

## Characterization of Indoor Air Quality in Relation to Ventilation Practices in Hospitals of Lahore, Pakistan

(Pencirian Kualiti Udara Dalam Ruang dengan Hubungan kepada Amalan Ventilasi di Hospital Lahore, Pakistan)

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### ABSTRACT

*Temporal variations of particulate matter (PM) and carbon dioxide ( $CO_2$ ) in orthopedic wards and emergency rooms of different hospitals of Lahore, Pakistan were investigated. Hospitals were classified into two groups, I (centrally air-conditioned) and II (non-central air-conditioned) based on the ventilation system. Statistical analysis indicated significantly lower PM and  $CO_2$  levels in centrally air-conditioned hospitals in comparison to non-central air-conditioned. The low indoor-outdoor (I/O) ratio of  $PM_{2.5}$  in the ward and emergency rooms of group I (0.62, 0.45) as compared to group II (0.70, 0.83), respectively, suggested that indoor spaces equipped with central air-conditioning systems efficiently filter particulates as compared to non-central air conditioning systems. Apart from the ventilation type, increased visitor and doctors' activities, and cleaning sessions were observed to contribute significantly to indoor air quality. This study adds up to the understanding of temporal variations in PM emissions and the role of ventilation systems in context of hospitals in the urban centers in Pakistan. The findings can inform the development of intervention strategies to maintain the appropriate air quality in health care built environment in developing countries.*

**Keywords:** Central air conditioning systems;  $CO_2$ ; HVAC; indoor air; particulate matter; split air conditioning systems

### ABSTRAK

*Variasi temporal jirim zarah (PM) dan karbon dioksida ( $CO_2$ ) di wad ortopedik dan bilik kecemasan daripada hospital yang berbeza di Lahore, Pakistan telah dikaji. Hospital telah dikelaskan kepada dua kumpulan, I (hawa dingin berpusat) dan II (hawa dingin tidak berpusat) berdasarkan daripada sistem ventilasi. Analisis statistik menunjukkan tahap PM dan  $CO_2$  adalah ketara rendah dalam hawa dingin berpusat jika dibandingkan dengan hawa dingin tidak berpusat. Nisbah dalaman-luaran (I/O) masing-masing daripada  $PM_{2.5}$  di dalam wad dan bilik kecemasan daripada kumpulan I (0.62, 0.45) dan kumpulan II (0.70, 0.83), menunjukkan bahawa ruang dalam yang dilengkapi dengan sistem hawa dingin berpusat menapis zarah secara cekap jika dibandingkan dengan sistem hawa dingin tidak berpusat. Selain daripada jenis ventilasi, peningkatan pelawat dan aktiviti para doktor serta sesi pembersihan telah diperhati memberi sumbangan besar terhadap kualiti udara ruang dalam. Kajian ini menambah pemahaman terhadap variasi temporal pengeluaran PM dan peranan sistem ventilasi dalam konteks hospital di kawasan pusat bandar Pakistan. Penemuan ini dapat memaklumkan pembangunan strategi intervensi untuk menjaga kualiti udara yang sesuai bagi pusat penjagaan kesihatan di negara yang membangun.*

**Kata kunci:** Bahan zarah;  $CO_2$ ; HVAC; sistem hawa dingin berpusat; sistem udara hawa dingin terpisah; udara dalam ruang

### INTRODUCTION

Air quality in health care facilities can be a substantial risk factor for the well-being of immune-compromised patients and staff, who particularly spend long hours in hospitals (Ling & Hui 2019). Indoor air quality (IAQ) is a complex

and dynamic problem in which physical, chemical, and biological pollutants produced both indoors and outdoors, can affect the health of the occupants. The most common pollutants of indoor origin in hospitals include both particle and gaseous emissions such as respirable suspended

particulates, carbon dioxide ( $\text{CO}_2$ ), volatile organic compounds (VOCs), carbon monoxide (CO), formaldehyde ( $\text{CH}_2\text{O}$ ), nitrous oxide ( $\text{N}_2\text{O}$ ), glutaraldehyde ( $\text{C}_5\text{H}_8\text{O}_2$ ), allergens, and bioaerosols (Śmiałowska et al. 2017). Relative humidity and temperature can considerably affect pollutants specifically bioaerosols count in hot and humid climates (Rasli et al. 2019).

The typical sources of these emissions include cleaning activities such as floor sweeping, dusting of surfaces, movement of people, medical procedures, indoor activities, infiltration from outdoor air, and ventilation practices (Baurès et al. 2018; Capolongo 2016). These emissions are significantly affected by meteorological factors, human activities, building design, management practices, seasonal variations, ventilation mode, and its maintenance (Moscato et al. 2017; Pereira et al. 2017). Among various air pollutants, particulate matter (PM) is of major concern. Apart from the indoor origin, particles from ambient sources can also become a vehicle for infectious aerosols and other adsorbed pollutants while being irritants on their own (Morakinyo et al. 2019; Tellier et al. 2019). The most concerning fractions of PM are fine ( $\leq$  to  $\text{PM}_{2.5}$ ) and ultra-fine ( $\leq$  to  $\text{PM}_{0.1}$ ) particles (Sturm 2016), and high levels of these whether of indoor or outdoor origin, contribute to the four leading causes of deaths in the world: heart diseases, Chronic Obstructive Pulmonary Diseases (COPD), strokes, and cancer (WHO 2016). Apart from direct health implications,  $\text{PM}_{2.5}$  can be a potential indicator of the possible existence of contaminants that could be risky for patients and health care workers (Ghio 2014; Milton et al. 2013). Therefore, limiting and controlling these particles can be helpful to manage hospital-acquired infections (Morawska & He 2014).

Ventilation plays an important role in controlling and removing contaminants from indoor and outdoor sources. Different type of ventilation system can affect the  $\text{PM}_{10}$  dispersal in the buildings and related risks to indoor air quality and occupant's health (Ali et al. 2017a). Many studies have discussed the role of different ventilation types in managing air quality in health care settings (Beggs et al. 2008; Yau et al. 2011). Moreover, various studies have used  $\text{CO}_2$  emissions as an indicator of ventilation adequacy in health care environments (Gilkerson et al. 2013; Sribanurekha et al. 2016). The outdoor pollutants infiltrating indoor air are diluted or removed by the ventilation system in place. Hence, another indicator frequently used to quantify the adequacy of ventilation is the indoor-outdoor ratio (I/O). The I/O ratio of PM has been broadly used in several studies to describe the association between indoor and outdoor air by offering a direct, simple understanding of the relationship (Bucur & Danet 2019; He et al. 2019). However, this ratio is flexible

depending upon various factors such as building design, indoor pollutant sources, particle deposition, penetration frequency, and air exchange rates (Shrestha et al. 2019). Most of the hospital facilities in Pakistan are localized in the urban areas, where high levels of air pollution have been consistently reported (Ahmad et al. 2019; Ali et al. 2017b). The country has faced over 128,000 deaths related to air pollution during 2017, and undergone a sheer increase in  $\text{PM}_{2.5}$  pollution since 2010 with the population-weighted and annual exposure levels of  $\text{PM}_{2.5}$  measured to be 76 and 58  $\mu\text{g}/\text{m}^3$ , respectively (Health Effects Institute 2019). Although ambient air quality is monitored via fixed-site stations in urban centers, data on air quality in health care environments is scarce (Asif et al. 2018; Gulshan et al. 2015; Nimra et al. 2015).

Presently, available evidence shows that the design and management of buildings, along with temperature, humidity, and ventilation rate can strongly influence the particulate and gaseous emission in health care facilities (Gola et al. 2019). The improved operations, housekeeping, and maintenance can help to reduce pollutant emissions in the microenvironments (Idris et al. 2020). There is a need to characterize indoor air quality in health care built environments to gain a better understanding of air pollutant emissions dynamics under different ventilation strategies in the context of hospitals in the urban centers in Pakistan. The current investigation was carried out as a case study to gain insights into the temporal characterization of particulate and gaseous emissions in the orthopedic wards and emergency rooms of public and private sector hospitals of Lahore, Pakistan with different ventilation systems in place.

## MATERIALS AND METHODS

Six hospitals (four public and two private) were selected from Lahore, based on their ventilation system as described by Jung et al. (2015). Group I hospitals used central air conditioning by the Air Handling Unit (AHU) while Group II hospitals used non-central air conditioning by split type. Permission was obtained from the hospital administration before sampling. The orthopedic wards and emergency rooms were selected for monitoring based on the findings of our previous study (Nimra et al. 2015) and a high risk of infection in orthopedic patients' rooms. Figure 1 depicts the general setup of the central air-conditioned (AHU) and non-central air (split type) conditioned hospital room. Brief characteristics of hospitals, collected from administration and official websites are given in Table 1. From each hospital, two sites i.e. orthopedic wards and emergency rooms were monitored for  $\text{PM}_{2.5}$ ,  $\text{PM}_{10}$ ,  $\text{CO}_2$  emissions

along with relative humidity (%RH) and temperature (°C). While the outdoor (ambient) site was monitored only for PM<sub>2.5</sub>. The study was carried during January - December 2017 with each site monitored four times during the whole year at an interval of three months.

Mass concentration of PM<sub>2.5</sub> and PM<sub>10</sub> was measured using real-time monitors: TSI DUST TRAK™ DRX 8533, and TSI DustTrak, Model 8520. Relative humidity (%RH), temperature (°C), and carbon dioxide (CO<sub>2</sub>) indoors were monitored using Aeroqual 500 series. DustTrak DRX model 8533 was employed for indoor sampling while ambient sampling was conducted for PM<sub>2.5</sub> only using DustTrak model 8520. Both DRX model 8533 and Aeroqual 500 series were factory calibrated before initiation of the study while DustTrak 8520 was calibrated against DRX by running both instruments side by side for four hours and a correction factor of 0.40 was calculated.

Each site was sampled from 9 a.m. to 5 p.m. to characterize the air quality and assess air hygiene levels in hospitals. The zero calibration for each instrument was done before sampling at each site. The instrument was placed at a height of 1 m and a distance of 1.5 m away from doors and/or windows. PM<sub>2.5</sub> monitoring in the outdoors was conducted in parallel to indoor sampling where the equipment was positioned at a height of 1 m above the ground and 50 m away from the main entrance of the building.

Time activity diaries were maintained for each sampling. The major defining activities identified at the selected sites were visiting hours, cleaning activities, doctor's round, and peak emergency hours (described below) which were observed to be conducted at specified times hence making it easy to study their impact upon air quality. One-hour data during which these specific activities were performed in each sampling campaign was separated for further analysis. *Visiting hours*: since the visiting hours are defined in the hospitals, the presence of the highest number of visitors and their physical movement were observed. *Cleaning*: including housekeeping, cleaning of floors and surfaces. *Doctor's round*: includes doctors visitation hours and movement of nurses for the general administration of medicine. *Peak emergency hours*: includes peak emergencies dealing hour with maximum visitors in an emergency.

The data was confirmed to be non-parametric by Kolmogorov-Simonov and Levene test which was analyzed by parametric test after normalizing data. An independent t-test was used to compare mean levels of PM and CO<sub>2</sub> between two groups. For the activities, one way ANOVA by Tukey HSD, LSD, and Games-Howell post hoc was used for analysis in the wards, while an independent t-test was used for emergency rooms. Moreover, to access the impact of outdoor PM<sub>2.5</sub>, hierarchical regression was performed controlling for confounding variables using SPSS v. 21.0.

TABLE 1. General Profile of the selected hospitals

Characteristics	Group I - Central air-conditioned (AHU), n=(2)	Group II Non-central air-conditioned (Split type), n = (4)
Building age (year)	17-25	26-74
Patient visit /month	9-30000	45000-75000
Bed strength/hospital	50-250	350-1000
Location	Urban busy road	Urban busy road

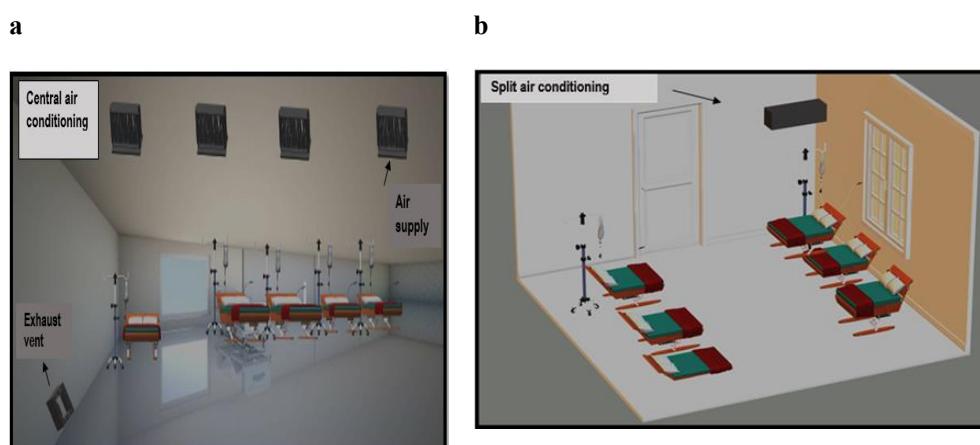


FIGURE 1. Representative diagram of the hospital room (a) centrally air-conditioned, and (b) non-centrally air-conditioned

## RESULTS

$\text{PM}_{2.5}$  and  $\text{PM}_{10}$  concentration in the wards and emergency rooms varied with the type of ventilation system (Table 2(a) -2(b)) and Figure 2(a) - 2(b)). In the wards, mean  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  were higher in group II ( $119 \pm 61$  and  $150 \pm 75 \mu\text{g}/\text{m}^3$ ), as compared to group I hospitals ( $89 \pm 56$  and  $117 \pm 74 \mu\text{g}/\text{m}^3$ ) (Table 2(a)). Similarly, in the emergency rooms, mean  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  were higher in group II ( $151 \pm 85$  and  $183 \pm 90 \mu\text{g}/\text{m}^3$ ), compared to group I hospitals ( $82 \pm 31$  and  $94 \pm 30 \mu\text{g}/\text{m}^3$ ) (Table 2(b)). Independent sample t-test indicated a statistically significant difference between groups I and II of wards as well as emergency rooms at 0.05 significance level.

Different activities in the wards and emergency rooms were observed to produce a pronounced impact

upon  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  concentrations. In the wards, mean  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  were highest during visiting hours in both groups as compared to doctor's round and cleaning activities (Table 2(a) and Figure 2(c) - 2(d)). One-way ANOVA showed statistically significant differences among the three different activities in the wards for both groups. The independent sample t-test also showed statistically significant differences between the groups. In the emergency rooms, mean  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  were highest during peak emergency hours in both groups as compared to cleaning activity (Table 2(b) and Figure 2(e) - 2(f)). One sample t-test and independent sample t-test showed a statistically significant difference in  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  concentrations during different activities, both within and between groups I and II, respectively.

TABLE 2(a). Average concentration of particulate matter ( $\mu\text{g}/\text{m}^3$ ) in the selected wards

PM concentration in:	Group I (n=2)		Group II (n=4)
	Central air-conditioned		Non- central conditioned
	(AHU) $\mu\text{g}/\text{m}^3$	Mean $\pm$ S.D	(Split type) $\mu\text{g}/\text{m}^3$
Wards	$\text{PM}_{2.5}$	89 ( $\pm 56$ )	119 ( $\pm 61$ )
	$\text{PM}_{10}$	117 ( $\pm 74$ )	150 ( $\pm 75$ )
Outdoor	$\text{PM}_{2.5}$	152 ( $\pm 33$ )	176 ( $\pm 59$ )
I/O ratio ( $\text{PM}_{2.5}$ )		0.62 ( $\pm 0.40$ )	0.70 ( $\pm 0.32$ )
Activities			
Visiting hours	$\text{PM}_{2.5}$	163 ( $\pm 37$ )	201 ( $\pm 66$ )
	$\text{PM}_{10}$	217 ( $\pm 60$ )	264 ( $\pm 93$ )
Doctors round	$\text{PM}_{2.5}$	103 ( $\pm 30$ )	139 ( $\pm 26$ )
	$\text{PM}_{10}$	133 ( $\pm 39$ )	171 ( $\pm 34$ )
Cleaning	$\text{PM}_{2.5}$	73 ( $\pm 20$ )	108 ( $\pm 37$ )
	$\text{PM}_{10}$	98 ( $\pm 26$ )	136 ( $\pm 45$ )

TABLE 2(b). Average concentration of particulate matter ( $\mu\text{g}/\text{m}^3$ ) in the selected emergency room

PM concentration in:	Group I (n=2)		Group II (n=4)
	Central air-conditioned		Non- central conditioned
	(AHU) $\mu\text{g}/\text{m}^3$	Mean $\pm$ S.D	(Split type) $\mu\text{g}/\text{m}^3$
Emergency rooms	$\text{PM}_{2.5}$	82 ( $\pm 31$ )	151 ( $\pm 85$ )
	$\text{PM}_{10}$	94 ( $\pm 30$ )	183 ( $\pm 90$ )
Outdoor	$\text{PM}_{2.5}$	179 ( $\pm 52$ )	184 ( $\pm 51$ )
I/O ratio ( $\text{PM}_{2.5}$ )		0.45 ( $\pm 0.10$ )	0.83 ( $\pm 0.40$ )
Activities			
Peak emergency hours	$\text{PM}_{2.5}$	102 ( $\pm 50$ )	268 ( $\pm 97$ )
	$\text{PM}_{10}$	122 ( $\pm 52$ )	306 ( $\pm 107$ )
Cleaning	$\text{PM}_{2.5}$	72 ( $\pm 22$ )	110 ( $\pm 35$ )
	$\text{PM}_{10}$	85 ( $\pm 20$ )	129 ( $\pm 30$ )

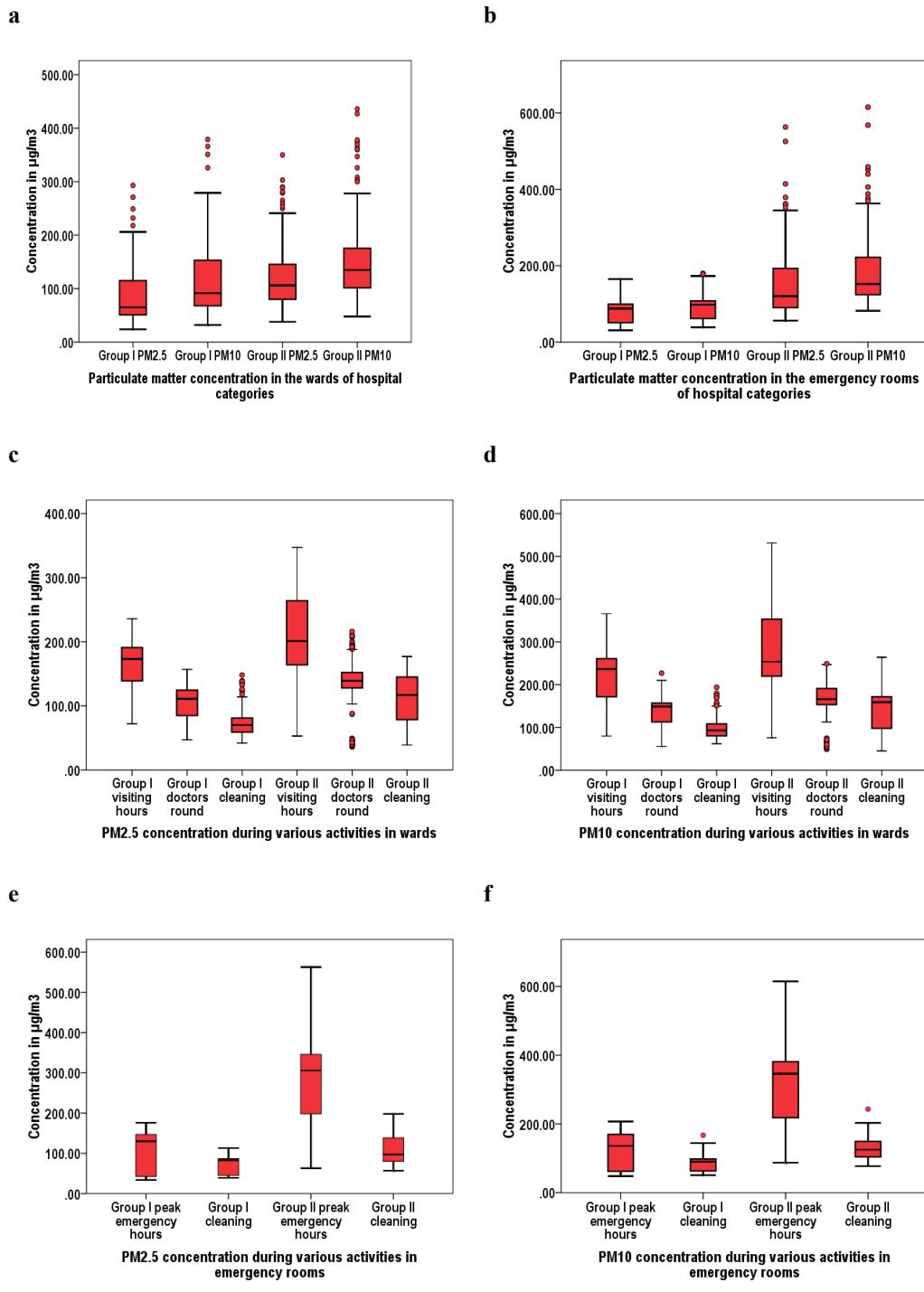


FIGURE 2. Summary statistics of PM<sub>2.5</sub> and PM<sub>10</sub> concentration in the hospitals: (a and b) particulate matter in the wards and emergency rooms, (c and d) PM<sub>2.5</sub> and PM<sub>10</sub> concentration during different activities in wards, and (e and f) PM<sub>2.5</sub> and PM<sub>10</sub> concentration during different activities in emergency rooms

The mean  $\text{PM}_{2.5}$  concentration in the outdoor environment monitored in parallel to the wards indoor was  $152 \pm 33$  and  $176 \pm 59 \mu\text{g}/\text{m}^3$  for the group I and II, respectively, while the mean  $\text{PM}_{2.5}$  concentration in outdoor parallel to emergency room indoor was  $179 \pm 52$  and  $184 \pm 51 \mu\text{g}/\text{m}^3$ , respectively (Table 2(a) - 2(b)). A significant difference was observed for  $\text{PM}_{2.5}$  outdoor concentration for the group I and II in the wards, but not for emergency rooms. The average I/O ratio of  $\text{PM}_{2.5}$  in the wards was  $0.62 \pm 0.40$  and  $0.70 \pm 0.32$  for the group I and II, respectively. However, the average I/O ratio of  $\text{PM}_{2.5}$  in the emergency rooms was  $0.45 \pm 0.10$  and  $0.83 \pm 0.40$

for the group I and II, respectively (Table 2(a) - 2(b) and Figure 3). Hierarchical regression analysis was employed, considering outdoor as an independent and indoor  $\text{PM}_{2.5}$  concentration as a dependent variable while controlling indoor confounding variables (relative humidity, carbon dioxide, temperature, and building age). It showed 38% variations in the  $\text{PM}_{2.5}$  levels indoors were contributed by outdoor in group II, while for group I the impact of outdoor  $\text{PM}_{2.5}$  was not statistically significant ( $p = 0.687$ ). In the emergency rooms, 54% variations in group II were contributed by outdoor whereas, for group I the impact of outdoor  $\text{PM}_{2.5}$  was also non-significant ( $p = 0.138$ ) (Table 3).

TABLE 3. Hierarchical regression between indoor  $\text{PM}_{2.5}$  and outdoor  $\text{PM}_{2.5}$  controlling for potential confounding variables

Hierachal regression between indoor and outdoor $\text{PM}_{2.5}$		Full model R <sup>2</sup>	R <sup>2</sup>	B-value	Standard error	T value	p-value
Wards	Group I	0.730	0.497	0.305	0.753	0.405	0.687
	Group II	0.637	0.384	0.341	0.127	2.681	<b>0.008</b>
Emergency rooms	Group I	0.889	0.881	0.260	0.173	1.503	0.138
	Group II	0.740	0.547	0.813	0.134	6.049	<b>0.000</b>

\*Full model R<sup>2</sup> is presented along with the contribution of outdoor  $\text{PM}_{2.5}$  individually (R<sup>2</sup>) for the model, applied on natural log converted data. Values in bold show  $P < 0.05$

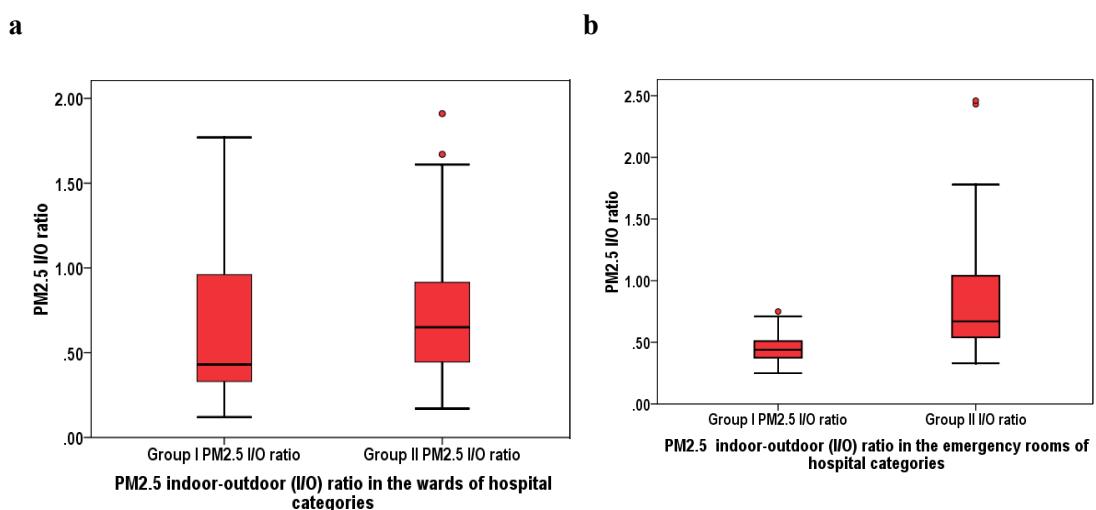


FIGURE 3. Statistics of Indoor-outdoor (I/O)  $\text{PM}_{2.5}$  ratio in the hospitals  
(a) wards, and (b) emergency rooms

Average relative humidity and temperature levels in the wards were  $47 \pm 04$  and  $26 \pm 02$  in group I, and  $37 \pm 09$  and  $29 \pm 05$ , respectively, in group II. In emergency rooms, the average relative humidity and temperature in the wards were  $37 \pm 14$  and  $27 \pm 02$  in group I, and  $45 \pm 06$  and  $28 \pm 04$ , respectively, in group II (Table 4). The %RH showed a positive direct relation with PM<sub>2.5</sub> at a significance level of 0.05.

CO<sub>2</sub> emissions in the wards and emergency rooms varied with the form of ventilation system. In the wards, the average concentration of CO<sub>2</sub> in groups I and II was  $712 \pm 273$  and  $1093 \pm 510$  ppm, respectively; while in the emergency rooms, the mean levels in groups I and II were  $782 \pm 329$  and  $939 \pm 421$  ppm, respectively. The independent sample t-test showed a statistically significant difference in CO<sub>2</sub> levels in the wards and emergencies of both groups at a 0.05 significance level (Figure 4).

TABLE 4. Summary statistics of relative humidity (%RH), temperature (°C) and CO<sub>2</sub> in the ward and emergency room categories

Parameters	Group I (n=2) Central air-conditioned (AHU)	Group II (n=4) Non- central conditioned (Split type)
	Mean ± S.D	Mean ± S.D
Wards	%RH 47 ( $\pm 04$ )	37 ( $\pm 09$ )
	Temperature (°C) 26 ( $\pm 02$ )	29 ( $\pm 05$ )
	CO <sub>2</sub> (ppm) 712 ( $\pm 273$ )	1093 ( $\pm 510$ )
Emergency rooms	%RH 37 ( $\pm 14$ )	45( $\pm 06$ )
	Temperature (°C) 27 ( $\pm 02$ )	28( $\pm 04$ )
	CO <sub>2</sub> (ppm) 782 ( $\pm 329$ )	939 ( $\pm 421$ )

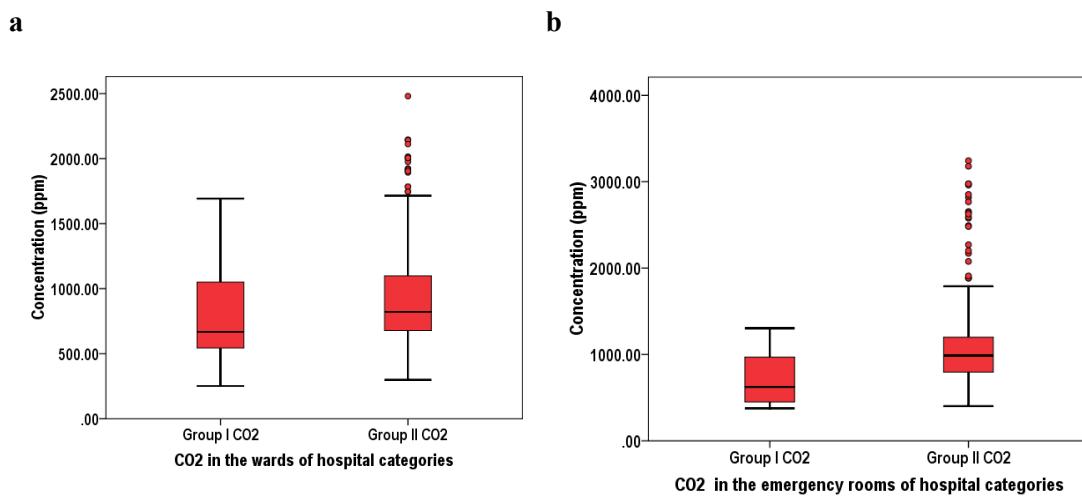


FIGURE 4. Summary statistics of CO<sub>2</sub> concentration and in the hospitals (a) wards and, (b) emergency rooms

## DISCUSSION

Monitoring and control of PM<sub>2.5</sub> particles in hospitals can assist health care personnel to gauge air hygiene and the efficacy of control measures such as ventilation systems (Pankhurst et al. 2012; Verkkala et al. 1998). Being capable of penetrating deep into the alveoli and hence the bloodstream, these fine particles play a major role in the transmission of microbial infections by adherence (Kressel et al. 2004); owing to their small size they can remain airborne for longer durations and could potentially carry infectious or other potential diseases causing agents (Armadans-Gil et al. 2013; Macher et al. 2019). Therefore, PM<sub>2.5</sub> particles may serve as a potential indicator of the existence of contaminants that can be fatal to immune-compromised patients in the hospital. Consequently, studies have been done to assess levels of particulate matter in relation to ventilation practices. Jung et al. (2015) discussed that centrally air-conditioned significantly reduce PM<sub>2.5</sub> and PM<sub>10</sub> as compared to non-centrally air-conditioned (split and window type). Moreover, they suggested that increased human activities and poor management practices result in high levels of particulates. Chamseddine et al. (2019) also found lower PM<sub>2.5</sub> and PM<sub>10</sub> concentration (range: 9-41 µg/m<sup>3</sup>) and (range: 24-55 µg/m<sup>3</sup>) in mechanically ventilated respectively as compared to the naturally ventilated hospitals (range: 20-86 µg/m<sup>3</sup>) and (range: 28-94 µg/m<sup>3</sup>), respectively.

The current study found significantly lower PM<sub>2.5</sub> and PM<sub>10</sub> concentrations in central air-conditioned (AHU) as compared to non-central air-conditioned (split type) hospitals which is in agreement with studies conducted by Fonseca et al. (2019), Jung et al. (2015), Lomboy et al. (2015), and Wang et al. (2006b), who reported low levels of PM in mechanically ventilated hospitals compared to other modes of ventilation. Similarly, Yau et al. (2011) and Zuraimi and Tham (2008) reported that ventilation type, human activities, and management practices significantly affect PM and CO<sub>2</sub> emissions. Indoor PM levels in the hospitals have been reported in various neighboring countries in South East Asia including China and the Philippines. In a study conducted in the urban tertiary care hospital of the Philippines, higher levels of PM<sub>2.5</sub> were reported in naturally ventilated areas as compared to mechanically ventilated (centrally air-conditioned) areas (Lomboy et al. 2015).

In China (Wang et al. 2006a), four public hospitals with different ventilation modes were evaluated for air quality. They reported average PM<sub>2.5</sub> and PM<sub>10</sub> ranged between 80-108 and 93-145 µg/m<sup>3</sup> respectively, which are almost the same for minimum levels but lower than observed levels (82-151 and 94-183 µg/m<sup>3</sup>,

respectively) in the present study. In another study in Iran (Mohammadyan et al. 2019), the average PM<sub>2.5</sub> levels (range: 38-55 µg/m<sup>3</sup>) were considerably less, but PM<sub>10</sub> (range: 112-227 µg/m<sup>3</sup>) was significantly higher than the levels reported in the current study.

Different activities performed in indoor environments have a major effect on the generation and re-suspension of PM (Ferro et al. 2004) as seen in the current study as well. Activities like cleaning, high visitor density, and doctors round increased the airborne particulates in hospitals. Movement of people can lead to resuspension of settled dust in different indoor environments (Gaidajis & Angelakoglou 2014; Jung et al. 2018; Pereira et al. 2017; Sidra et al. 2015; Tang et al. 2009). In the present study, elevated levels of PM<sub>2.5</sub> and PM<sub>10</sub> in the wards and emergency rooms were observed during high visitor density and peak emergency times, respectively (Table 2(a) - 2(b)); and coarse particles (PM<sub>10</sub>) mass concentration was higher than fine particles (PM<sub>2.5</sub>); a trend repeatedly observed in various previous studies (Ahwah et al. 2015; Doğan 2019; El-Sharkawy et al. 2014; Wang et al. 2006a, 2006b). Additional sources contributing to PM levels include the curtains and carpets in the hospitals (Verma & Taneja 2011). In another study, the average levels of PM<sub>2.5</sub> in different wards of a centrally air-conditioned hospital of Lahore ranged between 69-488 µg/m<sup>3</sup> (Gulshan et al. 2015). These levels were far higher as compared to PM<sub>2.5</sub> levels of 89 µg/m<sup>3</sup> in centrally air-conditioned wards in the present study. This was probably due to ongoing staff strikes, cracks in buildings, and decreased frequency of cleaning activities as reported by Gulshan et al. (2015).

The air pollutants generated outdoors from anthropogenic sources such as traffic have a significant association with indoor air (Radaideh et al. 2016). This was observed in the current study where the hierarchical regression showed a significant impact of outdoor PM<sub>2.5</sub> on indoor levels in non-centrally air-conditioned hospitals and, no significant impact in centrally air-conditioned hospitals (Table 3). This could be due to the efficient filtration of outdoor PM<sub>2.5</sub> in mechanically ventilated hospitals as also reported by Montgomery et al. (2015). These findings are also supported by the I/O ratios used to estimate the difference between indoor and corresponding outdoor concentrations which are dependent upon the location, different activities, building design, and ventilation type (Diapouli et al. 2013; Yang et al. 2018). In this study, the I/O of PM<sub>2.5</sub> (0.45-0.62) were lower in centrally air-conditioned hospitals as compared to 0.70-0.83 in non-centrally air-conditioned hospitals which is suggestive of improved filtration of particulates by filtration system as reported in various studies (Cavallo

et al. 1993; Chen & Zhao 2011; Peng et al. 2017). I/O ratios can be predictive of the IAQ of the hospitals and other buildings since naturally ventilated buildings or ones with inadequate air filtration systems have a higher I/O ratio (Ediagbonya et al. 2013; Mohammadyan et al. 2019; Wang et al. 2006a). Apart from ventilation, the other factor observed to affect I/O for  $PM_{2.5}$  in the present study was high visitor density. The hospitals with high visitor density and non-centrally air-conditioned were found to have a high I/O ratio for particulates as compared to low visitor density and centrally air-conditioned hospitals. This is consistent with the observations of Mohammadyan et al. (2017, 2016), and Tang et al. (2009). This situation calls for stringent air quality management practices in hospitals, particularly located in urban centers with high levels of particulate pollution.

These results can be useful in the development of efficient emissions control strategies in hospitals. The particle composition, concentration, shape, and size, hygroscopic growth, deposition, and re-suspension have been reported to be dependent on RH, although the process is complex and involves various other factors (Qian et al. 2014). The management practices, particularly, ventilation play a significant role in controlling the humidity, gases, and PM as reported by various studies (Escombe et al. 2007; Seppänen & Kurnitski 2009) and it was observed in this study that RH exhibited a direct relation with  $PM_{2.5}$  at a significance level of 0.01.

Another parameter that predicts IAQ is  $CO_2$ . Since occupant density is one of the prime  $CO_2$  sources, the indoor concentration of  $CO_2$  can be used to assess the adequacy of ventilation, pollutant concentration associated with occupant activity, and airborne infection risk (Rudnick & Milton 2003). In the present study, the mean  $CO_2$  concentration was 712-782 ppm in centrally air-conditioned sites, whereas 939-1093 ppm in the non-centrally conditioned sites while, ASHRAE 2017 recommends permissible levels to be 1,000 ppm. Similar levels of  $CO_2$  i.e. 643-875 ppm were reported in centrally air-conditioned ambulatory care centers of Malaysia, where the HVAC system was reported to provide adequate ventilation and improved IAQ (Sari et al. 2019). In another study conducted in a government hospital in Thailand,  $CO_2$  levels reported to be 267-1351 ppm, suggesting high patient numbers and insufficient ventilation to cause impaired air quality (Luksamijarulkul et al. 2019). Moreover, comparatively higher  $CO_2$  levels in non-centrally air-conditioned hospitals were also reported by many researchers as well (Fonseca et al. 2019; Zhou et al. 2015).

On the contrary, some studies have reported a high concentration of  $CO_2$  in mechanically ventilated indoor spaces as compared to naturally ventilated indoors (Jurado et al. 2014; Sribanurekha et al. 2016). This could be because other factors in addition to ventilation, such as occupant density and activities of the occupants also affect the indoor concentration of  $CO_2$ . It was noticed in the current study that hospitals can be a high source of PM that may pose serious health implications to immune-compromised patients as well as health care personnel. Various other studies have reported serious health problems in the health care facilities having a high concentration of PM and gaseous emissions like  $CO_2$  and VOCs (Bessonneau et al. 2013; Su et al. 2018).

The exposure risk to the patients and health care personnel can be significantly reduced by enforcement of existing ventilation guidelines and improved management practices in the hospitals.

## CONCLUSION

The effective management of air quality in the hospitals needs knowledge of spatio-temporal variations in pollutants. The centrally air-conditioned hospitals were found to improve IAQ by reducing  $PM_{2.5}$  and  $PM_{10}$  and  $CO_2$  emissions as compared to non-centrally air-conditioned hospitals. Among various activities conducted in hospital premises, the highest PM and  $CO_2$  concentrations were observed during visiting hours, suggesting a pronounced effect of human activities in determining air quality. The indoor  $PM_{2.5}$  concentrations in non-central air-conditioned hospitals showed a significant association with outdoor concentrations, signifying the impact of ambient air quality in urban centers on indoor quality. The real-time monitoring of particulates and  $CO_2$  can help to inform and evaluate the intervention strategies to maintain air hygiene in health care built environments. However, this study delivers a snapshot view of particulate and  $CO_2$  concentration from hospitals. Further studies should be conducted to understand the nature and magnitude of emissions in hospitals. Specifically, the biological and chemical characterization of PM emissions should be done for better air quality management in hospitals.

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## REFERENCES

- Ahmad, H.R., Mehmood, K., Sardar, M.F., Maqsood, M.A., Rehman, M.Z.U., Zhu, C. & Li, H. 2019. Integrated risk assessment of potentially toxic elements and particle pollution in urban road dust of megacity of Pakistan. *Human and Ecological Risk Assessment: An International Journal* 26(7): 1810-1831.
- Ahwah, T.F., Yuan-Gao, W., Ansah, O. & Menu, E.O.E. 2015. Assessment of indoor particulate matter in hospital environment a case study in China. *International Journal of Modern Engineering Research* 5(12) Version 1: 1-9..
- Ali, M.Y., Hanafiah, M.M., Khan, M.F. & Latif, M.T. 2017a. Quantitative source apportionment and human toxicity of indoor trace metals at university buildings. *Building and Environment* 121: 238-246.
- Ali, M.U., Rashid, A., Yousaf, B. & Kamal, A. 2017b. Health outcomes of road-traffic pollution among exposed roadside workers in Rawalpindi City, Pakistan. *Human and Ecological Risk Assessment: An International Journal* 23(6): 1330-1339.
- Armadans-Gil, L., Rodríguez-Garrido, V., Campins-Martí, M., Gil-Cuesta, J. & Vaqué-Rafart, J. 2013. Particle counting and microbiological air sampling: Results of the simultaneous use of both procedures in different types of hospital rooms. *Enfermedades Infecciosas y Microbiología Clínica* 31(4): 217-221.
- ASHRAE. 2017. *Ventilation of Health Care Facilities*. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Customer Service.
- Asif, A., Zeeshan, M., Hashmi, I., Zahid, U. & Bhatti, M.F. 2018. Microbial quality assessment of indoor air in a large hospital building during winter and spring seasons. *Building and Environment* 135: 68-73.
- Baurès, E., Blanchard, O., Mercier, F., Surget, E., Le Cann, P., Rivier, A. & Florentin, A. 2018. Indoor air quality in two French hospitals: Measurement of chemical and microbiological contaminants. *Science of The Total Environment* 642: 168-179.
- Beggs, C.B., Kerr, K.G., Noakes, C.J., Hathway, E.A. & Sleigh, P.A. 2008. The ventilation of multiple-bed hospital wards: Review and analysis. *American Journal of Infection Control* 36(4): 250-259.
- Bessonneau, V., Mosqueron, L., Berrubé, A., Mukensturm, G., Buffet-Bataillon, S., Gangneux, J.P. & Thomas, O. 2013. VOC contamination in hospital, from stationary sampling of a large panel of compounds, in view of healthcare workers and patients exposure assessment. *PloS ONE* 8(2): e55535.
- Bucur, E. & Danet, A. 2019. Indoor/outdoor correlations regarding indoor air pollution with particulate matter. *Environmental Engineering & Management Journal* 18(2): 425-432.
- Capolongo, S. 2016. Social aspects and wellbeing for improving healing processes' effectiveness. *Ann. Ist Super Sanita* 52(1): 11-44.
- Cavallo, D., Alcini, D., De Bortoli, M., Carrettoni, D., Carrer, P., Bersani, M. & Maroni, M. 1993. Chemical contamination of indoor air in schools and office buildings in Milan, Italy. *Proceedings of Indoor Air* 93: 45-49.
- Chamseddine, A., Alameddine, I., Hatzopoulou, M. & El-Fadel, M. 2019. Seasonal variation of air quality in hospitals with indoor-outdoor correlations. *Building and Environment* 148: 689-700.
- Chen, C. & Zhao, B. 2011. Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor. *Atmospheric Environment* 45(2): 275-288.
- Diapouli, E., Chaloulakou, A. & Koutrakis, P. 2013. Estimating the concentration of indoor particles of outdoor origin: a review. *Journal of the Air & Waste Management Association* 63(10): 1113-1129.
- Doğan, T.R. 2019. Investigation of indoor air quality in a hospital: A case study from Şanlıurfa, Turkey. *Doğa Afetler ve Çevre Dergisi* 5(1): 101-109.
- Ediagbonya, T.F., Tobin, A.E. & Legemah, M. 2013. Indoor and outdoor air quality in hospital environment. *Chemistry and Materials Research* 3(10): 72-78.
- El-Sharkawy, F.M. & Noweir, M.E. 2014. Indoor air quality levels in a University Hospital in the Eastern Province of Saudi Arabia. *Journal of Family & Community Medicine* 21(1): 39-47.
- Escombe, A.R., Oeser, C.C., Gilman, R.H., Navincopa, M., Ticona, E., Pan, W. & Moore, D.A. 2007. Natural ventilation for the prevention of airborne contagion. *PLoS Medicine* 4(2): e68.
- Ferro, A.R., Kopperud, R.J. & Hildemann, L.M. 2004. Source strengths for indoor human activities that resuspend particulate matter. *Environmental Science & Technology* 38(6): 1759-1764.
- Fonseca, A., Abreu, I., Guerreiro, M., Abreu, C., Silva, R. & Barros, N. 2019. Indoor air quality and sustainability management - Case study in three portuguese healthcare units. *Sustainability* 11(1): 101.
- Gaidajis, G. & Angelakoglou, K. 2014. Indoor mass concentrations of particulate matter in hospital environment. *Global Nest Journal* 16(5): 832-839.
- Ghio, A. 2014. Particle exposures and infections. *Infection* 42(3): 459-467.
- Gilkeson, C., Camargo-Valero, M., Pickin, L. & Noakes, C. 2013. Measurement of ventilation and airborne infection risk in large naturally ventilated hospital wards. *Building and Environment* 65: 35-48.
- Gola, M., Settimo, G. & Capolongo, S. 2019. Indoor air quality in inpatient environments: A systematic review on factors that influence chemical pollution in inpatient wards. *Journal of Healthcare Engineering* 2019: 8358306.
- Gulshan, T., Ali, Z., Zona, Z., Ansari, B., Ahmad, M., Zainab, M. & Colbeck, I. 2015. State of air quality in and outside of hospital wards in urban centres - A case study in Lahore, Pakistan. *Journal of Animal and Plant Sciences* 25(3): 666-671.

- Health Effects Institute. 2019. *State of Global Air 2019*. Special Report.
- He, K.Q., Yuan, C.G., Yin, L.Q., Zhang, K.G., Xu, P.Y., Xie, J.J. & Shen, Y.W. 2019. A comparative study on arsenic fractions in indoor/outdoor particulate matters: A case in Baoding, China. *Environmental Monitoring and Assessment* 191(8): 528.
- Idris, S.A.A., Hanafiah, M.M., Khan, M.F. & Abd Hamid, H.H. 2020. Indoor generated PM<sub>2.5</sub> compositions and volatile organic compounds: Potential sources and health risk implications. *Chemosphere* 255: 126932.
- Jung, C.C., Wu, P.C., Tseng, C.H., Chou, C.C. & Su, H.J. 2018. Contribution of indoor-and outdoor-generated fine and coarse particles to indoor air in Taiwanese hospitals. *Aerosol and Air Quality Research* 18(12): 3234-3242.
- Jung, C.C., Wu, P.C., Tseng, C.H. & Su, H.J. 2015. Indoor air quality varies with ventilation types and working areas in hospitals. *Building and Environment* 85: 190-195.
- Jurado, S.R., Bankoff, A.D. & Sanchez, A. 2014. Indoor air quality in Brazilian universities. *International Journal of Environmental Research and Public Health* 11(7): 7081-7093.
- Kressel, A., Linnenmann, C. & Mayhall, C. 2004. Nosocomial infection in obstetrical patients. In *Hospital Epidemiology and Infection Control*, edited by Mayhall, C.G. Philadelphia: Lippincott Williams & Wilkins. pp. 927-935.
- Ling, S. & Hui, L. 2019. Evaluation of the complexity of indoor air in hospital wards based on PM<sub>2.5</sub>, real-time PCR, adenosine triphosphate bioluminescence assay, microbial culture and mass spectrometry. *BMC Infectious Diseases* 19(1): 646.
- Lomboy, M.F.T.C., Quirit, L.L., Molina, V.B., Dalmacion, G.V., Schwartz, J.D., Suh, H.H. & Baja, E.S. 2015. Characterization of particulate matter 2.5 in an urban tertiary care hospital in the Philippines. *Building and Environment* 92: 432-439.
- Luksamijarulkul, P., Somjai, N., Nankongnap, N., Pataitiemthong, A., Kongtip, P. & Woskie, S. 2019. Indoor air quality at different sites of a governmental hospital. *Nursing and Palliative Care* 4: 1-5.
- Macher, J.M., Gold, D., Cruz, P., Kyle, J.L., Durrani, T.S. & Shusterman, D. 2019. Evaluation and management of exposure to infectious agents. *Handbook of Occupational Safety and Health* 3: 147-197.
- Milton, D.K., Fabian, M.P., Cowling, B.J., Grantham, M.L. & McDevitt, J.J. 2013. Influenza virus aerosols in human exhaled breath: Particle size, culturability, and effect of surgical masks. *PLoS Pathogens* 9(3): 1-7.
- Mohammadyan, M., Keyvani, S., Bahrami, A., Yetilmezsoy, K., Heibati, B. & Pollitt, K.J.G. 2019. Assessment of indoor air pollution exposure in urban hospital microenvironments. *Air Quality, Atmosphere & Health* 12(2): 151-159.
- Mohammadyan, Keyvani, S., Yazdani-Charati, J., Bahrami, A. & Yousefi-Nejad, R. 2017. Indoor and ambient air concentrations of respirable particles between two hospitals in Kashan (2014-2015). *Feyz Journal of Kashan University of Medical Sciences* 21(1): 66-73.
- Mohammadyan, M., Keyvani, S., Charati, J.Y., Bahrami, A. & Nejad, R.Y. 2016. An assessment of indoor and outdoor particulate matters concentrations at two hospitals in Kashan, Iran. *Journal of Disease and Global Health* 8(2): 55-59.
- Montgomery, J.F., Storey, S. & Bartlett, K. 2015. Comparison of the indoor air quality in an office operating with natural or mechanical ventilation using short-term intensive pollutant monitoring. *Indoor and Built Environment* 24(6): 777-787.
- Morawska, L. & He, C. 2014. Indoor particles, combustion products and fibres. In *Indoor Air Pollution*, edited by Pluschke, P. & He, C. Germany: Springer. pp. 117-147.
- Morakinyo, O.M., Mokgobu, M.I., Mukhola, M.S. & Godobedza, T. 2019. Biological composition of respirable particulate matter in an industrial vicinity in South Africa. *International Journal of Environmental Research and Public Health* 16(4): 629.
- Moscato, U., Borghini, A. & Teleman, A.A. 2017. HVAC management in health facilities. In *Indoor Air Quality in Healthcare Facilities*, edited by Stefano, C., Gaetano, S. & Gola, M. Germany: Springer. pp. 95-106.
- Nimra, A., Ali, Z., Khan, M.N., Gulshan, T., Sidra, S., Gardezi, J.R. & Colbeck, I. 2015. Comparative ambient and indoor particulate matter analysis of operation theatres of government and private (trust) hospitals of Lahore, Pakistan. *Journal of Animal and Plant Sciences* 25(3): 628-635.
- Pankhurst, L., Taylor, J., Cloutman-Green, E., Hartley, J. & Lai, K. 2012. Can clean-room particle counters be used as an infection control tool in hospital operating theatres. *Indoor and Built Environment* 21(3): 381-391.
- Peng, Z., Deng, W. & Tenorio, R. 2017. Investigation of indoor air quality and the identification of influential factors at primary schools in the North of China. *Sustainability* 9(7): 1180.
- Pereira, M., Knibbs, L., He, C., Grzybowski, P., Johnson, G., Huffman, J. & Dominski, F. 2017. Sources and dynamics of fluorescent particles in hospitals. *Indoor Air* 27(5): 988-1000.
- Qian, J., Peccia, J. & Ferro, A.R. 2014. Walking-induced particle resuspension in indoor environments. *Atmospheric Environment* 89: 464-481.
- Radaideh, J.A., Alazba, A.A., Amin, M.N., Shatnawi, Z.N. & Amin, M.T. 2016. Improvement of indoor air quality using local fabricated activated carbon from date stones. *Sains Malaysiana* 45(1): 59-69.
- Rasli, N.B.I., Ramli, N.A., Ismail, M.R. & Shith, S. 2019. Dependency of biological contaminants on temperature and relative humidity within praying halls of mosques. *Sains Malaysiana* 48(8): 1575-1581.
- Rudnick, S. & Milton, D. 2003. Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. *Indoor Air* 13(3): 237-245.
- Sari, K.A.M., Mastaza, K.F.A., Rahman, M.A.A., Saji, N., Muslim, R., Mustafa, M.S.S. & Ghing, T.Y. 2019. Assessment of indoor air quality parameters at Ambulatory Care Centre XYZ, Malaysia. *IOP Conference Series: Earth and Environmental Science* 373(1): 012013.

- Seppänen, O. & Kurnitski, J. 2009. Moisture control and ventilation. In *WHO Guidelines for Indoor Air Quality: Dampness and Mould*. World Health Organization.
- Shrestha, P.M., Humphrey, J.L., Carlton, E.J., Adgate, J.L., Barton, K.E., Root, E.D. & Miller, S.L. 2019. Impact of outdoor air pollution on indoor air quality in low-income homes during wildfire seasons. *International Journal of Environmental Research and Public Health* 16(19): 3535.
- Sidra, S., Ali, Z., Nasir, Z.A. & Colbeck, I. 2015. Seasonal variation of fine particulate matter in residential micro-environments of Lahore, Pakistan. *Atmospheric Pollution Research* 6(5): 797-804.
- Śmietowska, M., Marć, M. & Zabiegała, B. 2017. Indoor air quality in public utility environments - A review. *Environmental Science and Pollution Research* 24(12): 66-76.
- Sribanurekha, V., Wijerathne, S., Wijepala, L. & Jayasinghe, C. 2016. Effect of different ventilation conditions on indoor CO<sub>2</sub> levels. *International Conference on Disaster Resilience at Kandalama Sri Lanka*.
- Sturm, R. 2016. Local lung deposition of ultrafine particles in healthy adults: Experimental results and theoretical predictions. *Annals of Translational Medicine* 4(21): 420-428.
- Su, F.C., Friesen, M.C., Stefaniak, A.B., Henneberger, P.K., LeBouf, R.F., Stanton, M.L. & Virji, M.A. 2018. Exposures to volatile organic compounds among healthcare workers: Modeling the effects of cleaning tasks and product use. *Annals of Work Exposures and Health* 62(7): 852-870.
- Tang, C.S., Chung, F.F., Lin, M.C. & Wan, G.H. 2009. Impact of patient visiting activities on indoor climate in a medical intensive care unit: A 1-year longitudinal study. *American Journal of Infection Control* 37(3): 183-188.
- Tellier, R., Li, Y., Cowling, B.J. & Tang, J.W. 2019. Recognition of aerosol transmission of infectious agents: A commentary. *BMC Infectious Diseases* 19(1): 101.
- Verkkala, K., Eklund, A., Ojajärvi, J., Tittanen, L., Hoborn, J. & Mäkelä, P. 1998. The conventionally ventilated operating theatre and air contamination control during cardiac surgery—bacteriological and particulate matter control garment options for low level contamination. *European Journal of Cardio-Thoracic Surgery* 14(2): 206-210.
- Verma, N. & Taneja, A. 2011. Particulate matter exposure in hospitals of urban city located in northern central India. *The Indian Journal of Environment* 31(8): 624-634.
- Wang, X., Bi, X., Chen, D., Sheng, G. & Fu, J. 2006a. Hospital indoor respirable particles and carbonaceous composition. *Building and Environment* 41(8): 992-1000.
- Wang, X., Bi, X., Sheng, G. & Fu, J. 2006b. Hospital indoor PM<sub>10</sub>/PM<sub>2.5</sub> and associated trace elements in Guangzhou, China. *Science of The Total Environment* 366(1): 124-135.
- WHO. 2016. Ambient air pollution: A global assessment of exposure and burden of disease. <https://www.who.int/phe/publications/air-pollution-global-assessment/en/>.
- Yang, Z., Shen, J. & Gao, Z. 2018. Ventilation and air quality in student dormitories in China: A case study during summer in Nanjing. *International Journal of Environmental Research and Public Health* 15(7): 1328.
- Yau, Y.H., Chandrasegaran, D. & Badarudin, A. 2011. The ventilation of multiple-bed hospital wards in the tropics: A review. *Building and Environment* 46(5): 1125-1132.
- Zhou, Q., Lyu, Z., Qian, H., Song, J. & Möbs, V.C. 2015. Field-measurement of CO<sub>2</sub> level in general hospital wards in Nanjing. *Procedia Engineering* 121: 52-58.
- Zuraimi, M.S. & Tham, K.W. 2008. Effects of child care center ventilation strategies on volatile organic compounds of indoor and outdoor origins. *Environmental Science & Technology* 42(6): 2054-2059.
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