Influence of Outdoor Particulate Matter on Indoor Air Quality and Human Health Risks in Urban High-Rise Buildings

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Abstract. Urban areas are largely exposed to the penetration of outdoor particulate matter (PM) indoors, degrading indoor air quality (IAQ) and causing significant human health risks. This work evaluates the impact of outdoor-generated PM on IAQ in a high-rise residential building, keeping windows open and closed under controlled conditions. Real-time monitoring was conducted to assess PM levels and vertical variations, while respiratory deposition dose (RDD) and health risk (HR) were estimated across four demographic groups. Morphological and chemical characterization of PM was also performed. Results reflected higher PM concentrations on upper floors than lower ones, with peaks during morning and evening traffic hours. Indoor PM levels decreased notably when windows were closed, proving as an effective mitigation measure. RDD was higher in men due to greater tidal volume, while HR was lowest for children aged 8–10 years, possibly due to their better immune system. PM particles exhibited spherical, clustered, and irregular morphologies, mainly containing Na, Al, Si, C, K, and Ca, with trace Barium from vehicular emissions. These findings indicate the need for effective urban air quality management and mitigation strategies to reduce indoor human exposure to traffic-related PM.

Keywords: Indoor Air Quality; Particulate Matter (PM); Urban Air Pollution; Health Risk Assessment; Respiratory Deposition Dose; Morphological and Chemical Analysis

1 Introduction

Air pollution is an important global environmental problem affecting human health and environment. This problem is particularly prominent in urban areas experiencing high pollution levels due to vehicular emissions, industrial, and other anthropogenic activities. As per an estimate by the World Health Organization (WHO) [1], nine out of ten people

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worldwide breathe polluted air exceeding safety limits, which result in around seven million premature deaths annually.

Among various air pollutants, particulate matter (PM) has received considerable attention fur to their greatest health risk. Importantly, fine particles ($PM_{2.5}$) can penetrate deeper into the human respiratory system and can enter the bloodstream, elevating the risk of cardiovascular, respiratory, and carcinogenic diseases [2]. PM concentrations exceed both national and international standards in most of the Indian cities [3] with approximately 76.8% of India's population exposed to $PM_{2.5}$ levels above 40 μg/m³, the National Ambient Air Quality Standards (NAAQS) threshold, leading to millions of deaths and disability-adjusted life years [4].

Since individuals spend over 85% of their time indoors [5], indoor air quality (IAQ) studies are more important as compared to outdoors. Indoor PM sources include mainly PM infiltration from outdoor sources as well as indoor human and combustion activities, and building materials. In case of outdoor penetration of PM, traffic emissions, both exhaust (incomplete combustion) and non-exhaust (tire, brake, and road wear) are major contributors, with non-exhaust sources accounting for nearly 86% of vehicular PM, dominated by cars, buses, and heavy vehicles [6].

Moreover, there are limited studies focused on the direct impact of outdoor-generated PM on indoor environments, particularly in high-rise buildings. Furthermore, knowledge for respiratory deposition dosage (RDD) and health risk (HR) is crucial for assessment of long-term health effects, especially on children and the elderly people [7], since fine and ultrafine PM can reach deeper into alveolar regions and can cause severe health effects [8]. Morphological and chemical characterization further increases our understanding of PM sources and toxicity. Field Emission Scanning Electron Microscopy (FESEM) with Energy Dispersive X-ray Spectroscopy (EDX) can provide detailed insights into PM morphology and its elemental composition [9]. Particle shape, size, and composition are important parameters, impacting deposition behavior and health effects [9]. Soot-like agglomerates, irregular crustal particles, and metallic inclusions indicate vehicular and industrial origins [10]. Furthermore, presence of Na, Al, Si, C, K, and Ca, is associated with urban aerosols while trace elements such as Ba, Zn, and Pb are linked to traffic and industrial emissions [6, 8]. Heavy metals pose particular concern due to their persistence and toxic health effects [7].

Considering these identified research gaps, the present study evaluates the impact of outdoor-generated PM on IAQ and human health risks in a high-storey residential building situated near a busy roadway in the Malaviya National Institute of Technology (MNIT) Jaipur campus. Vertical and temporal variations in PM concentrations under different conditions were also explored. Moreover, RDD and HR for various demographic groups were computed, and PM morphology and chemical composition were studies. The findings of this study provide useful insights to people and policymakers for effective indoor exposure assessment and mitigation strategies to traffic-related PM in order to achieve health benefits indoors.

2 Material and methods

The current study was carried out under controlled indoor environmental conditions to analyze PM infiltration from outdoors. The steps followed for methodology consists of site selection, PM monitoring, RDD estimation, potential human HR evaluation, and morphological and chemical analysis of PM. Details of each step has been discussed in this Section 2.

2.1 Study Site and Experimental Setup

This study was conducted inside a high-storey residential building which was situated in proximity of a busy traffic road near the MNIT Jaipur campus. The surroundings of the site made it suitable choice for evaluating the infiltration of traffic-related PM into indoor environments. Experiments were performed inside a naturally ventilated room on the 9th floor of the building, while additional measurements were also taken on the 2nd floor to assess vertical variations. Human activities were minimized in order to restrict PM generation from indoor sources.

A personal air sampler (AP800) operating at a flow rate of 2.5 L/min was used to collect total PM, whereas a real-time PM sensor continuously recorded indoor concentrations of PM_1, $PM_{2.5}$, and PM_{10}. All the PM filters were conditioned in a desiccator for 24 hours before and after sampling in order to eliminate moisture and were then weighed for accurate measurement of PM mass concentrations.

2.2 PM Monitoring Plan

To evaluate the effect of outdoor PM infiltration, two experimental conditions were examined. Firstly, with windows open in order to assess outdoor PM penetration into the indoor environment. Secondly, with windows closed to examine the effectiveness of window closure as a mitigation strategy. For each condition, 8-hour personal exposure measurements were also conducted, while the real-time PM sensor recorded 24-hour concentration variations. Sampling was carried out over four weeks duration, covering both weekdays and weekends to capture variations in traffic-related PM emissions. Measurements were also taken on two different floors (2nd and 9th) to assess vertical PM variations within the building.

2.3 Respiratory Deposition Dose (RDD) Assessment

The RDD is defined as the quantity of inhaled PM deposited in different regions of the human respiratory system. Deposition fractions were calculated for the head (HD), tracheobronchial (TB), and alveolar (AL) regions using established models [7]. The RDD for each PM fraction was computed using Eq. 1 [11]:

$$RDDs(\mu g) = DF_i \times VT\left(\frac{m^3}{breath}\right) \times f\left(\frac{breath}{min}\right) \times PM_i\left(\frac{\mu g}{m^3}\right) \times T(min) \quad (1)$$

where, DFi is deposition fraction for PM of size i, PM_i is the mass concentration of PM of size i (μg/m³), VT is tidal volume (m³/breath), f is breathing frequency (breath/min), and T is exposure time (min). Individuals were assumed to be under light physical activity and VT and f were taken as 9.9×10^{-4} (female) and 12.5×10^{-4} m³/breath (male), with breathing frequencies of 21 and 20 breaths/min, respectively [12]. Deposition fractions for the HD, TB, and AL regions were determined as follows in Eqs. 2, 4-5 [12]:

$$DF_{HD} = IF\left\{\frac{1}{[1+\exp(6.84+1.183 ln d_p)]} + \frac{1}{[1+\exp(0.924-1.885 ln d_p)]}\right\} \quad (2)$$

where, d_p is the particle diameter (μm). The inhalable fraction (IF) was calculated using Eq. 3 as per ICRP model [12]:

$$IF = 1 - 0.5\left[1 - 1/(1 + 0.00076 d_p^{2.8})\right] \quad (3)$$

$$DF_{TB} = (0.00352/d_p) \times \left\{exp\left[-0.234(ln d_p + 3.40)^2\right] + 63.9\exp\left[-0.819(ln d_p - 1.61)^2\right]\right\} \quad (4)$$

$$DF_{AL} = (0.0155/d_p) \times \left\{exp\left[-0.416(ln d_p + 2.84)^2\right] + 19.11\exp\left[-0.482(ln d_p - 1.362)^2\right]\right\} \quad (5)$$

2.4 Human Health Risk (HR) Assessment

The HR assessment estimated the dose rate of PM exposure across four demographic groups: newborns, children (1 year), children (8–10 years), and adults. The dose rate was calculated using Eq. 6 [13]:

$$Dose\ Rate(\mu g/kg) = (BR/BW) \int_0^{24} C(t).Of(t).dt \tag{6}$$

where BR = age-specific breathing rate (L/min), BW = age-specific body weight (kg), C(t) = PM concentration at time t (μg/m^3), Of(t) = occupancy factor, representing the percentage of time spent indoors (assumed 0.9 in this study, i.e., 90% indoor time). The health risk (HR) index was then assessed using the ratio of dose rate to the lowest observed adverse effect level (LOAEL) as per the following Eq. 7 [13]:

$$HR = [(Dose\ Rates)/(Pollutant - specific\ LOAEL)] \tag{7}$$

A value of HR > 1 indicates potential health risks from PM exposure. The age-specific parameters are summarized in Table 1.

Table 1. Age specific breathing rate, body weight and LOAEL values for morbidity [14].

S.No.	Age Category	Inhalation Volume (m^3/day)	Body Weight (kg)	LOAELs (μg/kg/day)
1.	New-borns	0.80	3	14.7
2.	Children (1 year)	3.8	10	20.9
3.	Children (8-10 years)	10	30	27.5
4.	Adult	20	70	15.7

2.5 Morphological and Chemical Analysis of PM

Morphological and chemical characterization of traffic-related PM penetrating the indoor environment was done using FESEM coupled with EDX [9]. This is an advanced technique which provide high-resolution images and detailed elemental composition, thereby, giving precise source identification. Particle shape and surface properties gave an idea of sources such as vehicular combustion and resuspended dust, while elemental composition provided useful insights for presence of dominant elements and trace metal [15]. Overall, eight PM filters collected under both window-open and window-closed conditions were examined under FESEM-EDX analysis in this study.

3 Results and discussion

3.1 Variations in PM Concentration

This work measured concentrations of size-fractionated PM i.e., PM_1, $PM_{2.5}$, and PM_{10} under different indoor environmental conditions to evaluate impact of outdoor-generated PM on IAQ. It was observed that PM_{10} exhibited the highest concentration, followed by $PM_{2.5}$ and PM_1 which reflect a dominant presence of coarse particles within the indoor environment.

3.1.1 Effect of Window Conditions

Figure 1 illustrates PM levels under windows open vs windows closed conditions during weekdays and weekends. With windows open, $PM_{2.5}$ concentrations exceeded the NAAQS by 3.1 and 2.5 times on weekdays and weekends, respectively, while PM_{10} surpassed the limits by 2.2 and 1.7 times, respectively. These findings suggest that keeping windows open can lead higher infiltration of PM of outdoor origin with greater PM concentrations during weekdays due to increased traffic volume. However, keeping the windows closed notably reduced indoor PM concentrations with $PM_{2.5}$ and PM_{10} exceeded the standards by only 1.7 and 1.3 times on weekdays while remaining within limits on weekends (Figure 1).

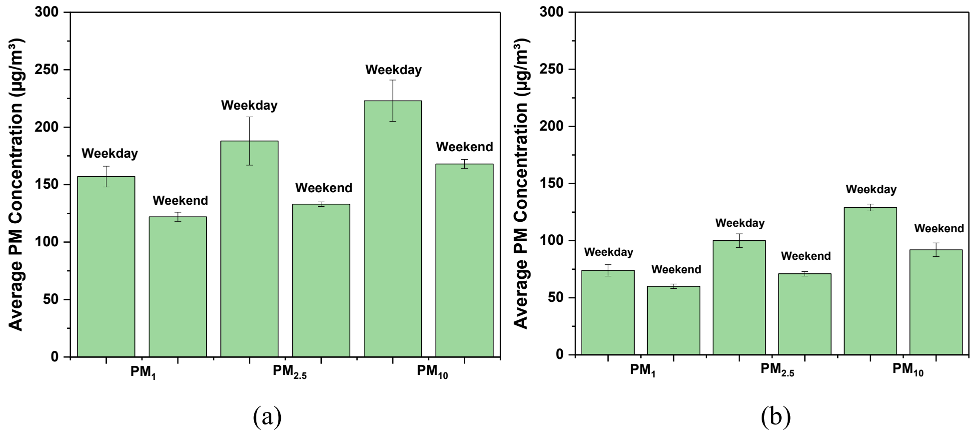


Fig. 1. Variations in size-fractionated PM concentration under (a) windows open and (b) windows closed conditions.

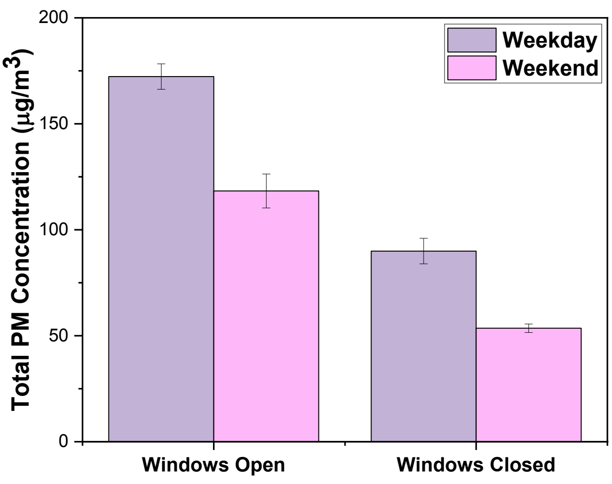


Fig. 2. Personal exposure assessment for total PM concentrations during weekdays and weekends under open and closed window conditions.

Additionally, result of personal exposure assessments has been presented in Figure 2 and it was again noticed that total PM concentrations were higher on weekdays (172.3 μg/m³) as compared to weekends (118.3 μg/m³). Overall, keeping the windows closed decreased PM_1, $PM_{2.5}$, and PM_{10} concentrations by 52±2%, 46±1%, and 45±3%, respectively, while personal exposure to inhalable total PM was reduced by 48±3%. These outcomes are supported by earlier studies which also concluded that ventilation barriers effectively reduce indoor exposure to outdoor pollutants [6]. The results demonstrate that closing windows can be an effective mitigation measure, especially during high-traffic periods in absence of an air cleaner indoors.

3.1.2 Diurnal Variations in PM Concentration

Diurnal variation patterns for the size-fractionated PM were also monitored and results are shown in Figure 3. It should be noted that two prominent peaks, one during morning (9:30 AM) and other during evening (8:30 PM) traffic rush hours were observed. However, the peaks occurred approximately 30 minutes later on weekends, which may be due to delayed traffic activity. This temporal pattern further confirms vehicular emissions as a dominant source of indoor PM.

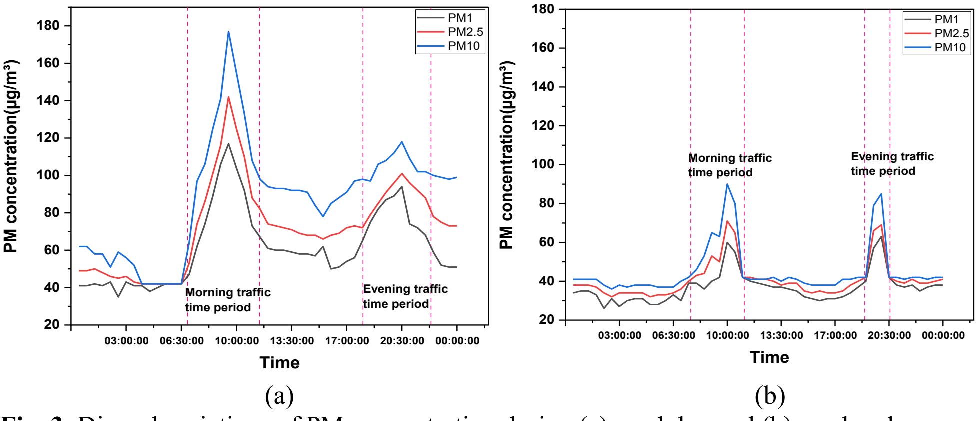


Fig. 3. Diurnal variations of PM concentration during (a) weekday and (b) weekend.

3.1.3 Vertical Distribution of PM in High-Rise Buildings

Figure 4 depicts the concentration of size-fractionated PM i.e., PM_1, $PM_{2.5}$, and PM_{10} measured on the 2nd and 9th floors of the building. It is important to note that PM concentrations were consistently higher on 2nd floor across all particle sizes as compared to 9th floor, indicating that lower floors are more affected by vehicular emissions and resuspended road dust from nearby traffic sources. Moreover, this difference was most prominent for PM_{10}, suggesting that since coarse particles heavier so they settle down by gravity and accumulate near ground level. Conversely, difference in PM_1 and $PM_{2.5}$ concentrations was smaller between floors, indicating that fine and ultrafine particles can remain airborne for longer durations and thereby, they can disperse more uniformly through vertical mixing and infiltration processes. Overall, the results highlight a vertical gradient in PM concentrations with lower floors facing higher PM exposure risks due to their proximity to outdoor emission sources. These results further emphasize the need for good ventilation design and air filtration strategies, especially in lower-level residential apartments situated near high-traffic areas.

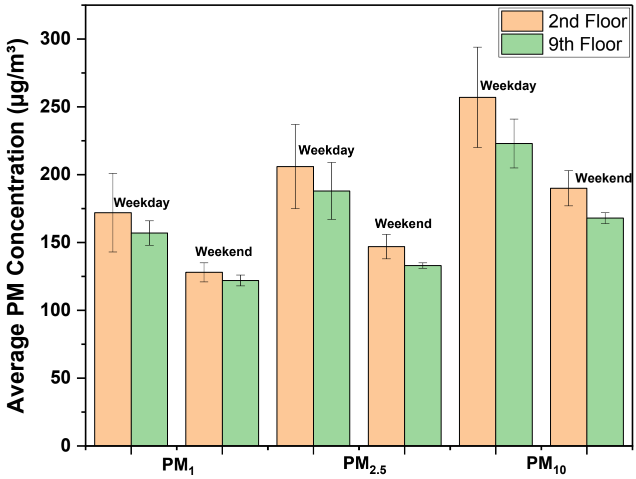
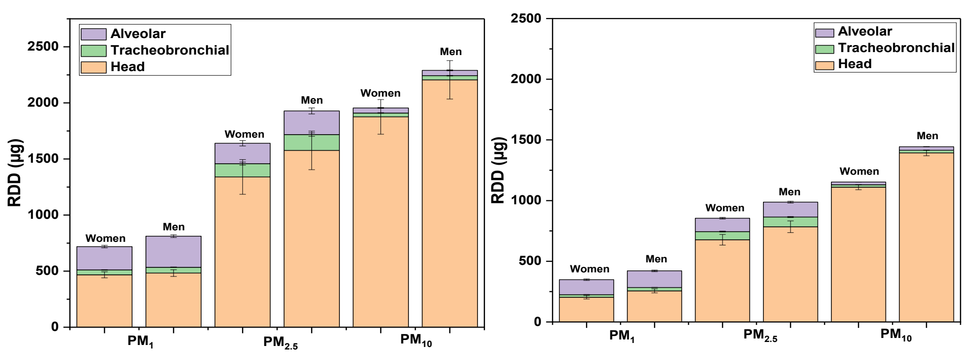


Fig. 4. Vertical variations of PM concentration between lower and upper floors during weekdays and weekends.

3.2 Respiratory Deposition Dosage (RDD) Assessment

Size-fractioned indoor PM concentrations revealed that PM_{10} exhibited the highest concentration, followed by $PM_{2.5}$ and PM_1, indicating a dominant presence of coarse particles within the indoor environment. Using PM concentration values, deposition dose has been estimated and Figure 5 presents RDD values for size-fractionated PM for men and women across the head (HD), tracheobronchial (TB), and alveolar (AL) regions. It can be seen that RDD values were higher in men due to their greater tidal volume and breathing rate [7]. Moreover, PM_1 deposition was highest in the alveolar region, indicating that finer particles penetrate more deeper into human respiratory tract causing higher health effects [8].

Furthermore, coarse particles (PM_{10}) were predominantly deposited in the head and tracheobronchial regions, potentially causing upper respiratory irritation and inflammation. RDD values were approximately 1.5 times higher on weekdays than weekends due to higher PM exposure from weekday traffic. It should be noted that closing windows significantly reduced RDD values under all conditions, emphasizing the need of ventilation control and air filtration in reducing PM exposure-related health risks.

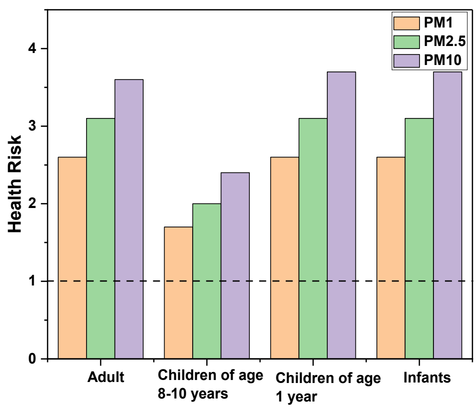


(a) (b)

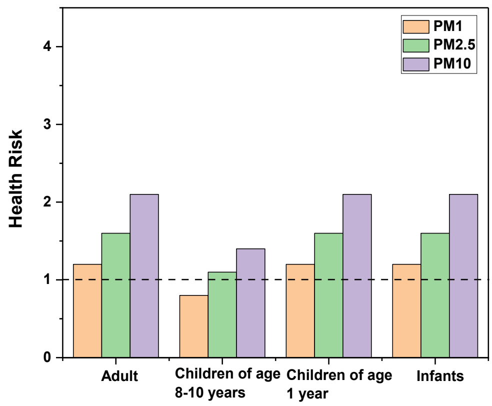
Fig. 5. RDD variations in different respiratory regions for (a) windows open and (b) windows closed conditions.

3.3 Human Health Risk (HR) Assessment

HR assessments were conducted for four demographic groups i.e., newborns or infants, children (1 year), children (8–10 years), and adults as demonstrated in Figure 6. The highest dose rate was recorded for 1-year-old children, due to their greater breathing rate-to-body weight (BR/BW) ratio. Conversely, children aged 8–10 years exhibited the lowest HR values, corresponding to higher LOAEL thresholds which may be attribute to their stronger immune system. With windows open, HR values exceeded 1 for all groups, indicating potential health risks from prolonged PM exposure. While keeping windows closed lowered HR values, they still remained above safe limits, suggesting the need for additional mitigation strategies such as use of air cleaner systems and improved urban emission control policies.



(a)



(b)

Fig. 6. Health risk (HR) for size-fractionated PM among different age categories under (a) windows open and (b) windows closed conditions.

3.4 Morphological and Chemical Characterization of PM

3.4.1 Morphological Analysis

Figure 7 presents images from FESEM analysis which showed three dominant particle morphologies. Firstly, spherical and clustered spherical particles associated with vehicular emissions, then irregular-shaped particles coming from road dust, soil resuspension, and construction activities [9]. Lastly, soot-like agglomerates were observed with characteristic of incomplete fuel combustion and traffic exhaust [10]. These observations again confirm that traffic emissions are the primary source of PM in the studied indoor environment.

3.4.2 Chemical Composition Analysis

Figure 8 gives results for EDX analysis which identified Na, Al, Si, C, K, and Ca as dominant elements and Ba in trace amounts. While Na, Al, Si, and Ca were attributed to soil dust and construction sources [15], carbon was found to be substantially higher at lower floors, indicating vehicular origins. Moreover, Ba was linked with brake wear and motor oil combustion which is common in traffic-related emissions. Again, weekday samples exhibited higher concentrations of traffic-derived elements as compared to weekends, confirming vehicular emissions as the primary source. It is noteworthy that elemental concentrations were significantly lower while keeping windows closed, again confirming the effectiveness of barrier-based mitigation strategies.

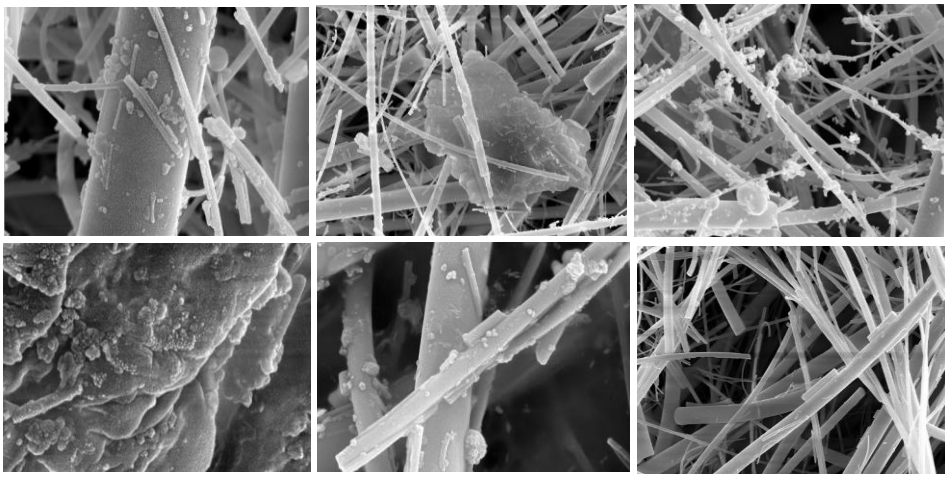
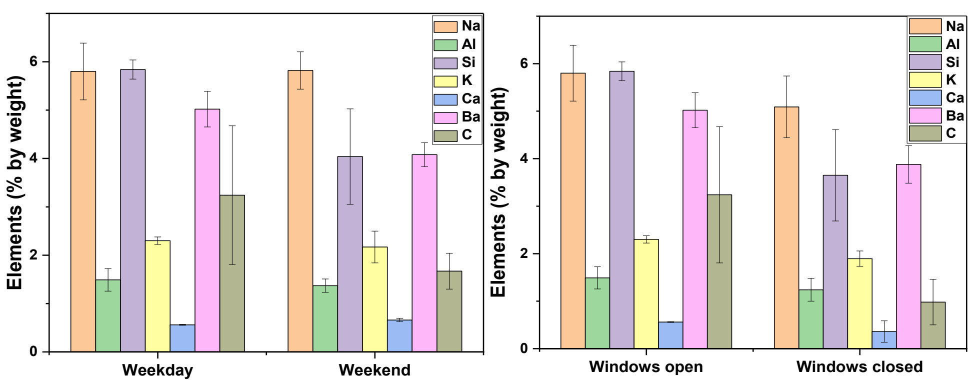


Fig. 7. Representative particle morphologies observed in FESEM analysis.



(a) (b)

Fig. 8. PM elemental composition observed for (a) weekday vs. weekend and (b) open vs. closed window conditions.

3.5 Practical Implications for IAQ and Public Health

The findings of this study indicate major impact of outdoor PM infiltration on IAQ and importance of practical mitigation measures like keeping windows closed during high-traffic hours which can greatly reduce indoor PM levels. Further to this, using indoor air cleaners, and implementing urban measures such as plantation and traffic control near residences can help limit PM exposure. Results provide useful insights for policymakers and urban planners, underscoring the need for stricter emission controls, improved ventilation, and detailed IAQ policies to protect public health. However, this study was limited to a single high-storey building with short-term monitoring without considering seasonal variations. In addition, detailed chemical speciation of PM was not conducted for human health risk assessment. Therefore, future studies are recommended across multiple buildings and seasons while incorporating detailed chemical speciation for better estimation of indoor health risks.

4 Conclusions

Impact of outdoor-generated PM on IAQ and human health in an urban high-storey residential building was analyzed in this work. Results revealed significant degradation in IAQ due to infiltration of traffic-related PM from outdoors. Size-fractionated PM study indicated the highest PM_{10} concentrations, followed by $PM_{2.5}$ and PM_1, reflecting strong contributions from traffic-related coarse and fine particles. Moreover, PM levels were found to be higher on weekdays with peaks during morning and evening traffic rush hours. Vertical variations showed higher PM concentrations on lower floors due to proximity to road emissions and resuspended dust. It is noteworthy that keeping windows closed decreased PM_1, $PM_{2.5}$, and PM_{10} levels by about 52%, 46%, and 45%, respectively, and reduced personal exposure about 48%, proving it as an effective mitigation measure. RDD and HR assessments reflected higher deposition in men due to their greater tidal volume, while infants showed the highest HR. Morphological and chemical analyses further confirmed vehicular origins with particles containing Na, Al, Si, C, K, and Ca, and trace Ba from brake wear. Overall, the study underlines the need for effective air filtration, stricter emission policies, placement of green buffers and traffic management near residential areas to further reduce PM exposure and improve public health in urbanized cities like Jaipur,

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References

1. WHO (World Health Organization), Air Pollution (2024). [Online]. Available: https://www.who.int/health-topics/air-pollution#tab=tab_1
2. N. R. Fold, M. R. Allison, B. C. Wood, P. T. B. Thao, S. Bonnet, S. Garivait, R. Kamens, and S. Pengjan, An assessment of annual mortality attributable to ambient PM2.5 in Bangkok, Thailand. Int. J. Environ. Res. Public Health, 17 (19), 7298 (2020). https://doi.org/10.3390/ijerph17197298
3. NAAQS (National Ambient Air Quality Standards), Revised Standards for Air Pollutants in India, Central Pollution Control Board, Notification, Government of India (2009). [Online]. Available: https://scclmines.com/env/docs/naaqs-2009.pdf
4. X. Bu, Z. Xie, J. Liu, L. Wei, X. Wang, M. Chen, and H. Ren, Global PM2.5-attributable health burden from 1990 to 2017: Estimates from the Global Burden of Disease Study 2017. Environ. Res., 197, 111123 (2021). https://doi.org/10.1016/j.envres.2021.111123
5. J. L. Adgate, G. Ramachandran, G. C. Pratt, L. A. Waller, and K. Sexton, Spatial and temporal variability in outdoor, indoor, and personal PM2.5 exposure. Atmos. Environ., 36 (20), 3255–3265 (2002). https://doi.org/10.1016/S1352-2310(02)00326-6
6. V. Singh, A. Biswal, A. P. Kesarkar, S. Mor, and K. Ravindra, High resolution vehicular PM10 emissions over megacity Delhi: Relative contributions of exhaust and non-exhaust sources. Sci. Total Environ., 699, 134273 (2020). https://doi.org/10.1016/j.scitotenv.2019.134273
7. S. K. Gupta and S. P. Elumalai, Exposure to traffic-related particulate matter and deposition dose to an auto-rickshaw driver in Dhanbad, India. Atmos. Pollut. Res., 10 (4), 1128–1139 (2019). https://doi.org/10.1016/j.apr.2019.01.018

8. A. Zwozdziak, M. Gini, L. Samek, W. Rogula-Kozlowska, I. Sowka, and K. Eleftheriadis, Implications of the aerosol size distribution modal structure of trace and major elements on human exposure, inhaled dose and relevance to the PM2.5 and PM10 metrics in a European pollution hotspot urban area. J. Aerosol Sci., 103, 38–52 (2017). https://doi.org/10.1016/j.jaerosci.2016.10.004
9. V. S. Chithra and S. M. Shiva Nagendra, Chemical and morphological characteristics of indoor and outdoor particulate matter in an urban environment. Atmos. Environ., 77, 579–587 (2013). https://doi.org/10.1016/j.atmosenv.2013.05.044
10. D. T. Tran, L. Y. Alleman, P. Coddeville, and J. Galloo, Elemental characterization and source identification of size resolved atmospheric particles in French classrooms. Atmos. Environ., 54 (5), 250–259 (2012). https://doi.org/10.1016/j.atmosenv.2012.02.021
11. Segalin, P. Kumar, K. Micadei, A. Fornaro, and L. T. Gonçalves, Size segregated particulate matter inside residences of elderly in the Metropolitan Area of Sao Paulo, Brazil. Atmos. Environ., 148, 139–151 (2017). https://doi.org/10.1016/j.atmosenv.2016.10.004
12. W. C. Hinds, Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles. New York: John Wiley & Sons, 233–259 (1999).
13. J. S. Pandey, R. Kumar, and S. Devotta, Health risks of NO2, SPM and SO2 in Delhi (India). Atmos. Environ., 39 (36), 6868–6874 (2005). https://doi.org/10.1016/j.atmosenv.2005.08.004
14. M. Kalaiarasan, R. Balasubramanian, K. W. D. Cheong, and K. W. Tham, Traffic-generated airborne particles in naturally ventilated multi-storey residential buildings of Singapore: Vertical distribution and potential health risks. Build. Environ., 44 (7), 1493–1500 (2009). https://doi.org/10.1016/j.buildenv.2008.07.012
15. S. M. Almeida, T. Faria, V. Martins, N. Canha, E. Diapouli, K. Eleftheriadis, and M. I. Manousakas, Source apportionment of children's daily exposure to particulate matter. Sci. Total Environ., 835, 155349 (2022). https://doi.org/10.1016/j.scitotenv.2022.155349