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Ventilation Strategies to Mitigate Air Pollution Impact on Hospital Professionals in Intensive Care Units in the Democratic Republic of Congo

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Abstract: This study critically examines the impact of indoor air quality (IAQ) on occupant health in two critical care units (ICUs) at Jason Sendwe Hospital (JSH) and General Carrier de Mine Hospital (GCMH) within the Southern DRC metropolitan area, focusing on their impact on occupant health and well-being. Utilizing a mixed methods approach that includes health questionnaires, continuous environmental monitoring (monitoring CO_2, VOCs, $PM_{2.5}$, PM_{10}, temperature, and relative humidity), and computational fluid dynamics (CFD) analysis, this research aims to identify correlations between environmental factors and the health of hospital staff and patients. The investigation was conducted across both the rainy and dry seasons, revealing significant seasonal variations in IEQ parameters and exploring the incidence of symptoms commonly associated with sick building syndrome among hospital staff. Higher CO_2, VOCs, and particulate matter levels during the dry season indicated the inadequacy of current ventilation strategies to maintain optimal air quality. This study proposes the implementation of air filtration and purification systems and the refurbishment of natural ventilation systems as effective measures to improve IAQ. Additionally, alternative ventilation strategies, including occupancy reduction and the integration of supply and exhaust ventilation, were explored to address the challenges of inadequate ventilation. The findings reveal the urgent need for hospitals to adopt ventilation strategies that ensure the health and well-being of occupants, highlighting the importance of continuous IAQ monitoring, community engagement, and the integration of advanced ventilation technologies in healthcare settings. This comprehensive exploration offers valuable insights for improving ventilation in ICUs, contributing to creating healthier indoor environments in hospital settings, especially in regions facing unique environmental challenges.

Keywords: indoor air quality; air change rate; ventilation strategies; intensive care units; health symptoms; computational fluid dynamics; DRC

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1. Introduction

Hospitals and healthcare facilities face unique challenges in designing ventilation strategies, especially during influenza pandemics that increase airborne transmission risks. These challenges vary significantly between regions and specific health facilities, necessitating tailored approaches to ensure adequate indoor air quality (IAQ) management [1–3]. The indoor thermal environment (IEQ) is also essential to inpatients' health and can impact

hospital professionals' efficiency [4–6]. Indoor air with hazardous pollutant concentrations above allowed limits impacts inpatients health, hospital staff happiness, and job productivity [7,8]. Several studies reveal that poor IAQ can affect both patient recovery and staff productivity [6,9–11]. Several studies revealed that the common pollutants found in hospitals are carbon dioxide (CO_2), volatile organic compounds (VOCs), fine particulate matter ($PM_{2.5}$), and suspended particulate matter, which is often linked to insufficient ventilation [12–14]. Several studies reveal that the use of mechanical ventilation can increase ventilation rates and decrease CO_2 levels [12,15,16]. However, ventilating a building can reduce hazardous pollutants from various sources, including building materials, occupant respiration, and other indoor activities [17]. However, ventilation rates in hospital buildings vary according to specific activities. The WHO guidelines and ASHRAE Standard 170 [18] specify that ICUs should maintain six air changes per hour (ACH) to preserve air quality. In contrast, operating rooms require 12 to 20 ACH to ensure sterility and minimize infection risks [19]. In many ICUs, mechanical ventilation systems are typically employed to maintain adequate ACH rates; hospitals often rely on natural ventilation in tropical sub-Saharan regions like the DRC. This preference stems largely from energy deficiencies in these countries, making natural ventilation a more feasible option for maintaining air quality in healthcare settings.

In hospital environments, indoor climate (IC) is limited [20–23]. Studies have shown that at least one investigation into indoor climate has been conducted in hospitals in sub-Saharan tropical countries [11,21]. Various aspects relevant to hospital buildings, such as ventilation systems [24], location (urban, industrial, rural) [25], and exposure to road traffic [26], have been examined alongside their impact on health and well-being [27]. Studies conducted in Lubumbashi, DRC, and Ndola town, Zambia, have highlighted significant pollution from mining activities, leading to the contamination of ambient air with fine particulate matter and posing severe health risks to the local population, especially children under 15 years old residing near these mining areas, due to poor air quality [28–31]. A recent study has highlighted a significant gap in research regarding IAQ within hospitals that use natural ventilation systems, especially those near mining industries in the DRC [11]. Considering the potential health implications for hospital professionals working in such environments, this oversight is critical. The proposed study focuses specifically on the indoor climate and the health symptoms experienced by healthcare professionals in these hospitals. Moreover, we identify effective strategies for mitigating indoor pollution.

2. Materials and Methods

2.1. Case Study Building

This study examines the intensive care units (ICUs) at two significant public hospitals in the southern cities of Lubumbashi and Kipushi in the Democratic Republic of Congo. The first facility, Jason Sendwe Hospital (JSH), established in 1925, is the largest healthcare facility in the Katanga province, with 1200 beds. This facility has a specialized ICU designed to accommodate 47 patients. This ICU is supported by a dedicated team of approximately 15 healthcare professionals who ensure comprehensive care around the clock. The General Carrier de Mine Hospital (GCMH) in Kipushi, dating back to 1922, addresses the health needs of a diverse populace that blends urban and rural characteristics. This hospital has a smaller capacity, with 460 beds, including an ICU designed to serve 37 patients. A notable aspect of both ICUs is their reliance on natural ventilation, a common feature in many hospitals across the DRC, where mechanical ventilation systems are not prevalent. In these hospitals, windows serve as the primary means of air circulation. However, the location of these hospitals in industrial areas poses unique challenges. Due to the high levels of pollution typically found in regions close to mining operations, the opening of windows is heavily restricted to prevent the ingress of polluted air, which could compromise the health of patients and staff. Additionally, as depicted in Figure 1, each ICU has manual, single-sided windows spanning the unit length. These windows are designed to open on

one side, which cannot promote ventilation or enhance air quality within the units despite the external pollution constraints.



Figure 1. Outdoor and indoor views of JSH (**a-1**,**a-2**);views of GCMH (**b-1**,**b-2**).

2.2. Data Acquisition

Field measurements were carried out uninterruptedly for five weeks in a naturally ventilated ICU during rainy and dry seasons, where the rainy season occurred in January and the dry season in July 2023. The TROTEC PC200 particle counter was used to measure the $PM_{2.5}$ concentrations. In contrast, the IEQ multi-probe device was used to monitor indoor climate parameters, including temperature, relative humidity, CO_2 levels, and the VOCs, following Bosch Measurement of Environmental Data Sheet 680 [32], presented in Table 1; the IEQ multi-probe device, connected via a USB stick to a computer, enabled real-time data acquisition and visualization, facilitating direct analysis [33]. The instruments were placed 2 m from the windows and doors and 3 m away from patient beds, situated 1.2 m above the floor to minimize disturbances from human activity and maximize relevance to the breathing zone of patients. However, both devices were calibrated, and Table 2 shows the details of the calibration of the devices. Moreover, the continuous data logged from the devices were rigorously evaluated and categorized according to the EN 16798-1 standard [34], which sets the standards for temperature, humidity, and air quality within the hospital.

Table 1. The VOC range.

IAQ Index Range	Air Quality Level	EN 16798-1 Approximate IEQ Category
0–50	Good	IEQ I (High Quality)
51–100	Average	IEQ II (Moderate Quality)
101–150	Little Bad	IEQ III (Moderate to Low Quality)
151–200	Bad	IEQ III (Moderate to Low Quality)
201–300	Worse	IEQ IV (Low Quality)
301–500	Very Bad	Below IEQ IV (Poor Quality)

Table 2. Monitoring equipment parameters.

Equipment	Calibration	Resolution and Settings	Device Range
IEQ multiprobe	Coverage factor (2), Probability (95%), T (±0.2 °C), CO_2 (±35 ppm), RH (±1%)	Probe, Sampling interval (5 s), Data logging via USB connection to a computer	CO_2 (ppm), Operative temperature (°C), RH, Pa, VOCs, Illuminance
Trotec PC220		1 μg/m^3	$PM_{2.5}$/PM_{10}, 0 to 2000 μg/m^3

2.2.1. Survey Questionnaires

The online questionnaire, developed using the "encuestafacil" platform and adhering to the ISO 7730:2005 Standard [35], was designed to assess the impact of IEQ parameters on health within healthcare settings. The questionnaire was in French and English, and the survey targets hospital staff work in the investigated ICU to establish a more explicit link between the time spent in the hospital and health outcomes. The questions addressed hospital professional health issues about the SBS syndromes and when the symptoms are most frequent. The questions included in this survey are the following: Do you notice symptoms during your work time? Is there a specific place at home or in the hospital where your symptoms worsen? This approach aims to understand correlations with common building-related syndromes, such as headaches. A copy of the complete survey is available in Supplementary Material.

2.2.2. Air Change Rate

Optimizing airflow in crowded classrooms is vital for reducing airborne contaminants. Windows and doors, such as fully opening windows, lower air movement and increase CO_2 and airborne concentrations. In this study, the average CO_2 concentrations in the ICUs in JSH and GCMH were a basis for estimating the ACH. Using CO_2 emission rates outlined in ASTM D6245 [36], where 0.0052 L/s for adults adjusted for typical age groups and an activity level of 1.2 metabolic equivalents (METs) [37], airflow rates (in L/s) were computed based on the ACH. However, the occupants in JSH comprised 47 patients, whereas the GCMH housed 31 patients in the ICU. However, the environments, airflow rate per occupant (Q), total fresh airflow rate (Qt), and air exchange rate (λ_V) were determined using the following formula:

$$Q = \frac{N \times G}{Ci - Co} \quad (1)$$

where

Q is the ventilation rate required;
N is the number of occupants;
G is the CO_2 generation rate per occupant;
Ci is the indoor CO_2 concentration (in ppm);
Co is the outdoor CO_2 concentration (in ppm).

Equation (2) illustrates the formula used to estimate the air exchange rate, λ_V:

$$\lambda_V = \frac{Q}{V} \quad (2)$$

where:

Q = Airflow rate per occupant (in m^3/h);
V = room volume (in m^3).

2.3. CFD Analysis

Computational fluid dynamics (CFD) was employed to analyze air movement and distribution within the ICU, enhancing the empirical data. The simulation, conducted by using ANSYS, focused on understanding airflow patterns and air circulation. CFD is a valuable tool for addressing complex challenges in indoor airflow, providing comprehensive insights into air and temperature distribution within buildings. This analysis is crucial for optimizing air quality and ensuring effective air management in critical environments like ICUs.

3. Results

3.1. Participation, Characteristics

The total number of questionnaires sent in was 215. The response rate from both hospitals, JSH and GCMH, was between 89% and 79%, respectively. The breakdown of the total number of responses received by gender is as follows: 37% of the hospital professionals were men, while 63% were women. The average age of the people who answered was 43 (the range was 25–54), and up to 87% were nurses. Based on their style or habits, 7% indicated they were smokers.

3.2. Survey Responses

Figure 2 shows the frequency of SBS symptoms among hospital staff during the rainy season, where 63% of hospital professional workers reported experiencing at least one health issue. In contrast, the most often reported health complaints were headache (56%), dry eyes (86%), sneezing (55%), and fatigue (88%) during the rainy season in the GCMH, while in the JSH, headache (56%), dry eyes (78%), sneezing (5%), and fatigue (82%) were reported. Figure 3 shows the health issues in the dry season; in GCMH and JSH, headache, dry eyes, sneezing, and fatigue made up 60%, 87%, 65%, and 87% of complaints. The least frequent complaints were related to heart symptoms such as irregular heartbeats (32%), respiratory issues (27%), and rash or irritated skin (63%), which were associated with at least one SBS symptom. However, the occupants' responses highlight the indoor air problems in hospital buildings, including stiffness, poor IAQ, and unpleasant smells, compromising health and comfort by promoting pollutant accumulation and microbial growth, exacerbating respiratory and allergic conditions, and diminishing overall environment quality.

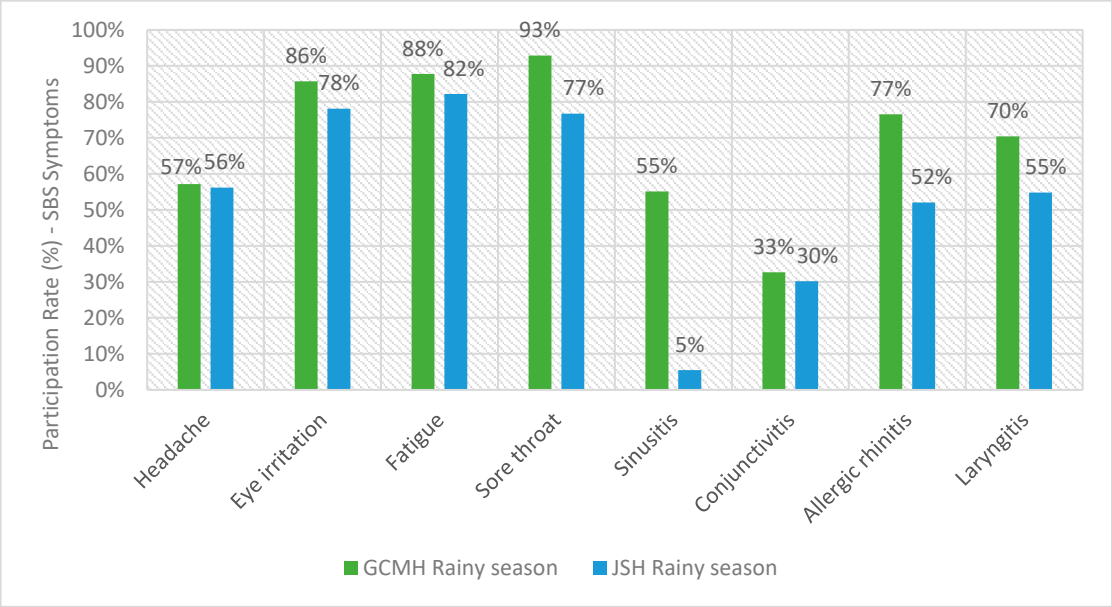


Figure 2. Frequency of health symptoms in hospital professionals during the rainy season.

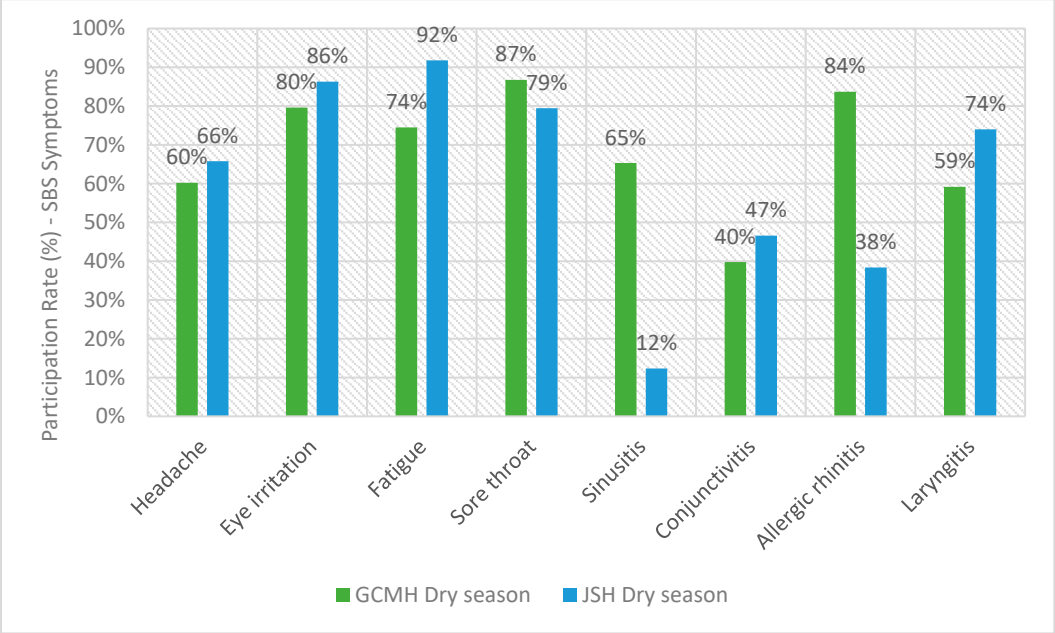


Figure 3. Frequency of health symptoms in hospital professionals during the dry season.

3.3. Physical Measurement Results

The objective results detail IC parameters over two seasons in the ICUs of GCMH and JSH. These findings, which include the mean temperature, humidity, and other variables during rainy and dry periods, are succinctly summarized in Table 3. This table shows each parameter's average values and variations, providing a clear overview of how seasonal changes impact the ICU environments.

Table 3. Seasonal IEQ. Data collected from GCMH and JSH.

GCM					JSH					
T (°C)	**RH (%)**	**CO_2 (ppm)**	**VOC Index**	**$PM_{2.5}$ µg/m^3**	**T (°C)**	**RH (%)**	**CO_2 (ppm)**	**VOC Index**	**$PM_{2.5}$ µg/m^3**	**Season**
28.3	53.2	1821	219	183	27.4	59.6	1993	215	143	Rainy
28.0	47.6	1733	208	183	26.8	58.8	1655	219	142	Rainy
28.4	50.8	1732	214	186	27.2	65.7	1767	202	149	Rainy
28.7	59.2	1880	232	186	27.3	61.0	1440	213	148	Rainy
27.7	46.1	1738	205	223	24.9	55.9	1437	228	141	Rainy
18.9	60.5	3173	162	243	20.9	53.5	2569	147	192	Dry
18.7	63.6	3105	168	241	20.5	52.9	2543	146	228	Dry
18.8	62.4	2920	166	213	20.7	54.3	2733	149	201	Dry
19.0	59.9	2614	161	240	21.3	52.5	2687	145	191	Dry
19.0	60.4	2456	162	284	19.8	51.2	2629	143	164	Dry

Table 3 shows the IC parameters for ICUs in two public hospitals. However, in the JSH, the temperature (T) ranges between 24.9 °C and 27.4 °C with an RH from 55.9% to 59.7% during the rainy months. In contrast, in the dry months, the T levels were from 19.8 °C to 20.9 °C with an RH of 51.2 to 53.5%. On the other hand, at the GCMH, the T varies from 27.7 °C to 28.3 °C with an RH from 46.1% to 53.2% in the rainy months and from 19.0 °C to 18.9 °C with an RH between 60.4% and 60.5% in the dry months. According to the CO_2, the peak CO_2 concentrations reach 1993 ppm during the rainy months and 2733 ppm during the dry months at the JSH, while in the GCMH, the peaks reach 1821 ppm in the rainy months and 3173 ppm in the dry months, which exceeded the recommended maximum of 1000 ppm the levels recommended by WHO and ASHRAE [38]. Additionally, Table 2

shows the $PM_{2.5}$ concentration within the ICUs, where the recorded $PM_{2.5}$ in JSHs varied between 141 and 143 $\mu g/m^3$ in the rainy and 164 and 192 $\mu g/m^3$ in the dry season. In the GCMH, the $PM_{2.5}$ levels are higher, ranging from 183 to 223 $\mu g/m^3$ in the rainy seasons and 243 to 284 $\mu g/m^3$ in the dry seasons, and these concentrations of PM exceed the level required within a building within 24 h according to the WHO [38].

Figure 4a-1,b-1 shows the mean and SD values of CO_2 concentrations in the ICU in the JSH and GCMH. The mean CO_2 concentrations at the JSH during the rainy season range from 1437 ppm to 1993 ppm, meaning they fall into Category III and IV zones, while in the dry season, they range from 2569 ppm to 2733 ppm, placing them in Category IV and the discomfort zone. At GCMH, CO_2 levels during the rainy season vary from 1738 ppm to 1821 ppm, classified under Category IV. In the dry season, they range from 2456 ppm to 3173 ppm, categorized as Category IV and the discomfort zone according to the EN16798-1 standard. These variations are attributed to patients being crowded in the ICU and inadequate ventilation in the ICU.

Figure 4b-1,b-2 shows the IAQ index scale for VOC concentrations as defined by the EN 16798-1 standard. The VOC levels at the JSH are categorized as Purple (Worse) in the rainy season and Pink (Bad) in the dry season, while in the GCMH, the VOC levels are Purple (Worse) during the rainy season and Pink (bad) during the dry season. This seasonal variation in VOC levels could be influenced by the increased use of disinfectants and cleaning agents during the rainy season, a practice typically intensified by the need to maintain cleanliness and sterility in response to higher flu rates and other infections. Additionally, specific maintenance activities or the use of solvents in medical procedures might introduce new sources of VOCs that vary with healthcare practices throughout the year. These high levels of VOCs can cause health issues, such as irritation and headaches, for occupants in the ICU. This finding aligns with a study conducted in a French hospital, which reported high VOC concentrations [39]. However, the findings show the necessity for adaptive ventilation strategies to effectively mitigate these pollutants, ensuring a healthier environment for ICU occupants regardless of seasonal changes.

Table 4 shows the seasonal change impact on IC and highlights those high seasonal variations in IC parameters, which strongly influence IAQ and have potential health implications. At the JSH, temperature (p-value: 0.000271), CO_2 levels (p-value: 0.000122), and VOC (p-value: 0.000062) exhibit highly seasonal differences. Relative humidity (p-value: 0.014127) and $PM_{2.5}$ levels (p-value: 0.031402) also demonstrate notable variability. Similarly, at the GCMH, there are pronounced seasonal fluctuations, especially in temperature (p-value: <0.00001), with high changes in CO_2 levels (p-value: 0.000066) and the VOC Index (p-value: 0.000006), as well as relative humidity (p-value: 0.0033) and $PM_{2.5}$ (p-value: 0.0056). The findings emphasize the substantial impact of seasonal changes on IAQ, which could affect the hospital's professional health issues.

Table 4. Seasonal variation in IC parameters and IAQ at JSH and GCMH.

	JSH		**GCMH**	
Parameter	**F-Statistic**	***p*-Value**	**F-Statistic**	***p*-Value**
T	37.856	0.000271	2637.95	<0.00001
RH	8.466	0.014127	17.05	0.0033
CO_2	50.088	0.000122	57.08	0.000066
VOC	63.410	0.000062	110.55	0.000006
$PM_{2.5}$	5.946	0.031402	14.09	0.0056

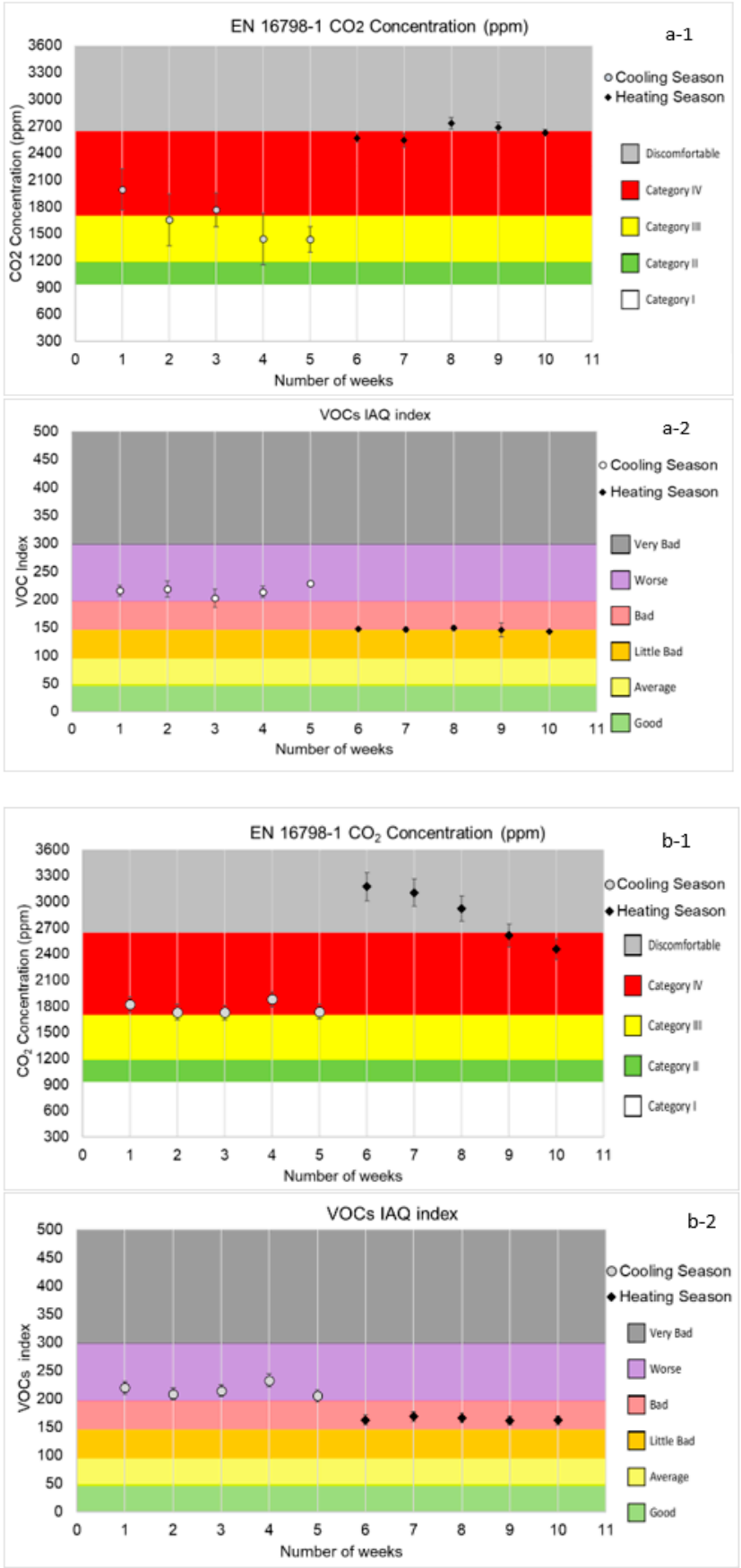


Figure 4. Mean and standard deviation of CO_2 and VOCs. (**a-1**,**a-2**) JSH; (**b-1**,**b-2**) GCMH.

Air Change Rate

Estimating air changes per hour (ACH) in ICUs is crucial for maintaining optimal air quality and is determined using average CO_2 concentrations. Specifically, concentrations were recorded at 2733 ppm (4920.1 mg/m^3) in the JSH and at 3173 ppm (5711.4 mg/m^3) in the GCMH. These elevated CO_2 levels indicate ventilation efficiency and are used to calculate the ACH rates in the respective ICU studies. Additionally, Table 2 presents the primary data on admitted patients and workers' fresh air flow rates for each ICU, including detailed air exchange rates (λV).

Table 5 shows the details of ACH and fresh air flow requirements in the ICUs, highlighting the importance of adequate ventilation for the health and safety of patients. This analysis compared the two ICUs with different volumes of 750 m^3 at the JSH and 500 m^3 at the GCMH. The findings indicate that while CO_2 levels often exceeded the advisable threshold of 800 ppm in these ICUs when patients were present, they remained below the Occupational Safety and Health Administration (OSHA) exposure limit of 5000 ppm. This suggests that a controlled environment still poses potential risks due to high CO_2 levels. To maintain CO_2 concentrations at the recommended level of 1000 ppm (1800 mg/m^3), the JSH would require a ventilation rate of 930 m^3/h with an ACH rate of 1.24 at the same time; the GCMH would require the same ventilation rate but a higher ACH of 1.86. Both the measured and calculated CO_2 values were higher than the desirable levels. However, the inadequate ACH in ICUs reveals that the ventilation systems were inoperative, likely contributing to the studied health symptoms. The EN 16798-1 guidelines recommend maintaining an airflow rate of 36 m^3/h per person for Category I environments and 25 m^3/h for Category II ones. Additionally, the study references ASHRAE 62.1-2016 and EN 15251:2007, which provide a flexible range of 9.0 to 36 m^3/h per person for adjusting ventilation rates to suit specific IAQ needs.

Table 5. Total airflow rate and air change.

Hospital	No. of Beds	Volume (m^3)	Ventilation Rate (m^3/h)	Air Change (ACH.)
JSH	47	750	239.14	0.32
GCMH	31	500	201.23	0.40

3.4. CFD Simulations for JSH and GCMH ICU

3.4.1. Characteristics of the Used Model

The model, designated as the JSH and measuring 25 × 8 × 3.5 m, incorporates three windows, each sized at 1.5 × 1.5 m, as illustrated in Figure 5a-1,a-2. This model is a prime example of integrating mechanical ventilation, boasting four inlets and outlets. Transitioning to the GCMH model showcased in Figure 5b-1, with dimensions of 20 × 7.10 × 3.5 m, it features two windows. Figure 5b-2 further expands this implementation, now including three inlets and outlets, offering a comprehensive overview of the ventilation system's evolution.

3.4.2. CFD Validation

The CFD simulations were meticulously validated across various geometric enclosures to ensure accuracy and reliability. The validation compared simulation results from three distinct mesh densities, 439,310 cells at 0.035 m (2× finest mesh), 156,619 cells at 0.07 m (baseline mesh), and 62,259 cells at 0.14 m (1/2× coarsest mesh), with experimental data and theoretical predictions. The performance metrics, including flow velocity profiles and pressure gradients, were analyzed. A crucial grid independence test confirmed that the simulation outcomes stabilized between the baseline and finest meshes, indicating the results' independence from mesh size beyond the baseline configuration. Analyses of critical simulation parameters, such as inlet velocity and turbulence model constants, ensured robustness against input variations. Ultimately, the validation process affirmed that

our CFD model effectively captures essential fluid dynamics within complex enclosures, delivering reliable results consistent with expected physical behaviors.

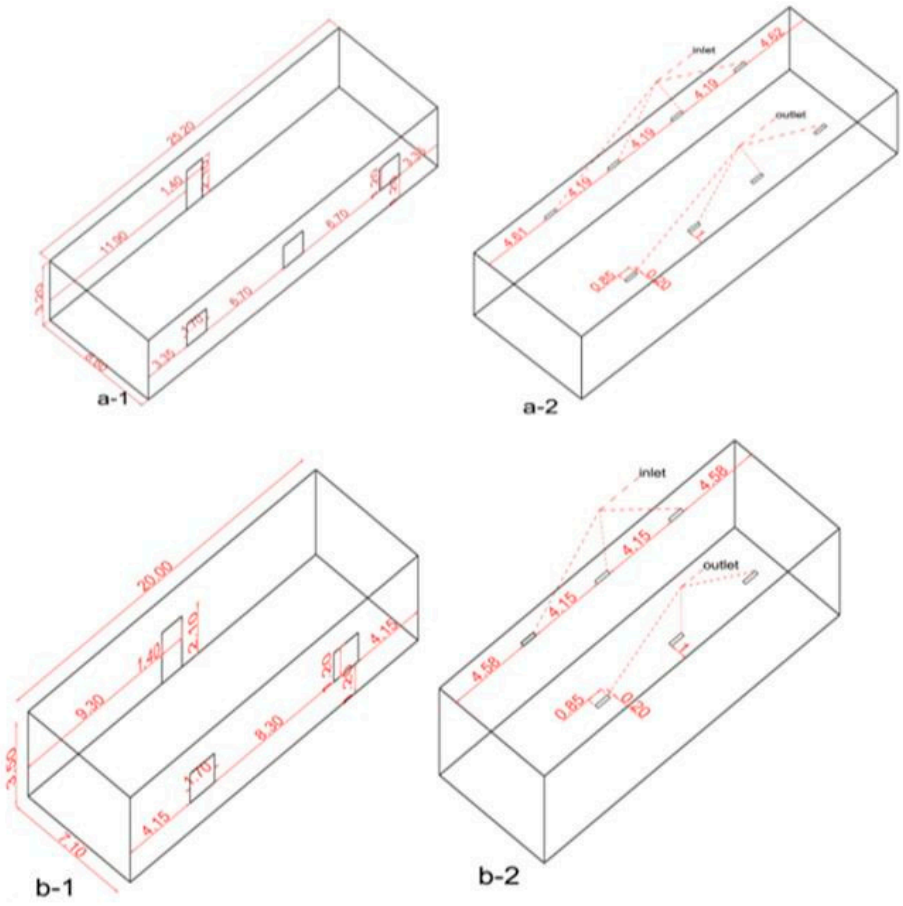


Figure 5. Characteristics of the used models for the JSH and GCMH ICUs.

3.5. Air Movement within the ICUs

In Figure 6a-1,b-1, the airflow patterns demonstrate the air movement in patient wards, with the single-sided natural and mechanical ventilation systems used in the ICU. Single-sided ventilation accumulates airborne contaminants, increasing the risk of infections among patients and healthcare workers, highlighting its limitations in critical care environments. In contrast, Figure 6a-2,b-2 shows that mechanical ventilation systems improve airflow patterns. Moreover, the placement of air inlets and outlets, as seen in Figure 5, ensures efficient air distribution and improved IAQ. This enhanced air movement reduces the presence of viruses and pathogens, making displacement ventilation the most effective strategy for maintaining a healthy ICU environment, enhancing patient safety, and reducing infection risks. The mechanical system effectively disperses fresh air throughout space, continuously diluting and removing contaminants. This can improve patient comfort and reduce the potential for pathogen transmission, thereby supporting better health outcomes in the ICU.

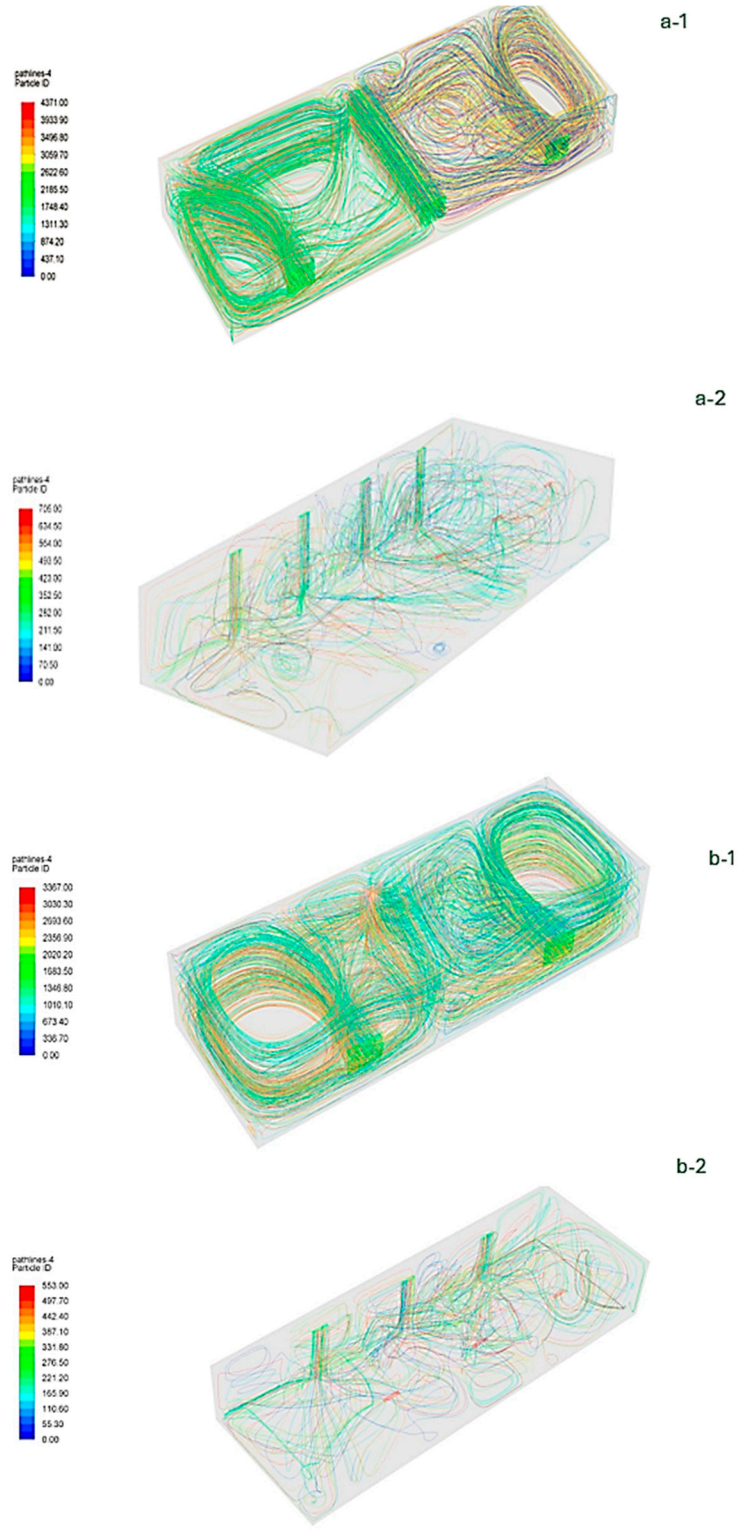


Figure 6. Different air inlets and outlets within the ICUs. The diagrams also display the air streamlines, which help visualize the airflow pattern throughout the unit.

4. Discussion

Table 3 presents the T and RH conditions in the ICU of the GCMH and JSH, compared against the EN 16798-1 standards for optimal IC conditions in healthcare settings. In the ICU in the GCMH, recorded temperatures occasionally fell below the comfort zone, reaching lows of 18.8 °C, potentially causing patient and hospital professional discomfort, indicating a broader issue within healthcare environments. This is similar to what was

reported in a study by Smith et al., which revealed that poor hospital temperatures could impact patient recovery and infection rates [34]. Moreover, the RH at the GCMH was within the recommended EN 16798-1 range during the rainy season but slightly exceeded the recommended range during the dry season. Meanwhile, in the JSH, the RH consistently exceeded 60%, per EN 16798-1 guidelines in the rainy season. The exceedance of the RH can increase the risk of infection spreading in ICU settings, where high humidity promotes the growth of bacteria and fungi, making patients more susceptible to hospital-acquired infections. In another study by Noti et al. [40], maintaining the RH at 40–60% decreased the infectiousness of the influenza A virus in the air, suggesting that controlling humidity could reduce the risk of respiratory virus transmission in hospitals. A similar study revealed that high RH (above 60%) promotes the growth of mold, fungi, dust mites, and pathogen spread [40]. According to the variation in the T and RH, it is essential to use HVAC systems in hospitals to maintain good IAQ conditions, and these ensuring conditions are crucial for promoting superior indoor air quality and safeguarding patient well-being in ICU settings [38], as recommended in the EN 16798-1 standard.

Figure 4a-1,a-2 shows that the average CO_2 concentrations in the JSH and GCMH (2733 and 3173 ppm) were higher than those in French hospitals (436–530 ppm) [41]. The CO_2 levels recorded in the ICU in the JSH and GCMH peaked at over 2500 ppm during the dry season, revealing that the CO_2 concentration was over the 1000 ppm threshold set by the EN 13779 [42] and ASHRAE Standard 62.1-2006. Similar studies by Lu et al. [43] in Beijing and Korsavi et al. [44] in the UK have reported that maximum CO_2 levels could reach up to 3000 ppm under specific conditions. A study in a Nigeria ICU revealed that high CO_2 concentrations were found in a crowded ward using natural ventilation [23]. As the ICU is a critical place, high CO_2 concentrations can impair cognitive function, increase fatigue, and exacerbate respiratory issues, which are vital health concerns in an ICU setting. The high CO_2 in the JSH and GCMH was due to the crowding of patients and inadequate ventilation, as windows and doors were closed almost all the time due to outdoor noise from the mining industries, as well as the weather during the dry season. This finding aligned with that of a study by Nyembwe et al. conducted in an ICU, which found high CO_2 concentrations in a crowded patient ward where windows were almost always closed in the dry season due to the cold outside [45].

Figure 4b-1,b-2 shows that the VOC index in both GCMH and JSH was much higher in the rainy and dry seasons compared with that in the studies conducted in French hospitals, where VOCs were identified as the predominant organic compounds [39]. In the GCMH, the VOC index reached 232.1, while the JSH hospital had a slightly lower index of 228, corresponding to 'Bad' according to the indoor air index recommended by the EN 16798-1 standard [34]. These levels are comparable to those reported in French hospitals. VOC concentrations ranged between 245.7 and 495.0 $\mu g/m^3$ and 13.6 and 20.3 $\mu g/m^3$ [41]. However, high VOC concentrations were mainly due to the disinfection and cleaning carried out in the ICU, where windows were nearly always closed due to weather and noise pollution from nearby industries. At the same time, in healthcare settings, the primary sources of VOC emissions often stem from the cleaning products used, highlighting the necessity of carefully selecting them to minimize their impact on indoor air quality [46].

Nevertheless, the high levels of VOCs in these ICUs can adversely affect the health of both patients and staff, potentially leading to symptoms such as irritation and dizziness, and a deterioration in patient conditions. Poor air quality from VOCs also increases the risk of infections and impedes recovery. According to a study by Nyembwe et al., many hospital workers reported illnesses linked to high VOC concentrations [45].

Table 3 shows that the $PM_{2.5}$ concentrations in the GCMH's ICU varied between 183.1 and 284.5 $\mu g/m^3$, while in the JSH's ICU, the levels were between 141 and 228 $\mu g/m^3$, which can cause health issues in occupants, as indicated via a subjective response from a hospital professional. Compared with those of another study, the findings in this study suggest concentrations higher than those typically observed in office environments (9–26 $\mu g/m^3$), other hospital settings (1.6 $\mu g/m^3$), and residential areas (16 $\mu g/m^3$) [41,47]. A similar

study reveals that higher PM levels in ICUs are influenced by factors such as the efficiency of ventilation systems and human activities, including movement and equipment operation, which can resuspend particles [48]. The external sources of pollution, particularly from vehicle emissions, also contribute to high indoor PM levels. $PM_{2.5}$ is particularly hazardous in settings like the DRC, where mining and industrial activities exacerbate health risks due to dust traffic, minerals, and bushfires during the dry season, which may cause health problems for hospital workers and cause patients to become highly vulnerable.

Moreover, a study by Nyembwe et al. on the correlation between outdoor and indoor PM in a hospital located in a mining industry zone revealed that high PM concentrations in hospitals were due to air infiltration from outdoor pollution [45]. A study revealed that higher $PM_{2.5}$ levels were recorded in summertime than in winter [16]. The influence of air conditioning use, window opening frequency, nearby emission sources, and ventilation performance may explain these seasonal differences [49]. The WHO has recently revised its air quality guidelines, lowering the safe exposure limit from $PM_{2.5}$ to PM $_5$ $\mu g/m^3$, putting the levels observed in this study above the new threshold but below the previous 10 $\mu g/m^3$ limit. Notably, sterilization processes in dental offices have led to records of summer $PM_{2.5}$ levels more than six times the median value, higher than the WHO 24 h guideline of 15 $\mu g/m^3$ [38]. A similar study in a Nigerian hospital ICU revealed that the $PM_{2.5}$ concentrations ranged from 95 to 178 $\mu g/m^3$, highlighting variability within hospital environments [22].

Table 5 illustrates that the ACH in the ICUs of the JSH and GCMH, which are 0.33 and 0.49, respectively, fall significantly below the recommended standards, typically requiring a minimum of six ACH for ICUs [19,50]. The standard also recommends an ACH of 12 for rooms taking airborne precautions and suggests a ventilation rate of 80 L per second per patient for a standard room size of $4 \times 2 \times 3$ m^3. Using a CFD model, Figure 6 demonstrates that the natural ventilation systems currently employed in these ICUs are inadequate. This inadequacy in air circulation may lead to poor IAQ, whereas implementing mechanical ventilation systems has shown a marked improvement in IAQ within the investigated rooms. That relates to research by Qian et al. conducted in Hong Kong, which documents that ACH levels between 18 and 24 can significantly reduce the risks of airborne infections, underscoring the critical need for robust ventilation strategies [51].

Similarly, research by Brundage et al. highlights how external environmental factors significantly impact indoor air quality in healthcare facilities [52]. The issues observed at the JSH and GCMH may mirror broader regional challenges, as indicated by studies focusing on healthcare infrastructure in similarly resource-limited settings [53]. To address these deficiencies, improving the ACH in these facilities is imperative. As suggested by the ASHRAE guidelines, upgrading ventilation systems and ensuring regular maintenance are vital strategies. The WHO guidelines on hospital ventilation systems also provide valuable insights into effective practices for enhancing air quality in healthcare environments [54].

4.1. Alternative Ventilation Strategies

Insufficient ventilation coupled with elevated CO_2, VOC, and PM levels has been identified as a significant contributor to health symptoms, prompting a critical need for improvements in IAQ. Traditional interventions involving increasing supply airflow were necessary due to potential problems, including a likely reduction in indoor temperature, the start of a drought, and an increase in overall energy consumption. The first alternative strategy centers on implementing air filtration and purification systems within the confines of the ICU. This approach aims to reduce $PM_{2.5}$ and VOC levels, thereby alleviating respiratory symptoms experienced by occupants. By employing advanced air cleaning technologies, this strategy seeks to create a healthier indoor environment, mainly targeting a reduction in particles and volatile compounds contributing to respiratory issues. This approach provides a targeted solution without compromising indoor temperature, thus addressing the limitations associated with increased supply airflow. The second alternative strategy involves a comprehensive refurbishment of the natural ventilation system,

encompassing supply and exhaust mechanisms. However, this strategy is not without its challenges. Moreover, it is characterized by its high costs, labor-intensive nature, and inherent risks associated with aging structures and materials. An alternative approach was developed to overcome this issue, a non-destructive method that preserves natural ventilation while minimizing the need for an extensive workforce. This novel strategy seeks to balance preserving existing structures and enhancing ventilation efficiency.

Enhancing supply and exhaust ventilation systems could lead to higher ventilation rates, consequently reducing CO_2 concentrations and improving symptoms experienced by occupants. However, this transition is not without complexities. Replacing natural ventilation with supply and exhaust mechanisms comes at a considerable cost, demanding a high level of design, implementation, and ongoing maintenance expertise. Challenges such as the risk of impurities entering through leaks and difficulties achieving proper ventilation balance necessitate a meticulously designed system, including constant pressure monitoring and adjustment. Additionally, installing new ducts and devices may slightly diminish the usable area of rooms. Despite these challenges, placing exhaust and air supply units in the attic simplifies logistical concerns. An in-depth analysis of health symptom sources highlights that the primary challenge lies in elevated CO_2 concentrations resulting from inadequate ventilation relative to the number of occupants. A proposed alternative solution involves a substantial reduction in the number of occupants, supported by calculations that estimate that maintaining a CO_2 concentration below 1350 ppm would be feasible with only 20 occupants compared to the initial 47. This approach offers a cost-effective means of addressing ventilation issues, with lower implementation, usage, and maintenance costs than those of the supply and exhaust ventilation strategy. However, it is not without its problems; reducing the number of building users may not be cost-effective at the authority level, as the rooms would not be used efficiently, and many patients would need to be relocated to other buildings. The limitation to adequately implementing the ventilation strategies proposed, apart from the policy gaps and poor hospital infrastructure in many hospitals of the Sub-Saharan African (SSA) region, including the DRC, is electric power availability to sustain HVAC systems and IC equipment in the hospital.

The characteristics of mechanical ventilation, such as airflow adjustment and thermal control, are inferred from typical features associated with this strategy. Information about the natural ventilation strategy is mainly derived from condition assessment reports and consultant analyses. Both strategies' risks, potential, and effects were conclusively determined from a thorough literature review and condition assessment reports. As both strategies have the potential to create a healthy indoor environment, the final decision rests on the priorities of decision-makers, weighing up factors such as cost-effectiveness, environmental impact, and overall effectiveness in improving IAQ. However, Table 6 presents a strategy to enhance air quality in ICUs, combining advanced ventilation, air purification, natural airflow enhancement, continuous monitoring, education, and maintenance to create a healthier environment efficiently.

4.2. Limitations

The current research has a limited scope and is limited in terms of participant selection. This study was restricted to two ICUs in hospitals in the DRC, which may not adequately represent other critical hospital areas, such as operating rooms or isolation rooms. Furthermore, the focus on hospital workers as subjects could mean that the research does not fully capture the experiences or impacts on other important groups, such as patients and visitors. This selective inclusion may limit the generalizability of the findings across different demographics and hospital settings. It may not fully represent varied responses to IAQ experienced by non-staff members. Future studies should perform pre- and post-implementation audits on ventilation enhancements in healthcare facilities to assess IEQ improvements, energy efficiency, and occupant health impacts. Other future research endeavors should consider complementing self-reported data with objective measures or additional validation methods to enhance the robustness and reliability of findings. This

holistic approach will help determine the overall benefits of improved ventilation systems on both environmental quality and occupant well-being.

Table 6. A comprehensive ventilation strategy for improved IAQ in overcrowded ICUs.

Component	Strategy Description	Implementation Details	Expected Outcome
Air Filtration and Purification	Integrate technologies to reduce $PM_{2.5}$ VOCs.	Use HEPA, activated carbon filters, and standalone purifiers.	Improved IAQ and reduced respiratory symptoms.
Natural Ventilation Enhancement	Improve the efficiency of natural airflow.	Optimize window designs for cross-ventilation.	Increased natural air exchange and improved air quality.
Mechanical Ventilation	Implement balanced supply and exhaust systems.	Install ductwork for air supply/exhaust; use energy recovery ventilators.	Lowered CO_2; enhanced IAQ control.
Occupancy Reduction	Limit ICU occupancy to reduce air pollutant generation.	Implement space management and scheduling protocols.	Decreased infection spread, CO_2, and PM.
IAQ Monitoring	Install systems for real-time air quality tracking.	Deploy IoT-enabled sensors for continuous data.	Early detection and mitigation of IAQ issues.

5. Conclusions

This study has explored IAQ and ventilation strategies within two critical care units in hospitals in the Southern DRC metropolitan area. Through a mixed-method approach that combined health questionnaires with continuous environmental monitoring and CFD analysis, we have gained insights into the correlation between environmental factors and occupant health in hospital settings, particularly in ICUs. This study's findings reveal variations in IC parameters between the rainy and dry seasons, with notable impacts on occupant health. The SBS symptoms among hospital staff underscore the critical need for improved ventilation strategies to mitigate adverse health effects. The study has highlighted the inadequacies of current natural ventilation, which is inadequate for ensuring optimal air quality, as evidenced by the high CO_2, VOCs, and PM levels, particularly during the dry season. The strategic implementation of air filtration and purification systems, alongside the refurbishment of natural ventilation systems, presents a promising approach to enhancing IAQ without compromising the hospital's architectural integrity or the well-being of its occupants.

Furthermore, the study's exploration of alternative ventilation strategies, including a reduction in occupancy levels and the integration of supply and exhaust ventilation, offers practical solutions to the challenges of inadequate ventilation. Hospitals can create a healthier indoor environment that safeguards the well-being of patients and staff by adopting a holistic approach that combines advanced ventilation technologies with strategic planning and community engagement. This study recommends a ventilation strategy and management of the IAQ and patient-overcrowded ICUs, considering the potential for enhancing air quality through mechanical ventilation. Future research should build on this foundation, exploring innovative ventilation technologies and their integration into existing healthcare facilities, assessing long-term health outcomes, and developing policy frameworks on IAQ in hospital design and renovation projects.

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