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Indoor penetration of ambient particulate pollution in a hospital maternity ward in Manila, Philippines: perspectives towards holistic city-level air quality management†

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Several studies have analyzed and reported the relationship between particulate matter (PM) in the air and its adverse health effects, primarily on fetal development and subsequent early childhood. This study aims to understand how outdoor air made up of mainly PM, influences indoor air quality in a naturally ventilated maternity ward in an urban hospital setting. The data collection site in this study was the Dr Jose Fabella Memorial Hospital, a maternity hospital located in Manila, Philippines. Indoor and outdoor $PM_{2.5}$ levels from November 2021 to June 2022 were investigated. A strong positive correlation (r^2 ranging from 0.78 to 0.98) was observed between the daily outdoor and indoor PM levels. While the median concentrations were above the World Health Organization (WHO) air quality guidelines, they were below the Philippine National Ambient Air Quality Guideline Values (NAAQGV) at the time of data collection. These results underscore the importance of updating guideline values. Indoor-to-outdoor diurnal ratios (*I*/*O*), ranging from 0.77 to 1.33, with peak times (indoor-source-dominated) between 12:00 and 13:00 and trough times (outdoor-source-dominated) between 04:00 and 05:00, offered insight into the times of the day dominated by indoor *versus* outdoor sources and highlighted the need for continuous air monitoring while providing additional protection in indoor spaces, such as clear indoor air quality guidelines combined with indoor ventilation and filtration requirements. These results highlight the need for a holistic air quality management approach which focuses concurrently on both ambient and indoor air quality in healthcare facilities. Naturally ventilated hospitals must be included as a priority monitoring site, as they are a critical in improving air quality in the context of public health protection.

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Environmental significance

This study underscores several important points: (1) the interconnectedness of indoor and outdoor air quality, (2) the vulnerability of sensitive populations such as patients in hospital maternity wards, who often have a lower socioeconomic status and may experience poor health compounded by cumulative effects, and (3) the need for robust and consistent air quality monitoring and updated air quality standards to protect public health. In alignment with the special theme of "Air Quality in Emerging Economic Regions", this paper discusses the capacity to measure indoor and outdoor air quality using air sensors in developing regions. These regions often have sparse air quality monitoring data relative to their population density. The paper suggests coupling data from these sensors with interventions to gain a better understanding of effective air quality management practices.

Introduction

Air pollution remains the top global environmental risk for premature mortality, linked to 8.1 million deaths in 2021.[1] More than half (58%) of the premature deaths are due to ambient (outdoor) air pollution, while 38% of the mortality is due to household air pollution, caused by fine particulate matter ($PM_{2.5}$), which has aerodynamic diameters ≤2.5 micrometers. The specific short- and long-term health effects of air pollution exposure on the lungs, heart, tissues, and other body parts are well documented in the literature[2,3] together with the emphasis that infants and children, the elderly, and pregnant women face the highest share of the health burden.[1]

Health risks related to air pollution are dependent on the exposure of the public to poor air quality. The majority of people spend time indoors, mostly at home, then in the workplace or at school. In Metro Manila, Philippines, activity data show that people spend 84% of their time in indoor environments.[4]

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Ensuring good air quality is therefore of utmost importance, with guidelines provided by the World Health Organization (WHO),[5] the US Occupational Safety and Health Administration (OSHA), and other similar agencies per country. Household air pollution is mainly linked with inefficient cookstoves and the use of solid fuels and biomass, but there are other sources of indoor air pollution that must be addressed.[6] In addition, indoor air eventually gets contaminated with outdoor air, causing indoor air to contain both indoor- and outdoor-generated pollution.[4,6–8]

Populations that are most vulnerable to air pollution health impacts can be found in health facilities such as hospitals, clinics, and health centers. While out-patient check-ups may only require a few hours, patients seeking consultations are likely already experiencing illnesses that can be aggravated by air pollution to a greater extent even at acute exposures. This study focuses on a birthing hospital because maternal exposure to $PM_{2.5}$ and ultrafine particles during pregnancy creates a window of vulnerability for fetal development and children's long-term health.[9] Low birth weight has also been correlated with $PM_{2.5}$ exposure and depending on the period of gestation during which the mother was exposed, the odds ratio can be as high as 1.018 (highest in the first trimester) per $\mu g\ m^{-3}$ increase in the mother's $PM_{2.5}$ exposure.[10] Pregnancy-induced hypertensive disorders and preeclampsia are 57% and 31%, respectively, more likely to occur in women per 5 $\mu g\ m^{-3}$ increments of ambient $PM_{2.5}$ they are exposed to (ref. 11). Infants exposed to particulate matter can also develop respiratory and neuropsychological health effects.[12–14]

In the Philippines, air quality is monitored under the Philippine Clean Air Act. In line with this, air quality status reports are released by the Department of the Environment and Natural Resources (DENR). In the DENR's National Air Quality Status Reports, the annual nationwide and geometric $PM_{2.5}$ and PM_{10} mean (per region) were reported. Manila City is in the National Capital Region (NCR), which has 32 air quality monitoring stations. Table 1 summarizes the annual nationwide and geometric $PM_{2.5}$ mean for the NCR and the Philippines from ref. 15 and 16.

The Philippine national ambient air quality guideline values (NAAQGV) for criteria pollutants are defined and implemented by the Department of Environment and Natural Resources. The NAAQGVs are based on the WHO air quality guideline values and interim targets. Table 2 summarizes the WHO 2021 guideline values and the Philippine NAAQGVs available during data collection for this study.

The majority of tertiary hospitals in the country have wards that are naturally ventilated (open windows and no air conditioning), highlighting the importance of understanding the contribution of outdoor air pollution to indoor air quality, as discussed in previous indoor air quality studies in the Philippine General Hospital wards.[17,18] These previous studies viewed air quality improvement in the context of hospital facility management and occupational safety, but as national and local governments expand air quality monitoring networks and develop measures towards air quality improvement, locations such as hospitals with vulnerable populations should be prioritized for air quality monitoring and action. In this study, we aim to understand the influence of outdoor air pollution on indoor air quality in a birthing hospital, specifically in its maternity ward, through parallel hourly $PM_{2.5}$ measurements in the naturally ventilated ward and right outside the hospital building. We investigated temporal trends as well as indoor–outdoor ratios and compared them to observed behaviors and activities. From these findings, we propose interventions to reduce indoor air pollution at the hospital management level and beyond. We also provide perspectives on how hospital air quality could be a model and should drive overall air quality management efforts at the national and local government levels.

Methods

Outdoor and indoor air monitoring

The establishment of a hybrid air quality monitoring network in the City of Manila was prioritized in the Asia Blue Skies Program to provide baseline information on the status of air in the city

Table 1 Annual average $PM_{2.5}$ and PM_{10} concentrations for the National Capital Region (NCR) and Nationwide average $PM_{2.5}$ and PM_{10} concentrations in the Philippines from 2013 to 2021 as reported in National Air Quality Status Reports. PM_{10} concentration values were gathered from the Philippines' 2016–2018 report, while $PM_{2.5}$ concentrations were gathered from the 2021 report[15,16]

	$PM_{2.5}$		PM_{10}	
Year	NCR annual mean[a] (μg per NCM)	Nationwide annual mean[a] (μg per NCM)	NCR annual mean[a] (μg per NCM)	Nationwide annual mean[a] (μg per NCM)
2013	28.67	—	69	51
2014	35.25	35.25	51	52
2015	27.2	23.19	50	46
2016	26.85	20.36	46	39
2017	36.36	20.71	53	41
2018	20	20.36	47	39
2019	27	24.13	45	35
2020	—	14.78	—	27
2021	—	15.16	43	26

[a] Philippine standards express concentration in μg per NCM, where "NCM" stands for normal cubic meter—the volume of dry gas which occupies a cubic meter measured at twenty five degrees Celsius (25°) at an absolute pressure equivalent to seven hundred and sixty (760) mm Hg.

Table 2 Guideline values for ambient air quality[15,16]

	WHO (2021) guidelines		Philippine national ambient air quality guideline values	
Parameter	Averaging time	Air quality guideline ($\mu g\ m^{-3}$)	Averaging time	NAAQGV ($\mu g\ m^{-3}$)
PM_{10}	Annual	15	Annual	60
	24-hour	45	24-hour	150
$PM_{2.5}$	Annual	5	Annual	25
	24-hour	15	24-hour	35

which can guide the clean air action planning process. Manila, with a population of over 1.85 million,[19] only had one[2] continuous air quality monitoring station managed by the Department of Environment and Natural Resources – Environmental Management Bureau (DENR-EMB). Non-reference air sensors provide an opportunity to fill data gaps that cannot be covered by reference monitoring stations that require more investments, technical capacity, and operational requirements. This monitoring station was complemented by the project's air quality sensors which were installed in different locations in the city. Identifying health facilities as a hotspot of vulnerable populations, Dr Jose Fabella Memorial Hospital, a maternity hospital, was prioritized as a monitoring site for both outdoor and indoor $PM_{2.5}$.

Hourly $PM_{2.5}$ concentrations were measured outside and inside the hospital using Clarity Node-S sensors which are solar-powered IoT air quality monitoring systems. They measure PM through laser light scattering and transmit data through global cellular communications. The range for PM measurements is 0–1000 $\mu g\ m^{-3}$, with a 1 $\mu g\ m^{-3}$ resolution. Other technical specifications of the sensor can be accessed through **https://www.clarity.io/products/clarity-node-s**. Data from the sensors were accessed from the manufacturer's data dashboard and corrections were applied to ensure accuracy, as explained in the next section. For the outdoor measurements, a summary of measurement sites is given in Table 3.

For the monitoring site in the hospital, the sensor was installed in a pole near the emergency room entrance, following standard siting protocols (*i.e.*, minimum of 3 meters height from the ground, inlet clear of obstructions, far from exhausts, *etc.*) adjusted for exposure monitoring using portable sensors. In the indoor monitoring site, the main priority was the exposure of vulnerable populations, but additional considerations include proximity to an electricity outlet since the solar panel of the sensor will not work indoors, availability of a post suitable for sturdy sensor installation, and locations of electric fans for air not to be directly blown into the inlet. The maternity ward on the second floor was selected for the measurements. This ward had an area of 608 m^2, (6544 ft^2), a ceiling height of 3.3 m (10.8 ft), and an average occupancy of 300 (combination of mothers and newborn infants). The ward has a high turnover rate—mothers and babies stay for only 24 hours after giving birth, except for those with complications or needing additional hospital care. This ward always had natural ventilation, *i.e.*, open windows all the time and had multiple fans that blow air around. The air change rate (expressed in air changes per hour or ACH) was not measured due to sensitivities of patients, but Qian *et al.* estimated that the ACH for such conditions was between 19 and 69 ACH, in which case the indoor air is replaced once every 0.9 to 3 minutes.[20]

Data corrections

The Clarity Node-S has been shown in the past to be strongly correlated with reference $PM_{2.5}$ but may experience a mean absolute error (MAE) of up to about 14 $\mu g\ m^{-3}$ in an environment with mixed ambient sources.[21] As part of the establishment of the air quality sensor network in the city, a collocation experiment was done with the DENR-EMB reference station in Mehan Garden, Manila, which measures PM mass concentrations through a Teledyne 640 analyzer (**https://www.teledyne-api.com/products/particulate-instruments/t640**). The sensor was installed in the railings of the reference station housing, around 1 meter from the inlet of the Teledyne instrument. The correction equation for this study was based on collocation data from August 29, 2020 to May 23, 2022 (total of 633 days), excluding periods where the reference instruments were under maintenance (total of 39 missing days). Sensor data were complete for the whole period, demonstrating high data capture above the 75% minimum required by the DENR-EMB. The comparison of Pearson

Table 3 Location siting details for the outdoor and indoor sampling

Location	Device ID	Height from ground (m)	Start date	End date	Parameters
Outdoor (ER entrance area)	AXNYHPCH	3.5	November 17, 2021	June 29, 2022	*T*, RH, number, and mass concentration of $PM_{2.5}$
Indoor (2nd floor, ward 4)	APRY1ZBH	14	December 29, 2021	September 5, 2024	*T*, RH, NO_2, number and mass concentration of $PM_{2.5}$

coefficient (r^2), root mean square error (RMSE) and MAE shows the need for a multiple linear regression (MLR) correction of raw sensor data using temperature and relative humidity data to ensure higher accuracy of air quality measurements. Comparing the uncorrected and corrected data, the r^2 improved from 0.64 to 0.81; the RMSE from 11.03 to 2.75; and the MAE from 8.20 to 2.15 μg m^{-3}. The relative accuracy of the sensor measurements with respect to the reference station ranged from 91.6 to 97% for the whole duration of the collocation study. The MLR correction was thus applied to all raw sensor measurements prior to use. All data presented herein have already been corrected using R; all plots shown were created using Wolfram Mathematica.

Results

Daily and diurnal trends

Ambient daily 24-hour $PM_{2.5}$ averages are monitored by the DENR-EMB and checked with respect to the Philippine National Ambient Air Quality Guideline Values (NAAQGV) stipulated in the Philippine Clean Air Act of 1999, which also states that the basis of the guidelines is the WHO Air Quality Guidelines (WHO AQG). The daily 24-hour $PM_{2.5}$ averages from January to June 2022 in the hospital indoor and outdoor sites are shown in Fig. 1, with respect to 24-hour $PM_{2.5}$ NAAQGV and WHO AQG. Blue gridlines indicate the NAAQGV (light blue) and WHO standards (dark blue). While only 2.2% and 3.9% of the indoor and outdoor daily 24-hour average values for indoor and outdoor, respectively, exceeded the Philippine NAAQGV standard of 35 μg m^{-3} $PM_{2.5}$, comparing the same daily indoor and outdoor daily 24-hour average values to the WHO standard of 15 μg m^{-3} $PM_{2.5}$ increases that number to 69.4% and 73.3%, for indoor and outdoor respectively. In other words, only 30.6% and 26.7% of the indoor and outdoor $PM_{2.5}$ values are within the threshold set by the WHO. In a separate study in another hospital in Manila, 24-hour indoor $PM_{2.5}$ averages in naturally ventilated indoor locations were observed to be between 24.6 and 32.8 μg m^{-3}, slightly lower than the NAAQGV standard.[18] In 2020, a study by Enoveso observed indoor $PM_{2.5}$ in an unnamed hospital in Manila surrounded by mobile pollution sources and reported mean indoor $PM_{2.5}$ concentrations ranging from 21.27 to 31.11 μg m^{-3}.[17] Because these studies reported 24-hour $PM_{2.5}$ averages, the instantaneous concentrations at peak indoor $PM_{2.5}$ concentrations during the daytime, such as outliers in Fig. 3, might be missed.

Fig. 2 shows day-of-the-week, diurnal, and diurnal-per-month averages for the campaign. For the diurnal-per-month, only January to June data are shown. There is no stark difference between weekends and weekdays, but Wednesday and Saturday show peak average $PM_{2.5}$ concentrations for indoor and outdoor averages. On the other hand, the diurnal shows multiple peak periods—for the indoors, 06:00 to 09:00 and 09:00 to 12:00 and a smaller peak around 19:00. For the outdoor diurnal, the morning peaks are the same, albeit opposite in trend, and another peak later in the day about the same time as the indoor peak. These peaks are also apparent in the per-month diurnal averages (Fig. 2(c)), albeit with less of a difference between the AM and PM peaks for both May and June. Separating the diurnals by months (ESI Fig. 7†) shows a similar diurnal trend—all indoor peaks at or close to noon are high for all months (January–June) and a morning diurnal that could be characteristic of outdoor PM emissions caused by vehicle traffic is also observed. A peak is also evident as an afternoon peak, albeit slightly lower than the morning peak. This is supported by a spatiotemporal analysis of human mobility in 2018 by Liu, K., where the author mapped hourly density of human mobility in Manila from 00:00 to 24:00 and noted inflow and outflow trips in four time periods: (1) 00:00–08:00; (2) 08:00–12:00; (3) 12:00–16:00; and (4) 16:00–24:00. In this study, the population group that goes to school traveled more in the 00:00–08:00, while older groups travel at 08:00–12:00.[22] Moreover, the peak-time of mobility was noted to occur at 00:00–08:00 (morning commute) and 16:00–24:00 (commute to return home).[22]

A more robust way of looking at the $PM_{2.5}$ measurements is by looking at the five-number summary (box-and-whisker plots), as shown in Fig. 3. A five-number summary is a more informative way of looking at the averages without being skewed by the presence of outliers; however, looking at the extreme points is also warranted. Because of the lack of contextual information and knowledge of events surrounding the extreme concentrations during this period of time, an inference cannot be made about the possible sources of pollution during these very high periods. This calls for a dedicated framework where activity data are collected in conjunction with air quality monitoring, so that

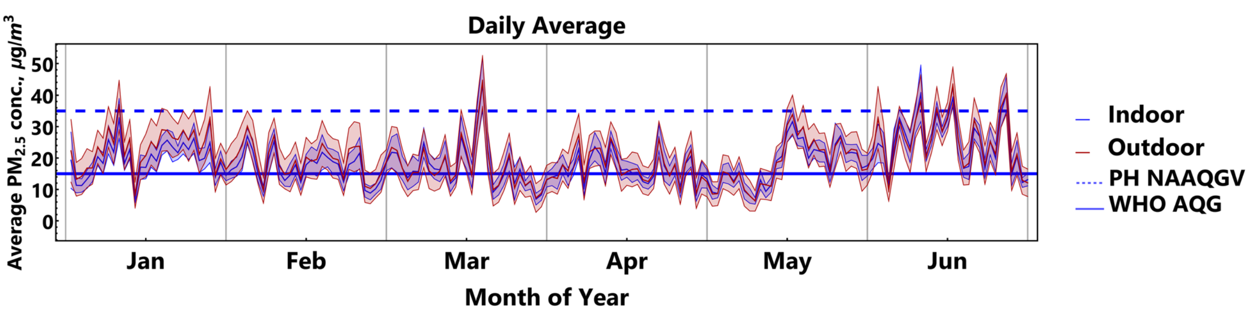

Fig. 1 Daily 24-hour $PM_{2.5}$ average for all months. The solid horizontal blue gridline is the WHO AQG (15 μg m^{-3} $PM_{2.5}$); the dashed horizontal blue line is the Philippine (PH) NAAQGV at the time of the study (35 μg m^{-3} $PM_{2.5}$). The shading signifies a 95% confidence interval around the mean. On an hourly comparison, there is more scatter than averaging the $PM_{2.5}$ values in a day, *i.e.*, the average indoor $PM_{2.5}$ concentrations measured in a day agree well with the average measured outdoor $PM_{2.5}$.

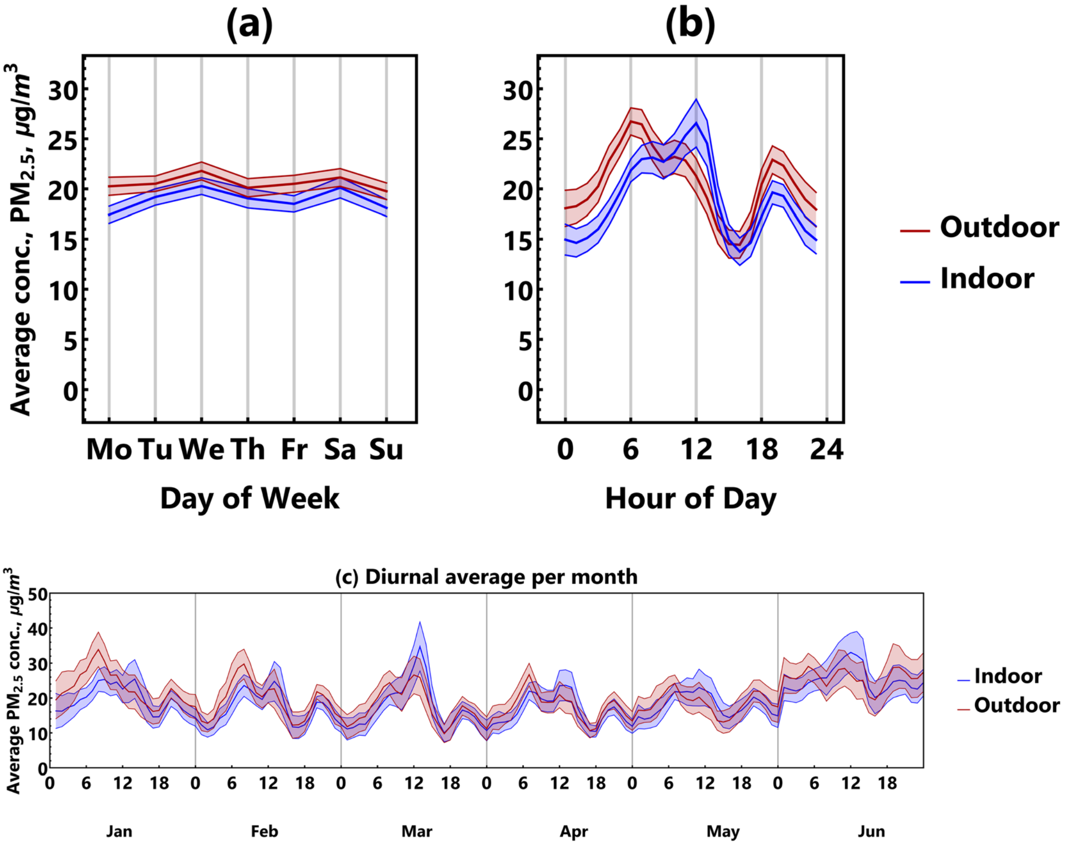

Fig. 2 (a) Day-of-the-week and (b) diurnal average $PM_{2.5}$ concentration for the whole campaign, which lasted from November 2021 to June 2022. (c) The diurnal average for all months (January to June 2022). November and December are not shown since they do not have a consistent indoor–outdoor pair of measurements. All bars represent 95% confidence intervals around the mean.

interventions can be designed for extreme events and instantaneous periods of high $PM_{2.5}$ concentrations. Fig. 3 shows that all median values are at or above the WHO's 15 μg m^{-3} $PM_{2.5}$ AQG but below the Philippine NAAQGVof 35 μg m^{-3} $PM_{2.5.}$ The 75% daily quantile is also below the Philippine NAAQGV. However, all outliers and far outliers are above the NAAQGV. It is important to note that Fig. 3 shows all hourly points (N = 5365), while Fig. 1 show a daily 24-hour $PM_{2.5.}$ Thus, instances of exceedances are higher on an hourly basis. A 24-hour average is not sufficient to show acute personal exposure, especially in highly polluted and dynamic areas such as densely populated

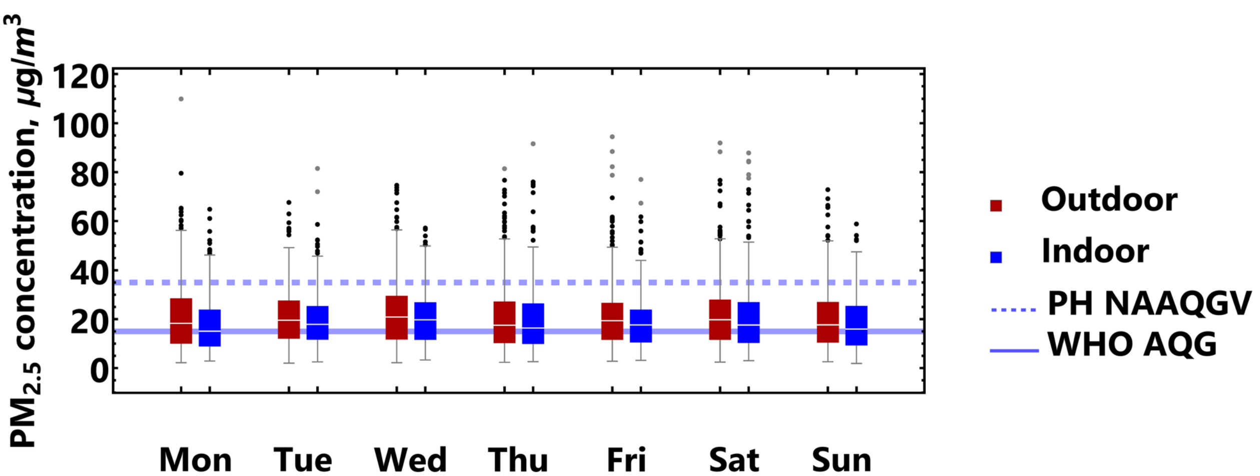

Fig. 3 Five-number summary (box-and-whisker) plots for day-of-the-week indoor and outdoor $PM_{2.5}$. The solid horizontal blue gridline is the WHO AQG (15 μg m^{-3} $PM_{2.5}$) and the dashed blue horizontal line is the Philippine (PH) NAAQGV (35 μg m^{-3} $PM_{2.5}$), which were the applicable standards at the time of data collection. The black and gray points are outliers and far outliers, respectively.

urban areas; thus, it is recommended that $PM_{2.5}$ be reported at a more granular frequency than diurnal averages.

Indoor–outdoor $PM_{2.5}$ relationships

Linear fits using ordinary least squares regression were found to explain the indoor–outdoor relationship well, as exhibited in Fig. 4(a) and (b); the fit (solid black) line lies close to the 1 : 1 (dashed) line. A previous study by Lu *et al.*[23] showed an exponential relationship between indoors and outdoors; however, this was not observed here. The difference in the nature of the relationship between indoor and outdoor between the Lu *et al.* study and this study may be explained by the very high exchange rate in this study, as opposed to a lag of the outdoor to indoor entrainment exhibited in Lu *et al.* Another reason may be the sampling height difference.

Fig. 4 shows a strong correlation between the indoor and outdoor mass concentrations across the whole mass concentration range. However, looking at the indoor-to-outdoor mass concentration ratio (I/O) would give insight into the relative contributions of indoor *versus* outdoor sources. Fig. 5(a) and (c) show that the I/O ratio is notably highest at noontime; there is a consistent diurnal trend regardless of the day of the week (*e.g.*, weekend *vs.* weekday). I/O trends are not expected to follow a diurnal pattern, but the presence may indicate a trend related to external factors such as human activities or circadian patterns. Moreover, the range of I/O ratios usually observed is usually greater than 0.5 but less than 3, indicating the strength, level of relationship, and interdependencies of indoor and outdoor PM.[24–27] In the Manila hospital study by Lomboy *et al.*, previously described above, the researchers reported a similar

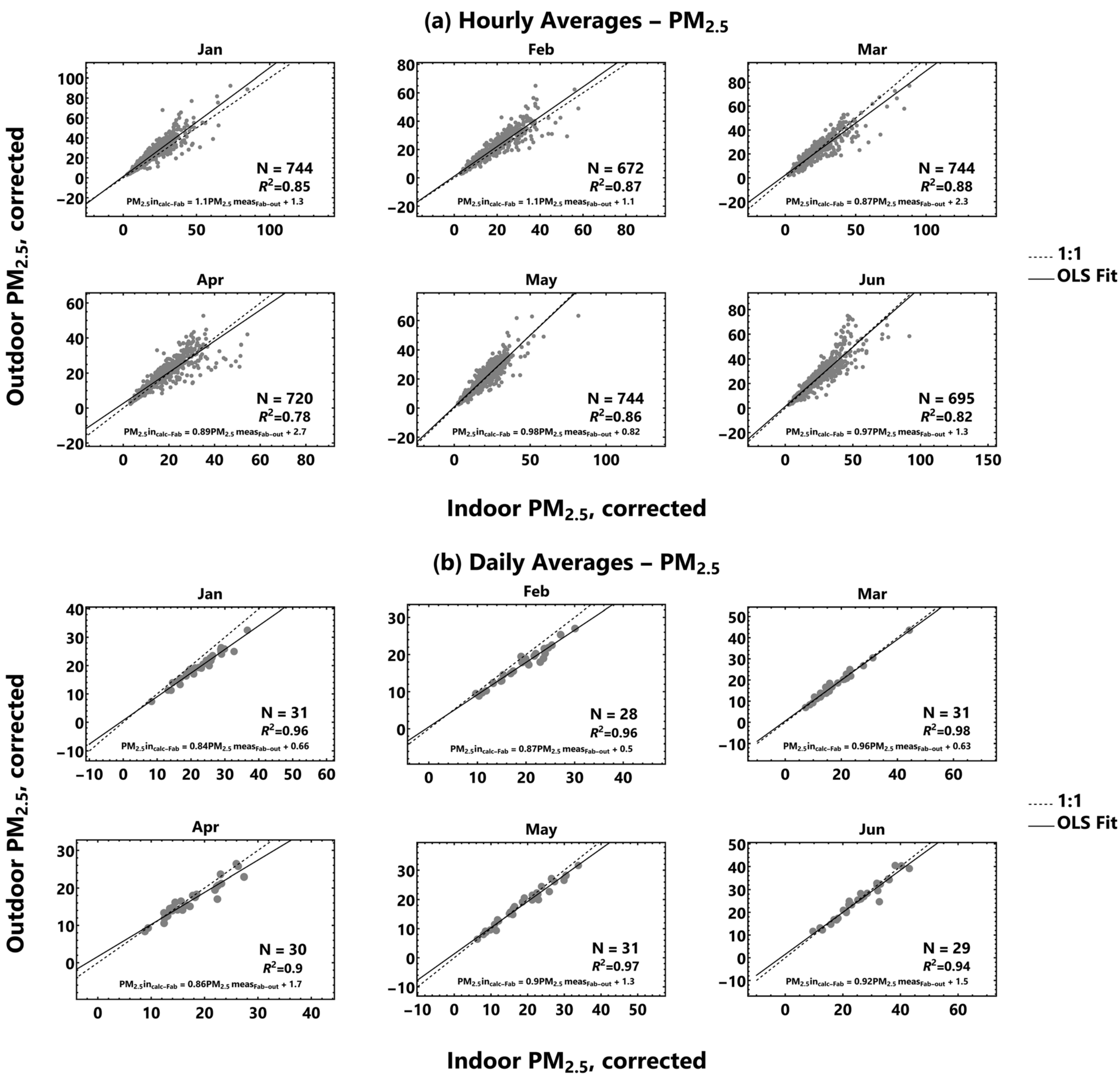

Fig. 4 (a) Hourly and (b) daily average $PM_{2.5}$ data comparison for each month.

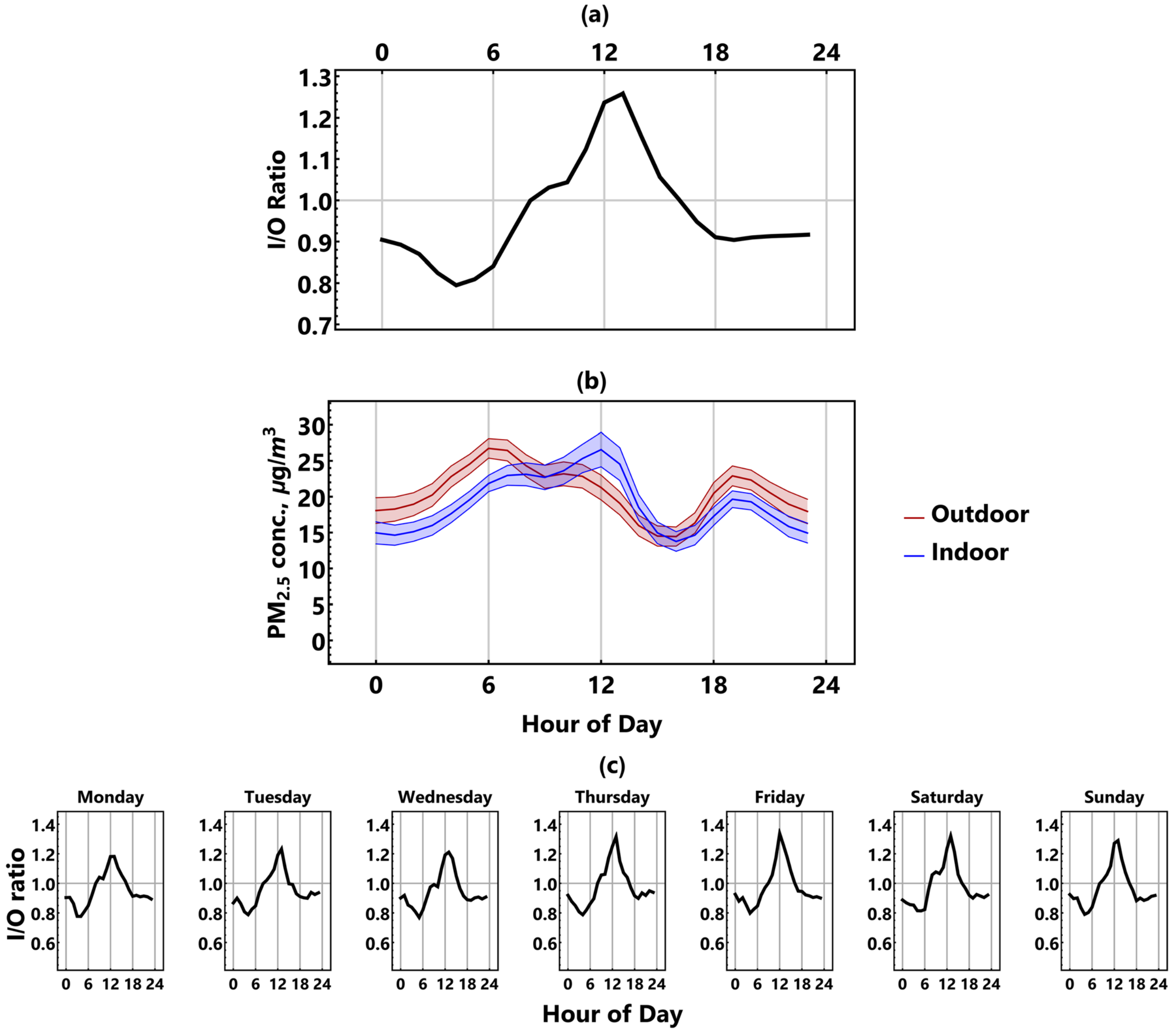

Fig. 5 (a) Indoor/outdoor (*I*/*O*) ratio, (b) diurnal average and (c) diurnal *I*/*O* by day-of-the-week. The shading on (b) signifies the 95% confidence interval around the mean.

maximum *I*/*O* (1.34) and much lower minimum *I*/*O* (0.26) in a similar indoor environment (*i.e.*, a naturally ventilated hospital specialty ward in the department of pediatrics; the hospital was situated in a similar ambient environment).[18]

During the daytime (08:00 to 14:00), the *I*/*O* is more than 1, indicating the strength of possible indoor sources; conversely, from 15:00 until before 08:00, the *I*/*O* is less than 1, indicating the strength of outdoor sources, which may be counterintuitive to human activity patterns outdoors but may be explained by human activities indoors that were either observed, reported by hospital staff during this study, or reported in the literature in other studies.[17,18] During the daytime, there is an increase in human activity indoors (*e.g.*, walking) that may contribute to the resuspension of indoor dust and thus contribute to $PM_{2.5}$ directly. There could also be an increase in gaseous emissions indoors (volatile organic compounds or VOCs from consumer products that the persons wear, skin emissions, cleaning products, *etc.*[28–33]) that can react with outdoor ozone coming in and may contribute to secondary PM formation; however, because this study was limited to measuring PM, and no measurements of VOCs and ozone were made, the nature of secondary sources of PM cannot be determined and can only be hypothesized based on indoor sources studied in the past as well as anecdotal knowledge of human activities in the hospital. With that said, it has been shown that the entrainment of ozone, even at low concentrations (less than ten ppb), can generate up to 40 μg m^{-3} for particles in the 1.2–500 nm size range.[34] However, with very high ACH, it seems more likely that the primary indoor source would be mechanical resuspension,[35–39] unless the indoor VOC sources are in the hundreds of ppb, in which case PM can form quickly (*e.g.*, in the order of minutes).

Human activities during the daytime at or surrounding the hospital that can contribute to resuspension and mechanical generation of dust include activities within hospital wards; conduct of medical rounds; construction and repair activities around the area; dusting or changing of beddings that can resuspend bioaerosols; delivery of food to patients using trolleys; collection, movement, and transport of garbage before noon. On the other hand, there are also specific activities that can generate particles smaller than $PM_{2.5}$, including fire incidences in nearby areas; phototherapy (usage of blue light); usage of UV light for sanitization of areas during the height of the COVID-19 pandemic; and the use of mist sprays.

Since Dr Jose Fabella Memorial Hospital operates 24 hours daily, high mobility in the facility even beyond midnight may be caused by emergency medical cases or patient admissions. Healthcare workers with different shifting schedules may also contribute to this. Moreover, there are nearby public utility vehicle terminals with jeepneys and tricycles that operate even during late hours and as early as 04:00. The surrounding residential and commercial establishments could also contribute to the increased pedestrian and vehicular traffic around the hospital vicinity. Peak measurements for $PM_{2.5}$ which start at 06:00 can also be attributed to residual nighttime pollutant concentrations, low planetary boundary layer height, and increase in vehicular traffic emissions as part of the morning rush.[40]

Discussion

Failing to address the effects of air pollution can lead to a broad range of health complications for affected populations. As such, actions need to be taken, and interventions informed by observed air pollution trends should be designed to improve the air quality and health of the general public.

For example, many studies have suggested air filters improve respiratory health and indoor air quality.[41–45] These can be installed within a building's ventilation or centralized air conditioning systems or using standalone air purifiers. A hospital's heating, ventilation, and air conditioning (HVAC) system, if it exists, can be optimized by regularly inspecting the area, exhausts, and vents. Localized fans with filters, *e.g.*, Corsi-Rosenthal boxes,[46] may filter the resuspended $PM_{2.5}$ from human activity. Other physical adsorbents may also be applicable (a few studies have explored other air-purifying technologies, such as electrostatic precipitators and negative ion generators, both of which operate by producing ions that bind to particles, promoting deposition, *e.g.*, ref. 47 and 48) Because the addition of fans can also work oppositely, *i.e.*, the presence of wall fans in the hospital maternity ward can introduce outdoor air to the indoors faster, periods of high outdoor PM (*I*/*O* less than 1, *e.g.*, midnight to around 08:00 in Fig. 5(a) and (c)) can lead to a quick entrainment of outdoor to indoor PM; thus, it is important to ensure that an efficient filtration system for any air intake (either natural or mechanical ventilation) is present. The hospital's outdoor environment has mobile sources of air pollutants, *e.g.*, tricycles idling or waiting for passengers, and area sources, *e.g.*, eateries (hole-in-the-wall restaurants) along one side of the road. Indoor exposure to outdoor pollution may be reduced by closing the windows, especially when the *I*/*O* is less than 1 (*i.e.*, from 15:00 until before 08:00) when the outdoor source overwhelms the indoor sources. In an urban area like the Dr Jose Fabella Memorial Hospital location, vehicle emissions may be a major source; thus, reducing vehicular emissions, such as reducing NO_x by filtration or addressing traffic flow management within the hospital vicinity may be greatly beneficial in improving the quality of air that penetrates the indoor environment. For example, mapping out the route of emergency vehicles to minimize idling near wards or identifying peak vehicular hours in the nearby roads will help identify and further characterize the outdoor emissions that make their way to the indoors.

When outdoor PM is low, indoor PM is also reduced when *I*/*O* is below 1, so interventions such as closing the windows or employing filtration systems may be less necessary. However, during hours of high indoor activity, the indoor $PM_{2.5}$ compared to the outdoor $PM_{2.5}$ slightly increases. For such scenarios, one intervention may not be enough. To reduce outdoor $PM_{2.5}$ coming indoors, windows must be closed, and outdoor air brought to the inside must go through a high-efficiency filter. Staying indoors and closing windows also protect against air pollution. These levels of protection vary with the type of indoor environment depending on the opening of windows, the use of air conditioners and air purifiers, and the building's location, age, and condition. A study by Lin *et al.* (2009) showed that higher concentrations of indoor $PM_{2.5}$, blood pressure, and heart rates occur with open windows than with closed ones.[49] Another study by Reisen *et al.* (2019) reached a similar conclusion, proving that leaving windows and doors closed leads to reduced $PM_{2.5}$ concentrations.[50] In recent years, improvements to indoor air (such as construction of a building with better air conditioning and air filtration systems) have been underway in Fabella hospital as an intervention to address this issue.

During sensitive hospital operations and procedures (*e.g.*, surgeries, chemotherapy, *etc.*), proper ventilation and an air-cleaning device that removes radicals or ozone are recommended, but only clear the air using adsorbents or HEPA filters. Ventilation ensures good air recirculation and pollutants are not localized within a person's breathing space. In addition, a filtration or air cleaning device ensures that even if polluted outdoor air is brought inside, it gets filtered through and adsorbed rather than recirculated.

Frequent floor cleaning with non-PM forming agents is recommended. Lomboy *et al.* (2015) reported that in a similar hospital in Manila, sodium hypochlorite was used as a cleaning agent.[18] Chlorine-based cleaners are known to initiate chlorine radical chemistry that can quickly form secondary PM.[51,52] Chemical-free floor scrubbing technologies and vacuums equipped with HEPA filters are also recommended for cleansing and sanitizing.[53] In many cases, technologies that employ UV-C irradiation (such as disinfecting lamps) are typically used for germicidal disinfection and decontamination; however, it is recommended that this is used in conjunction with other disinfection and air filtration methods to reduce unwanted prolonged exposure to UV-C.[54] It is also recommended to use only a specific wavelength (*e.g.*, 222 or 254 nm) instead of a wide-range UV lamp to prevent unwanted radical reactions that can lead to atmospheric oxidation and secondary PM generation.

Other interventions that can help improve the air quality inside maternity wards, such as in this study, include adding indoor and outdoor air quality monitoring systems and changing the hospital layout so that the rooms of the vulnerable patient groups are away from the emission sources and the main roads. However, as noted in the results above, fans may increase the recirculation of polluted air indoors; thus, it is recommended to complement this with efficient filters or other materials that adsorb PM and gaseous indoor pollutants. Further investigation of interventions, such as the effect of air conditioning on air quality, is also warranted—for example, the hospital in this study had a 12-person air-conditioned ward besides the ward without air conditioning.

These interventions were formally submitted to the hospital administration in September 2023 for their consideration. In April 2024, the new Dr Jose Fabella Memorial Hospital became operational. Compared to the old facility which had big wards with more than 50 beds each as described in this study, the new hospital has mostly air-conditioned rooms with only an eight-bed capacity. In most tertiary hospitals in the country that have yet to be improved, the indoor–outdoor air quality conditions would likely be similar to that of the old Fabella Hospital. The results and recommendations from this study would thus still be relevant in these health facilities to reduce exposure of patients (especially pregnant women who just gave birth, and newborn babies) and healthcare workers from poor air quality, while emphasizing the message that air quality management requires a holistic approach that involves addressing outdoor and indoor air pollution sources in parallel.

Data availability

Datasets generated during and/or analyzed during the current study are not publicly available due to ongoing government collaborations, but may be available from the authors upon reasonable request.

Author contributions

CMFR led the writing and performed the literature review and data analysis; EGT collected, cleaned and analyzed the data and provided the methodology; DLB and MPB contributed material to the manuscript and provided comments. All authors read and approved the final manuscript.

Conflicts of interest

CMFR is affiliated with OpenAQ, an air quality nonprofit organization funded by philanthropic organizations, corporate sponsorships and subcontracts funded by public and private partners. OpenAQ has a non-financial data-sharing partnership with Clarity Movement Co., but this study was done independent of OpenAQ's activities. There are no other competing interests to disclose.

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