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RESEARCH PAPER

Spatiotemporal variation of Particulate Matter & Risk of Exposure in the Indoor-Outdoor Residential Environment: a case study from Urban City Delhi, India

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Abstract

Humans spend close to 90% of their time within the indoor environment. Deteriorating indoor air quality, especially high PM_{10}, $PM_{2.5}$ and PM_1 is slowly becoming a major concern. A study was carried out, for two years, to characterize the spatiotemporal variation of PM in the indoor-outdoor environment across different residential setups (R1, R2, R3, and MC) in the Delhi region. The study established correlation between monthly variations of Indoor/Outdoor (I/O) ratios and meteorological factors. The results showed Spatio-temporal variation in the average mass concentrations of PM_{10} recorded peak values during the winter season (avg. 514± 72.15 µg/m^3) and minimum concentration was observed during monsoon (avg. 91.41± 22.64 µg/m^3) months. Among all the sites, the mixed cluster (MC), a residential cum commercial zone reported the highest particulate matter concentration (avg. 308.10 ±37.23 µg/m^3) and while Residential area (R2) reported the least concentration (avg. 244.9± 27.65 µg/m^3) within the indoor environment. The I/O ratios of particulate matter were observed to be highest in January (I/O ratio1.6) and lowest in June month (I/O ratio 0.8). PM_{10}, $PM_{2.5}$, and PM_1 dynamics were found to be critically influenced by meteorological factors, regular household activities, and diverse building designs. The short- or long-term exposure of particulate pollutants (beyond the permissible limits) can increase the probability of acute health effects, so there is an utmost requirement to collect better and systematic information about actual exposure levels experienced in different urban residential environments.

Keywords: Indoor air quality, particulate matter, urban built-up, meteorological parameters, indoor-outdoor ratio.

INTRODUCTION

Over the past two to three decades, there has been a sharp increase in the population of Delhi which results in the rampant growth of unplanned, unauthorized constructions activities like the increasing number of unauthorized colonies or slum clusters along with unplanned development of commercial and industrial zones and steep increase of vehicular density (National commission on population, 2020). These widespread changes deteriorated urban air quality into the “severe” hazardous category and ranked Delhi among the top of the most polluted cities in the world (Garg & Gupta, 2020; Jethva et al., 2018). Ambient and indoor air pollution especially in relation to Particulate matter (PM) have become a great health challenge not just in Delhi but in other parts of the world as well. Regulatory authorities of each country undertake various research monitoring programs to understand the trends of indoor air quality (IAQ) in diverse land-use configurations. Over the last few years, several publications (Fromme et al., 2007; Ohura et

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al., 2009; WHO, 2010; Franck et al., 2011; Canha et al., 2012) have attempted to establish the link between indoor air quality (IAQ) and public health. Different building characteristics like its design, structure, and air circulating systems may lead to variation in the air exchange rate between the building and outdoor environment which may impact IAQ (Chen & Zhao, 2011; Massey et al., 2012; Karakas et al., 2013). PM is one of the main culprits for indoor air pollution which directly affects human health (Valavanidis et al., 2008) and is generally classified based on mass median aerodynamics (diameter is less than 10 µm, 2.5 µm, and 1 µm respectively). In the outdoor environment, the main sources of particulate matter are construction activities, resuspension of dust from unpaved roads, fields, smokestacks, and biomass burning. Cooking, smoking, and cleaning habits are primarily responsible for indoor PM concentration (Jones et al., 2000; Ferro et al., 2004; Arhami et al., 2010; Barraza et al., 2014). The finer fraction of particulate matter ($PM_{2.5}$ and PM_1) typically consists of a mixture of particles (nitrates and sulfates) emitted from combustion-related activities viz. tobacco smoking and cooking (Wang et al., 2012). Outdoor PM particles can enter into the indoor environment either by penetrating through open windows and doors or via cracks and fissures of the building structure (Hystad et al., 2009) which is also influenced by the compactness and age of the building structure, older structures are more prone to infiltration of PM (Meng et al., 2005; Wan et al., 2015). In an urban area, the higher outdoor concentration of PM (mainly contributed by traffic emissions) is directly responsible for raising indoor PM concentration (Jones et al., 2000; Loupa et al., 2007). Fine particles are found to have the most severe effects on health, often reported higher rates of heart and respiratory-related mortality and morbidity cases (Tainio et al., 2000; WHO, 2006; Wu et al., 2018). The current study attempts to describe seasonal size-based particulate matter dynamics within diverse urban built-up environment and also envisage their probable contributing source in reference to variation of Indoor/outdoor (I/O) ratios.

MATERIAL AND METHODS

The study area is comprised of the north campus of the University of Delhi which is located in the north district of Delhi. The study site is an urban campus that roughly spans an area of 2 square km, situated between 28.0401" N to 28.448" N latitude and 77.012" E to 77.36" E longitude. The selection of houses was purely based on diverse land-use area, building carpet area, socioeconomic status of occupants which directly influence the choice of lifestyle activities, especially household activities that varies in residential (R) and mixed cluster zone (MC). The residential zone (R1, R2, and R3) is pure residential housing area devoid of any commercial activities, whereas the mixed cluster area is an integrated urban development where both residential and commercial activities take place side-by-side signifying mixed land use pattern. In this study, 12 houses (three houses in each category) within the university residential complex and in the adjacent mixed land-use sites were selected as sampling locations (after obtaining prior consent from the occupants). The occupants in the houses of residential areas (R1, R2, and R3) were regular employees of the University of Delhi and different house types are allotted to employees according to their pay scale. The R1 (lower economy house) were allocated for clerical and cleaning staff, R2 (Mid economy house) for junior officers and junior faculties, and R3 (Higher economy house) for university officers and senior scale faculties. Detailed monitoring sites and their location specificity are represented in Table 1 & in figure 1.

Standard questionnaires were formulated to know about the daily activities of the occupants both in indoor and outdoor environments.

In the R1 site (lower economic zone), the employees were living in a one-room apartment and the mean number of occupants was 5 to 7 people. The occupants' density in the category of the two-room apartment (R2 and MC) was calculated to be 4 to 7 and 6 to 8 people respectively whereas, in R3 (3 rooms apartment), it was 4 to 6 people (Table 2).

Table 1. Characteristics of selected study sites

Type of houses	Carpet Area (in Square meter)	Distance from Major road (in meter)	Area under kitchen (in Square meter)	No. of Windows & Rooms	Opening area/floor area (%)	Age of building (in yrs)	Major Renovation Done (before)
R1	41-43	75 ±7.6	5.2	2 & 1	10.95	25	24-30 Months
R2	77-80	69±12.6	8.4	5 & 2	12.1	25	24-30 Months
R3	110-142	71 ±25.2	11.9	8 & 3	12.8	24	24-28 Months
MC	55-75	55±14.1	7.8±1.2	3 & 2	8.1	28±2.65	36-48 Months

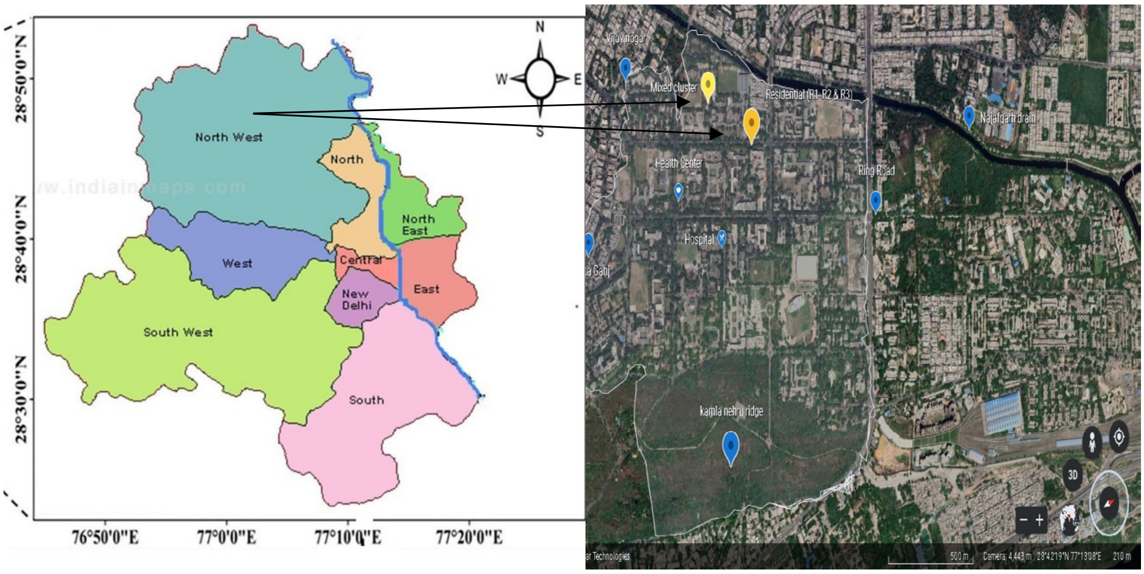


Fig. 1. Map of the study sites in Delhi (Source: Google maps)

Table 2. Occupant density and household characteristics of the study sites

VARIABLES	*R1* *Mean± SD*	*R2* *Mean± SD*	*R3* *Mean± SD*	*MC* *Mean± SD*
Number of Occupants	5 to 7	4 to 7	4 to 6	6 to 8
Separate kitchen	No	Yes	Yes	No
Electric Chimney/Exhaust	No	Yes	Yes	No
Avg. Cooking hours (hr.)	5.33±0.76	4.17±0.29	3.5±0.5	5.66±0.58
Cooking frequency	4-5 times	3- 4 times	3 times	4-5 times
Avg no. of Smoker present	1.67±0.58	1.33±0.58	1.67±1.52	2±1
Avg Monthly electricity consumption (in unit):	217±32.72	249±43.27	334±84.24	219±39.31
Monthly income in Indian Rupee	35,000-40,000	65,000-75,000	85,000-1,20,000	25,000-45,000

R: Residential flats, MC: Mixed cluster

Table 3. Seasonal classification and avg. meteorological variability of Delhi

Months	Season	Avg Temperature (in °C)	Avg Humidity(in %)
December-February	Winter	7-24	42-52
March-May	Pre Monson (Summer)	28-42	23-39
June-September	Monsoon	28-40	58-66
October-November	Post Monsoon	20-33	44-54

Source: IMD, 2016

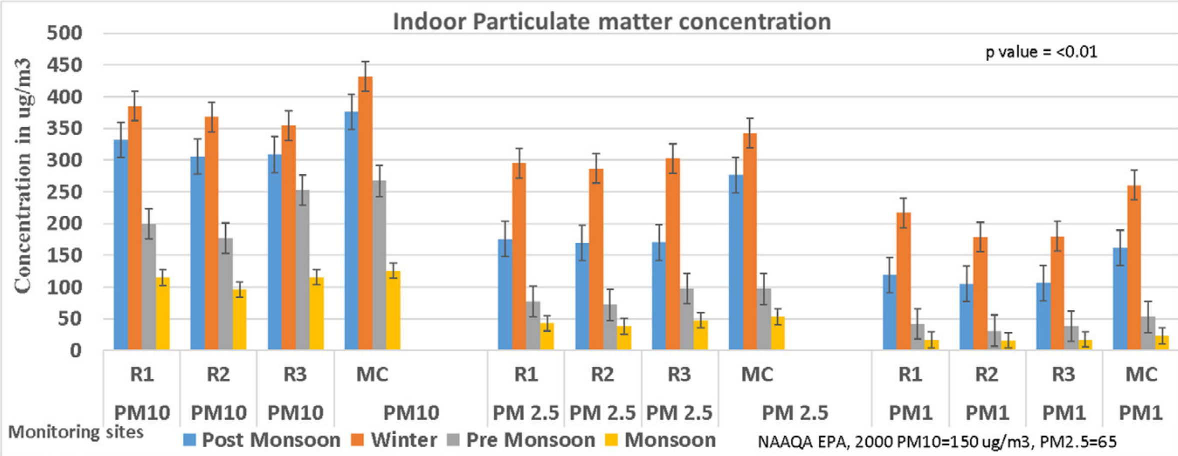
In the mixed cluster zone, on average, each family had 2-3 children along with grandparents living together. Limited air exchange was reported inside the building due to the presence of a lesser number of windows or prolonged hours of closing of windows which revealed a lack of awareness amongst the dwellers regarding ventilation and its benefits. Average monthly income and electricity consumption, both were maximum in R3 (high economic) dwellers while R1 and MC (low-medium economic) showed similarity in economic status (Table 2). Delhi climate is composite, influenced by monsoon season so it is humid, sub-tropical, and hot-dry type. Extreme temperature variability was observed during summer (temperature reached up to 45° C) and winter months (low as 2-3 °C). During the winter months, to avoid outdoor chilling temperature, doors and windows were found to be closed for most of the sampling hours at sampling sites. Only R2 (mid economy) and R3 (high economy) sites have separate kitchens. Due to limited area in low economy houses in R1 (41-43 M^2) and the mixed cluster (55-75 M^2), frequent activities like cooking was also carried out in indoors (R1: 5.33±0.76 and for MC: 5.66±0.58 hours/day) which ultimately contributes to higher risk among the dwellers. Average cooking hours for R2 (mid economy) and 3 (high economy) sites were reported to be less-4.17±0.29 hour/day and 3.5±0.5 hour/day, respectively (Table 2). Through the extensive survey, it was found that in all the monitoring sites (low to high economy class), only cleaner cooking fuel, liquefied petroleum gas (LPG) had been in use, and only the male occupants engaged in smoking.

The study was conducted for two consecutive years (2018 & 2019) during post-monsoon and monsoon season as per the seasonal classification of nodal agency, IMD (Table 3). For measuring $PM_{10,}$ $PM_{2.5}$ & PM_1 concentration, we used a pair of portable GRIMM aerosols spectrometers, model-11A (OPC, Grimm Aerosol Technik, Germany) sampler. The sampler is based on light scattering technology which efficiently collects real-time data of size segregated PM concentration ($PM_{10,}$ $PM_{2.5,}$ and PM_1) in high resolutions. The GRIMM sampler has 31 cut points and measures PM size fraction in the range between 0.25 μm to 32 μm. The frequency of indoor and outdoor PM sampling was done twice a month for eight-hours duration as per the guidelines of nodal agency, Central Pollution Control Board, India guidelines (Kamyotra et al., 2011). For Indoor sampling, samplers were kept inside the living room, and for outdoor just outside the main entrance of each selected site. During sampling, onsite meteorological data (relative humidity and ambient temperature) were also recorded using Kestrel Pocket (4500 NV, USA) weather meter.

Statistical analyses were performed using SPSS software (v.22). Descriptive statistics including the mean concentration and standard deviation were used to investigate the seasonal dynamics of PM. Paired T-Test was used to compare indoor-outdoor and seasonal variation of PM ($PM_{10,}$ $PM_{2.5}$ & PM_1) concentration. Pearson correlation coefficients were used to analyze their association.

RESULTS AND DISCUSSION

Figure 2 represents the seasonal variation of average mass concentration of PM ($PM_{10,}$ $PM_{2.5}$ & PM_1) in a diverse indoor environment. The maximum concentration of PM_{10} was reported during winter months (range 354 ±42.72 to 431.78± 40.72 μg/m^3) followed by the post-



R: Residential flats, MC: Mixed cluster

Fig. 2. Indoor Particulate matter dynamics at different monitoring sites (Total N=576) (p<0.01)

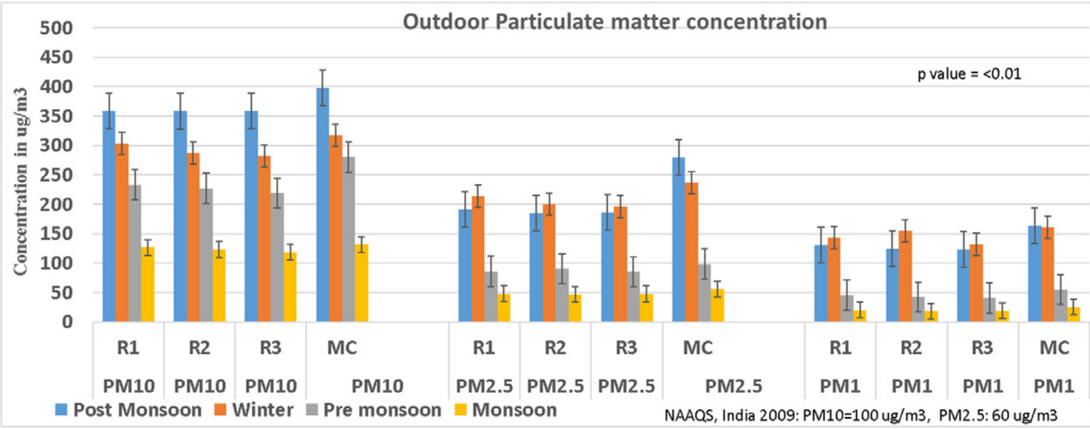
monsoon month (305 ±25.21 to 375.85± 51.85 μg/m³) and as expected, the lowest values were recorded during monsoon month (range 95.93±30.71 to125.49 ± 19.12 μg/m³). Throughout the experimental period, among all four sites, the maximum concentration of PM_{10} value was reported at mixed land-use sites (commercial cum residential site) compared to pure residential sites (R1, R2 & R3) indicating the role of human activity in indoor pollution. During winter months, PM_{10} concentration indoors reached almost 4 times higher value (up to 582.21 ±38.71 μg/m³ for 24 hours at mixed cluster) than National Ambient Air Quality guidelines (150 μg/m³) (NAAQS- EPA, 2000). Following similar trend, maximum values of indoor $PM_{2.5}$ & PM_1 mass concentration (24-hour average) were reported during the winter season (342.18±21.94 μg/m³ & 260.78±44.84 μg/m³ at mixed clusters respectively) and minimum values were observed during monsoon season (38.8±13.49 μg/m³ for $PM_{2.5}$ & 15.48±8.28 μg/m³ for PM_1 at R2 zone).

The seasonal trend of $PM_{2.5}$ mass concentration follows an almost similar pattern to the profile of PM_{10} (Cheng et al., 2006) (Fig. 2). Among all the monitoring sites, the mixed land used site (MC) recorded the highest $PM_{2.5}$ (average 196.53±133.17 μg/m³) concentration which ranged between 53.18 to 342.18 μg/m³. Similarly, maximum PM_1 value (average 136.53±133.17 μg/m³) was observed in the indoor environment of the mixed cluster (ranged between 23.24 to 260.64 μg/m³). $PM_{2.5}$ concentration showed almost 5 times higher value during winter and post-monsoon months in comparison to EPA guidelines (65 μg/m³). Seasonal PM_1 dynamics also reported similar trend, but were unable to assess its exposure risk as guidelines for PM_1 are still missing which is urgently needed to address public health issues. According to (Chen et Al., 2017) being a smaller particle size, PM_1 is more harmful than $PM_{2.5}$. PM_1 is more likely to penetrate deeper into the respiratory system carrying more hazardous trace elements adsorbed on the surface. These trace elements adsorbed on PM surfaces are easily diffused into the lung fluids and thus, it poses a great danger to human health (Biglari et al., 2017; Zwozdziak et al., 2016). Within indoor environment, PM has diverse emission sources primarily due to the activities of occupants (like smoking, cooking, burning gas stoves, cleaning, and dusting), along with outdoor infiltration of PM based on the location of the building (Jones et al., 2000; Kwon et al., 2015; Srivastava & Jain, 2003; Yen et al., 2019) (Table 4)**.** As we are aware during the winter months in Delhi, high PM concentrations (PM_{10}, & $PM_{2.5}$) in the ambient air are supposed to be one of the major reasons for indoor air pollution. A similar observation has also been reported by other researchers in different cities (Reizer and Juda-Rezler, 2016; European Environment Agency, 2017).

In outdoor environment, seasonally PM_{10} concentrations were observed to be maximum

Table 4. List of daily activities performed by inhabitants.

Activities	Time
Breakfast ((Tea/Coffee, bread /Roti, vegetable, different Indian snacks etc.)	6.30 to 8.30 am
Lunch preparation (Rice, bread/roti, pulses, veg/nonveg food items)	9.30 to 11.30 am
Lunch (rotis and vegetables etc.)	12.30 to 1.30 am
Dinner preparation (Rice, bread/Roti, pulses, veg/ non veg. food items)	8 to 9.30 pm
Smoking (Approx 2 members in a house)	6 to 8 minutes/cigarette



R: Residential flats, MC: Mixed cluster

Fig. 3. Seasonal variation of particulate matter in outdoor environment (N=576)

during the post-monsoon season (ranged between 355.15 ±42.72 to 398.33±38.62 µg/m^3) and lowest during the monsoon season (range varied between 118.42 ±142.72 ±12.16 µg/m^3) (fig 3). This is maybe due to the washout or scavenging process which reduces the pollution load and cleans the air further during monsoon season (Sharma et al., 2014; Trivedi et al., 2014; Y. K. Tiwari et al., 2013). The highest PM_{10} and $PM_{2.5}$ concentrations were recorded in the outdoor environment of the mixed cluster zone during the post-monsoon season (398.06±40.18 µg/m^3 and 279.15 ±30.86 µg/m^3 respectively). Post monsoon season in India is the transition phase between the monsoon and winter season. Many temporal variation studies consider the post-monsoon season part of the winter season in Delhi (S. Tiwari et al., 2012; Sharma et al., 2014, 2016).

PM_1 concentrations were observed to be maximum during winter months (varied between123.41 ±24.25 to 163.96±20.21 µg/m^3). Local pollution emissions sources (vehicular traffic and construction activities) were observed to be majorly responsible for the higher concentrations of PM at mixed land use site, MC. In Delhi, the higher outdoor concentrations of PM_{10}, $PM_{2.5}$, and PM_1 in the post-monsoon & winter season could be directly attributed to the local influencing climatic and geographical factors (Nagar et al., 2019; Trivedi et al., 2014). Tiwari et al. 2012 explained higher PM concentrations during winter & post-monsoon in the north India region were due to the lower mixing height and low wind speeds. In addition, monitoring sites were located at a busy city intersection with high levels of vehicular emissions. Besides vehicular traffic, biomass burning was also found to be another major responsible factor for particulate emissions in the outdoor environment. According to Ravindra et al. 2019, lower wet particulate deposition is the foremost reason for higher air pollution during the colder months. PM concentrations (especially PM_{10}) increased during the post-monsoon/ summer season, most likely because Delhi is usually affected by southwestern sand and dust storms (Sen et al., 2016). Due to the larger size of dust particles, PM_{10} concentrations increased significantly, contrary to fine PM concentrations. During monsoon season, there are more intensive convective air currents and more rainfall, so PM is more effectively removed, leading to minimum PM concentrations. According to Kumar et al., 2020, Delhi's air quality is controlled by the impact of emissions from the surrounding local sources of neighboring states.

Monthly distribution of size segregated particulate matter in an indoor-outdoor environment: The concentration of size segregated PM (PM_{10}, $PM_{2.5}$, and PM_1) varies in ambient air under the influence of various meteorological factors, such as atmospheric temperature, relative humidity, rainfall, wind speed, and wind direction as well as depending on diverse emitting sources (Akyuz and Cabuk 2009; Peteraki et al. 2010).

Besides spatial variation, temporal (seasonal or monthly) variation of each fraction of PM (PM_{10}, $PM_{2.5}$, PM_1) is also quite distinct. $PM_{10-2.5}$ fraction contribution was comparably high within total PM during April, May, June, and July months whereas $PM_{2.5}$ & PM_1 fraction was visibly increasing onward month of September till February. Various studies (Gopalaswami, 2016; Nkundabose, 2020; Tyagi et al., 2010) reported that a majority of the winds coming to Delhi are Westerly, which comes from the western and north-western part of India and within Delhi, most of the winds have northern, north-eastern and north-western directions, except in monsoon months (July – September). Variation of size fraction of PM depends on the types and sources of PM particles. Winds from the north-western part bring particles from the Thar Desert (Tiwari et al., 2015; Guttikunda and Gurjar, 2012) whereas winds from the south-western coast bring particles rich in sea salt (Rao et al., 2016; Tiwari et al., 2012). In general, PM_{10} in Delhi contributed most to the PM concentrations load compared to the other fractions ($PM_{2.5}$ and PM_1). This could be considered more of a local and urban scale emission problem, contributors are combustion process, fugitive dust from roads, and resuspension by vehicular movements and majority from construction activities. In terms of public health issues, standardized dust mass fractions had been classified as respirable ($PM_{10-2.5}$), thoracic ($PM_{2.5-1}$), and alveolic (PM1). Monthly variation of thoracic and alveoli values indicated a high risk of upper and lower respiratory systems of inhabitants on a seasonal basis. The higher contribution of smaller particles in total PM pointed towards emission sources in an indoor and outdoor environment (Mainka & Zajusz-Zubek, 2019).

Indoor and Outdoor pollutants concentration ratios (I/O ratios): The ratio of indoor-to-outdoor pollutant concentrations (I/O) may represent the relationship between indoor and outdoor environments, which is very easy to understand and widely used as an interpreting tool. I/O ratio is one of the way to identify emission sources (either indoor or outdoor) and assessment of risk due to site specific exposure. The I/O relationships of every building depend on the type of ventilation, respective outdoor microclimatic variability, and indoor activities (Jones et al., 2000) such as cleaning, cooking, working, etc., even the number of footfall count is influencing PM concentration within the indoor environment (Karakas et al., 2013; Urso et al., 2015). Calculated monthly I/O ratios at all the residential sites varied between 0.7 to 2.0 for PM fractions (PM_{10}, $PM_{2.5}$, PM_1). In general, when I/O ratios are greater than 1 indicating the source of emission are indoor. Evaluation of indoor air quality by quantifying the I/O ratio indicated inferior air quality of indoor air due to internal sources of emission which meant almost all pollutants sources were indoor borne compared to outdoor sources. Coarse particles are mainly formed through mechanical processes, such as dust carried by wind and loose soil, while fine fractions can be released by combustion of fuels or the process of air particle formation (Hussein et al., 2014). In the houses where I/O ratios are more than 1, residents have high exposure to PM. The results of the study showed I/O ratios of PM_{10}, $PM_{2.5,}$ and PM_1 were more than 1 in all the sites (R1, R2, R3, and MC) during winter months (December, January, and February) indicating that indoor concentration of PM is higher than outdoor concentration. During winter months generally, doors and windows remained mostly

Table 5. I/O ratios of color gradients in different months at different monitoring sites

Season	Months	R 1 PM$_{10}$	R 1 PM$_{2.5}$	R 1 PM$_1$	R 2 PM$_{10}$	R 2 PM$_{2.5}$	R 2 PM1	R 3 PM$_{10}$	R 3 PM$_{2.5}$	R 3 PM$_1$	Mixed Cluster PM$_{10}$	Mixed Cluster PM$_{2.5}$	Mixed Cluster PM$_1$
Post Monsoon	Oct	0.9	0.9	1.0	0.9	0.9	0.9	0.8	0.8	0.8	0.9	0.9	0.9
	Nov	1.0	0.9	0.9	0.9	1.0	0.9	0.9	0.9	0.9	1.0	1.1	1.0
Winter	Dec	1.1	1.2	1.3	1.1	1.2	1.1	1.1	1.4	1.2	1.0	1.3	1.3
	Jan	1.6	1.7	1.9	1.5	1.7	1.5	1.5	1.5	1.3	1.6	1.7	2.0
	Feb	1.4	1.4	1.3	1.3	1.4	1.2	1.1	1.4	1.3	1.4	1.2	1.4
Pre Monsoon	Mar	0.9	1.0	1.0	0.9	0.9	0.9	0.9	1.1	1.1	1.3	1.2	1.1
	Apr	0.9	1.0	1.0	0.8	0.9	0.8	0.9	0.9	0.8	1.0	1.0	1.0
	May	0.9	0.8	0.8	0.8	0.8	0.7	0.6	0.7	0.8	1.0	1.0	1.0
	Jun	0.8	0.9	1.0	0.7	0.8	0.7	0.6	0.8	0.9	0.9	0.9	0.9
Monsoon	Jul	1.0	0.9	0.9	0.8	0.8	1.0	0.8	1.0	0.9	1.0	1.0	0.9
	Aug	0.8	0.9	0.8	0.7	0.8	0.8	0.8	0.9	0.9	0.9	1.0	0.9
	Sep	0.9	0.9	0.8	0.8	0.9	0.8	0.8	0.9	0.9	1.0	0.9	0.9
	Avg.	1.01	1.04	1.05	0.94	0.99	0.94	0.89	1.04	0.98	1.07	1.10	1.11
		R 1			R 2			R 3			Mixed Cluster		

R: Residential flats; MC: Mixed Cluster

<1: desirable | 1:optimum | >1: not desirable

closed which led to less air exchange. Due to stable weather during the winter season wind velocity is lower compared to the warmer season which is also responsible for the accumulation of indoor pollutants within buildings (Guhathakurta et al., 2020).

Overall results depicted a different picture for the understanding of indoor air quality (Table 5). Levels of indoor pollution showed maximum value in the mixed cluster zone (MC) followed by R1 (low economy class), R3 (high economy class), and R2 (mid economy class). Unplanned construction could lead to faulty design of the building, insufficient ventilation attributed to the high I/O ratio among mixed cluster houses (Massey et al., 2012). Even after having the largest built-up area, better mechanical ventilation, and low occupation density in the high economy class (R3), the status of indoor air pollution was not good which indicated issues in the lifestyle practices of the residents such as keeping the windows, balconies closed to keep their home clean/ dust free and also to prevent leakage of air-conditioned air, creating insulation or for privacy/ security reasons. R2 (Mid economy class) site showed that the residents kept their windows open for ventilation. These practices help the mixing of ambient air and act as diluents in reducing pollution load. According to Cann et al., 1999, ambient pollutants can seep inside a building through various leaks, cracks, and joints; in contrast, a building can also attenuate the pollutants in filtering inside up to 30%. As evident from Table 5 (color gradients), the monthly outdoor environment (influenced by local meteorology) also played an important role in governing the indoor and outdoor concentrations of pollutants.

Role of meteorology on outdoor and indoor PM concentration: Generally, meteorological factors (temperature and humidity) and outdoor particulate matter concentration directly influenced the indoor PM concentration (Nadali et al., 2020; Saramak 2020). meteorological changes with the season, so do the pollution concentration. The Pearson correlation coefficient (r) test is used to check the association between indoor-outdoor PM concentration with meteorology (temperature and humidity) (Table 6). The correlation coefficient value (r) was calculated to know the strength of association between each meteorological parameter with PM$_{10}$, PM$_{2.5}$ & PM$_1$. In the case of outdoor samples (in all respective sites), PM$_{10}$ value with temperature showed moderately negative correlation (R3 showed highest -0.62 and MC showed

Table 6. Correlation matrix between indoor -outdoor temperature and relative humidity

	Outdoor PM_{10}				Outdoor $PM_{2.5}$				Outdoor PM_1			
Outdoor	R1	R2	R3	MC	R1	R2	R3	MC	R1	R2	R3	MC
Temp.	**-0.61**	**-0.60**	**-0.62**	-0.57	**-0.85.**	**-0.83**	**-0.84**	**-0.82**	**-0.85**	**-0.84**	**-0.84**	**-0.84**
Humid.	-0.10	-0.11	NS	-0.02	NS	0.16	NS	0.26	0.22	NS	0.19	NS
	Indoor PM_{10}				Indoor $PM_{2.5}$				Indoor PM_1			
Indoor	R1	R2	R3	MC	R1	R2	R3	MC	R1	R2	R3	MC
Temp.	**-0.72**	**-0.75**	**-0.68**	**-0.76**	**-0.81**	**-0.82**	**-0.81**	**-0.86**	**-0.78**	**-0.82**	**-0.86**	**-0.87**
Humid.	0.21	NS	0.07	0.13	0.27	0.29	NS	0.21	NS	NS	0.23	NS

(p value < 0.05) NS: non-significant

Table 7. Correlation between indoor and outdoor PM concentration in different residential premises

	PM_{10}				$PM_{2.5}$				PM_1			
Indoor	R1	R2	R3	MC	R1	R2	R3	MC	R1	R2	R3	MC
	0.89	**0.89**	**0.91**	**0.88**	**0.95**	**0.95**	**0.96**	**0.95**	**0.94**	**0.97**	0.97	0.9[illegible]
Outdoor	R1	R2	R3	MC	R1	R2	R3	MC	R1	R2	R3	MC

(p value < 0.05)

lowest -0.57) and fine particles (PM_1 and $PM_{2.5}$) represented strong negative correlations with temperature among all outdoor sites. Whereas in the case of the indoor environment temperature established a strong negative correlation with PM concentration but a weak correlation was established between relative humidity and PM (Table 6). Another study (Massey et al., 2012) in Agra, India also reported a moderate to strong inverse correlation between temperature with indoor-outdoor PM concentration.

To know how Indoor PM concentration is influenced by outdoor PM concentration the value of the Pearson correlation coefficient (r) between indoor & outdoor PM concentration can be used as an indicator of infiltration (Chithra & Shiva Nagendra, 2012; Kwon et al., 2015; Sidra et al., 2015). A significant strong positive correlation (r values between 0.88 to 0.97) was observed between indoor & outdoor PM concentration. R3 (high economy) site showed strongest correlation (r value= 0.91) followed by mixed cluster (r-value =0.88). Indoor Fine particles (PM_1 and $PM_{2.5}$) showed a very strong correlation with outdoor fine particles, which indicated infiltration of outdoor PM into the indoor environment (Table 7). The presence of more windows and balconies in R3 types probably influence indoor PM which led to high r values (Chen & Hildemann, 2009; Mathew et al., 2014). The earlier studies conducted by various researchers (Habil et al., 2019; Massey et al., 2012; Sidra et al., 2015) also observed strong correlations between indoor and outdoor PM concentration.

Seasonal PM concentration variation due to indoor activities: To know about diurnal and hourly PM concentration variation with time in an indoor and outdoor environment, 24 hours-based monitoring was done in mixed cluster houses. Using the formulated questionnaire, background information of residents and their regular daily activities (time and duration, etc.) were collected (Table 4). Based on the indoor activities, PM concentration varied with time. The 24-hour indoor averages of PM_{10}, $PM_{2.5}$, and PM_1 were 296.08 μg/m^3, 92.2 μg/m^3, 52.38 μg/m^3 for summer and 489.65 μg/m^3, 282.21 μg/m^3, 179.95 μg/m^3 in winter respectively. As recorded Indoor PM concentrations during the winter season were quite high as compared to summer months. This was reflected in the seasonal average data reflected too (Fig 2 and 3). From late-night to early morning time (from 22:00 hrs to 6:00 hrs) in the winter month, when

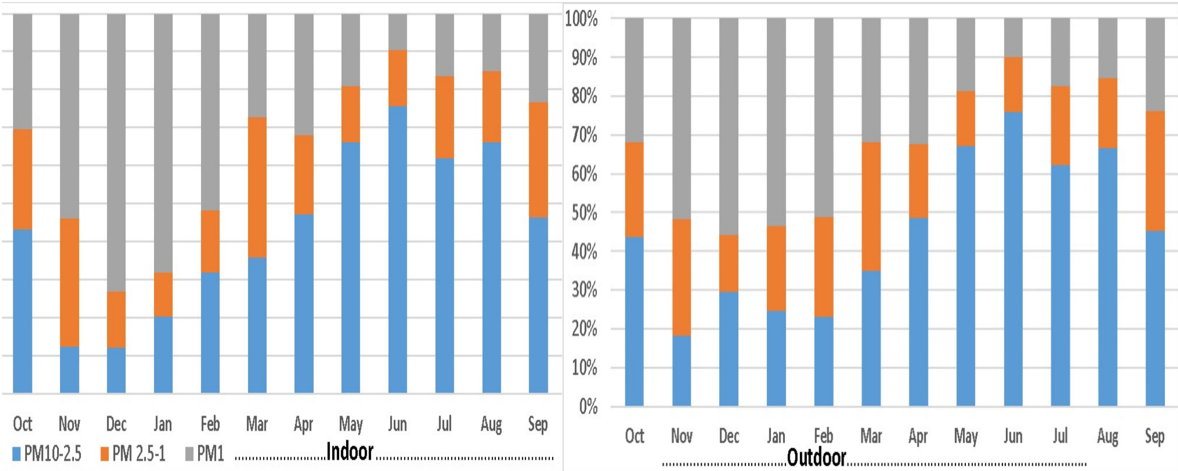


Fig. 4. The monthly distribution of the percentage of size segregated particulate matter ($PM_{10\text{-}2.5}$, $PM_{2.5\text{-}1,}$ and PM_1).

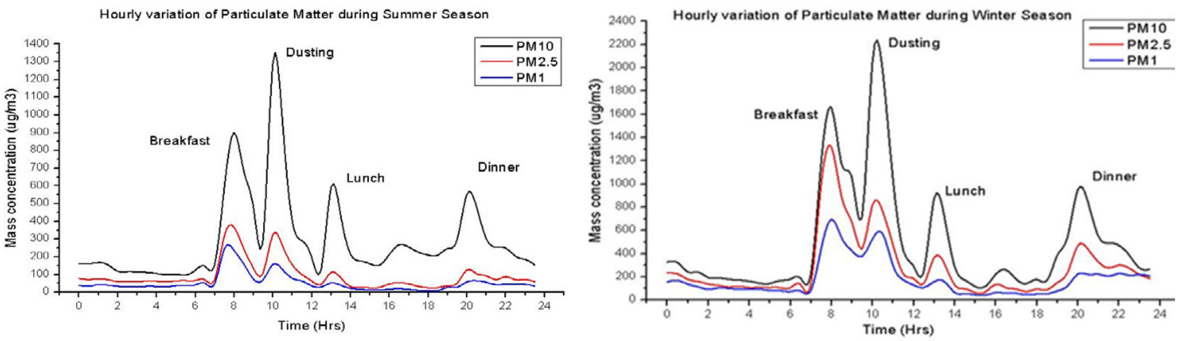


Fig. 5. Hourly variation of PM10, PM2.5, and PM1 in an indoor environment during pre-monsoon (summer) and winter season

occupants are in sleep or less active, PM mass concentrations were lowest (129.25±26.28 μg/m³, 204.96±61.06 μg/m³ during summer and winter respectively). During dusting (sweeping and cleaning) PM_{10} concentration showed a marked increase in comparison to cooking time. Dusting, sweeping activities, and usage of the ceiling fan led to the re-suspension of settled dust. During cooking, the spike in PM concentration was observed which could be attributed to the bread-making process on a pan, which involved frying (Fig.5). The suspension of the finely ground flour might have also contributed to the coarse size fraction. These results are supported by other researchers (Ferro et al., 2004; Glytsos et al., 2010; Patel et al., 2020), that coarse and fine particle concentration depends on the types of indoor activities and the number of occupants living in indoor spaces.

Limitations of the study: during and after conducting studies we experience some limitations like

1. Indoor monitoring is always challenging as it needs consent and cooperation from building dwellers for regular onsite monitoring. Regular monitoring also requires more number of instrumental facilities for prolonged monitoring which was also limited as we had two instruments for each pollutant (simultaneously for indoor and outdoor monitoring). To address this issue we have prioritized regular monitoring with more number of observations but restricted our monitoring sites within 12 flats (triplicate houses representing each classified site, R1. R2. R3 & MC).

2. Unavailability of an anemometer during the study, we were unable to explain the role of wind speed and direction in outdoor and indoor pollution dispersion.

CONCLUSION

The present study demonstrated the spatial and temporal variations of PM and their associated size fractions at different residential settings of Delhi.

1) Spatial monitoring of Seasonal PM fractions (PM_{10}, $PM_{2.5}$, and PM_1) during pre-monsoon, monsoon, post-monsoon & winter seasons suggested that the high mass concentration at any site does not provide information on local pollution emission source, rather their trend analysis depicted a better understanding of the influence of local meteorology and the dweller's pollutant emitting lifestyle practices based on their socio-economic status. Specifically, indoor PM concentration depends on various factors like building design, outdoor PM concentration, and indoor routine activities (such as cooking, dusting, floor-sweeping, smoking, etc.).

2) As there are no indoor air quality guidelines available in India, results were compared with NAAQS-EPA standards. Average concentrations of PM_{10} and $PM_{2.5}$ were found to be 4 to 6 times higher (in comparison to EPA guidelines) indoors as well as outdoors. Seasonal PM_1 dynamics was also reported a similar increasing trend, till now guidelines for PM_1 have been missing. Being ultrafine in size PM_1 is expected to be more harmful than others and a major public health concern.

3) Among all four sampling sites, the mixed cluster site (commercial cum residential use) reported the highest PM concentration compared to pure residential sites which is clearly highlighted the importance of building design, ventilation, indoor activities, and surrounding influence of microhabitat.

4) Indoor and outdoor ratios were highest during the winter season (varies between 1 to 2) and minimum during pre-monsoon season (0.6 to 0.8). Generally in North India, dwellers usually closed the doors during chill winter season to avoid heat losses which resulted in the accumulation of PM concentration.

Delhi being India's capital need to address the problem of fine and ultra-fine particle pollution in an urban built-up environment. I/O relation indicated the source of indoor PM concentration and reason for seasonal public health risk. In the future, for better indoor air quality, the planners should focus on building design along with different coping strategies. The information obtained from our study is especially important for understanding the current state of the art of urban indoor pollution in developing country.

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CONFLICT OF INTEREST

The authors of this research article declare that they have no Conflict of interest.

LIFE SCIENCE REPORTING

No Life Science threats were practiced in this study.

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