Chapter

Evaluation of Particulate Matter Pollution in Micro-Environments of Office Buildings—A Case Study of Delhi, India

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Abstract

High level of particulate matter in an office building is one of the prime concerns for occupant's health and their work performance. The present study focuses on the evaluation of the distribution pattern of airborne particles in three office buildings in Delhi City. The study includes the Assessment of PM_{10}, $PM_{2.5}$ and PM_1 in the different indoor environments, their particle size distribution, I/O ratio, a correlation between pollutants their sources and management practices. The features of buildings I, II, and III are old infrastructure, new modern infrastructure, and an old building with good maintenance. The results indicate that the average concentrations of PM_{10}, $PM_{2.5,}$ and PM_1 are found in the range of 55–150 μg m^{-3}, 41–104 μg m^{-3} and 37–95 μg m^{-3}, respectively in Building I, 33–136 μg m^{-3}, 30–84 μg m^{-3} and 28–73 μg m^{-3}, respectively in Building II and 216–330 μg m^{-3}, 188–268 μg m^{-3} and 171–237 μg m^{-3}, respectively in Building III. The maximum proportion of the total mass contributed by $PM_{0.25–1.0}$ i.e., up to 75%, 86%, and 76% in the meeting room of Building I, II and III, respectively. The proportion of ultrafine particles was found higher in the office area where the movement was minimum and vice versa. The higher I/O indicates the contribution of the presence of indoor sources for ultra-fine and finer particles. Further, possible strategies for indoor air pollution control are also discussed.

Keywords: ultrafine particulate matter, size segregated particles, distribution pattern, indoor sources, indoor/outdoor ratio, office buildings

1. Introduction

Indoor Air Quality (IAQ) refers to the level of air pollutants and thermal (temperature and relative humidity) conditions that affects the health, comfort, and performance of the occupants inside a building. The high concentration of air pollutants indoor is a major concern in Delhi city, which has been many times reported as one of the polluted cities of the world [1]. The major sources in an office building are infiltration of ambient air pollutants; emissions from office equipment like printers, xerox. Etc.; emission of VOCs from building materials, re-suspension of floor dust; emission from cleaning chemicals among them [2]. In addition to the sources, poor ventilation builds the pollutant level indoors [3]. The increasing level of pollutants needs to be managed as it can affect occupant's health, comfort, and work output. Researchers in the past showed evidence that the air within residential and other commercial buildings including offices can be more polluted than the outdoor air even in the largest and most industrialized cities [4–7]. It is also reported that the health risks may be greater due to exposure of air pollutants indoor than outdoor as people spend more time in indoor environment, be it office or at home.

There are no specific criteria pollutants and standards defined to categorize classes of indoor air quality i.e. satisfactory or hazardous. Generally, researchers focus on the CO_2 level and thermal comfort parameters for Indoor air quality, which are indicators of sick building syndrome [8, 9]. There is limited information available on the high exposure of indoor particulate matter in buildings, especially working offices, where people spend almost 8–9 hours daily and are exposed. Limited research is carried out on size segregated PM in indoor air in cities of developing countries where outside PM levels are higher [10–12]. Researchers also observed that fine and ultrafine particles are more harmful than coarse particles irrespective of indoor or ambient environments [13].

In the past, Wargocki et al. [14] have experimented in a typical office environment in which two exposure conditions were produced i.e., with and without emission source where the same office staff worked for 5 h in each condition. The productivity of the staff was found 6.5% less in poor air quality and experienced significantly increased incidences of headache i.e., a symptom of sick building syndrome [15]. Fisk [16] concluded relatively strong evidence of relationships among characteristics of buildings and indoor environments, which influence the occurrence of communicable respiratory illness, allergy and asthma symptoms, sick building symptoms, and worker performances. It is also reported that any improvement in IAQ by a factor of 2–7 can increase occupant's productivity in offices.

In the recent past, some studies are carried out to assess the Indoor PM_{10} and $PM_{2.5}$ levels in school buildings and residential buildings in different Indian cities (**Table 1**). The major objectives of these studies were to assess PM exposure on children, who are more sensitive [22, 23, 26]. Kulshreshtha and Khare [21] have found average PM_{10} concentrations in the range of 373–894 μg m^{-3} in winter and 107–199 μg m^{-3} during summer in a residential building in Delhi. The $PM_{2.5}$

Author/ City	Type of Building	Pollutant Concentration	Study Period/ Sampling duration	Key Findings of the Study
Saraga et al. [17]/ Goudi, Athens	Museum	$PM_{2.5}$: 20.3 ± 2.69 μg/m^3 (Summer)	Jun 22 - Jul 2, 2007/ 24 hr	The higher number of occupants and re-suspension of PM leads to elevated fine particles levels.
	Smoker's Office	$PM_{2.5}$: 37.6 ± 27.3 μg/m^3 (Summer)	July 16–22, 2007/ 24 hr	
	Non-Smoker's Office	$PM_{2.5}$: 30.7 ± 6.7 μg/m^3 (Summer)	July 23–27, 2007/ 24 hr	
Razali et al. [18] / Malaysia	School	$PM_{2.5}$: 22 ± 6 μg/m^3 (Summer) PM_{10}: 35 ± 11 μg/m^3 (Summer)	June 14–July 1, 2011,/ 8 hr., day time	The classroom location and the movement of students in and out of the classrooms influence the PM concentrations.
Zwoździak et al. [19]/ Wrocław, Poland	School	$PM_{2.5}$: 59.8 ± 21.6 μg/m^3 (Winter) and 13.5 ± 4.1 μg/m^3 (Summer) PM_{10}:	Winter (Dec.09 – Jan. Mar, 10) Summer (Apr.-Jun.,10,)/08 hr.	Fine and coarse particles were generated by indoor sources i.e. dust re-suspension due to children activities

Author/ City	Type of Building	Pollutant Concentration	Study Period/ Sampling duration	Key Findings of the Study
		68.5 ± 21.8 μg/m^3 (Winter) and 43.8 ± 17.9 μg/m^3 (Summer)		
Taneja et al. [20]/ Agra, India	Residential Rural & Urban	PM_{10}: 245 μg/m^3 (rural) and 339 μg/m^3 (urban)	Oct. 04 – Dec. 05/24 hr	The concentrations of $PM_{2.5}$ and PM_{10} were higher inside during the winter. Coarse particles were generated by indoor sources i.e. cooking, burning, etc.
Kulshreshtha & Khare [21]/ Delhi, India	Residential Homes	PM_{10}: 373–894 μg/m^3 (Winter) and 107–199 μg/m^3 (Summer); $PM_{2.5}$: 197–713 μg/m^3 (winter) and 34–60 μg/m^3 (Summer) PM_1:169–623 μg/m^3 (winter) and 23–36 μg/m^3 (Summer)	Winter and Summer season of 2008, Hourly average	The PM concentrations were significantly higher during the winter period. Emission from the kitchen is the dominant source of Indoor particles in small houses with poor ventilation.
Goyal and Khare [22]/ Delhi, India	School	$PM_{2.5}$: 30–160 μg/m^3 (Non Winter); 110–789 μg/m^3 (Winter) $PM_{10:}$ 19.5–110.6 μg/m^3 (Non Winter) and 77.3–713.1 μg/m^3 (Winter)	(Aug., 06, Sep. 06, Apr., 07); (Nov., 06, Dec., 06, Jan.-Feb., 07)/ 6 hr	The results of this study indicated that the concentration of pollutants particularly PM is influenced by the occupant's activity.
Chithra & Nagendra [23]/ Chennai, India	School	$PM_{2.5:}$ 61 ± 29 μg/m^3 (Winter) and 32 ± 16 μg/m^3 (Summer) PM_{10}: 149 ± 69 μg/m^3 (Winter) and 95 ± 61 μg/m^3 (Summer)	Winter (Jan.- Mar. 11) Summer (Apr.-May 11)/24 hr	A strong seasonal variability with poor IAQ was observed during winter. Human activity seems to be an important factor influencing the coarse particle level.
Datta et al. [24]/ Delhi, India	Office & School	$PM_{2.5:}$ 43.8 μg/m^3 (Office) -22.8 μg/m^3 (School) (Summer)	June–July 2015/ 8 hr., day time	The study indicates that the occupant density in the air-conditioned non-residential buildings plays a vital role in controlling indoor air pollution levels inside the building.
Gupta et al. [25]/ Delhi, India	Office	$PM_{2.5}$: 116.5 ± 67 μg/m^3 (Winter)	Jan.- Feb., 18	A higher concentration of $PM_{2.5}$ in the building could be due to its maximum proximity to urban busy roads and poorly maintained HVAC ducting system, which may lead to infiltration and more leakages of $PM_{2.5}$ from outdoors.

Table 1.
Indoor air quality in different types of buildings.

concentrations in the range of 197–713 μg m^{-3} in winter and 34–60 μg m^{-3} in summer while PM_1 found in the range of 169–623 μg m^{-3} in winter and 23–36 μg m^{-3} in summer, respectively in a low and medium-income group house where emissions from kitchen are generally high due to Indian cooking style. The results indicate a higher level of PM concentration during the winter season. However, the level of $PM_{2.5}$ and PM_{10} in western cold countries is comparatively very less [19, 25]. Recently, Gupta et al. [25] have reported $PM_{2.5}$ concentration level as 116 ± 67 μg m^{-3} in one of the office buildings in Delhi during the winter period. The higher level of $PM_{2.5}$ might be due to the penetration of ambient $PM_{2.5}$, which is generated from nearby high traffic roads.

The high level of indoor PM (PM_{10}, $PM_{2.5,}$ and $PM_{1.0}$) in the office building is an emerging issue in view of its adverse effects on working productivity and health. There is a need to assess it comprehensively at different locations in the city for different types of office buildings.

The present study is an attempt to assess the size of fractioned PM in different sections of the office buildings. The study has monitored the different size PM in different building sections like staff cabin, meeting/conference room, office halls, accountant room, and outside building in Delhi city. PM monitoring is carried out in three different types of buildings. The particle size distribution plot of each monitoring location has been carried out and compared to further correlate with the sources. The correlation between sites for a particular size PM is calculated along with the Indoor/outdoor ratio.

2. Materials and methods

2.1 Site description

Three different types of office buildings are considered in the present study to assess the PM levels in the indoor environment. The buildings are named Building I,

Figure 1.
Delhi's map showing site I, II, and III.

Locations	Direction wrt Centre of Delhi	Types of Building/ Features/ Old or New (approx. age)	Surrounding Landuse features
Building I/ Site I	South Delhi	Typical office building, lots of old files, close cabins, poor ventilation, congested place, approach, 30–40 years old, etc.	Located in the institutional area, Medium density traffic road outside building, residential area on one side of the building, and green forest area on the other side
Building II/ Site II	South Delhi	Modern office building, clean and spacious Hall, New infrastructure, 1–2 years old building, no open files, located at the lower ground floor, Office is part of a shopping mall having eateries, offices, coffee shops and retail shops etc.	High-density traffic road, Car parking outside the building, covered by Residential area on three sides and open land on one side
Building III/ Site III	Central Delhi	Old and very well maintained building hall, high movement of people for meeting/discussions, no public dealing office, daily cleaning activities through cleaning reagents, etc.	Smooth traffic movement outside, commercial area nearby and lots of green areas

Table 2.
Building types and surrounding features at site I, II, and III in Delhi.

Building II and Building III located at sites I, II and III, respectively. Sites I and II represent South Delhi, while site III represents Central Delhi, as shown in **Figure 1**. Building I is a traditional office building with old infrastructure, Building II is a newly constructed office space (with Modern Infrastructure) and Building III is an old Building, but maintained very well. The details of the buildings and surrounding site features are described in **Table 2**.

3. Instrumentation and monitoring protocol

PM monitoring was carried out using a laser aerosol monitor (GRIMM Aerosol Technik Gmbh & Co. KG, Ainrig, Germany, Mini-LAS Model 11R) [27]. The instrument captures every single particle ranging from 0.25 to 32 μm and classifies it into 31 size range channels. The instrument was calibrated before monitoring. The data were recorded and stored at every 6-second interval. The monitor provides concentration levels at the cut of point of $PM_{1.0}$, $PM_{2.5}$, and PM_{10} which are generally monitored for health exposure and from a regulatory compliance point of view.

Monitoring was carried out for 1 day each at all the three sites in December 2018 (Winter) on different dates. At each location of the building at all three selected sites, 15 minutes of measurement was recorded. The monitor was placed in the center of each room (about 1 m above the floor), which corresponds to the breathing zone of the sitting occupants, and the outdoor monitor was placed at least 1.5 m away from any obstacle at a height of 1 m above the ground. The details of the monitoring protocol followed are summarized in **Table 3**. The photographs of monitoring locations for Buildings I and II are shown in **Figure 2**, whereas photographs were not taken at site III due to security reasons. Based on the discussion with the office staff about their comfort and visualizing the situations of the Heating, Ventilating and Air Condition (HVAC) system, in each compartment of all three buildings, building I am categorized as poor ventilated, however, buildings II and III as good ventilated. Kulshreshtha and Khar [21] have correlated the

Location	Monitoring Details	Monitoring Locations
Building I	Monitoring was carried out in the second week of December 2018, during 10 am to 3 pm, monitoring was carried out for 15 minutes at each of the selected locations.	1. Halls A-I mainly occupied by staffs (Vol.315–350 m^3 of each) 2. Account department (Vol. 84 m^3) 3. Meeting rooms (150 m^3) 4. Conference room (294 m^3) 5. Common area at entrance (360 m^3) 6. Outdoor air in front of the entrance gate. PM monitor was placed at an average height of 1 m above ground. Poor Ventilation System
Building II	Monitoring was carried out in the first week of December 2018, during 11 am to 3 pm, monitoring was carried out for 15 minutes at each of the selected locations.	1. Halls mainly occupied by clerical/ technical staffs, (Vol. 210–280 m^3) 2. Staff Cabin (Vol. 27m^3) 3. Conference (315 m^3) 4. Meeting room (215 m^3) 5. Cafeteria/Pantry (60 m^3) 6. A common indoor area at the entrance (20 m^3 and Reception (60 m^3) 7. Outdoor air at entrance. PM monitor was placed at an average height of 1 m above ground. Good Ventilation System
Building III	Monitoring was carried out during the last week of December 2018 from 10 am to 1 pm for one day. The monitoring was carried out for a period of 15 minutes each at the selected locations.	1. Meeting Room/Hall (Vol. 12000 m^3) 2. Common Indoor area. (3000 m^3) PM monitor was placed on the table of an average height of 1.2 m in the meeting room and chair of height 0.40–0.45 m in the common area Good Ventilation System

Note: Vol. – Volume of indoor space where monitoring was carried out. These volumes are calculated based on tentative measures of length, width, and height of indoor compartments.

Table 3.
Monitoring protocol adopted in each building.

ventilation parameters with the comfort level of occupants in a residential building where poor indicate inadequate ventilation and a high potential for complaints and Good indicate satisfaction for all occupants.

4. Results and discussion

4.1 Status of indoor PM_{10}, $PM_{2.5,}$ and PM_1 concentration

Generally, the particles are monitored in terms of PM_{10} (particles having aerodynamic diameter ≤ 10 μm), $PM_{2.5}$ (particles having aerodynamic diameter ≤ 2.5 μm), and PM_1 (particle having aerodynamic diameter ≤ 1.0 μm) for regulatory as well as health exposure assessment in ambient as well as in the indoor environment. Additionally, the particles are defined as Ultrafine (<1 μm), Fine or accumulation mode (1 to 2.5 μm) and Coarse particle (> 2.5 μm) as described by Tiwary & Williams [28]. A similar assessment was carried out in the present study as well to evaluate the level of these particles. The monitored data of PM_{10}, $PM_{2.5,}$ and $PM_{1.0}$ concentrations were analyzed statistically and are summarized in graphical form in **Figures 3** to **5** for Buildings I to III, respectively.

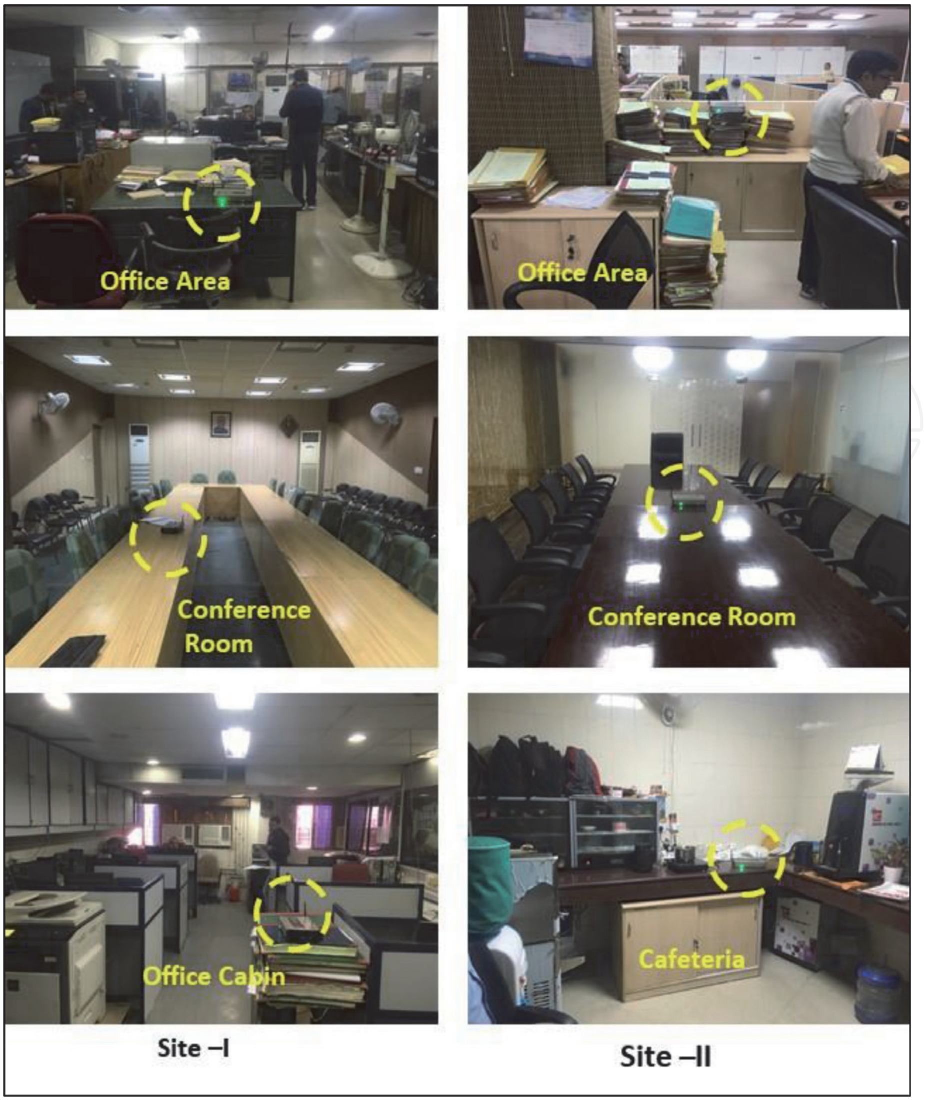

Figure 2.
Photographs showing monitoring location in building I and II (Note: Building III photographs not taken due to security reason).

The average concentrations of PM_{10}, $PM_{2.5,}$ and $PM_{1.0}$ in Building I were found to be 101 μg m^{-3} (range 55–150 μg m^{-3}), 72 μg m^{-3} (range 41–104 μg m^{-3}) and 64 μg m^{-3} (range 37–95 μg m^{-3}), respectively. The concentration of particulate matter was found higher in the account's department compartment and Halls E and

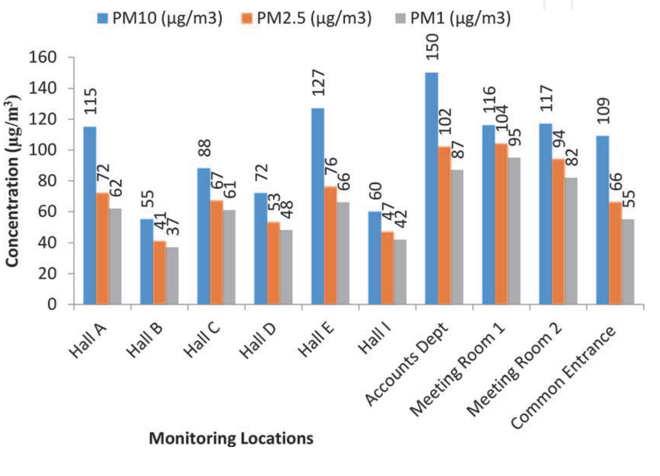

Figure 3.
Average PM concentration in different indoor rooms at building I.

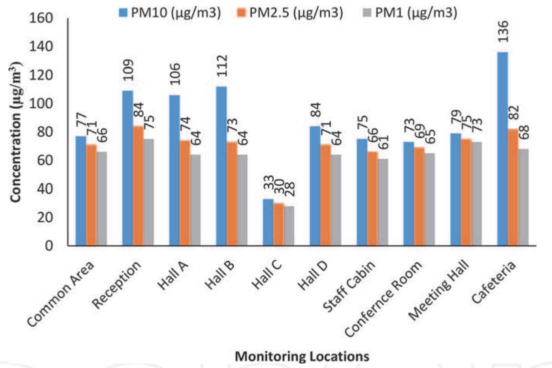

Figure 4.
Average PM concentration in different indoor rooms at building II.

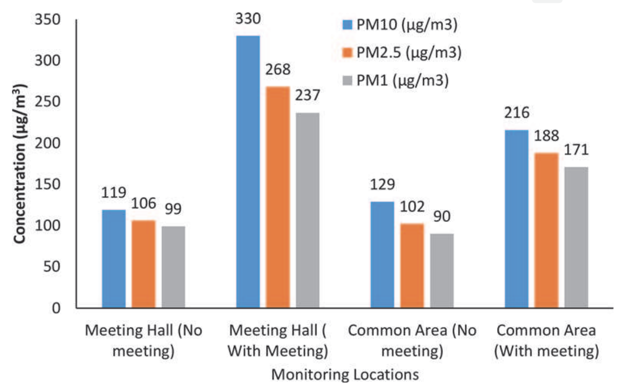

Figure 5.
Average PM concentration in different indoor rooms at building III.

Hall A, which might be due to higher activities and deposition of particles on files that move here and there on daily basis along with the staff.

At Building II, the average levels of PM_{10}, $PM_{2.5}$, and PM_1 were 88 µg m^{-3} (range 33–136 µg m^{-3}), 70 µg m^{-3} (range 30–84 µg m^{-3}) and 63 µg m^{-3} (range 28–73 µg m^{-3}), respectively. The concentrations of all three fractions of PM were found higher at the reception area and in the cafeteria/ pantry area, which is directly correlated with the high activity area. The high level of PM_{10} at reception and halls A and B (next to the reception area) might be due to the high movement of staff and visitors in the office compared to other office areas.

At Building III, the concentrations of PM_{10}, $PM_{2.5}$, and PM_1 were found in the range of 119–129 µg m^{-3}, 102–106 µg m^{-3} and 90–99 µg m^{-3}, respectively during non-meeting hours, however, these values during meeting hours were found to be high as 216–330 µg m^{-3}, 188–268 µg m^{-3} and 171–237 µg m^{-3}, respectively. This difference might be due to the penetration of PM due to the opening and closing of doors from the entrance gate to the lobby area and then the lobby gate to outside due to the high movement of people. The meeting was going during the monitoring and about 60–70 persons were present in the meeting hall.

Each of the compartments of respective buildings varied notably in dimension, number of doors, frequency of closing and opening, and the number of units of air filtration vents as described in **Tables 2** and **3**. The combination of these variables provided highly variable ventilation conditions and huge differences in indoor PM concentrations. A higher proportion of ultrafine particles also indicates the possibility of bio-aerosols in indoor spaces, which needs to be assessed and managed from a health impact point of view.

Further, the correlation between the size of the room/halls (indoor volume, m^3) and size segregated particulate concentrations were estimated for Building I and II.

The correlation coefficient (r^2) values for PM_{10}, $PM_{2.5}$ and PM_1 were estimated to be −0.35, −0.55, −0.54, respectively at Building I and − 0.19, −0.28, −0.28 at Building II. The negative correlation means larger halls/rooms increase the dispersion of particles, which results in low concentrations. It is also important to note that particulate concentrations at Building I (Old infrastructure and poor ventilation) have a good negative correlation with the size (volume) of the indoor compartments/rooms as compared to Building II (Modern infrastructure and good ventilation). It might be due to the impact of a good ventilation system, which dominated the impact of room size. Further, the fine and ultra-fine particles have a good correlation with the size of the room compared to coarser particles.

4.2 Particle size distribution in indoor work environment

The particles in the atmosphere may be primary or secondary, solid, or liquid depending upon their formation/sources. In the air, particles remain in suspended form for a longer time depending upon their sizes, which vary from very ultra-fine particles (nm) to coarse fine particles (μm). In literature, it is reported that ambient air particles below 2.5 μm are called fine particles which are further divided into transient nuclei (<0.1 μm) and accumulation range (0.1–2.5 μm). The fine particles are mainly generated due to primary emissions (controlled combustion activities, bio-aerosols, secondary aerosol, room air freshener, room cleaner spray in Indoor environments etc.). The particles in the size range of 2.5–100 μm are called coarse particles and are generated from wind-blown dust, sea spray etc. [29, 30].

In the present study, particle size between 0.25 μm to 32 μm is monitored at different 31 intervals. The fraction of different sized particle mass is compared between different indoor work environments and then with the ambient air. The fraction of total mass (%) contributed by different size range particles are described in **Tables 4-6** and **Figure 6**.

In Building I, the maximum mass was contributed by particles of size range 0.25–1.0 μm, in the range of 33–55% in Halls (Staff sitting area with half-sized individual cabin). These values for meeting rooms were even higher, being in the range of 60–75% (empty room during monitoring). The second dominant particle size range was 2.5–10 μm, which contributed 27–40% of the total mass in Halls, 12–21% in meeting rooms, however, the contribution at the common building entrance was 38%. The proportion of particle size 10–32 μm was between 11 and 24% (except Hall D, 5% only), 4–7% in meeting rooms, and 18% at the common entrance gate. In ambient air the mass contribution by particles of size 0.25–1.0 μm, 2.5-10 μm and 10-32 μm was found as 7%, 48%, and 41% respectively, which seems to be opposite to the trend of mass distribution in the different indoor environment except for the common entrance area.

In Building II, which is a modern office and located in the lower ground floor of a shopping mall (no direct opening in the ambient environment), the trend of particle size distribution was more or less similar with more percentage of ultrafine particles (0.25–1.0 μm); in the range of 36–64% in Office Halls, 82–86% in conference/meeting rooms, 30% at Main entrance of the Mall. In this building, the pantry area is near to the office staff sitting area and where the dominant particle size range was 2.6–10 μm with 40% of the total mass.

In Building III, a similar trend was observed for the meeting hall and common Indoor lobby area during non-meeting hours. However, during meetings, the proportion of ultrafine particles decreased from 78–64%, whereas particles of 2.6–10 μm increased from 13–22%. This indicates the re-suspension of particles due to the movement of people in the indoor environment. In the meeting hall, approx. 60–70 people were present during the meeting, which enhanced the particle concentrations even in the presence of sufficient ventilation systems.

Particle Size Range (µm)	Hall A	Hall B	Hall C	Hall D	Hall E	Hall I	Accounts Department	Meeting Room 1	Meeting Room 2	Common Entrance	Outside (Ambient Air)
0.25–1.0	41	48	55	55	33	50	43	75	60	35	7
1.1–2.5	8	6	6	8	7	7	8	9	10	9	5
2.6–10	40	27	27	31	35	27	32	12	21	38	48
10–32	11	18	12	5	24	14	17	4	7	18	41

Table 4.
Proportion of mass (%) contributed by different size particles in the different indoor compartment of building I.

Particle Size Range (µm)	Hall A	Hall B	Hall C	Hall D	Common Area (Lobby)	Staff Cabin	Conference Room	Meeting Hall	Cafeteria	Reception	Main Entrance	Ambient Air
0.25–1.0	38	36	55	64	78	70	82	86	30	53	30	18
1.1–2.5	8	7	7	10	9	8	8	5	9	9	13	7
2.6–10	31	37	12	21	11	18	8	7	40	28	47	31
10–32	22	19	26	4	1	3	0	1	21	9	10	44

Table 5.
Proportion of mass (%) contributed by different size particles in different indoor compartments of building II.

Particle Size Range (μm)	Meeting Hall (No meeting)	Common Area (No meeting)	Meeting Hall (With Meeting)	Common Area (With meeting)	Ambient Air
0.25–1.0	78	62	64	73	39
1.1–2.5	6	10	9	8	8
2.6–10	13	25	22	16	35
10.1–32	3	3	5	3	19

Table 6.
Proportion of mass (%) contributed by different size particles in different indoor compartments of building III.

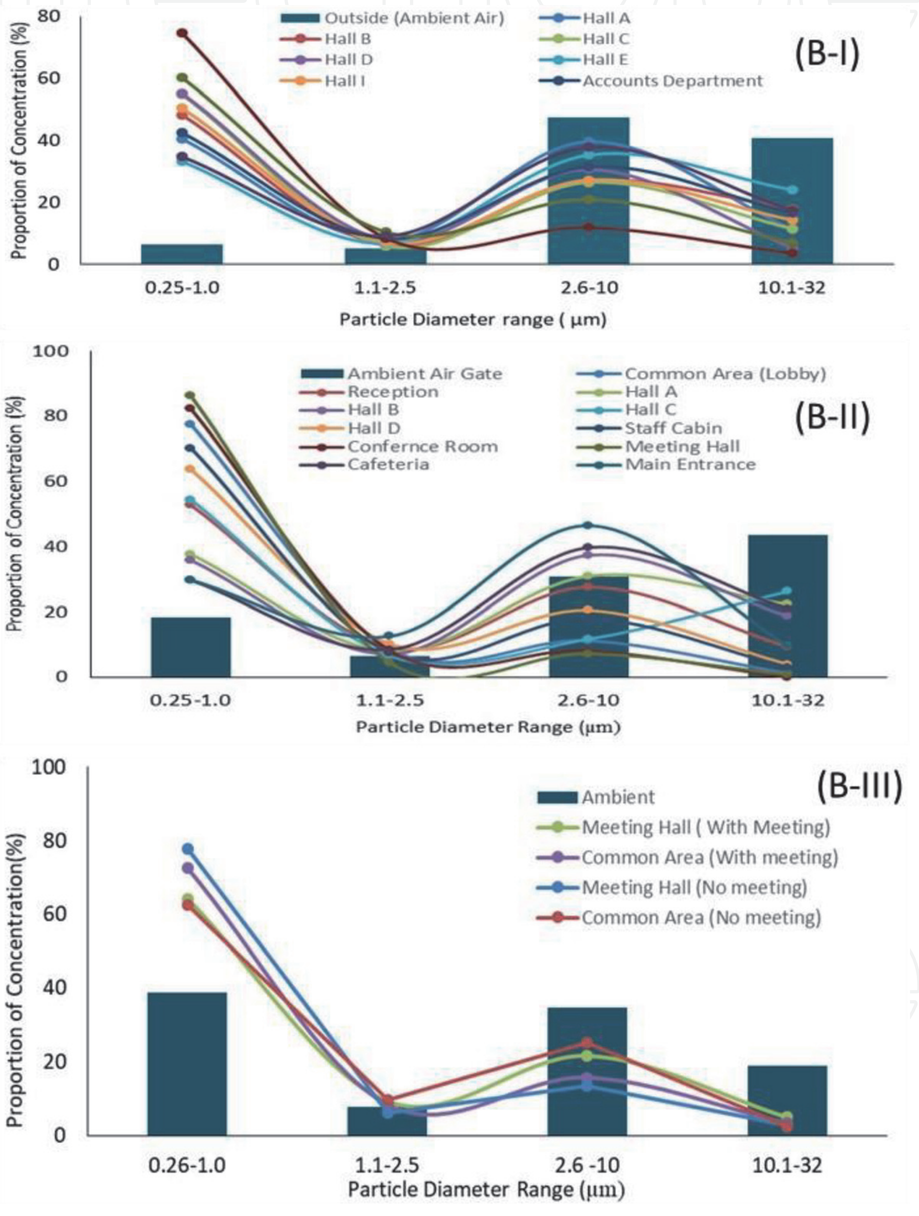

Figure 6.
Proportion of mass (%) contributed by different size particles in building I, II, and III.

It is observed that the proportion of finer particles is maximum in the indoor environment where the activity level is minimum (meeting rooms), followed by staff sitting area and then common building entrance (high people movement). It indicates that ambient air particles are more influenced by windblown dust particles from road and construction dust and natural dust. The particle size distribution indoor indicates the possibility of accumulated particles and bio-aerosol which are generally found in the range of fine particle size (diameter < 1 μm).

Norhidayah et al. [31] also found a dominant particle size range 0.3–0.5 μm in an office building in Malaysia and reported printing and photocopier machines as the major source of particles which is supported by work carried out by Massey and Taneja [13]. They have found that photocopier and printer machines generated accumulation phase particles i.e., 0.25–1.0 μm, and air freshener and cleaner generate particles of size l μm. Similarly, Tang et al. [32] reported a significant increase in fine and ultra-fine particle concentration in 43 out 62 office's rooms. They reported the average size of emitted particles in the range from 0.23 and 20 μm.

4.3 The ratio of Indoor/Outdoor (I/O) PM Concentrations

The I/O ratio of a pollutant is generally calculated to evaluate the possibility of intrusion of outdoor pollution inside the building. In the present study, the I/O ratio of size segregated PM (range 0.25–1.0 μm, 1.1–2.5 μm, 2.6–10 μm, and 10.1–32 μm) is calculated for each compartment of each building where monitoring was carried out as shown in **Figure 7**.

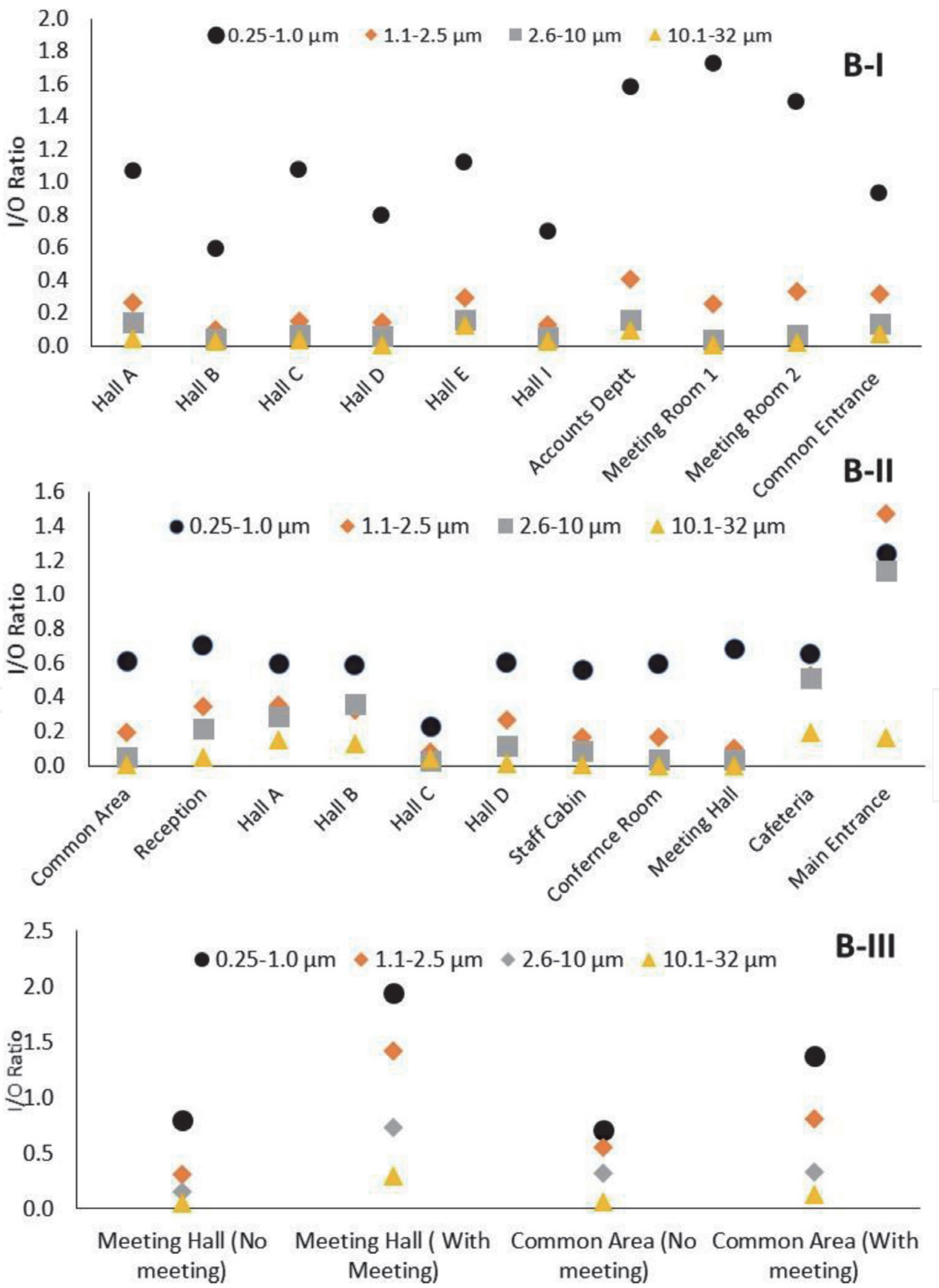

Figure 7.
Indoor/outdoor (I/O) ratio of size segregated PM in building I, II, and III.

In Building I, the I/O of ultrafine particles (0.25-1 μm) was found higher as compared to fine and coarse sized particles in all indoor compartments of the building. The I/O ratio of ultra-fine particles in the meeting/conference room (non-active area) was found maximum in the range of 1.6–1.7 when compared to other compartments of the building where office staff movement was more (0.5–1.1). Secondly, particles of size 1.1–2.5 have a higher I/O ratio in the range of 0.1–0.4. The I/O of coarse sized particles in the range of 10.1- 32 μm is lowest in all building compartments (up to 0.1).

In Building II, the I/O of ultrafine particles was found higher in the range of 0.6–1.2 (except Hall C of 0.2) compared to fine and coarse sized particles in all indoor compartments of the building. The particle size of 1.1–2.5 μm and 2.6-10 μm was more or less similar in the range of 0.1–0.4 except the cafeteria/pantry and main entrance. The values at the cafeteria/pantry were 0.5 for both sizes ranged particles and 1.2 and 1.5 for the main entrance area. The I/O of coarse sized particles in the range of 10.1- 32 μm is lowest in all building compartments (up to 0.2).

The I/O ratio pattern of Building III is more or less similar to Building I during non-meeting hours which is found to be 0.8, 0.3, 0.2, and 0.1 in the meeting hall for particle sizes of 0.25–1.0 μm, 1.1–2.5 μm, 2.6-10 μm and 10.1–32 μm, respectively. However, during meeting hours, these I/O values were found to be higher as 1.9, 1.4, 0.7 and 0.3, respectively. The occupants found the I/O ratio in Building III higher because of the opening and closing of the door many times during the monitoring period.

It is inferred that fine and ultrafine particles have higher I/O at all three sites, which might be due to the presence of Indoor sources and/or poor ventilation. Building II and III are well maintained, ventilated, and have modern infrastructure compared to Building I. This is reflected by low I/O values in all indoor compartments of Building II compared to Building I for ultrafine and fine particles. At Building III, there were no open files on desks, no cafeteria activities like Building II, however, still I/O was found >1 for the finer particles. Based on the discussions, it was found that regular cleaning of the tables, chairs and other areas was carried out through cleaning spray in the meeting room, which might generate fine aerosols. Similar observations were found by Goyal and Kumar [33], they found that I/O ratio for PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ varied from 0.37–3.1, 0.2–3.2 and 0.17–2.9 respectively, at a commercial building in Delhi city. In one of the office buildings in Delhi, the I/O ratio of $PM_{2.5}$ was found to be 0.28–1.07 μg m^{-3}, which indicates that indoor $PM_{2.5}$ sources exist in the building apart from infiltration from outdoors [25]. The findings in developed countries also indicate average I/O ratios of $PM_{2.5}$ between 0.4 and 0.9 in an office room in Beijing and Xi'an cities in China [34, 35] and 0.62 ± 0.14 in Milan, Italy [36].

The analysis indicates that fine and ultrafine particles are dominantly generated from indoor activities at the monitoring location, which is not directly connected with outdoor gate (e.g. reception area, common entrance area etc). High I/O ratio for ultrafine and fine particles neglect the hypothesis of intrusion of outside PM in a mechanical ventilated building as coarse particles do not have such trend in I/O ratio.

5. IAQ management approach

Adequate and properly designed ventilation systems are the most effective strategies for achieving IAQ objectives. Smart planning of building uses and internal layout may help prevent many unnecessary IAQ problems. The mixed-use buildings having common facilities like Xerox facilities, pantry area among others should be properly ventilated and disconnected from the main office sitting area by the air-filter. There should be proper storage spaces for the old office records. The partitioning of the layout may affect the effectiveness of air distribution resulting in stagnant zones with poor air quality, which needs to be taken care of by architectural planning and ventilation engineering. Housekeeping is important in preventing IAQ problems as it keeps dust levels down and removes dirt, which could otherwise become sources of contamination, including mold growth. The cleaning schedule should be arranged according to occupancy patterns and activity levels. Daily cleaning of surfaces and vacuuming of floors is advisable for areas with high occupancy or which are in constant use during the day. The use of eco-friendly or non-toxic chemicals for cleaning also improves IAQ.

Numerous studies are available that strongly suggest that foliage plants in offices may improve health and reduce discomfort symptoms [37, 38] Kobayashi et al. [39] tested more than 20 plants to improve indoor air quality. Gawrońska, & Bakera [40] concluded that Spider plants (*Chlorophytum comosum* L.) phytoremediation particulate matter from indoor air. Torpy & Zavattaro [41] tested *Chlorophytum comosum* (Spider Plant) and *Epipremnum aureum* (Pothos) and concluded that indoor green plants can significantly reduce particulate matter concentration and hence improve Indoor Environment Quality (IEQ).

6. Conclusion

The study has focussed on the assessment of size segregated particulate matter (PM) in different indoor environments of three office buildings located in different parts of Delhi city. The PM concentrations were found higher in the indoor environment where activities were high but had poor ventilation. The levels of PM in the old building were found higher compared to the newly built office building having the modern infrastructure and well-maintained activities/files etc. The presence of people and activities generated re-suspended particles greater than 2.5 $\mu g\ m^{-3}$, which is noticed when compared PM concentration in the common area, reception area with office cabin area and meeting room with and without meeting hours. The indoor/outdoor ratios were greater for ultrafine and fine particles than coarser particles, which indicates presence of sources of finer particles indoors in all three buildings. Further, the meeting room/conference hall has a higher portion of ultra-fine particles of the total PM concentration. Further, correlation between room size (Indoor volume) and size segregated PM concentration found good negative correlation with finer particles in both buildings. This helps the indoor air quality managers to decide the suitable technology for the improvement of IAQ in different compartments of an office building.

Currently, the country does not have any IAQ standards nor have any monitoring protocol for Indoor air quality assessment. Therefore, it is suggested that country should come out with regulatory framework for IAQ assessment in different types of buildings. The findings of the present study suggest that any proposed IAQ standards should cover ultrafine (PM_1) and fine particle ($PM_{2.5}$) instead of coarser particles especially in office buildings.

Authors' contribution

Saurabh Mendiratta: Monitoring and Original writing, Sunil Gulia: Methodology, Data Analysis, Review, and Re-writing, Prachi Goyal: Monitoring and review, S.K. Goyal: Concept, Methods and Review.

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