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# Distribution and the trend of airborne particles and bio-aerosol concentration in pediatric intensive care units with different ventilation setting at two hospitals in Riyadh, Saudi Arabia

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ABSTRACT

*Objective:* To examine the distribution and the trend of airborne particles and bio-aerosol concentration in pediatric intensive care units (PICUs) in two tertiary care hospitals with different ventilation setting.
*Methods:* Hospitals A but not B is provided with a central HEPA filter. PICUs in both hospitals were categorized into protective environment (PE) with room HEPA filter, semi-protective environment (SPE) with portable air-purifier, and non-protective environment (NPE) with neither system. Fine particles (≤ 2.5 μm) and coarse particles (≤ 10.0 μm) were obtained using optical particle counter (Lighthouse Handheld 3016) and total bacterial (TBC) and fungal (TFC) counts were obtained using Andersen air sampler.
*Results:* Hospital B had significantly higher levels of fine and coarse particles (in all room), TBC (in PE), but not TFC compared with matched rooms in hospital A. In hospital B, the levels of fine particles, coarse particles, and TBC were lowest in SPE ($p < 0.001$, $p = 0.004$, and $p = 0.006$, respectively) while TFC was lowest in NPE ($p = 0.014$). Airborne particles, TBC, and TFC had variable trends with some of the indoor peaks follow outdoor peaks. Gram-positive bacteria (69 %) were the predominant bacteria in hospital A while bacterial flora (70 %) were the predominant bacteria in hospital B ($p < 0.001$ for each).
*Conclusions:* The levels of airborne contaminants and microbial counts in PICUs are significantly affected by the ventilation system and to less extent by outdoor levels. The results indicated that advanced filtration system and central HEPA filters play a significant role in the reduction of indoor fine particulates and TBC.


## Introduction

Health care facilities has a unique environment in terms of indoor air quality and vulnerable patient population. Healthcare facilities are usually provided with a central heating, ventilation and air conditioning (HVAC) system, which is designed to manage important air parameters that include air flow (pressure differentials), air changes per hour (ACH), relative humidity (RH), and temperature [1]. However, indoor air parameters vary in different healthcare facilities based on the scope of service provided and patient vulnerability including Intensive Care Units (ICUs). Nevertheless, the standards within ICUs vary from country to country based on the established guidelines pertaining HVAC system [2]. Several factors contribute to interrupting indoor air quality and pose a risk of transmission of infection and other respiratory complications among patients. These include but not limited to, number of beds, nebulization process, and cleaning activities [3,4]. Hence, examining the level of particulate airborne contamination and microbial air contamination as well as the factors that promote the indoor contamination, including overcrowding, inadequate ventilation, increased movement, and tropical climate conditions are very important [5]. Adverse health effects other than hospital acquired

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infections (HAI) caused by respirable particulate matters (PM) have been well documented [6]. For example, aerosolization from patient breathing or coughing, transmission through the ventilation system, or simple turbulence that stirs up particulate matter in the room can all cause airborne contamination [7]. Maintaining adequate air parameters along with high efficiency particular air (HEPA) filters integrity is crucial for proper indoor air quality [8].

A study done in Taiwan monitored temperature, relative humidity (RH), carbon dioxide ($CO_2$), suspended PM, and bacterial concentrations in post-recovery room and areas surrounding the operating theaters suggested a long term monitoring of the air parameters [9]. In another single center study done in Australia that measured indoor air particles and bio-aerosols in pediatric intensive care unit (PICU) found that indoor air contaminants are generally generated from indoor sources [4]. Another study was conducted within hospital clean rooms in Taiwan with different classes and indoor bio-aerosols pointed to the human sources of bacterial levels [10].

Although a number of indoor air pollutants and indoor environments have been explored in Saudi Arabia, data on indoor air quality of hospital are still limited. The primary goal of the present study was to evaluate the distribution and the trend of airborne particles and bio-aerosol concentration in pediatric intensive care units and outdoor in two tertiary care hospitals with different ventilation setting.

## Materials and methodology

### *Rooms setting*

Three patient rooms at two different tertiary care hospitals in Riyadh, Saudi Arabia were chosen for this study. All rooms in each hospital are located in PICU and connected to the same Air-Handling Unit (AHU). Rooms were labeled based on air specifications and HEPA filter status as follow: 1) protective environment (PE), 2) semi-protective environment (SPE) and 3) non-protective environment (NPE) and the two hospitals were labeled as hospital A and hospital B. Temperature, relative humidity (RH), relative pressure were obtained along with air particles readings and air sampling from the wall-mounted monitors installed in each room at both hospitals and additionally verified by the portable particle counter. However, air changed per hour (ACH) readings were obtained from the HVAC maintenance department log sheet for each room. Details of room setup are shown in Table 1.

Both hospitals are equipped with advanced HVAC systems. However, hospital A has newer HVAC system compared to hospital B (built in 2011 and 1990 respectively). Only hospital A is provided with a central HEPA filter. In both hospitals, PE rooms are provided with a built-in HEPA filters downstream (supply grill in the room). SPE rooms are provided a hospital grade portable air-purifier provided with HEPA filter, carbon filter, and UV light was placed in the room within 3 m of the patient's breathing zone. NPE rooms are not provided with built-in HEPA filters downstream nor portable air-purifiers. Fig. 1 sows a summarized schematic diagram of the ventilation system setup of examined rooms at both hospitals. HEPA filters at hospital A were replaced according to manufacturer's recommendations on 6th week while HEPA filters in hospital B were replaced on 8th week of the study.

**Table 1**
HEPA filter status and air specifications of patient rooms in the two hospitals.

| Hospital | Room | Central HVAC HEPA filter | Room HEPA filter | Portable Air-Purifier | Pressure | ACH |
|---|---|---|---|---|---|---|
| Hospital-A | PE | Yes | Yes | No | Positive | > 12 |
| | SPE | Yes | No | Yes | Neutral | < 12 |
| | NPE | Yes | No | No | Neutral | < 12 |
| Hospital-B | PE | No | Yes | No | Positive | > 6 |
| | SPE | No | No | Yes | Neutral | < 6 |
| | NPE | No | No | No | Neutral | < 6 |

ACH is the acceptable minimum level for PE rooms. HEPA, high-efficiency particulate absorbing; HVAC, heating, ventilation and air conditioning; PE, protective environment; SPE, semi-protective environment; NPE, non-protective environment (NPE); ACH, air changed per hour.

### *Sampling*

Air sampling was conducted at daytime during working hours between 10 AM and 1:00 PM from January to April 2021. The visits were conducted to obtain air samples from patient rooms (indoor) and air intake (outdoor). They were done once or twice a week for a four-month period. Air sampling included obtaining PM readings and collecting microbial samples for TBC and TFC from all indoor and outdoor sites. Both devices (microbial sampler and particle counter) were placed side by side in each room within patient breathing zone and 1 m from the floor. Additionally, the number of people (patient, housekeepers, visitors, medical team) in each room and weather status were observed and recorded. Outdoor reading was obtained from the air-intake of the AHU feeding the three targeted rooms.

### *Particular matter counting*

A previously calibrated optical particle counter (Lighthouse Handheld 3016 six-channel laser particle counters) was used to measure the number of particles in six diameter ranges: 03, 0.5, 1.0, 2.5, 5.0, and 10.0 (um) for 1 min at a flow rate of 2.8 L/min, according to the manufacturer's instructions. The number of particles was then categorized into two groups; fine particles (≤ 2.5 µm) and coarse particles (≤ 10 µm). The temperature and relative humidity displayed on the same device along with particles count were also recorded.

### *Microbial air sampling*

Air samples for TBC and TFC were collected using Spin air IUL sampler, based on the principle of the Andersen air sampler with a sampling rate 100/L. A 90 mm Petri dish with Sabouraud and blood agar for TFC and TBC isolation (respectively) were used. The volume of air sampled from indoor (PE, SPE, and NPE) and outdoor were 1000 L, 500 L, 200 L, and 200 L (respectively) according to the laboratory guidelines in both hospitals. Air sampler was calibrated prior to staring the study and the stage head was sterilized with 70 % alcohol swab after every sampling process to avoid cross-contamination.

### *Culture processing*

According to the guidelines of laboratories at the two hospitals, the air-sample media were incubated at 30 °C for 5–7 days and 35 °C for 48 h for fungal and bacterial count, respectively. Plates then counted and identified for the number of colonies on each plate in colony forming unit per cubic meter ($CFU/m^3$) according to the following formula; $CFU/m^3$ = CFU counted area on the agar /sample volume (Liter) X 1000 (Liter).

### *Statistical methods*

Statistical analysis was done by using SPSS package version 27.0. Categorical data such as distribution of bacterial and fungal microorganisms were presented as number and frequency. Continuous data such as the level of airborne contaminants including PMs and microbial counts were presented as means and standard deviations (SD). Airborne contaminants were compared between different ventilation setups and were plotted overtime. Differences in airborne contaminants between different rooms within each hospital were compared using Kruskal-Wallis test. Differences in airborne

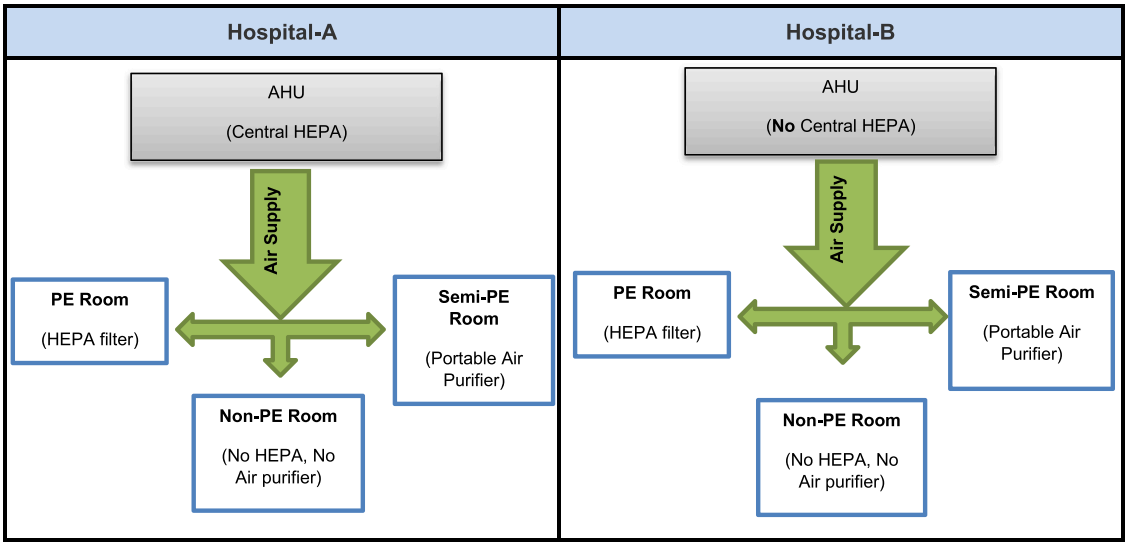


**Fig. 1.** A schematic diagram of HEPA filters distribution among patient rooms within the two hospitals. Abbreviations: HEPA, high-efficiency particulate absorbing; AHU, air handling unit; PE, protective environment; SPE, semi-protective environment; NPE, non-protective environment.

contaminants between the same rooms between the two hospitals were compared using Mann-Whitney test. All P-values were two-tailed All and were adjusted for multiple comparisons. A p-value < 0.05 was considered significant.

## Results

Table 2 shows the average masses of airborne contaminants and microbial counts in PICU with different ventilation setups in the two hospitals. The levels of fine particles, coarse particles, TBC, and TFC in both hospitals were much higher in outdoor than indoor rooms. In hospital A, the levels of fine particles, coarse particles, TBC, and TFC were not different between the three indoor rooms. Pressure (WG) was highest in PE ($p < 0.001$) while Temperature was lowest in NPE ($p = 0.006$). In hospital B, the levels of fine particles, coarse particles, and TBC were lowest in SPE ($p < 0.001$, $p = 0.004$, and $p = 0.006$, respectively), TFC was lowest in NPE ($p = 0.014$), and Temperature was highest in PE ($p = 0.004$). Hospital B had significantly higher levels of fine and coarse particles (in all room), TBC (in PE), pressure (in SPE and NPE) and Temperature (in PE and NPE) compared with matched rooms in hospital A. On the other hand, TFC was not significantly different in matched rooms in the two hospitals.

Table 3 below shows a summary of contaminants concentration level, average number of people and relative pressure of all rooms at the two hospitals on a weekly basis. Fig. 2 shows the weekly trends of PM concentrations in the two hospitals. Outdoor fine and coarse particles concentrations reached a peak between 9th-12th weeks in hospital A (1168.62 µg/m$^3$ and 1995.6 µg/m$^3$, respectively) and between 13th-16th weeks in hospital B (1119.57 µg/m$^3$ and 2691.96 µg/m$^3$, respectively). In PE rooms, fine particle concentration reached

**Table 2**
Levels of airborne contaminants of particulate matters masses and microbial counts in pediatric intensive care units with different ventilation setups in two tertiary care hospitals.

| | PE | | SPE | | NPE | | Outdoor | | Sig[1] | Sig[2] |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD | | |
| **Hospital-A** | | | | | | | | | | |
| Fine ≤ 2.5 µm mass (ug/m3) | 1.3 | 2.0 | 1.3 | 1.3 | 2.6 | 5.4 | 193.9 | 175.7 | | PE, SPE, NPE |
| Coarse ≤ 10 µm mass (ug/m3) | 6.1 | 8.4 | 4.5 | 4.2 | 3.8 | 4.8 | 323.1 | 338.6 | | PE, SPE, NPE |
| TBC (CFU/m3) | 16.7 | 25.4 | 17.9 | 23.4 | 16.8 | 19.4 | 379.5 | 464.1 | | PE |
| TFC (CFU/m3) | 0.7 | 2.7 | 0.5 | 2.2 | 0.3 | 1.1 | 20.8 | 12.6 | | |
| Number of people | 1.2 | 1.5 | 0.9 | 1.0 | 0.5 | 0.8 | | | | NPE |
| Room pressure (WG) | 0.026 | 0.046 | 0.004 | 0.015 | 0.002 | 0.009 | | | PE/SPE<br>PE/NPE | SPE, NPE |
| Temperature (C) | 23.0 | 1.2 | 23.0 | 1.0 | 21.8 | 1.1 | 25.6 | 6.6 | PE/NPE<br>SPE/NPE | PE, NPE |
| **Hospital-B** | | | | | | | | | | |
| Fine ≤ 2.5 µm mass (ug/m3) | 9.2 | 9.9 | 3.1 | 2.8 | 8.9 | 9.7 | 192.5 | 185.0 | PE/SPE<br>SPE/NPE | PE, SPE, NPE |
| Coarse ≤ 10 µm mass (ug/m3) | 39.2 | 38.2 | 14.3 | 10.5 | 26.9 | 17.4 | 680.9 | 934.7 | PE/SPE<br>SPE/NPE | PE, SPE, NPE |
| TBC (CFU/m3) | 25.2 | 23.5 | 21.7 | 23.0 | 68.8 | 69.1 | 80.5 | 55.7 | PE/NPE<br>SPE/NPE | PE |
| TFC (CFU/m3) | 1.3 | 2.3 | 1.0 | 4.0 | 0.3 | 1.1 | 31.8 | 26.1 | PE/NPE | |
| Number of people | 1.3 | 0.9 | 1.7 | 1.5 | 2.0 | 0.9 | | | | NPE |
| Room pressure (WG) | 0.025 | 0.028 | 0.025 | 0.022 | 0.029 | 0.028 | | | | SPE, NPE |
| Temperature (C) | 24.4 | 1.6 | 23.0 | 0.9 | 23.0 | 0.9 | 28.9 | 5.6 | PE/SPE<br>PE/NPE | PE, NPE |

SD, standard deviation; Sig, significance; TBC, total bacterial count; TFC, total fungal count; CFU, colony-forming unit; PE, protective environment; SPE, semi-protective environment, NPE, non-protective environment. Sig1 tests the difference between the three rooms within each hospital using Kruskal-Wallis test (significant p-value < 0.05). Sig[2] tests the difference between the same rooms between the two hospitals using Mann-Whitney test (significant p-value < 0.05). All p-values were adjusted for multiple comparisons.

**Table 3**
Indoor and outdoor levels of contaminants concentrations, number of people and relative pressure at the tow tertiary care hospitals.

| | Hospital-A | | | | | Hospital-B | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Weeks | 1st-4th | 5th-8th | 9th-12th | 13th-16th | 17th-20th | 1st-4th | 5th-8th | 9th-12th | 13th-16th | 17th-20th |
| Fine Particles (µg/m3) | | | | | | | | | | |
| PE | 1.52 | 11.83 | 2.42 | 1.19 | 9.84 | 15.45 | 73.88 | 38.12 | 37.37 | 19.84 |
| SPE | 6.1 | 4.98 | 6.36 | 2.57 | 5.34 | 7.93 | 8.67 | 11.01 | 13.3 | 21.29 |
| NPE | 27.92 | 4.73 | 1.2 | 14.57 | 2.64 | 11.72 | 60.24 | 40.81 | 25.05 | 39.49 |
| Outdoor | 542.27 | 532.55 | 1168.62 | 885.39 | 748.88 | 260.51 | 535.51 | 973.44 | 1191.57 | 895.45 |
| Coarse Particles (µg/m3) | | | | | | | | | | |
| PE | 9.54 | 41.41 | 8.39 | 7.43 | 54.76 | 61.27 | 244.9 | 109.33 | 266.97 | 101.83 |
| SPE | 15.45 | 10.04 | 16.64 | 15.17 | 32.15 | 40.61 | 31.62 | 37.86 | 79.95 | 96.03 |
| NPE | 17.03 | 18.15 | 4.19 | 28.86 | 8.25 | 31.89 | 57.27 | 134.35 | 170.16 | 144.29 |
| Outdoor | 776.32 | 816.93 | 1995.6 | 1921.15 | 952.3 | 804.69 | 918.54 | 2691.96 | 5585.1 | 3618.12 |
| Total Bacterial Count (CFU/m3) | | | | | | | | | | |
| PE | 35 | 98 | 4 | 116 | 81 | 157 | 112 | 95 | 54 | 86 |
| SPE | 28 | 148 | 22 | 72 | 87 | 76 | 118 | 100 | 20 | 120 |
| NPE | 55 | 60 | 45 | 175 | 0 | 390 | 310 | 380 | 60 | 236 |
| Outdoor | 2425 | 1225 | 1390 | 1910 | 640 | 290 | 285 | 255 | 500 | 280 |
| Total Fungal Count (CFU/m3) | | | | | | | | | | |
| PE | 1 | 12 | 0 | 1 | 0 | 1 | 10 | 5 | 2 | 7 |
| SPE | 0 | 10 | 0 | 0 | 0 | 2 | 18 | 0 | 0 | 0 |
| NPE | 5 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 |
| Outdoor | 55 | 80 | 100 | 100 | 80 | 25 | 175 | 120 | 260 | 56 |
| Average number of people | | | | | | | | | | |
| PE | 0.250 | 1.750 | 0.000 | 2.250 | 1.750 | 1.000 | 1.250 | 0.750 | 2.500 | 1.250 |
| SPE | 0.750 | 1.000 | 0.500 | 0.250 | 1.750 | 1.000 | 0.500 | 2.250 | 3.000 | 1.750 |
| NPE | 0.500 | 0.250 | 0.000 | 1.000 | 0.750 | 2.250 | 2.500 | 1.750 | 2.000 | 1.500 |
| Average Relative Pressure (W.G.) | | | | | | | | | | |
| PE | 0.014 | 0.014 | 0.019 | 0.066 | 0.016 | 0.037 | 0.057 | 0.012 | 0.020 | 0.002 |
| SPE | -0.003 | 0.000 | 0.000 | 0.012 | 0.012 | 0.023 | 0.056 | 0.012 | 0.008 | 0.024 |
| NPE | -0.002 | 0.000 | 0.010 | 0.000 | 0.000 | 0.020 | 0.055 | 0.012 | 0.012 | 0.046 |

PE, Protective Environment room; SPE, Semi Protective Environment room; NPE, None Protective Environment room; CFU, Colony Forming Unit; W.G., Water Gauge.

the peak in both hospitals between 5th-8th weeks (11.83 µg/m$^3$ and 73.88 µg/m$^3$, respectively), and coarse particle concentration reached the peak in hospital A between 17th-20th weeks (54.76 µg/m$^3$) and 13th-16th weeks (266.97 µg/m$^3$) in hospital B. In SPE rooms of hospital A and B, fine particle concentration reached the peak between 9th-12th weeks (6.36 µg/m$^3$) and 17th-20th weeks (21.29 µg/m$^3$) respectively, and coarse particle concentration reached the peak between 17th-20th weeks for both hospitals (32.15 µg/m$^3$ and 96.03 µg/m$^3$, respectively). In NPE rooms of hospital A and B, fine particle concentration reached the peak between

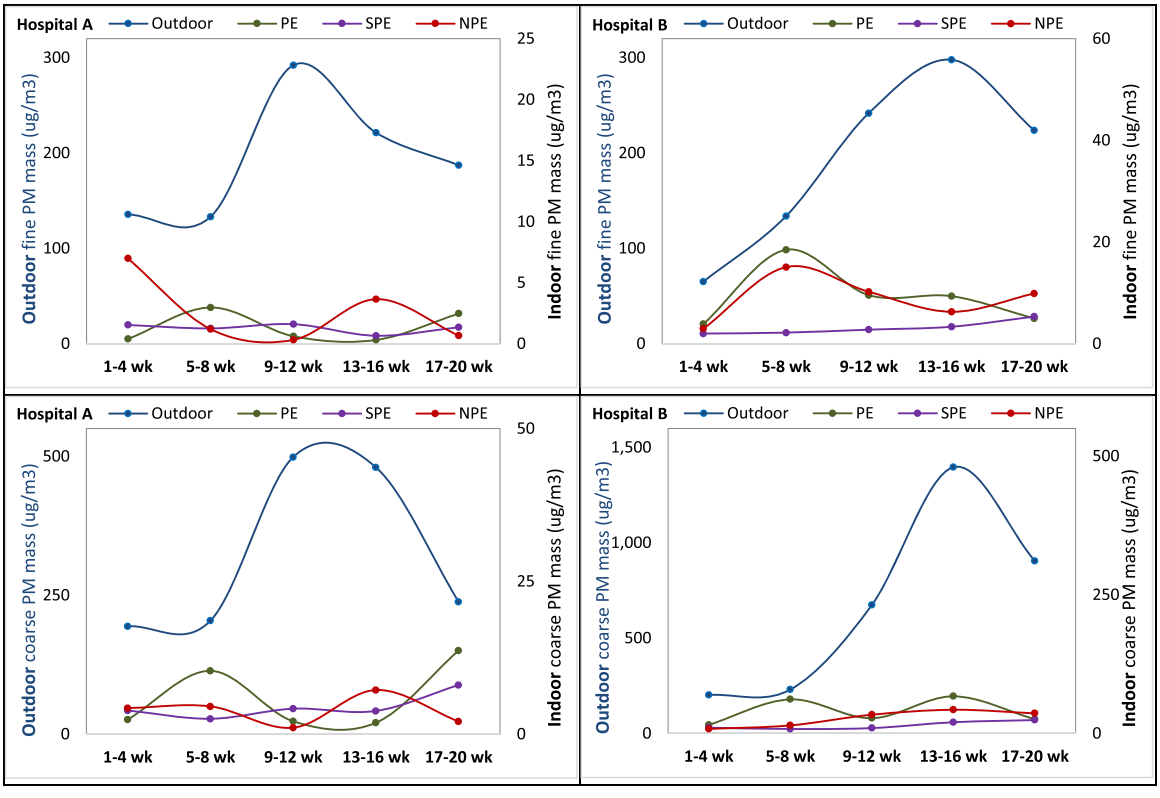


**Fig. 2.** Weekly trends of particulate matters masses in pediatric intensive care units with different ventilation setups in two tertiary care hospitals.

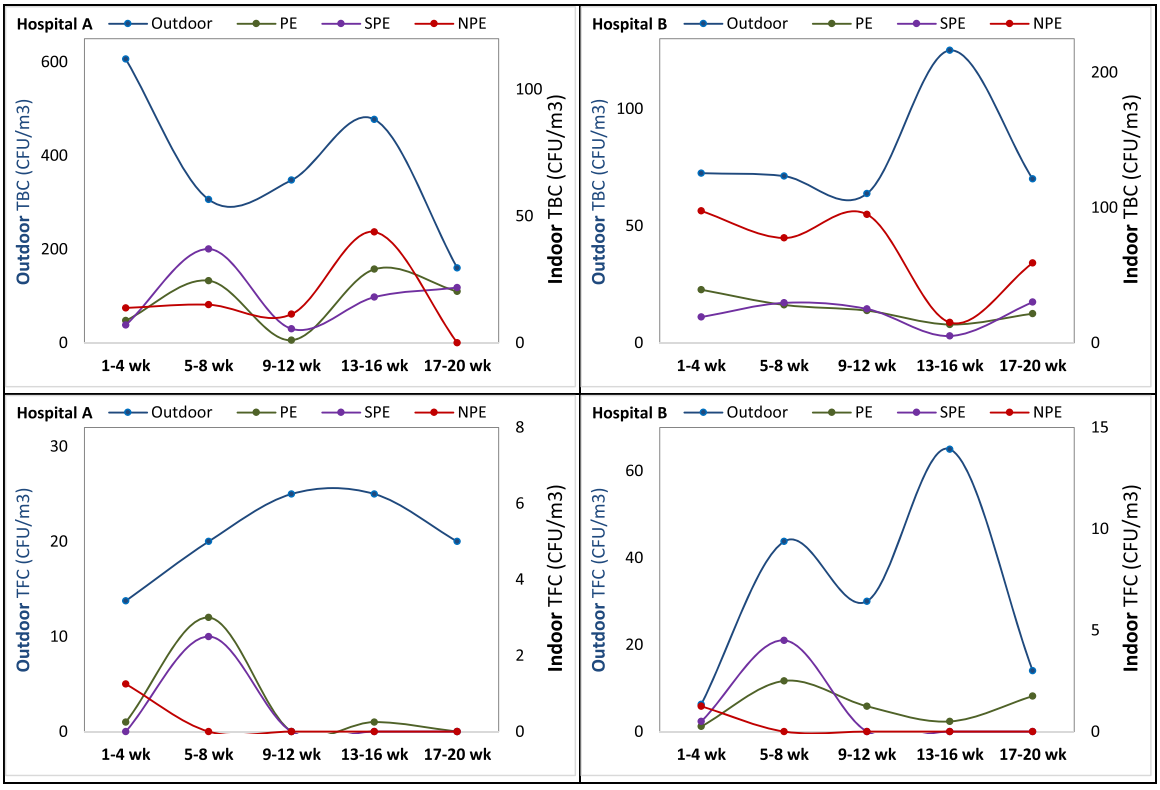


**Fig. 3.** Weekly trends of microbial counts in pediatric intensive care units with different ventilation setups in two tertiary care hospitals.

1th-4th weeks (27.92 μg/m$^3$) and 5th-8th weeks (60.24 μg/m$^3$) respectively, and coarse particle concentration reached the peak between 13th-16th weeks for both hospitals (2.86 μg/m$^3$ and 170.16 μg/m$^3$, respectively).

Fig. 3 shows the weekly trends of microbial counts in the two hospitals. Outdoor TBC reached a peak between 1st and 4th weeks in hospital A (2425 cfu/m$^3$) and between 13th-16th weeks in hospital B and (500 cfu/m$^3$). Outdoor TFC reached a peak between 9th-16th weeks in hospital A (100 cfu/m$^3$) and between 13th and 16th weeks in hospital B (260 cfu/m$^3$). In PE room, TBC reached the peak between 13th-16th weeks (116 cfu/m$^3$) in hospital A and between 1st and 4th weeks (175 cfu/m$^3$) in hospital B, and TFC reached the peak between 5th and 8th weeks in both hospitals (12 cfu/m$^3$ and 10 cfu/m$^3$, respectively). In SPE room, TBC reached the peak between 5th and 8th weeks (148 cfu/m$^3$) in hospital A, and 17th-20th weeks (120 cfu/m$^3$) in hospital B, and TFC reached the peak between 5th-8th weeks in both hospitals (10 cfu/m$^3$ and 18 cfu/m$^3$, respectively). In NPE room, TBC reached the peak between 13th-16th weeks in hospital A (175 cfu/m$^3$) and 1st-4th weeks in hospital B (390 cfu/m$^3$). However, TBC indoor level was higher than outdoor levels between 1st and 12th weeks in hospital B. TFC reached the peak between 1st-4th weeks in both hospitals (5 cfu/m$^3$ for both hospitals).

Table 4 and Fig. 4 show the microbial distribution within PICU at the two tertiary care hospitals. With regard to the outdoor bacterial bio-aerosols, gram-positive bacteria were the predominant microorganisms in hospital A, followed by bacterial flora then gram-negative bacteria (69 %, 28 % and 3 % respectively), while bacterial flora was the predominant microorganisms isolated at hospital B, followed by gram-positive and then gram-negative (69.4 %, 30.3 % and 0.3 % respectively) with $p < 0.001$ significance in each hospital. The same predominant microorganisms finding was replicated in all types of indoor rooms at both hospitals. On the other hand, other fungi were the predominant microorganisms in PE, SPE and outdoor (39 %, 100 % and 80 % respectively) with $p < 0.001$significance. While in NPE room *Alternaria spp* and *Aspergillus spp*. were the two microorganisms isolated (60 % and 40 % respectively). In hospital B. *Alternaria spp*. was the highest among all microorganisms isolated in NPE room and outdoor (100 % and 23 % respectively), *Penicillium spp*. was the predominant fungi isolated in SPE room (90 %) and *Monilia spp*. in PE room (36 %).

## Discussion

### *Indoor PM concentrations*

The current study showed that outdoor concentration of PMs in both hospitals were much higher than indoor levels. This finding is in agreement with Mohammadyan et al. who demonstrated that mean outdoor levels of fine particles (PM 1.0 and PM 2.5) and coarse particles (PM10) were much higher than indoor levels in hospital microenvironments [11]. Hospitals in developed countries, such as Europe and Taiwan, have typically low mean indoor PM concentrations. According to Baurès et al. [12], Jung [13], and Loupa et al. [14], PM 2.5 and PM10.0 have mass concentrations of < 20 and < 25 μg/m$^3$, respectively. These findings are in line with the current findings at all rooms except coarse particles in PE and NPE rooms at hospital B (39.2 μg/m$^3$ and 26.9 μg/m3 respectively). The values measured in South Korea (PM10, 57 μg/m$^3$) and China (PM2.5, 98 and 124 μg/m$^3$) were significantly higher, reaching levels of up to 250 μg/m$^3$, respectively [15]. In another study done at the University Hospital at eastern region, in Saudi Arabia, hospital recorded mean indoor and outdoor PM10 mass concentrations were 255 μg/m$^3$ and 344 μg/m$^3$, respectively [16]. The result indicated higher coarse particles (PM10) than all indoor rooms, similar to hospital A outdoor (323.1 μg/m$^3$) and lower than hospital B outdoor (680.9 μg/m$^3$). The mean interior PM10 mass concentration in four hospitals in Guangzhou, China, was 128.13 μg/m$^3$, ranging from 61 to 250 μg/m$^3$, while the mean indoor PM2.5 mass concentration was 99 μg/m$^3$, ranging from 4.9 to 215 μg/m$^3$ [17].

**Table 4**
Microbial distribution within PICU at the two tertiary care hospitals.

| Facility | HOSPITAL-A | | | | HOSPITAL-B | | | |
|---|---|---|---|---|---|---|---|---|
| Location | PE | SPE | NPE | Outdoor | PE | SPE | NPE | Outdoor |
| **Bacterial count (CFU/m3)** | | | | | | | | |
| Gram positive | 289 (87 %) | 285 (80 %) | 250 (75 %) | 5775 (76 %) | 129 (25 %) | 131 (30 %) | 815 (59 %) | 200 (12 %) |
| Gram negative | 7 (2 %) | 2 (1 %) | 25 (7 %) | 1490 (20 %) | 1 (1 %) | 4 (1 %) | 5 (0.5 %) | 285 (18 %) |
| Bacterial flora | 38 (11 %) | 70 (19 %) | 60 (18 %) | 325 (4 %) | 374 (74 %) | 299 (69 %) | 556 (40.5 %) | 1125 (70 %) |
| **Fungal count (CFU/m3)** | | | | | | | | |
| Alternaria spp. | 0 (0 %) | 0 (0 %) | 3 (60 %) | 26 (7 %) | 1 (4 %) | 2 (10 %) | 5 (100 %) | 145 (23 %) |
| Aspergillus spp. | 0 (0 %) | 0 (0 %) | 2 (40 %) | 17 (4 %) | 4 (16 %) | 0 (0 %) | 0 (0 %) | 85 (13 %) |
| Fusarium spp. | 0 (0 %) | 0 (0 %) | 0 (0 %) | 6 (2 %) | 1 (4 %) | 0 (0 %) | 0 (0 %) | 22 (3 %) |
| Penicillium spp. | 0 (0 %) | 0 (0 %) | 0 (0 %) | 17 (4 %) | 3 (12 %) | 18 (90 %) | 0 (0 %) | 75 (12 %) |
| Chaetomium spp. | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 2 (8 %) | 0 (0 %) | 0 (0 %) | 135 (21 %) |
| Cladosporium spp. | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 1 (4 %) | 0 (0 %) | 0 (0 %) | 25 (4 %) |
| Curvularia | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 4 (16 %) | 0 (0 %) | 0 (0 %) | 22 (3 %) |
| Helminthosporium | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 38 (6 %) |
| Rhizopus spp. | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 45 (7 %) |
| Monilia spp. | 0 (0 %) | 0 (0 %) | 0 (0 %) | 12 (3 %) | 9 (36 %) | 0 (0 %) | 0 (0 %) | 44 (7 %) |
| Other molds | 1 (7 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) |
| Other fungi | 13 (93 %) | 10 (100 %) | 0 (0 %) | 308 (80 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) |

PE, Protective Environment room; SPE, Semi Protective Environment room; NPE, None Protective Environment room.

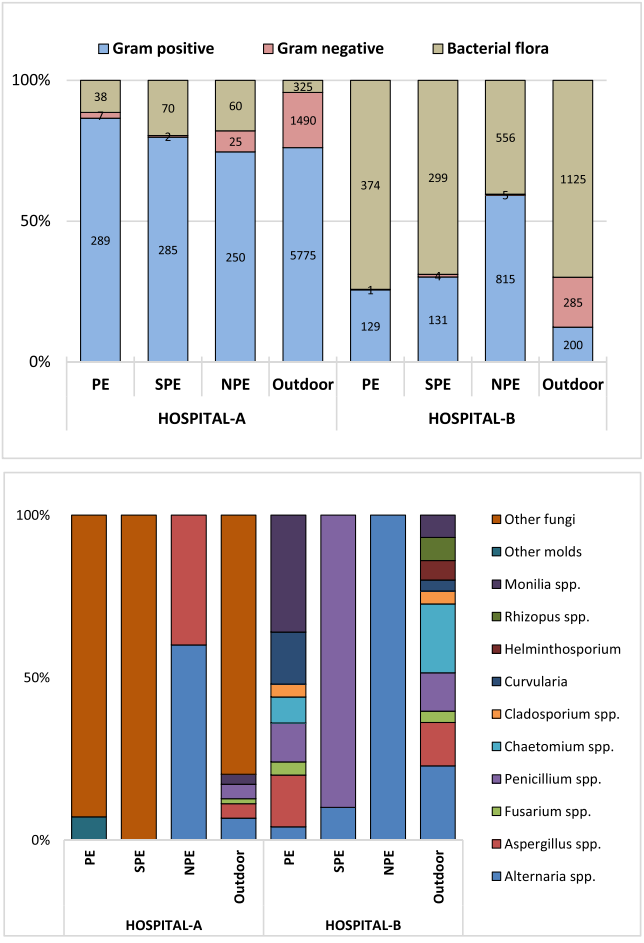


**Fig. 4.** Distribution of bacterial (above) and fungal (below) in PICU at the two tertiary hospitals.

*PM distributions in Hospital A and Hospital B*

Indoor coarse and fine particles concentrations were found to be much higher in hospital B for all rooms compared with matched rooms in Hospital A. It is suggested that HEPA filter installed in the central AHU and feeds all rooms, along with the newer HVAC system in hospital A have a great impact on the lower levels of both fine and coarse particles. These findings are consistent with Jung et al. Jung ($year$) [13], who demonstrated that coarse and fine particles concentrations were higher at the hospitals with non-central air conditioning systems. Moreover, Ren Y.F. demonstrated that ventilation systems that are equipped with advanced filtration tools are considered an effective strategy for indoor air quality improvement [18]. Furthermore, PE rooms in particular has significantly lower levels of all contaminants compared to the same room at hospital B which is linked to an additional factor over HEPA filters and newer HVAC system which ACH. The current results are consistent with Parvizi et al. and Liang et al. who proved that increasing the ACH could reduce particulate matter and microbial counts concentrations [19,20]. Furthermore, levels of fine particles, coarse particles and TBC were lowest in SPE room at hospital B. Since the average rooms' relative pressure were almost the same and the finding may be related to the effectiveness of the portable air purifier placed in this room.

*PM concentration trends*

It was noticed that the outdoor PMs concentration in the current study reached the peak in hospital A and B between 9th-12th and 13th-16th weeks respectively during a sandstorm. Nevertheless, coarse particle concentrations reached the peak during similar/closer periods in most of the rooms at both hospitals which suggest that the predominant source of indoor coarse particles contamination is outdoor infiltration. This finding is in line with El-Sharkawy & Noweir who reported that indoor levels of coarse particles in hospital environments could be greatly affected by outdoor sources [16]. The increased indoor/outdoor (I/O) PM mass ratios suggested that outdoor air is most likely the primary source of the problem [13,14,17,21]. The same was observed in the current study for all air contaminants except for TBC in NPE room at hospital B where the (I/O) ratio was reversed. This finding could be related to the number of people in NPE room where the average number of people in this room was the highest among the three rooms.

*Indoor microbial concentration*

The current study showed that outdoor levels of TFC in both hospitals were much higher than indoor levels. Additionally, TBC was higher indoor than outdoor between 1st-12th weeks in NPE room at hospital B. Moreover, hospital B had higher levels of TBC and TFC concentrations in all rooms compared with matched rooms in hospital A. These variations in the results between the two hospitals

may be related to some factors that were monitored over the course of this study including 1) highest number of people, 2) low relative pressure, 3) lack of central and portable HEPA filtration and 4) low ACH in hospital B. The current study also showed that the average number of people in all rooms of hospital B was higher compared with matched rooms in hospital A. In addition, the study demonstrated that hospital B had significantly higher temperature (in PE and NPE in particular) compared with matched rooms in hospital A. Our findings are consistent with Hwang et al. who found a significant relationship between total airborne bacteria and temperature [15]. However, our findings were not in agreement with Mousavi et al. who indicated that the bio-aerosol count was not affected by the temperature and the number of people attending the room [22].

### *Microbial distributions in Hospital A and Hospital B*

The current study shows that the predominant bacterial species in hospital A was gram-positive bacteria, while the predominant bacterial species in hospital B was bacterial flora. The same finding was replicated in outdoor at both hospitals with regard to the predominant microorganisms; i.e. gram-positive in hospital A and bacterial flora in hospital B. Within the rooms in each hospital, gram negative bacteria were generally low but found to be the highest in NPE rooms, which is an indication of outdoor environmental sources due to less filtration. On the other hand, gram-positive bacteria and normal flora were found in PE room in hospital A and NPE room in hospital B that is in line with the highest number of people in these two rooms at both hospitals. This finding is in agreement with Huang et al. and Yu et al. who measured the levels of airborne microorganisms in intensive care units and suggested that the number of patients in the room can lead to increased levels of airborne counts [23,24]. On the other hand, other fungi were the predominant microorganisms in PE, SPE and outdoor which might may be related to outdoor infiltration in these two rooms. In NPE, however, the only two microorganisms isolated were *Alternaria spp* and *Aspergillus spp*. which is probably an indication of indoor source.

### *Strengths and limitations of the study*

The study is unique in bridging a local data deficiency regarding the impact of ventilation system over controlling the airborne contaminants in PICU in Saudi Arabia. However, we did not examine the association between temperature and relative humidity with airborne contaminants distribution, particularly TBC and TFC. Additionally, air volume variable was not monitored in this study. Nevertheless, the finding are valuable and the limitations are unlikely to significantly change the conclusions.

### *Conclusions*

In conclusions, the current study revealed that the levels of airborne contaminants and microbial counts in PICUs are significantly affected by the ventilation system and to less extent by outdoor levels. The results indicated that advanced filtration system and central HEPA filters play a significant role in the reduction of indoor fine particulates and TBC. The study also demonstrated that room's number of people and relative pressure in PICU rooms could affect the distribution of TBC and fine particles in particular. Therefore, it is recommend to implement strict measures to control the number of people in PICU in addition to maintaining rooms' relative pressure for protective environment precisely. Implementation of such measures could improve indoor air quality, and hence, benefit patients' outcomes.

## Ethics approval

The study obtained all required approvals from the Institutional Review Board of King Abdullah International Medical Research Center (SP20–386-J).

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## CRediT authorship contribution statement

**Waleed Alghamdi:** Idea, literature search, and writing. **Abdullatif Neamatallah:** Idea and critical review. **Majid Alshamrani:** Idea and critical review. **Fahad Al Mehmad:** Idea and critical review. **Aiman El-Saed:** Analysis and critical review.

## Data Availability

Will provided upon reasonable request.

## Conflict of interest

All authors have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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