m/s	0.30±0.05	0.30±0.09	0.05±0.01	0.06±0.00	0.07±0.03	0.19±0.04	0.37±0.09	0.17±0.04	0.24±0.05	0.11±0.00	0.08±0.01
CO_2	1000ppm	337±27.60	341±23.83	566±43.60	766±65.76	775±38.18	316±23.46	295±17.51	298±26.39	324±10.48	522±77.3	478±2.59
CO	10ppm	0.13±0.23	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	0.09±0.12	0.01±0.02	0.07±0.11	0.00±0.00	0.00±0.00
O_3	0.05ppm	1.45±1.60	1.04±0.87	0.07±0.00	0.01±0.00	0.01±0.00	0.09±0.09	1.71±0.95	0.20±0.09	1.91±1.18	0.01±0.01	0.01±0.01
TVOC	3ppm	58.8±47.50	38.6±6.45	188.3±168.00	275.8±89.24	246.2±95.25	72.1±20.05	38.7±20.84	24.8±5.59	82.9±34.99	545±137.13	318.8±35.62
CH_2O	0.1ppm	0.08±0.01	0.14±0.01	0.02±0.00	0.06±0.00	0.04±0.00	0.06±0.00	0.07±0.00	0.06±0.01	0.16±0.05	0.02±0.00	0.04±0.00
PM_{10}	0.15mg/m^3	0.11±0.022	0.10±0.003	0.07±0.015	0.05±0.00	0.05±0.00	0.00±0.005	0.08±0.012	0.07±0.006	0.11±0.019	0.02±0.005	0.01±0.002
Bacterial count	500 CFU/m^3	78.8±0.69	57.4±0.69	46.7±1.63	134.9±4.95	46.7±1.63	37.7±24.12	56.6±7.40	34.0±6.33	81.9±9.24	50.6±0.85	28.5±0.71
Fungal count	1000 CFU/m^3	31.2±0.86	10.1±0.82	11.7±0.78	15.8±0.71	11.7±0.78	20.0±4.91	33.1±0.42	19.7±1.35	17.4±3.07	9.6±0.71	6.6±0.78

Relative humidity in all wards remained generally within or close to the standard recommended range of 40–70%. Naturally ventilated wards exhibited a wider variability (59–73%) in comparison to mechanically ventilated wards (60–67%), indicating a greater interaction with outdoor climatic conditions. In the morning, Rh in naturally ventilated wards ranged from 61.6 ± 2.09% (WC) to 73.4±2.40% (WE), while in mechanically ventilated wards, the Rh showed narrower values between 62.0±0.52% (WR3) and 67.7±0.19% (WH). Ward that recorded the highest Rh value in naturally ventilated ward was ward WE (73.4±2.40%), while for mechanical ventilated wards, the highest Rh value was shown in a WG ward in the evening (67.3±0.33%). The Mann–Whitney test found no statistically significant difference between systems (Z = –0.471, p = 0.638), and Rh levels remaining relatively consistent within all wards (Table 3).

Table 3: The Mann–Whitney test comparing IAQ parameters concentration between natural and mechanical (air-conditioned) ventilated hospital wards

IAQ Parameter	Ventilation type	Z	Asymp. Sig. (2-tailed)	Mean Rank
Temperature	Natural	-6.462	0.000	44.50
	Air-conditioned			10.50
Rh	Natural	-0.471	0.638	35.23
	Air-conditioned			32.75
Air movement	Natural	-6.071	0.000	43.90
	Air-conditioned			11.95
CO_2	Natural	-6.461	0.000	24.50
	Air-conditioned			58.50
CO	Natural	-3.785	0.000	39.50
	Air-conditioned			22.50
O_3	Natural	-5.828	0.000	43.52
	Air-conditioned			12.85
TVOC	Natural	-5.047	0.000	26.69
	Air-conditioned			53.25
CH_20	Natural	-6.287	0.000	44.17
	Air-conditioned			11.30
PM_{10}	Natural	-4.886	0.000	42.06
	Air-conditioned			16.35
Bacterial count	Natural	-1.751	0.080	37.21
	Air-conditioned			28.00
Fungal count	Natural	-4.428	0.000	41.34
	Air-conditioned			18.08

*Significant at $p < 0.01$

Air movement, as a key indicator of ventilation efficiency, was significantly higher in naturally ventilated wards (0.13–0.37 m/s) than in mechanically ventilated wards (0.05–0.15 m/s). Five out of six naturally ventilated wards were having airflow rates within the standard recommended range of 0.15–0.50 m/s. This indicates that the air exchange was sufficiently adequate to dilute and remove airborne microbial contaminants. This study found out that ward WD had the highest mean velocity (0.37±0.09 m/s, PM), followed by Ward WB (0.31±0.05 m/s, AM), indicating an effective cross-ventilation during active occupancy. Conversely, wards with mechanical ventilation had consistently low air velocities, with the lowest recorded in Ward WR1 (0.05±0.01 m/s). This indicates that air mixing is limited within enclosed HVAC environments. The Mann–Whitney test revealed a very strong difference ($Z = -6.071$, $p < 0.000$), with naturally ventilated wards having a higher mean rank (43.90) than mechanically ventilated wards (11.95) (Table 3). This confirms that natural ventilation is better at diluting air and more effective at removing airborne microbial contaminants than mechanical systems.

Chemical parameters further emphasised the performance advantage of natural ventilation, showing its superior ability to dilute indoor-generated contaminants relative to mechanically ventilated systems. Carbon dioxide (CO_2) concentrations indicated a clear contrasts between ventilation types. In naturally ventilated wards, the concentration CO_2 in the air in the morning ranged from 322±19.69 ppm to 383±44.95 ppm. This is far lower than those measured in mechanically ventilated wards, which recorded higher concentrations ranged from 476±15.32 ppm to 918±89.57 ppm. In the evening, naturally ventilated wards kept CO_2 levels low (295–341 ppm), while mechanically ventilated wards remained elevated (478–775 ppm). Although all wards complied with the standard of 1000 ppm, the noticeable elevations in mechanically ventilated spaces indicate inadequate dilution of exhaled CO_2, indicative of closed HVAC systems with limited outdoor-air exchange. The Mann–Whitney test showed a significant difference ($Z = -6.461$, $p < 0.000$), with naturally ventilated wards exhibiting a lower mean rank (24.50 vs 58.50). This result demonstrates that natural ventilation is more effective at air exchange and dilution capacity than mechanical systems, which tend to retain exhaled air (Table 3).

Carbon monoxide levels were negligible across all wards and continually well below the standard threshold of 10 ppm, demonstrating the absence of combustion-related contamination. Minor increases noticed in a few naturally ventilated wards (≤ 2.28 ppm) were probably caused by exhaust infiltration from cars on the nearby roads, rather than indoor combustion sources. Overall, these CO findings verify that both ventilation systems maintained safe exposure profiles. The Mann–Whitney test demonstrated that mean rank values were marginally higher in naturally ventilated wards (39.50 vs 22.50, $Z = -3.785$, $p < 0.000$) (Table 3), reflecting the occasional outdoor infiltration effects associated with external traffic emissions.

Ozone (O_3) levels fluctuated from 0.01 ppm to 1.91 ppm, and during the day in natural ventilated wards occasionally rose above the 0.05 ppm standard level. This was probably due to outdoor photochemical ozone intrusion. Mechanically ventilated wards, on the other hand, kept O_3 levels close to zero, since it filtered the air well and limited outdoor-air exchange, except for Ward WR1 (0.07±0.00 ppm), went slightly above the guideline value. The Mann–Whitney test corroborated these results, demonstrating significantly higher mean ranks for naturally ventilated wards (43.52 vs 12.85, $Z = -5.828$, $p < 0.000$) (Table 3), and verifying greater ozone intrusion linked to direct ambient air exchange. The biggest distinction between the two ventilation types was in the TVOC level. The average morning TVOC levels in naturally ventilated wards were recorded between 104.6±88.9 ppm and 283.4±288.2ppm. In contrast, mechanically ventilated wards showed far higher levels, peaking at 385.4±255.2ppm (WR3) in the morning and reaching extreme evening levels of 545±137.1ppm (WH). These levels exceeded the standard guideline of 3 ppm. Conversely, TVOC levels in naturally ventilated wards significantly decreased in the evening (24.8–82.9ppm), indicating the effectiveness of open-air pathways in removing accumulated pollutants. The Mann–Whitney test revealed a significant difference ($Z = -5.047$, $p < 0.000$), with naturally ventilated wards having lower mean ranks (26.69 vs 53.25) (Table 3). This shows that mechanical ventilation without sufficient make-up air or proper filtration can raise the risk of chemical exposure, even while maintaining thermal comfort.

Formaldehyde (CH_2O) concentrations remained consistently low and were typically below the permissible limit of 0.1 ppm. However, two naturally ventilated wards were observed to have minor exceedances, namely wards WF = 0.16±0.05 ppm and WB=0.14±0.01 ppm. The consistently low levels of CH_2O in all wards suggest that effective chemical dispersion and rapid degradation. This indicates that both ventilation systems maintained aldehyde levels within the standard requirements. The Mann–Whitney test indicated that naturally ventilated wards exhibited higher mean ranks (44.17 vs 11.30, $Z = -6.287$, $p<0.000$) (Table 3), which may be attributed to occasional off-gassing and outdoor aldehyde infiltration.

The levels of PM_{10} concentrations likewise stated below the standard limit (≤ 0.15 mg/m^3) in all wards. In naturally ventilated areas, they ranged from 0.02 to 0.11 mg/m^3, and in mechanically ventilated areas they ranged from 0.01 to 0.07 mg/m^3. The slightly higher concentrations in naturally ventilated wards were caused by minor resuspension of settled dust and infiltration of outdoor particles. Overall, the consistently low PM_{10} concentrations in all wards verify that the air was effectively diluted and minimal resuspended of particle. These results indicates that both ventilation systems successfully maintained particulate levels within acceptable indoor air quality limits. The Mann–Whitney test showed that the mean ranks were significantly greater under natural ventilation (42.06 vs 16.35, $Z = -4.886$, $p < 0.000$) (Table 3). This suggests minor outdoor dust ingress, does not exceed safety thresholds.

The biological findings verified the trends observed in the chemical parameters, reflecting the combined influence of air movement, occupant activity, and ventilation efficiency on microbial dispersion. The concentration of airborne bacterial varied greatly between wards and types of ventilation. In naturally ventilated wards, morning bacterial loads were generally greater, ranging from 34.5±3.24 CFU/m^3 (WD) to 163.1±1.73 CFU/m^3 (WA). Mechanically ventilated wards also recorded higher morning bacterial counts, between 45.0±3.96 CFU/m^3 and 143.4±1.00 CFU/m^3, suggesting limited air dilution within recirculated systems. Despite these variations, all wards met the ICOP IAQ (2010) microbial threshold of ≤ 500 CFU/m^3, indicating all wards were under acceptable bacterial air quality limit across both ventilation strategies. The Mann–Whitney test showed no statistically significant difference between systems ($Z = -1.751$, $p = 0.080$). However, naturally ventilated wards exhibited higher mean ranks (37.21 vs 28.00) (Table 3).

The concentrations pattern of fungal were also similar and remained well below the standard limit of 1000 CFU/m^3. The overall levels ranged from 6.6 CFU/m^3 to 96.2 CFU/m^3. Natural ventilated wards WA had the highest concentration of fungi (96 CFU/m^3, AM). Mechanically ventilated wards consistently exhibited low fungal counts (<20 CFU/m^3), while naturally ventilated wards demonstrated modest temporal variation, reflecting active air exchange and dynamic airflow that reduced spore stagnation. Although natural ventilation may permit limited ingress of outdoor spores, the overall amount of fungal load stayed low and clinically insignificant. The Mann–Whitney test showed statistically significant differences ($Z = -4.428$, $p < 0.001$), with naturally ventilated wards having a higher mean rank (41.34 vs 18.08) (Table 3). This confirms that natural air exchange processes are associated with greater fungal variability.

Statistical Analysis

The Mann–Whitney test showed statistically significant differences for microbial counts between ventilation types (natural and air-conditioned) for TFC only. To discover the environmental predictors that significantly influenced the fungal counts across hospital wards, a multiple linear regression analysis was performed (Table 4). The final model kept five predictors-temperature, CO_2, CH_2O, PM_{10}, and room density. This was achieved using the backward elimination method (criterion: probability of F-to-remove$\geq$0.10). The regression model was statistically significant ($R^2 = 0.162$; $F(5,62) = 2.397$; $p = 0.0047$), indicating that these environmental factors accounted approximately 16.2% of the differences in fungal counts. Temperature exhibited a positive significant correlation with fungal counts ($\beta = 2.823$, $p = 0.019$), suggesting that high indoor temperature promote temporary increases in fungal spore concentration probably due to enhanced dispersion and metabolic activity at higher temperatures. In contrast, CH_2O showed a significant negative association ($\beta = -154.249$, $p = 0.041$), which means that aldehyde-based cleaning or disinfection solutions may prevent fungi from growing and propagating.

Table 4: Multiple linear regression analysis of environmental predictors of fungal concentration in hospital wards

Fungal count score: $R^2 = 0.162$, F (5,62), F = 2.397, p =0.0047

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% CI	
β	β	Std Error	Beta			Lower bound	Upper bound
(Constant)	-88.959	46.927		-1.896	0.063	-182.765	4.848
Temperature	2.823	1.168	0.584	2.416	0.019	0.488	5.158
CO_2	0.043	0.030	0.367	1.419	0.161	-0.017	0.103
CH_2O	-154.249	73.970	-0.361	-2.085	0.041	-302.112	-6.386
PM_{10}	124.303	102.567	0.215	1.212	0.230	-80.724	329.331
Room density	2.424	1.327	0.314	1.826	0.073	-0.229	5.076

Dependent variable: Fungal count

The other three predictors, namely CO_2 (β = 0.043, p = 0.161), PM_{10} (β = 124.303, p = 0.230), and room density (β = 2.424, p = 0.073), were not significant, but they did exhibit positive coefficients, which means that particulate levels and higher occupancy may have impact on the prevalence of fungal. These results reveal that chemical composition, specifically CH_2O and temperature, have the biggest impact on shaping fungal behaviour; however, the effects of occupant load and particle concentration are less clear. Overall, the regression model underscores that environmental microclimate and chemical disinfectant activity are key determinants of fungal variability within hospital environments, reflecting the complex interplay between thermal conditions, pollutant dynamics, and microbial ecology.

DISCUSSION

This study presents compelling evidence-based confirmation that the type of ventilation significantly impacts IAQ and microbiological safety in hospital settings. Across eleven wards from surgical, medical, orthopaedic, and emergency departments, naturally ventilated wards consistently exhibited higher air dilution performance compared to mechanically ventilated wards. The Mann–Whitney tests revealed significant differences ($p<0.05$) among nearly all of the IAQ parameters. Regression analysis identified that temperature and CH_2O were significant predictors of fungal variability ($R^2 = 0.162$, p = 0.0047). These findings collectively validate the hypothesis that natural ventilation is essential in mitigating airborne microbial contaminants by improving airflow, pollutant dispersion, and microbial dilution efficiency. This align with the findings of Onmek *et al.,* (2020), who reported that naturally ventilated wards were able to maintain bacterial and fungal concentrations below the limits set by NIOSH and WHO, highlighting the effectiveness of this ventilation method.[15]

The physical parameters has further supported this relationship. In this study, naturally ventilated wards showed significantly higher air movement (0.13–0.37 m/s) than mechanically ventilated wards (0.05–0.15 m/s), consistent with findings by Lv *et al.,*(2022) and Savanti *et al.,* (2022)[21,22]. Higher temperatures in naturally ventilated wards (30.2–33.1°C) supported buoyancy-driven convection processes as noted by Chew (2023), which warmer indoor air enhances vertical mixing and accelerates airborne microbial contaminants clearance.[23] In contrast, mechanically ventilated wards maintained stable thermal comfort (22–25°C), but this stability may permit stagnation zones and pollutant accumulation and consequently worsen the IAQ.[24]

The chemical parameters identified in this study further validate the impact of ventilation type on pollutant dynamics. In this study, naturally ventilated wards consistently demonstrated lower concentrations of CH_2O, TVOC, and CO_2, than mechanically ventilated wards (Mann–Whitney tests, $p<0.05$). Carbon dioxide (CO_2) in naturally ventilated wards in this study exhibited concentrations ranging from 295–383 ppm, significantly lower than the 476–918 ppm measured in mechanically ventilated wards, demonstrating more effective air exchange in natural ventilated wards aligning with Gola *et al.,* (2019) who reported that insufficient ventilation result in elevated indoor CO_2 level.[25] These findings are consistent with Roberts *et al.,*(2022), who observed a significant reduction in CO_2 levels from 2000 ppm to 500 ppm upon opening windows at 6:00 a.m. in the Paediatrics ward of Tamale Hospital, Ghana following the earlier use of air conditioning.[26] Three high CO_2 peaks were also documented in the air-conditioned Emergency Department at Accra Hospital in Ghana, where windows stayed closed all day. Both observations reinforce that wards with natural ventilation maintain lower CO_2 levels than those with mechanical ventilation. This shows that naturally ventilated areas are better at diluting exhaled pollutants and improving IAQ.[26] Elevated CO_2 levels have also been reportedin mechanically ventilated hospitals in Lahore, Pakistan, (712 ppm to 1093ppm)[27] and Malaysia at Medical Clinic 1 and Medical Clinic 2 in University Hospital, Klang Valley (1484ppm-1668ppm), which were greater than the acceptable ICOP IAQ level.[28]

TVOC concentrations showed the most noticeable difference between the two forms of ventilation. Mechanically ventilated wards had very extreme high evening concentrations of up to 545ppm, far exceeding the standard limit of 3ppm. On the other hand, naturally ventilated wards showed major evening reductions (24.8–82.9ppm). This trend is consistent with observations that natural ventilation facilitates effective dilution of pollutants that have built up over the day, which is in line with studies by Dbouk *et al.,*(2022) that claim open airflow enhances contaminants dispersion in tropical hospital settings.[29] Supporting this, Riveron *et al.,* (2021) found that the TVOC levels were significantly lower in the summer (634.2±682.9 μg/m³) than in the winter (1,089.0±1,582.8 μg/m³) at Glenfield General Hospital (GGH) and Leicester Royal Infirmary (LRI), United Kingdom. They attributed this seasonal decline to increased window opening and natural airflow, which complemented the mechanical ventilation system in use.[30] Moldovan *et al.,*(2024) have also highlighted the urgent need for effective and flexible ventilation techniques in hospitals to minimize chemical pollution to a minimum.[31] These results collectively, underscore the critical importance of natural ventilation in mitigating VOC accumulation, especially in tropical climates where solar-driven buoyancy and cross-ventilation facilitate pollutant removal and enhance IAQ stability.

Formaldehyde (CH_2O) levels remained low and within the standard limit of 0.1 ppm, with only minor exceedances in two naturally ventilated wards, WF (0.16 ± 0.05 ppm) and WB (0.14 ± 0.01 ppm). The Mann–Whitney test indicated a significant difference ($Z = -6.287$, $p<0.001$), with naturally ventilated wards exhibiting slightly higher mean ranks (44.17). However these concentrations were substantially lower than those reported in other hospital settings for example by Rao *et al.,* (2023) who recorded mean CH_2O concentrations as high as 2.4ppm in operating rooms in Puducherry, India-particularly 1.2ppm near anaesthesia workstations and 1.0ppm adjacent to surgical teams during electrocautery use-values that far exceed recommended safety limits, underscoring the risks of pollutant buildup in sealed HVAC environments.[32] This is in contrast to the current findings, where both natural and mechanical ventilation systems in Malaysian hospitals successfully kept aldehyde levels well below the safety limits set by the government. This suggesting an efficient pollutant dispersion and degradation under tropical climatic conditions.

Regression analysis elucidated the relationship between CH_2O and TFC. A significant negative association ($\beta = -154.249$, $p = 0.041$) demonstrated that elevated CH_2O concentrations were associated with reduced fungal loads. This supports evidence that aldehyde-based cleaning and disinfection agents exert inhibitory effects on fungal viability and sporulation, as also documented by Khalil *et al.,* (2022) who reported significant decreases in airborne mold concentrations subsequent to formaldehyde-based disinfection, demonstrating efficacy at exposure durations of 15 min, 6 h, and 24 hours.[33] Overall, these results highlights there is a dynamic balance between controlling pollution and microbial inhibition.

PM_{10} levels in natural or mechanical ventilation wards stayed below the standard limit of 0.15 mg/m³, indicating all the wards were compliant with regulatory standards. The Mann–Whitney test indicated a significant difference ($Z = -4.886$, $p < 0.001$) between naturally and mechanically ventilated wards, with a higher mean ranks for natural ventilation (42.06) compared to mechanical ventilation (16.35) which consistent with findings by Chamseddine *et al.,* (2019), who reported elevated PM_{10} concentrations in naturally ventilated hospitals.[34] Despite this, PM_{10} is not an effective predictor of airborne fungal levels (β = 124.303, p = 0.230), as the positive association observed in the model was not statistically significant.

Microbial findings in this study were below the standard limit and parallel those of Kotgire *et al.,*(2020), who observed that bacterial and fungal concentrations in naturally ventilated wards fluctuate throughout the day with higher concentrations typically recorded in the morning compared to the evening.[35] In this investigation, the morning bacterial counts (34.5–163.1 CFU/m^3) were higher in naturally ventilated areas because of medical activities and occupancy. Such activity-driven increases are consistent with Ye *et al.,*(2025), who documented similar transient peaks in airborne bacteria after morning operations and staff activity.[36] By evening, microbial counts declined significantly, reflecting the self-purging capacity of open-air ventilation.[29] Overall microbial contaminants count in this study ranged between 19.9–163.1 CFU/m^3 (bacteria) and 6.6-96.2 CFU/m^3 (fungal). The magnitude of microbial contaminants concentrations in this study were markedly lower compared to the findings by Bozic and Iliβ(2019), where fungal counts ranging from 20-1125 CFU/m^3, while bacterial levels varied between 30-6295 CFU/m^3.[37] The results of this study also revealed that areas without HVAC systems moderately higher fungal and bacterial counts than those with mechanical ventilation. This trend aligns closely with the findings of Bozic and Ili (2019), which demonstrated that wards with air handling units experienced a decline in fungal counts, whereas natural ventilated spaces exhibited increased airborne fungal concentrations.[37]

The regression models (p = 0.0047) indicates that ventilation-driven environmental conditions significantly have a big effect on fungal variability. Temperature was identified as a significant predictor (β = 2.823, p = 0.019), suggesting that elevated temperature correlate with higher instantaneous fungal concentrations. This pattern likely reflects increased air exchange and outdoor spore infiltration rather than enhanced indoor fungal proliferation as wards with natural ventilation have higher temperatures and stronger buoyancy-driven airflow,[23] which allows greater dispersion and dilution of airborne microbial contaminants as explained by Lipczynska *et al.,* (2022).[38] Similar effects were described by Vourinen *et al.,* (2020) who pointed out that changes in temperature can influence the activation or deactivation of microbial contaminants.[39] However, this interpretation contrasts with the findings of Alrayess *et al.,* (2022), who reported that natural ventilation and fan-coil units can, under specific climate or conditions, aggravate indoor fungal concentrations.[40] Mechanically ventilated wards operate under cooler and more stable thermal conditions that keep outdoor-air from coming in, but allow air recirculation. Unfortunately, if systems are poorly maintained, potential microbial buildup is likely to occur.[37]

Although HVAC systems are effective in managing thermal comfort and filter contaminants, as also claimed by Shajahan *et al.,*(2019), who found out that different HVAC configurations can reduce or eliminate pathogenic microorganisms,[41] these pathogenic microorganisms, due to their diverse natures, behaviours, and release mechanisms, remain particularly challenging to predict and control as mentioned by Argyropoulos *et al.,*(2023) in their study.[42] This complexity is compounded by the recent emergence of new and identified respiratory diseases[43], which underscores the continuing vulnerability of the indoor environment. Steiner *et al.,* (2020) has also demonstrated that the human respiratory system is highly complex and readily absorbs airborne microbial contaminants, thereby amplifying the health risks posed by enclosed spaces.[44] More concerningly, Argyropoulos *et al.,* (2023) claimed that as of 2023, global efforts are still ongoing to prevent and regulate the emission of chemical pollutants and biological agents, including pathogenic microorganisms.[42] This indicates that stakeholders must improve ventilation strategies.

In this context, comparing with current mitigation technologies presents a meaningful point of view. Brady *et al.,* (2025) discuss several engineering controls designed to reduce concentrations of airborne microbial contaminants in healthcare environments.[45] Among them are high efficiency particulate air (HEPA) filtration and ceiling-mounted ultraviolet germicidal irradiation (UVGI). According to Brady *et al.,*(2025), numerous studies have demonstrated that both approaches substantially decrease the airborne microbial contaminants level.[45] However, important limitations remain. Rao *et al.,* (2020) and Otter *et al.,* (2023) note that some air-purification systems emit considerable noise, which may disrupt patient care[46,47]. Brady *et al.,* (2025) further point out that these technologies are typically difficult to use since they cost a lot of money to install, maintain, operate, and monitor the systems effectively.[45] These limitations highlight the practical challenges faced by hospitals, especially those with few resources to rely on engineered solutions for controlling airborne microbial contaminants. From the results of this study, we can conclude that natural ventilation offers a more dynamic,cost-effective, energy-efficient, and biologically self-cleansing system, suited for tropical climates.

CONCLUSION

These findings collectively underscore that engineered mitigation technologies, including HEPA filtration, and UVGI systems are effective, however, their implementation in public hospitals is hindered by financial, infrastructural and operational constraints. In this practical reality, the empirical evidence from this study indicates that the kind of ventilation has a big impact on the safety of microbes and the quality of the indoor air. Compared to mechanically ventilated wards, naturally ventilated wards continually experienced better air dilution, pollution dispersion, and microbial decrease. Overall, the results show that natural ventilation is a dynamic, cost-effective, energy-efficient, and biologically self-cleansing airflow system that works especially well in tropical climates. It is still a very good way to lower the risk of airborne microbial contaminants in healthcare settings with limited resources.

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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 University 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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