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RESEARCH ARTICLE

A look at an urban tertiary hospital's indoor air pollutants using source apportionment of $PM_{2.5}$

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ABSTRACT

Background: Ironically, the hospital which is believed to be a healthy and safe place can be dangerous to health. Pollutants such as particulate matter 2.5 microns ($PM_{2.5}$) can be present in hospital indoor air and may adversely affect the health of the hospital occupants.

Objective: This study aims to identify and apportion Possible sources of indoor PM2.5 in an urban tertiary care hospital in the Philippines

Methods: $PM_{2.5}$ measurements were conducted in two naturally ventilated wards (NVWs), two mechanically ventilated wards (MVWs), and a roof deck near the hospital. Mass concentrations with analytical uncertainties of thirteen elements (Al, Na, S, Si, Cl, K, Ca, V, Fe, Zn, Br, Hg, Pb) from $PM_{2.5}$ measurements were utilized with Positive Matrix Factorization (PMF) receptor model to identify and apportion possible sources of indoor $PM_{2.5}$.

Results: In NVWs and MVWs, four types of sources were identified including sodium and chlorine sources, crustal emissions, anthropogenic sulfur sources, and road dust. Cleaning agents used in the hospital were identified as an anthropogenic indoor source of sodium while the other factors mainly came from outdoor sources.

Conclusion: The contribution of anthropogenic outdoor pollutants such as road dust and sulfur sources to indoor $PM_{2.5}$ is highlighted in the study. The types of indoor and outdoor sources of indoor $PM_{2.5}$ can be influenced by the type of ventilation.

Keywords: *source apportionment, positive matrix factorization, $PM_{2.5}$, hospital indoor air, naturally ventilated wards, mechanically ventilated wards, indoor air pollutants*

Introduction

Air pollution, also known as a silent killer, is the world's greatest environmental risk to health with fine particulate matter or $PM_{2.5}$ transporting toxicants such as heavy metals and allergens that are responsible for decreased lung function, respiratory, and cardiovascular diseases [1,2]. These microscopic pollutants are responsible for 7 million premature deaths globally every year from diseases such as cancer, stroke, heart, and lung disease due to their capacity to penetrate respiratory and circulatory systems [1]. Many pollutants and sources are abundant outdoors, but exposure to indoor air pollutants is of greater concern since people spend about 90% of their time indoors where some pollutants can be 2-5 times higher in concentration than those found outdoors [3]. Synthetic building materials, personal care products, pesticides, and household cleaners can contribute to indoor air pollution [3]. Outdoor $PM_{2.5}$ can also infiltrate various indoor environments [2]. In light of these, several studies have characterized $PM_{2.5}$ and conducted source apportionment in indoor settings such as hospitals, schools, retirement communities, and homes [2,4,5,6,7,8,9].

The hospital, which is perceived as a place of healing and recovery can be a place where an unseen threat such as air pollution lurks. Air quality inside hospitals, like in any other indoor environment, can be influenced by various indoor and outdoor activities. In a study by Raysoni *et al.*, it was shown that indoor particles are mostly of outdoor origin [10]. Outdoor air has consistently been emphasized as a major source of indoor air pollution. Various factors and mechanisms such as air exchange rate, window gaps and fissures on walls, and central air conditioning use have been proven to contribute to the indoor infiltration of outdoor $PM_{2.5}$ [11,12,13]. Addressing this environmental health issue, especially in hospitals, requires an efficient indoor air quality management strategy [14]. Currently, no studies exist on the apportionment of sources of indoor air pollution in Philippine hospitals. The investigators aimed to generate information on the pollutant sources, their location, and extent of contribution to hospital indoor air pollution.

Potential contributors of $PM_{2.5}$ in the indoor air of an urban tertiary care hospital in the Philippines were investigated in this study using source apportionment analysis with a receptor model, Positive Matrix Factorization (PMF).

Methodology

Study Site

The hospital, with 14 clinical departments, has a 1500-bed capacity and is in a reclaimed area in Metro Manila (Figure 1) whose shoreline is about 600 meters away. Surrounding it are main streets which are heavily traversed by public utility buses, jeepneys, vans, tricycles, as well as private vehicles including motorcycles. The hospital is also located between two train stations. Neighboring the hospital are several academic institutions and commercial buildings. Dormitories, food establishments, clinical laboratories, and drug stores are situated in the same block across the hospital. It is also nearby one of the biggest malls in Manila. The site was chosen because patients are mostly from low to lower-middle socioeconomic status who are immunocompromised and have increased susceptibility to adverse health effects of $PM_{2.5}$ [15,16].

The hospital building is comprised of eight (8) floors. The $PM_{2.5}$ samples were obtained from four wards, namely the Pediatrics ward (Pedia) and Medicine ward (Med) which are both on the ground floor, the Central Intensive Care Unit (CENICU) on the second floor, and the Neonatal Intensive Care Unit (NICU) on the fourth floor. All the selected study sites were non-partitioned and multiple-bed wards. The Pedia and Med are naturally ventilated wards (NVWs) while the CENICU and NICU are mechanically ventilated wards (MVWs). In this study, natural ventilation is defined as the use of open windows and electric fans in the absence of a window-type or a centralized air conditioning system. On the other hand, mechanically ventilated wards are those with closed windows and centralized and/or window-type air conditioning systems.

Data Collection

Mass concentrations and analytical uncertainties of thirteen elements (Al, Na, S, Si, Cl, K, Ca, V, Fe, Zn, Br, Hg, Pb)

Figure 1. *Map of the sampling site. Surrounding establishments are mainly commercial and residential. Commercial establishments include hotels, bars, restaurants, food chains, and business centers. Mixed-use areas include schools, churches, and industrial establishments. The sampling site is situated near a bay and a park.*

were used as input to PMF. Briefly, indoor and outdoor collection and measurement of $PM_{2.5}$ were previously done. Harvard impactors (HIs) were strategically located in the four (4) sampling sites and at an outdoor site on an elevated platform at a roof deck approximately 212 meters from the study site. The mass concentration of $PM_{2.5}$ was initially determined by impactor volumetric measurement wherein the samples are collected in filters at a specific flow rate and time. Air sampling made use of the Leland Legacy Sampler for $PM_{2.5}$. The sampler drew air into an inlet in the Harvard Impactor. The fine particulates were collected in polytetrafluoroethylene (PTFE) membrane filters which were analyzed gravimetrically using a microbalance. After gravimetric analysis, the $PM_{2.5}$ samples were brought to the Harvard School of Public Health for analysis by X-ray Fluorescence spectrometry. A more detailed description of the sampling methodology and chemical analysis can be found elsewhere [15].

Some constituents of $PM_{2.5}$ such as elemental and organic carbon, and nitrates were not measured due to lack of equipment. Ocular inspections were done for all the 4 study sites using an observation checklist (for details, see supplemental document 1). Key Informant Interviews (KIIs) and self-administered questionnaires with selected hospital personnel were conducted in order to validate the observed and documented potential $PM_{2.5}$ indoor sources.

The key informants include the head nurses of each of the four study wards, and a staff engineer from the engineering and technical services office of the hospital. This study received institutional review board approval prior to its conduct and informed consent from all key informants were obtained.

Data Analysis

Descriptive statistics for indoor and outdoor concentrations of $PM_{2.5}$ and related elements were calculated. Correlation coefficients to evaluate the relationship among indoor $PM_{2.5}$, outdoor $PM_{2.5}$, and the related elements were estimated using SPSS Statistics 20 and Microsoft Excel 2010. In addition, t-tests for difference of mean concentrations of indoor and outdoor $PM_{2.5}$ and their related elements between NVWs and MVWs, between Med and Pedia, and between NICU and CENICU were computed. P-values of ≤ 0.05 were considered statistically significant.

Using the concentrations and corresponding uncertainties of the 13 elements of indoor $PM_{2.5}$, PMF analysis was performed to identify sources and profiles of indoor $PM_{2.5}$. Data were classified based on the 4 sampling sites and the types of ventilation. The PMF 5.0 software of US EPA was downloaded for free and utilized in the study. Three to seven factors were used to identify potential sources of indoor air pollution in all the 4 sites. The optimal number of factors was determined after analyzing the results as recommended by the European Guide to achieve multiple solutions. In the analysis, runs were not randomly started and seed number 25 was specified for all runs in order for the results to be replicable [17,18]. Each PMF base model run generated the primary PMF output of profiles and contributions. The optimal number of factors was identified after analyzing the goodness of fit Q-values for the entire run, the scaled residuals, the G-space plots, and the physical meaningfulness of the factor profiles and contributions [18]. Sources were identified using major marker species based on established references. The interpretation of results relied on the physical meaningfulness of the factor profiles and contributions. The identified source factors were linked to the physical sources of emissions based on the closeness of the derived source profiles to those reported in the literature, available information on local emission sources, results of the ocular surveys and KIIs of the hospital staff [19].

Results

The analysis of mass concentrations of indoor $PM_{2.5}$ and the 13 elements from the 4 sites yielded the results summarized in Table 1.

The mean (standard deviation, SD) of indoor $PM_{2.5}$ concentrations for the NVWs were 28.55 (10.08) $\mu g/m^3$ and 31.11 (9.91) $\mu g/m^3$ for Pedia and Med, respectively, while the concentrations for the MVWs were 21.81 (6.64) $\mu g/m^3$ and 20.61 (6.10) $\mu g/m^3$ for CENICU and NICU, respectively. In addition, the mean indoor concentration of the 13 elements ranged from 3.06 ng/m^3 to 1,142.30 ng/m^3. Furthermore, indoor $PM_{2.5}$ were statistically significantly lower in MVWs than NVWs (p-value < 0.05). In NICU, sulfur was the dominant element of the site with a mean concentration 742.63 (398.82) ng/m^3, followed by sodium, 288.97 (194.52) ng/m^3. It was also the dominant element, with a concentration of 1142.30 (659.58) ng/m^3, in the Pedia ward. Concentrations of several elements were higher in NVWs than MVWs, however, for sodium, chlorine, and iron, concentrations were not statistically different between the two types of ventilation.

Table 2 summarizes the sources, their major elemental components, and the identified factors for the study sites by ventilation type stratification. Major elemental components of

Table 1. *Comparison of indoor concentrations of PM2.5 and elements in study sites [mean (SD: standard deviation)].*

Study sites									
Element	**Med**	**Pedia**	**p-value**	**CENICU**	**NICU**	**p-value**	**NVWs**[1]	**MVWs**[2]	**p-value**
Al (ng/m^3)	-	-	-	31.78 (17.12)	33.54 (16.29)	0.58	-	-	-
Na (ng/m^3)	248.29 (107.52)	343.95 (129.74)	< 0.01	247.3 (95.00)	288.97 (194.52)	0.17	303.30 (144.61)	266.02 (148.93)	0.06
S (ng/m^3)	1108.66 (626.71)	1142.30 (659.58)	0.79	803.98 (409.95)	742.63 (398.82)	0.43	1125.79 (640.87)	721.35 (328.02)	< 0.01
Si (ng/m^3)	69.10 (34.67)	64.34 (36.91)	0.49	35.55 (16.92)	41.34 (21.49)	0.12	69.46 (40.28)	34.54 (13.70)	< 0.01
Cl (ng/m^3)	55.62 (57.75)	74.48 (55.48)	0,14	44.81 (40.09)	78.86 (108.14)	0.12	65.13 (57.15)	69.70 (126.99)	0.73
K (ng/m^3)	315.15 (103.52)	317.63 (119.23)	0.91	197.86 (40.61)	227.63 (93.56)	0.04	316.42 (111.28)	226.98 (81.62)	< 0.01
Ca (ng/m^3)	75.80 (34.51)	78.04 (44.59)	0.77	73.53 (30.16)	169.59 (45.43)	< 0.01	73.60 (35.34)	116.72 (60.98)	< 0.01
V (ng/m^3)	5.55 (3.50)	4.53 (2.38)	0.08	3.35 (2.14)	3.06 (1.81)	0.45	4.73 (2.47)	3.14 (1.87)	< 0.01
Fe (ng/m^3)	86.59 (35.11)	84.48 (30.83)	0.75	92.31 (44.78)	58.69 (21.87)	0.00	81.62 (27.16)	84.25 (66.62)	0.70
Zn (ng/m^3)	91.49 (46.56)	87.29 (44.94)	0.65	51.73 (18.76)	53.05 (27.71)	0.75	86.63 (41.55)	51.74 (21.70)	< 0.01
Br (ng/m^3)	6.20 (4.68)	7.03 (5.93)	0.39	5.83 (4.67)	-	-	6.62 (5.34)	4.79 (3.98)	< 0.01
Hg (ng/m^3)	8.16 (6.31)	8.52 (6.85)	0.78	5.62 (4.43)	5.96 (4.35)	0.68	8.12 (6.21)	5.63 (4.19)	< 0.01
Pb (ng/m^3)	23.14 (13.39)	20.10 (10.31)	-	15.00 (8.38)	11.88 (7.27)	0.04	20.47 (10.25)	13.58 (8.02)	< 0.01
Indoor $PM_{2.5}$ (ug/m^3)	28.55 (9.99)	31.11 (9.70)	0.18	21.81 (6.59)	20.61 (6.03)	0.33	29.85 (9.97)	21.27 (6.40)	< 0.01

[1] Naturally Ventilated Wards (NVWs): Medicine and Pediatrics wards

[2] Mechanically Ventilated Wards (MVWs): Neonatal ICU and Central ICU

Table 2. *Types and number of factors obtained for the NVWs and MVWs*

Sources		Major components	NVWS[1]	MVWS[1]	Pedia	Med	NICU	CENICU
1	Sodium and chlorine sources (cleaning agents and sea salt)	Na-Cl	+	+	-	+	+	+
2	Anthropogenic sulfur sources (Vehicle exhaust, industrial emissions)	S	+	+	+	+	+	+
3	Road dust (break and tire wear, railroad tracks wear)	Zn, Pb, Ca, Si, Fe	+	+	+	+	+	+
4	Crustal emissions	Ca, Si, Fe	+	+	+	+	+	+
	Total no. of factors		4	4	3	4	4	4

[1] *Naturally Ventilated Wards (NVWs): Medicine and Pediatrics ward*
[2] *Mechanically Ventilated Wards (MVWs): NICU and CENICU*

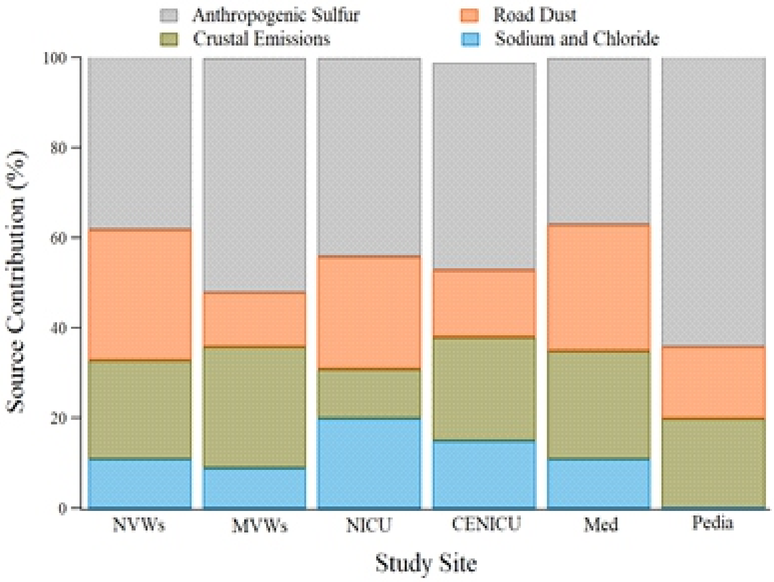

Figure 2. *Source contributions of the four factors across all study sites*

each factor served as basis for the identification of the potential source. Four distinct source types were identified from the PMF results including sodium and chlorine, anthropogenic sulfur, road dust, and crustal emissions. In addition, only 3 factors were identified in the Pedia ward while 4 factors were found in the other sites.

Figure 2 shows the source contributions of the factors across all the study sites. Contributions from sulfur sources were highest among the PM2.5 concentrations in all the study sites. However, either road dust or crustal emissions was the second highest. The results also showed that sodium and chlorine sources, which had the least contribution, were not present in the Pedia ward, but were present in three out of four sampling sites. Their absence in the site may be attributed to the limitations of the PMF receptor model.

As seen in Table 3, when the sites were stratified according to type of ventilation, sodium and chlorine sources were present in both the NVWs and MVWs. Aside

Table 3. *PM concentrations of each source across all sampling sites ($\mu g/m^3$)*

Source	NVWs	MVWs	NICU	CENICU	Med	Pedia
Anthropogenic sulfur	0.820 (39%)	0.861 (52%)	0.750 (44%)	0.735 (46%)	0.756 (37%)	0.876 (64%)
Road dust	0.618 (29%)	0.198 (12%)	0.435 (25%)	0.243 (15%)	0.576 (28%)	0.212 (15%)
Crustal emissions	0.463 (22%)	0.438 (27%)	0.187 (11%)	0.371 (23%))	0.495 (24%))	0.268 (20%)
Sodium and chlorine	0.227 (11%)	0.153 (9%))	0.337 (20%)	0.246 (15%)	0.228 (11%)	-

[1] *Naturally Ventilated Wards (NVWs): Medicine and Pediatrics ward*
[2] *Mechanically Ventilated Wards (MVWs): NICU and CENICU*

from crustal emissions and potentially sea salt, all other factors are anthropogenic, as evidenced by their enrichment factors which exceeded 1.

Discussion

The sources of $PM_{2.5}$ of a hospital in the Philippines can be both indoor and outdoor and can be anthropogenic and/or natural in origin. Data from a previous study on $PM_{2.5}$ concentrations in a hospital reported significant levels of $PM_{2.5}$ of both NVWs and MVWs indoors but the possible sources have been revealed by this study [15]. The average $PM_{2.5}$ Indoor/Outdoor (I/O) concentration ratios suggest that indoor $PM_{2.5}$ were from outdoor sources. Half of the sampling sites had average $PM_{2.5}$ concentrations that exceeded the 24-h World Health Organization (WHO) guideline value of 25 $\mu g/m^3$. Associated elements also showed that there is significant contamination from anthropogenic origins. Since $PM_{2.5}$ is comprised of elements which may vary significantly in terms of sources and toxicities, understanding the $PM_{2.5}$ sources and their contributions is a vital requirement for the formulation of effective control strategies for $PM_{2.5}$ in the hospital wards [20,21].

Four distinct source types using the PMF method, a standard approach to $PM_{2.5}$ source apportionment studies, were identified [22]. Previously measured I/O ratios of $PM_{2.5}$ and enrichment factors (EF) support this study's findings that the sources can all be traced to outdoor sources except for sodium and chlorine with I/O ratios exceeding unity in all the study sites [15]. This implies significant contributions from indoor origins of the said source. The findings are likewise supported by the KIIs conducted with the hospital staff which revealed that the indoor use of cleaning agents, particularly household bleach or sodium hypochlorite (NaOCl) in both NVWs and MVWs may be a potential indoor source of Na and Cl. NaOCl is used in cleaning the wards at 8-hour intervals and in soaking medical apparatus and reusable tools for disinfection. Drugs and other chemicals used in hospital activities are also potential indoor sources of Na and Cl including intravenous fluids which could be improperly disposed or accidentally spilled in the wards [23]. Nevertheless, because the hospital is situated near a bay area, sea salt should not be overlooked since it could contribute to the measured Na and Cl concentrations.

The high EF and low I/O ratios of sulfur in all sites indicate that sulfur originated primarily from anthropogenic outdoor sources [15]. Sulfur is an excellent marker of vehicular and industrial emissions. Considering traffic data in 2015 which showed that an average of 12,000+ vehicles pass through the main and side streets of the hospital, it is hypothesized that vehicle emissions could be a major source of sulfur in the study sites [14]. However, other sulfur sources cannot be ruled out due to the lack of measurement of black carbon, organic carbon, elemental carbon, nitrates, ammonium, and sulfates.

Consistent crustal emissions were also found in all the study sites. Considering the density and movement of people in and out of the wards, they are likely to introduce crustal emissions upon entry to the study sites [24]. Re-suspension of particles is likely to occur as well with an occupant density of 0.32 and 0.28 in the Pedia and Med wards, respectively, and a high level of activity based on daily observations [15].

Road dust, composed of crustal elements with high concentrations of zinc (Zn) and lead (Pb), was identified as another source in all the sites. We hypothesize that tailpipe emissions as well as brake and tire wear could be a good source of Zn, while asphalt pavements could both emit Zn and Pb [25,26]. Since the hospital is situated between two light rail stations, the steel railroad tracks coated with Zn could also be a good source of Zn emissions due to the wear and tear of the tracks [26]. Moreover, Pb from motor vehicle exhaust and from the pre-war Pb-painted cover walls of the wards may also be a source of lead emissions. However, I/O ratio of Zn and Pb in all sites suggests that these elements originated from outdoor sources [15].

$PM_{2.5}$ concentrations contributed by three of the four identified sources were lower in MVWs than in NVWs (Table 3). This finding is in agreement with a study suggesting that indoor air quality is significantly better in mechanically ventilated homes than in those using exclusively natural ventilation [27]. The $PM_{2.5}$ concentration from the road dust source in NVWs was found to be 3 times higher than that in MVWs. Possible reasons for the three-fold increase in concentration could be the ground floor location of the NVWs and the proximity of the Pedia ward to the emergency room driveway which helps increase resuspension of road dust. Furthermore, previous investigations on the vertical variability of air pollutants yielded results showing variations of concentrations of parameters based on floor height within urban areas [28,29]. A study by Zauli Sajani in 2018 which showed small monotonic vertical gradient for $PM_{2.5}$ with ground-top differences equal to 4% to 11% support this as well [30]. Some pollutants such as Fe, Sb, and Sn from brake wear and resuspension have predominant ground-level sources [31]. However, it was found that the $PM_{2.5}$ concentration contributed by anthropogenic sulfur source was slightly higher by 0.041 ug/m^3 in MVWs than in NVWs. Interviews with the hospital administration and staff revealed that the ventilation system of MVWs was shut down every day for several hours in the night. Infiltration of outdoor $PM_{2.5}$ sources to MVWs is very likely to occur. It is hypothesized that it will be difficult to prevent infiltration which may result to the $PM_{2.5}$ concentration contributed by outdoor sources of MVWs being almost the same as the NVWs particularly for anthropogenic sulfur and crustal emission sources. Nonetheless, this finding warrants further investigation.

The application of PMF receptor model provided understanding of the sources of indoor air pollution of a hospital in the Philippines. This may be the first study in the Philippines to determine and quantify the identifiable sources of indoor air pollution and to determine the possible sources and contributions of elements associated with $PM_{2.5}$ based on the type of ventilation used. The results led to the establishment of a baseline for the understanding of the characteristics and sources of indoor air pollution in an urban tertiary care hospital in the Philippines. Moreover, the findings may contribute to advancements in environmental health in the Philippines by providing evidence-based strategies in controlling the quality of indoor air in our hospitals, an area that the public considers as safe and clean.

Several constraints were also encountered such as limited resources during the time of sampling which prevented the measurement of elemental carbon, organic carbon, and nitrates. These parameters would have provided more significant in-depth directions regarding traffic-related contributions. The sampling period was, likewise, limited to a total of five months, thus, seasonal variation of the sources could not be established. Procedures to consider the differences in the elevation of the sampling sites were also not conducted. Nevertheless, more studies are needed to generate information regarding the sources of hospital indoor air pollution in the Philippines. Future studies are recommended to increase the sample size and extend the sampling period to at least one year to include the changes in the season and establish seasonal variation of the sources.

Conclusions

Positive Matrix Factorization can be used to identify sources contributing to indoor $PM_{2.5}$ in hospitals with different types of ventilation. Four types of sources namely sodium and chlorine sources, anthropogenic sulfur sources, crustal emissions, and road dust were identified in both NVWs and MVWs. Crustal emissions were the sole natural source of air pollution in the hospital. The other pollutants were anthropogenic in origin and most of them originated from the outdoor environment. Adequate mechanical ventilation systems should be in place to effectively prevent outdoor particle infiltration. The contribution of anthropogenic indoor pollutants to indoor $PM_{2.5}$ could be a major concern of hospitals in the Philippines and should be addressed by administrative measures. Engineering controls such as reinforcement of ventilation systems against anthropogenic and natural outdoor pollutants should likewise be implemented as a priority of hospitals in the Philippines.

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