Evaluation of Indoor Air and Natural Ventilation Complexity in Hospital Wards in the Democratic Republic of Congo (DRC.)

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Abstract: This study critically evaluates indoor air quality (IAQ) and natural ventilation systems in Democratic Republic of Congo (DRC) hospital wards, which are crucial for patient and hospital staff health. Parameters such as temperature, humidity, particulate matter (PM), carbon dioxide (CO2), and volatile organic compounds (VOCs) are analyzed to understand IAQ complexity. The study, conducted in two hospitals near mining areas, assesses the IAQ parameters during the dry season and employs statistical analyses to define the correlations between indoor and outdoor climate conditions. Findings reveal higher CO2 concentrations, VOC indices, PM2.5, and PM10 levels surpassing WHO standards in University Clinics of Lubumbashi (UCL) and University Clinics of Mbuji-Mayi (UCMM) inpatient wards, particularly during specific activities like visiting hours. Evaluation of ventilation systems highlights insufficient air changes per hour (ACH) compared to recommended healthcare norms, underscoring the pressing need for improved ventilation strategies. However, the study acknowledges limitations arising from its focus on two selected wards, potentially limiting the representativeness of IAQ across diverse healthcare settings in the region. Nevertheless, the research emphasizes the critical significance of IAQ in healthcare environments, advocating for enhanced ventilation, improved air filtration, and robust health protocols to ensure the safety of patients and healthcare workers, particularly in resource-limited contexts like the DRC.

Keywords: Indoor Air Quality, Natural Ventilation, Hospital Wards, Particulate Matter, Carbon Dioxide, Temperature, Humidity.

Introduction

Indoor air quality in healthcare facilities is increasingly recognized due to its impact on the health of immune-compromised patients and the staff who spend extended periods in these environments [1]. Indoor Air Quality (IAQ) is a dynamic and multifaceted issue in such settings. It includes a range of physical, chemical, and biological pollutants that originate both within and outside the facility, influencing the well-being of occupants. Common indoor contaminants in hospitals include a mix of particulate and gaseous emissions such as respirable suspended particulates, carbon dioxide (CO_2), volatile organic compounds (VOCs), carbon monoxide (CO), formaldehyde, nitrous oxide, glutaraldehyde, allergens, and bioaerosols [2]. The proliferation of these pollutants, especially bioaerosols, is significantly influenced by environmental factors like relative humidity and temperature, particularly in hot and humid climates. The sources of these emissions vary, including everyday cleaning activities, people's movement, medical procedures, and the building's ventilation system [3], [4]. These air pollutants are caused by meteorological conditions, human activity, building equipment, seasonal variations, and the mode and maintenance of ventilation systems [5]. Among these pollutants, particulate matter (PM), particularly fine ($PM_{2.5}$) and ultra-fine ($PM_{0.1}$) particles, pose significant health risks. Besides the risk associated with chemical composition, these particles can carry infectious biological contaminants and other pollutants, contributing to considerable health issues like heart disease, respiratory conditions, and lung cancer, thereby impacting global mortality rates [6]. In this context, PM levels are crucial not only for direct health reasons but also because high $PM_{2.5}$ levels can indicate the presence of other hazardous pollutants; therefore, ventilation is critical in mitigating these risks by controlling and removing contaminants [7]. Various studies have explored the role of different ventilation types in managing IAQ in healthcare settings [8], with CO_2 concentration often used as an indicator of ventilation adequacy [9].

Another essential measure is the PM's indoor-outdoor ratio (I/O), which offers insights into the relationship between indoor and outdoor air quality [10]. In the DRC, most hospital facilities are located in urban areas with high air pollution levels [11], [12]. The country has experienced significant health impacts on children and women due to air pollution from mining industries [13], [14]. However, data on IAQ in healthcare environments is scarce [11]. Evidence suggests that building design, management, temperature, humidity, and ventilation rate significantly influence particulate and gaseous emissions in healthcare facilities [4]. However, the critical need to assess indoor air quality in hospitals in the DRC, particularly near

mining areas, is vital. Mining activities can release a range of pollutants that severely compromise air quality. In hospital environments, where patients' immune systems are often compromised, exposure to these pollutants can exacerbate health issues, hinder recovery, and increase the risk of hospital-acquired infections.

Therefore, understanding and improving indoor air quality in these settings is a health imperative and a necessary step towards ensuring safer, more effective healthcare environments in regions impacted by mining activities.

Methods

The study was conducted in two hospitals in the DRC, each uniquely influenced by nearby mining activities and utilizing natural ventilation. The first, University Clinics of Lubumbashi (UCL), situated seven kilometers from Ruashi Mine, offers insights into air quality impacts in a commercial zone. The second, University Clinics of Mbuji-Mayi (UCMM) in Kasai, is close to a diamond mine and provides a contrast in a residential setting. This selection of hospitals near mines in differing environments (commercial and residential) allows for a comprehensive analysis of indoor air quality influenced by natural ventilation and mining activities. Hospital A, in the residential area, has a capacity of 122 beds, an operation theatre, a general ward, and an outpatient facility, handling an average of 110 patients daily and 682 monthly. Meanwhile, Hospital B, also in a residential setting, had a 92-bed capacity, with a daily patient arrival of 30 and an average of 800 monthly.

Figure 1 (a) illustrates the UCL façade and (b) the UCMM facade.

Objective measurement methods have been used to evaluate IAQ and estimate the Airflow and Air Change rates (ACH) in the selected hospitals. The indoor climate parameters include $PM_{2.5}$, PM_{10}, CO_2 levels VOCs, RH, and temperature, alongside assessing outdoor $PM_{2.5}$ and PM_{10} levels. The IAQ monitoring occurred in the dry season from June to July 2023 in each intensive care unit (ICU) in the selected Hospitals. IAQ parameters were assessed using a TROTEC PC200 Particle Counter to measure the $PM_{2.5}$ and $PM_{1.}$ It estimates PM data by converting particle counts to mass using built-in algorithms and standard particle properties assumptions. Moreover, the Multiprobe loggers were used to monitor operative temperature, RH, $CO_{2,}$ and VOC and sampling and sampling periods occurred from 8 a.m. to 5 p.m. for ten days, including weekdays and weekends: five days at UCL (Lubumbashi) and five days at UCMM (Mbuji-Mayi). Data was collected during visitor influx, cleaning time, doctor visitation, and peak times in the ICU. The monitoring instruments were positioned at a height of one meter and distanced at least 1.5 meters from doors and windows where the instrument did not interfere with activity in the ICU or medical apparatus. In contrast, outdoor monitoring was carried out 50 meters from the main hospital entrance.

Figure 2: (a) illustrates the UCL indoor and (b) the UCMM.

Statistical Analysis

ANOVA was used to analyze the standard deviation (SD). Moreover, the Pearson correlation analysis and linear regression analysis were used to determine the correlation between the indoor and outdoor indoor climate parameters in the studies of ICU hospitals.

Results

The results of this study demonstrated that UCL had a time average CO_2 concentration of 3870 ± 553 ppm, while the UCMM had a lower average of 2600 ± 51 ppm. With a reference value of 1000 ppm, suggested as a maximum for indoor environments by most international standards, these findings emphasize the significant role of ventilation systems and external factors in influencing indoor air quality in hospital environments. In particular, the UCL also showed consistently higher levels of both $PM_{2.5}$ and PM_{10} in inpatient wards, with recorded values from 183 to 186 µg/m3 for $PM_{2.5}$ and from 492 to 648 µg/m^3 for PM_{10}. This was notably higher than the results for UCMM, where $PM_{2.5}$ levels ranged from 113 to 135 µg/m^3 and PM_{10} levels from 277 to 439

Table 1. Mean and SD concentration of IAQ parameters in the selected wards.

		Indoor						Outdoor		
	Date	To (°C)	RH (%)	CO_2 (ppm)	VOC Index	$PM_{2.5}$ µg/m	PM_{10} µg/m	To (°C)	$PM_{2.5}$ µg/m	PM_{10} µg/m
UCL	1	22.8	55.8	3002	174	183	637	18.8	208	727
	2	22.1	54.3	2951	244	187	649	18.9	243	734
	3	21.6	60.3	2953	159	184	517	18.9	242	595
	4	21.1	50.4	2829	173	186	498	18.9	213	743
	5	20.8	46.6	2887	176	187	492	19	240	724
UCMM	1	20.9	66.3	2040	225	113	439	21.6	230	553
	2	20.7	58.7	1752	222	113	375	21.3	216	533
	3	20.8	65.7	1967	214	136	421	21	215	525
	4	21.0	67.0	2063	215	118	389	20.9	229	548
	5	21.0	56.1	1539	206	126	277	20.9	236	500

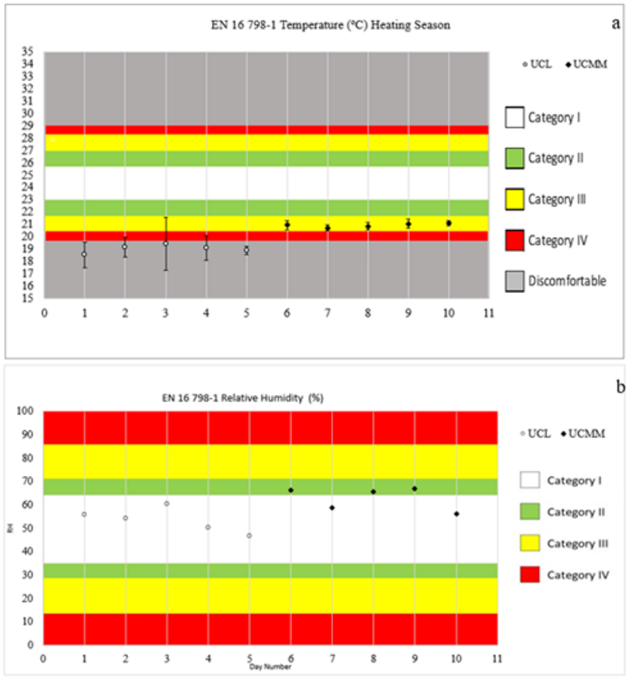

Figure 3: (a) presents the average of the operative temperature and (b) RH in CUL and CUMM.

µg/m^3 in the ICUs. However, the PM levels in both hospitals have surpassed the 24-hour PM standard set by WHO [15]. The effects of various activities taking place in these environments were also noticeable. In particular, the highest levels of $PM_{2.5}$ and PM_{10} were recorded during visiting hours in the wards, surpassing even those observed during medical rounds and cleaning duties. Focusing on UCL and UCMM, comparing indoor and outdoor $PM_{2.5}$ levels in hospital wards reveals significant disparities. UCL showed an average of 208 and 243 µg/m3 for $PM_{2.5}$ and PM_{10}, respectively, while for UCMM, the values ranged from 215 to 236 µg/m^3 and 499 to 553 µg/m^3. The contrast between the outdoor $PM_{2.5}$ levels in these two wards was highly pronounced.

Figure 3 shows the results of the average operative temperature values of the recorded time series, categorized according to EN 16798-1 requirement in each of the ICUs. Figure 3a ranks all measures considering the heating season requirements of EN 16798-1 while. ICUs were investigated during the heating seasons as per the HVAC use dry seasons. According to EN 16798-1, the UCL's operative temperature (To) ranges from 18°C to 21 °C. It corresponds to the discomfort categories, while in the UCMM, the To goes from 21°C in category III during the heating season for people of sedentary activity, being the limits of the four categories defined as represented in Figure 3. The average of the To values in the ICU can be verified; specifically, they were within categories IV and discomfort, indicative of uncomfortable thermal environments in the ICU. Using the heating season requirements, in the ICU in UCL, the measured mean Ta values were not in the discomfort zone; significantly, the ICU in UCL was found in the discomfort category at a mean To of 18.8°C. Using the heating season EN 16798-1 requirement in the UCMM to evaluate the mean To level in the ICU had inadequate thermal environments. The two hospitals were in the discomfort category.

Figure 3. b depicts the mean RH and Standard Deviation (SD) for all evaluated ICUs. Indoor RH levels play a crucial role in IAQ and thermal comfort, influencing the conditions conducive to the reduced infectivity of aerosolized viruses. The EN 16798-1 standards delineate specific RH in ICU, which ranges differently in the IUCL. The RH ranges from 45% to 60% for Category I and UCMM from 60% to 65% for Category II. This RH range links with suitable conditions for ICUs, as it helps maintain comfort levels and reduce viral transmission risks. Viruses become dormant at RH levels ranging from 40% to 60%. Airborne transmission, a significant mechanism of viral propagation, is highly influenced by RH, with an indoor RH of roughly 50% recommended to reduce transmission hazards.

Furthermore, determining the impact of temperature and relative humidity in SARS-CoV-2 transmission emphasizes the significance of effective indoor climate regulation. Conditions with more than 75% RH and temperatures over 20°C may exacerbate viral propagation, whereas continuous daily temperatures above 30°C with concomitant mean RH less than 78% may reduce transmission. As a result, maintaining precise RH ranges

remains critical for maximizing IAQ, guaranteeing thermal comfort, and perhaps lowering the danger of viral transmission, particularly in sensitive areas such as ICUs. Furthermore, EN 16798-1 shows that RH should be between 35% and 50%. Because viruses become dormant at 40% to 60% RH, comfort should be maintained at or above 40% for lower infectivity of aerosolized viruses. When compared to other modes, RH has the most significant effect on airborne transmission modes; thus, maintaining RH at similar values of 50% is advised.

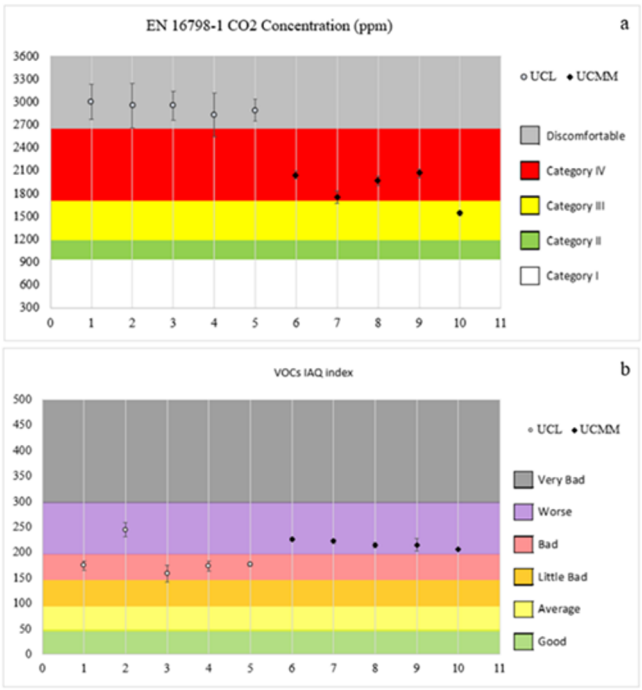

Figure 4 (a) presents the mean and SD of CO_2 and (b) the VOCs in UCL and CUMM.

Figure 4a shows the mean and the SD values of CO_2 concentration in the investigated UCL and UCMM. By simple descriptive statistics, the mean value of CO2 concentration levels considered in UCL is 2887 to 3001 ppm, corresponding to the discomfort zone, while for UCMM, it was 1538 to 2065 ppm, corresponding to categories II and IV according to EN16798-1 standard. Moreover, figure 4 (b) shows the IAQ Index scale based on VOC concentration according to EN 16798-1. the results of the average value of the time series of the VOCs index presented graphically in Figure 4b shows that VOC levels in the UCL range between Pink (Bad) and Purple (Worse) while for the UCMM are in the purple (Worse). With these values for the IAQ VOC-based index, it is expected that neither of the ICUs surveyed was within the acceptable range according to the EN16798-1 standard. Moreover, a similar study was performed in a French hospital that revealed high VOC concentrations [16].

Table 2. presents the correlation between Indoor climate parameters at UCL.

	Ta	RH	CO2	VOC	PM2.5	PM10	Ta (out)	PM2.5 (out)	PM10 (out)
Ta	1,00								
RH	0,61	1,00							
CO2	0,86	0,67	1,00						
VOC	0,27	-0,08	0,16	1,00					
PM2.5	-0,65	-0,78	-0,69	0,51	1,00				
PM10	0,90	0,38	0,75	0,66	-0,26	1,00			
Ta (out)	-0,89	-0,62	-0,60	0,02	0,74	-0,66	1,00		
PM2.5 (out)	-0,35	0,06	0,05	0,36	0,37	-0,13	0,66	1,00	
PM10 (out)	0,04	-0,72	-0,30	0,45	0,55	0,28	-0,02	-0,43	1,00

Table 3. presents the correlation between Indoor climate parameters in UCMM.

	Ta	RH	CO2	VOC	PM2.5	PM10	Ta (out)	PM2.5 (out)	PM10 (out)
Temp	1,00								
RH	0,06	1,00							
CO2	-0,05	0,98	1,00						
VOC	-0,57	0,41	0,54	1,00					
PM2.5	0,09	0,02	-0,13	-0,66	1,00				
PM10	-0,43	0,85	0,89	0,76	-0,13	1,00			
Ta (out)	-0,45	0,19	0,29	0,91	-0,61	0,56	1,00		
PM2.5 (out)	0,89	-0,17	-0,23	-0,35	-0,20	-0,49	-0,11	1,00	
PM10 (out)	-0,16	0,79	0,88	0,80	-0,58	0,83	0,57	-0,16	1,00

Table 2. presents the correlation between various indoor and outdoor climate parameters at UCL. Indoor temperature is significantly correlated with CO_2 (0.86) and PM_{10} (0.90), indicating a significant increase in these pollutants with rising temperatures. However, a notable inverse relationship exists between indoor and outdoor temperature (-0.89) and indoor $PM_{2.5}$ (-0.65). RH shows a moderate positive correlation with indoor temperature (0.61) and CO_2 (0.67) and a negative correlation with indoor $PM_{2.5}$ (-0.78) and outdoor PM_{10} (-0.72). CO_2 levels also positively correlate with indoor PM_{10} (0.75). Meanwhile, a negative correlation with the outdoor temperature (-0.60) suggests a complex relationship between IAQ and external environmental conditions. However, the VOC Index correlations significantly correlate with indoor PM_{10} (0.66) and $PM_{2.5}$ (0.51). Particulate matter dynamics are exceeding, with indoor $PM_{2.5}$ negatively correlated with indoor temperature and RH.

In contrast, indoor PM_{10} shows positive correlations with indoor temperature and CO_2 but negative correlations with outdoor temperature. The outdoor temperature has a significant impact on IAQ. Moreover, the outdoor temperature has a strong inverse correlation with indoor temperature and a positive correlation with indoor $PM_{2.5}$.

Table 3 presents the IAQ in UCMM and reveals complex relationships between indoor and outdoor climate parameters. The indoor temperature has a very low correlation with RH and CO_2, indicating these parameters are largely independent of temperature within the indoor environment. However, a high correlation between CO_2 levels and RH (0.98) suggests that factors like human occupancy significantly impact humidity and CO_2 concentrations. The VOC Index negatively correlated with indoor temperature (-0.57). Nonetheless, it shows a strong positive correlation with outdoor temperature (0.91), highlighting the influence of external temperatures on indoor air quality.

Furthermore, $PM_{2.5}$ has a very low correlation with RH and CO_2. However, the correlated VOC Index (-0.66) suggests that factors affecting VOCs might decrease $PM_{2.5}$ levels. In contrast, PM_{10} is highly correlated with RH (0.85) and CO_2 (0.89), indicating high correlations between outdoor $PM_{2.5}$ and indoor temperature (0.89), and outdoor PM10 closely relates to indoor CO_2 levels (0.88) and RH (0.79).

Air Change rate

IAQ significantly depends on Air Exchange per Hour (ACH) and airflow patterns in ICUs, which are crucial for controlling infectious aerosols. Patient and staff movements, equipment operation, and window and door usage influence ACH in ICUs. Mathai et al. found that opening windows fully in patients' wards is the best method to mitigate cross-contamination, supporting cross-ventilation over recirculating air to minimize airborne infections. In the ICUs studied, the average CO2 concentration was 4322 ppm (7779.6 mg/m^3) in UCL and 3019 ppm (5434.2 mg/m^3) in UCMM. Based on this, the airflow rate per occupant (Q), the total fresh air flow rate (Qt), and air exchange rate (λ_V) were calculated:

$$Q = \frac{N \times G}{Ci - Co}$$

Where:

Q is the ventilation rate required,
N is the number of occupants,
G is the CO2 generation rate per occupant
Ci is the indoor CO2 concentration (in ppm),
Co is the outdoor CO2 concentration (in ppm).

Calculate the total fresh air flow rate in UCL and UCMM wards; essential factors like occupant numbers, room volume, and the size of openings are considered, as detailed in Table 2. However, the Air exchange rate (λV) is calculated from the equation for λV is given as:

$$\lambda V = Q / V$$

Where:
Q = Airflow rate per occupant (in m³/h)
V = room volume (in m³)

To achieve the recommended concentration value of 1000 ppm (1800 mg/m^3), 2.34 air exchanges per hour in UCL would be needed. Meanwhile, the UCMM would need 2.31 air exchanges per hour.

Table 4 shows the total airflow rate and Air change.

Hospital	No. of bed	Room volume (m^3)	area with opening (m^2)	Total Airflow rate (m^3/h)	Air Change (ACH)
UCL	47	750	5.5	250	0.33
UCMM	31	500	5.4	248	0.49

Table 4 presents the number of beds, ward volume, area of openings for natural ventilation, airflow rates, and ACH for the UCL and UCMM. A notable observation is the higher total airflow rate in UCMM, despite having fewer beds than UCL, suggesting a more efficient ventilation per patient. This observation aligns with the findings of Lee [17], revealing that natural ventilation, without supplementary air purification methods, often fails to meet the required air quality standards in hospital settings. This efficiency is crucial in healthcare settings for controlling airborne disease transmission. The ACH rates, a critical measure of how frequently the air in the ward was replaced with fresh air, are relatively high in both hospitals, indicating effective ventilation systems. These rates are essential in maintaining indoor air quality, especially in environments prone to the spread of infections.

Discussion

Temperature and relative humidity

The To and RH in ICUs of UCL and UCMM hospitals, when compared against EN 16798-1 standards, reveal a significant challenge in maintaining optimal indoor climate conditions for patient care. At UCL, the To fell below the comfort range at 18.8°C, potentially leading to discomfort, consistent with findings that underscore the importance of temperature in patient recovery and infection control [18], [19]. Similarly, UCMM experienced discomfort temperatures, highlighting a common issue across healthcare settings.

Moreover, the RH levels in UCMM hospitals were above the standard 40% to 60% range, fundamental for minimizing the infectivity of aerosolized viruses, aligning with research indicating the critical role of humidity in airborne virus transmission (Yang et al., 2009; Kudo et al., 2019). These deviations underscore the need for stringent HVAC management to achieve the EN 16798-1 standards, essential for enhancing indoor air quality and patient safety in ICUs [15], [20].

Ambient Parameters

CO_2 is emitted from people in the room, and its concentration is influenced by the number of people present, the volume of the room, and the air exchange rate. The study indicates that the median CO_2 concentrations in certain facilities in UCL and UCMM (3001 and 2065 ppm) were higher than those in French hospitals (436-530 ppm) [3]. This disparity is likely attributable to the differing air

exchange rates: residential areas typically have a lower exchange rate of 0.3 volumes per hour [21], whereas hospitals have a more robust rate ranging from 1 to 11 volumes per hour [3], compared to the 0.3 to 0.8 volumes per hour noted in the current study. Notably, the sterilization rooms in dental offices and the consulting areas in dental and general practitioner offices exhibited increased indoor air stuffiness. These rooms, mainly ventilated through window openings, are a less frequent practice in contrast with other areas that benefit from combined natural and mechanical ventilation, enhancing the removal of CO_2 and other pollutants.

Particulate Matter

The PM concentrations, as observed in the study, showed a median value of UCL′s had significantly higher PM2.5 (183-186 µg/m^3) and PM10 (492-648 µg/m^3) levels and in UCMM's ICUs (PM2.5: 113-135 µg/m^3, PM10: 277-439 µg/m^3). And that higher spectrum compared to office buildings (9–26 µg/m^3) [22] but higher than hospitals (1.6 µg/m3) [3] and lower than dwellings (16 µg/m^3) [21]. $PM_{2.5}$ levels are influenced by ventilation efficiency and human activities within space. The presence of people and activities, such as movement that resuspends particles, contribute to increased $PM_{2.5}$ concentrations [23]. Additionally, indoor $PM_{2.5}$ levels are affected by the infiltration of outdoor pollutants, primarily from traffic sources [24]. Many facilities in the study were situated in residential areas near $PM_{2.5}$ sources, such as car parks or major roads. Interestingly, $PM_{2.5}$ concentrations were higher in summer than in winter, a finding inconsistent with other studies that reported higher winter levels [22]. This discrepancy could be due to varying indoor environmental conditions like building features, window-opening habits, emission sources, and ventilation systems [24]. The WHO has updated its air quality guidelines, lowering the recommended exposure limit for $PM_{2.5}$ from 10 to 5 µg/m^3. This study's median $PM_{2.5}$ level was below the WHO's previous long-term exposure guideline but exceeded the newly recommended limit. Specific areas, such as sterilization rooms in dental offices during summer, recorded $PM_{2.5}$ concentrations over six times higher than the median. The highest values exceeded the WHO's 24-hour exposure recommendation of 15 µg/m^3 [15]. Given these findings and the WHO guidelines, there is a pressing need for protective measures in these workplaces to mitigate health risks associated with $PM_{2.5}$, which is known to increase morbidity and mortality from cardiovascular and respiratory diseases.

Volatile Organic Compounds (VOCs)

The VOC concentrations were high in both ICUs. Similar to the study in French hospitals, these compounds were also the primary organic compounds quantified [16]. The median VOCs index in UCL and UCMM (244.9 and 225.5) correspond to Bad and Worse. Comparable to those in French hospitals (245.7 to 495.0 µg/m^3 and 13.6 to 20.3 µg/m^3, respectively) [25]. However, due to analytical limitations, the actual maximum alcohol concentrations could be higher. These concentrations might be attributed to the increased opening of windows during summer. The primary sources of these VOCs are likely healthcare and cleaning activities. The common component in disinfectants and deodorants for its fragrance [2] was detected in almost all rooms, supporting this assumption. In pharmacies, limonene could also originate from perfumes. As for formaldehyde, a long-term emitter, it is released from building materials and decorations. Moreover, the potential sources of aldehydes cleaning products [26] are usually used in healthcare settings for cleaning surfaces, respectively.

Ventilation

The Air Changes per Hour (ACH) in the ICUs of UCL and UCMM, which stand at 0.33 and 0.49 ACH, respectively, fall very short of the recommended ACH standards, typically a minimum of 6 ACH for ICUs. This gap is significant, as ACH is crucial to maintaining air quality and controlling infection in healthcare settings [27]. Lower ACH rates can compromise air quality, heightening the risk of hospital-acquired infections, a concern highlighted in studies by Qian et al. [28].

Contributory factors to these lower ACH rates may include the architectural design, the facility's age, and the impact of external environmental factors, such as pollution from nearby mining activities. This is supported by research like that of Brundage et al. [29], which found that external environmental factors significantly impact indoor air quality in healthcare facilities. The findings at UCL and UCMM might reflect a broader regional issue, as indicated by studies focusing on healthcare infrastructure in similar resource-limited settings [30]. Improving the ACH in these facilities is imperative. Upgrading ventilation systems and ensuring regular maintenance are potential strategies, as suggested by the guidelines of ASHRAE. Additionally, the WHO's guidelines on hospital ventilation systems provide valuable insights into effective practices in healthcare settings WHO Guidelines [31].

Practical implication

The research highlights the imperative need for designing and renovating hospital infrastructure, focusing on optimizing natural ventilation considering local environmental and climatic conditions. This study underscores the necessity of implementing robust health and safety protocols in hospitals, including enhanced air filtration, regular air quality monitoring, and air purifiers, particularly in areas housing vulnerable patients. It also emphasizes the importance of staff training in understanding and maintaining ventilation systems and the impact of air quality on health. These findings provide substantial evidence for policymakers to develop and enforce specific guidelines and minimum standards for hospital ventilation in the DRC.

Additionally, they highlight the role of community education in increasing public awareness about the importance of indoor air quality, potentially influencing policy and practice in public health spaces. This study also paves the way for further research to develop more efficient and cost-effective solutions for improving natural

ventilation in hospital settings in the DRC and similar environments globally. The collective impact of these implications could significantly enhance patient and healthcare worker safety, ultimately contributing to the overall improvement of health outcomes in the region.

Study limitations

The focus on a specific number of hospital wards in the DRC may not fully represent the region's diverse range of healthcare settings. Future research should expand to include more hospitals and consider the variations in indoor air quality across different seasons and climatic conditions. Investigating the specific sources of indoor pollutants in hospital environments can also provide a more comprehensive understanding and aid in developing targeted interventions.

Conclusion

This study provides a critical insight into the IAQ in hospital wards in the DRC, particularly near mining areas, and its implications for patient and staff health. The findings reveal concerning levels of (PM2.5 and PM10), CO2, and VOCs exceeding WHO standards in the UCL and UCMM, indicating a significant health risk, especially during peak activities such as visiting hours. These elevated levels correlate strongly with inadequate natural ventilation systems, which fall short of recommended ACH for healthcare settings.

The correlation between indoor and outdoor climate parameters revealed through this study highlights the complexity of IAQ in healthcare facilities and the significant influence of external factors, particularly in regions with high pollution levels from mining activities. The inadequacy of the natural ventilation systems, as evidenced by the insufficient ACH, further exacerbates the situation, emphasizing the critical need for enhancements in building designs and ventilation systems, particularly in places like the DRC.

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