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Particulate matter deposition in the human respiratory system: A health risk assessment at a technical university

Salman Khan[1], Veerendra Sahu[1], Nachimuthu Manoj Kumar[2], Bhola Ram Gurjar[1,*]

[1] Department of Civil Engineering, Indian Institute of Technology Roorkee, Uttarakhand, India
[2] Centre for Research on Energy and Clean Air, Bengaluru, India

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CORRESPONDING AUTHOR:

bhola.gurjar@ce.iitr.ac.in
Tel: (+ 91) 1332 284 319
Fax: (+ 91) 1332 284 319

ABSTRACT

Introduction: This study quantified Particulate Matter (PM) deposition and its clearance in the Human Respiratory Tract (HRT) at different microenvironments of a university. The university is located adjacent to the National Highway (NH 334) and main bus stop of the city, thus highly affected by PM pollution.

Materials and methods: The deposition calculations were performed using a widely accepted MPPD 3.04 model. Three seasons (summer, winter and monsoon), seven microenvironments (including three Lecture Hall Complexes (LHCs), a library, two laboratories and outdoor), and different activity patterns associated with each microenvironment were considered.

Results: The deposited mass of coarse fraction ($PM_{2.5-10}$) in different HRT regions follows the order: pulmonary (0.5%)<tracheobronchial (2%)<head (or extrathoracic region) (97.5%). In the case of lobar region, because of the larger volume of lower lobes, they received higher deposition (53%) than the middle (8%) and upper lobes (39%). Further, the sitting activity level was found to be most critical for lobar deposition. The total deposited mass in the HRT was maximum outdoors and minimum at the library. The difference in winter and monsoon deposition was 100% for $PM_{2.5-10}$, 75% for $PM_{1-2.5}$ and 126% for PM_1. The clearance rate of PM_1 is such that 1.5 % of particles in the tracheobronchial and 64% in the pulmonary region remained even after six months.

Conclusion: The results implied that physical activity levels, mode of inhalation and particle size significantly influence regional deposition. For instance, heavy exercise causes greater deposition in the head region, whereas sitting activity contributes to higher pulmonary and tracheobronchial deposition.

Introduction

Particulate Matter (PM) is a concoction of atmospheric liquid droplets and minute particles emitted from diverse sources like domestic combustion and traffic. Based on aerodynamic diameter (d_p), PM can be divided into coarse (d_p>2.5 μm), fine (0.1<d_p <2.5 μm) and ultrafine particles (d_p<0.1 μm) [1]. The ultrafine particles

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are generally stored in the alveolar regions, whereas fine and coarse particles are deposited in the tracheobronchial and extrathoracic regions [2].

PM pollution has become a global problem, every year 2.1 million deaths are ascribed to PM pollution. Furthermore, the spread of airborne diseases (such as COVID-19) is also linked to the deposition of PM particles inside the lung [3, 4]. Since people are exposed to both outdoor and indoor PM pollution, health risk assessment can be effectively calculated when both outdoor and indoor microenvironments' respiratory deposition doses and its clearance are considered. Further, the region-specific deposition pattern in the lungs is crucial for knowing the risks of particular diseases. The PM deposition into different regions of the Human Respiratory Tract (HRT) (i.e., head or extra thoracic region, pulmonary, and Tracheobronchial (TB) region) depends on the exposure interval, PM concentration and human physiological parameters such as health, gender, age, lung morphology and activity patterns (walking, running, standing, cycling, etc) [5, 6].

This study aims to figure out the most critical microenvironment in a technical university based on students' exposure and corresponding PM deposition in diverse microenvironments (such as Lecture Hall Complexes (LHCs), library, labs, outdoor) during different seasons. Then, PM clearance and associated health risks were also predicted. This type of study has not been given prime importance in the Indian context. Knowing deposition estimates and related health risks, efficient air pollution mitigation policies can be formulated.

Materials and methods

Sampling site and instrumentation

This study was performed within the campus of Indian Institute of Technology (IIT) Roorkee, a premier technical university of India founded in 1847 in Roorkee city. The institute (29.8644 N, 77.8963 E) covers around 1480,000 m^2 and houses over 7500 students. The main bus-stop of Roorkee city and the national highway (NH 334) is adjacent to it. Further, many industries (such as cement and glass), tourist spots lie in its vicinity. Thus, the university is heavily influenced by PM pollution. The primary ambient pollution source is continuous vehicular movement (including motorcycles, cars and buses) in and around the institute. The climatic conditions of Roorkee include harsh winters (1-2 °C), moderately hot summers (42-43 °C), and an average rainfall of 1160 mm.

PM monitoring was conducted for two months in monsoon (August and September), three months in winter (December to February), and three months in summer (April to June), starting from August 2018 to June 2019. Size segregated PM samples were collected using aerosols spectrometer (model 1.109, Grimm) in a total of seven microenvironments including three Lecture Hall Complexes (LHC1, LHC2 and LHC3), a library, two laboratories (Environmental Engineering Lab (EEL) and Instrumentation Lab (INL)), and outdoor (For monitoring sites see Fig. 1). The INL lab uses wall mounted split air conditioners, while the EEL features both air conditioning and ceiling fans. The library relies on a centralized HVAC system, and LHCs has ceiling fans. The microenvironments are classified as mixed-ventilated due to frequent door and window openings. During winters, room heaters are also employed. Occupancy levels are as follows: LHCs (80-100 occupants), library (70-80), and laboratories (2-4). Continuous monitoring, at 1-min intervals, took place over three consecutive days in each season for each indoor microenvironment. Outdoor monitoring occurred for two consecutive days in each season at each of the five locations (O1 to O5) to cover most of the campus. The instrument was located 1.3 m above the floor, near the breathing height of the students. The study area and monitoring characteristics are more elaborated in our previous study [7]. Model calculations were performed using average seasonal concentrations. While selecting microenvironments, we considered three parameters: PM concentrations,

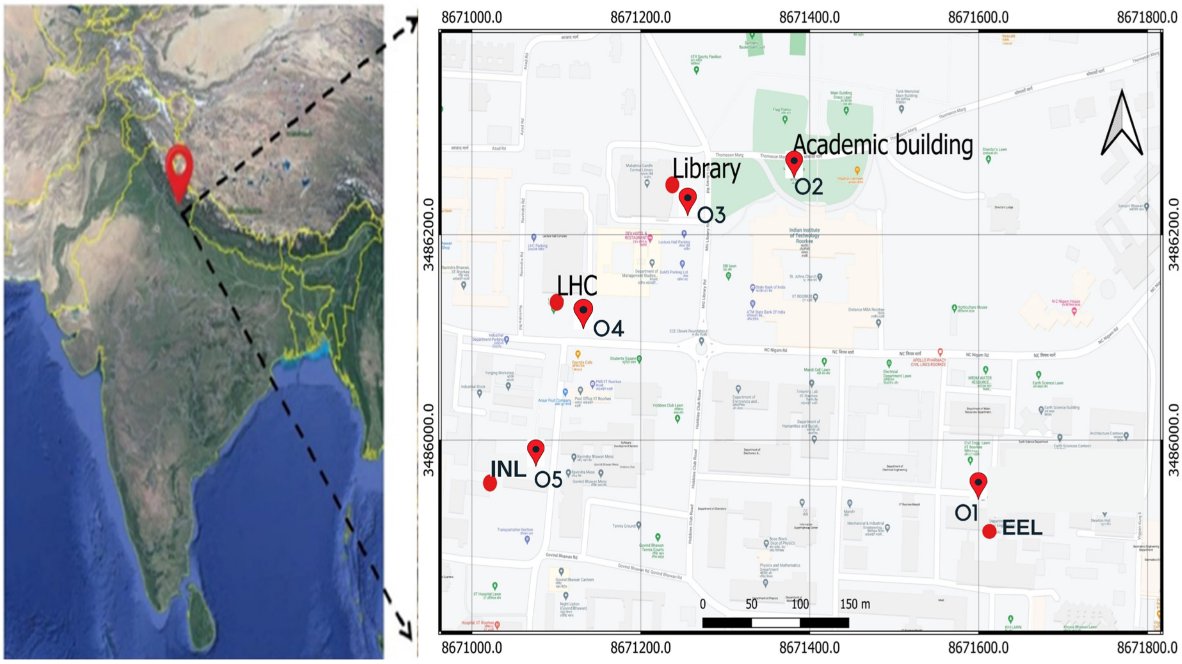

Fig. 1. Location of study area and monitoring sites (red pointers) in the university

related activities, and exposure period. The indoor microenvironments were having activities like light exercise (walking) and sitting, whereas outdoors were associated with light (walking) and heavy exercises (such as running and cycling). The time spent by the students and related activities in different microenvironments is shown in Table 1.

Deposition modeling in HRT

The deposition of size segregated PM particles into different components of HRT (pulmonary, TB and head) was evaluated by the Multiple-Path Particle Dosimetry (MPPD-V 3.04) model, developed by the Chemical Industry Institute of Toxicology (USA). This model has undertaken numerous years of development and authentication and is currently among the best particle dosimetry models. It has been extensively used in many applications, such as clinical studies of animals and humans and targeted drug delivery in lung diseases [8, 9]. The features and utility of this model to quantify PM deposition have been discussed in previous studies [5, 8, 10].

Briefly, the MPPD model requires the following input parameters: particle characteristics (density, shape factor and size distribution), mass concentration and lung morphological parameters of the exposed subjects (Breathing Frequency (BF), Functional Residual Capacity (FRC), Tidal Volume (TV) and Upper Respiratory Tract (URT) volume. Depending upon the physical exertion levels such as heavy exercise, light exercise and sitting, the morphological parameters vary as shown in Table 1. These values are taken from earlier studies [11-15] for adult subjects. The density of the particles as 1 gm/cm^3 and spherical particles (shape factor=1) was considered. For all the activities, the nasal breathing route was adopted. Once these input parameters were specified, size segregated deposition fraction (DF) was evaluated for different regions of the HRT. 'DF' is defined as "the ratio of the number of specific size particles deposited in a particular region (head, TB, and pulmonary) to the number of same size particles entering the airways" [16]. The model estimates DF by considering different mechanisms such as impaction, sedimentation and diffusion within the respiratory tract. Further, these DF values were used to evaluate deposited mass and clearance rates. The following equation was used to estimate deposited mass [14, 15].

$$\text{Deposited mass } (\mu g) = \text{BF (breaths/min)} \times \text{TV } (m^3/\text{breath}) \times C\ (\mu g/m^3) \times T\ (\text{min}) \times DF \quad (1)$$

Where, 'BF' is breathing frequency, 'TV' is tidal volume, 'C' is the mass concentration (outdoor or indoor), 'T' is the time spent in each activity and 'DF' is particles' deposition fraction in HRT (dimensionless). The clearance rate of submicron particles (PM_1) was evaluated because they penetrate deep into the lungs than the coarse particles (≥2.5 µm). To estimate clearance rate, the default model values were considered: tracheal mucus velocity as 5.5 mm/min, the rate of clearance in the pulmonary-interstitial regions to the tracheobronchial segment (mentioned as slow, medium, and fast) were 10^{-4}, 10^{-3} and 2×10^{-2} per day, respectively and rate of lymph node clearance=2×10^{-5} per day. The exposure period of five days per week up to four weeks was considered because the institute is 5-day working. The clearance in the pulmonary region may last up to several months [17, 18]. Therefore, the post-exposure period was adopted as six months to examine the clearance process comprehensively, and no deposition was considered in that period.

Table 1. Morphological parameters based on activity patterns in different microenvironments

Microenvironment	Activity	Time (h)	BF (breaths/min)[a]	TV (cc)[b]	URT (ml)[c]	FRC (ml)[d]
LHC1/LHC2/LHC3	Sitting	5	12	750	50	2418
Library	Sitting	2	12	750	50	2418
EEL / INL	Light indoor	3	20	1250	50	2418
Outdoor	Light outdoor	1.5	20	1250	50	2418
Outdoor	Heavy	2	26	1920	50	2418

[a]: US EPA [11], [b]: ICRP [12], [C]: [15], [d]: [13, 14]

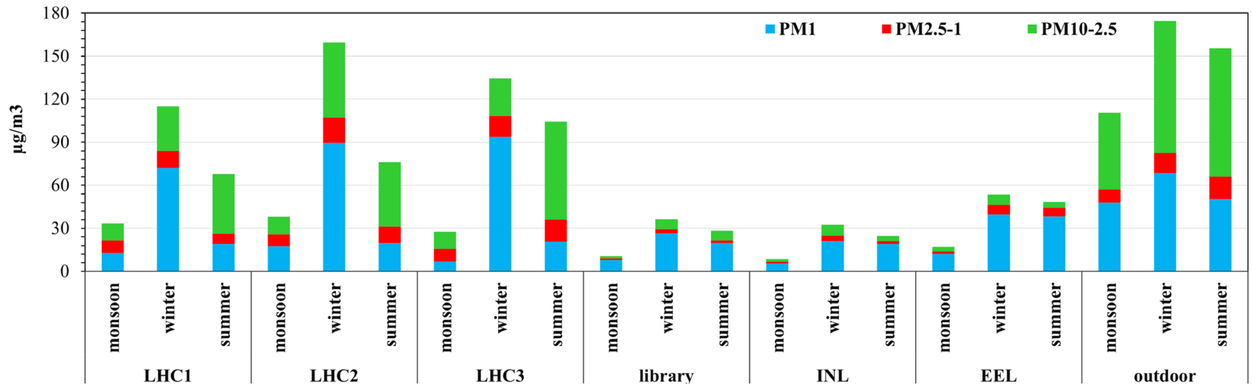

Fig. 2. Seasonal variations of daily average concentrations at different microenvironments

Results and discussion

PM exposure variability

The mean concentrations of $PM_{2.5-10}$, $PM_{1-2.5}$ and PM_1 measured at different microenvironments during the three seasons are shown in Fig. 2. The lower concentrations were found in the monsoon and the highest in the winter season. Greater contributions from heating systems and traffic combined with less vertical mixing caused higher concentration in the winters, whereas wet deposition in the monsoon was responsible for its lower levels [7, 19]. Among different microenvironments, the lowest concentration was found in the Instrumentation Lab (INL) and the maximum at outdoors. Notable variation was found in the PM levels in different microenvironments due to distinct sources of PM particles, particle resuspension (vacuum cleaning, brushing and walking), a discrepancy in the number of occupants, and ventilation (natural or mechanical). The PM concentrations ranged from: PM_1 (5.4 to 93.7 µg/m^3), $PM_{1-2.5}$ (0.88 to 18 µg/m^3) and $PM_{2.5-10}$ (1.7 to 92 µg/m^3) during different seasons. Except for outdoors, the concentration of PM_1 in all the microenvironments exceeded $PM_{1-2.5}$ and $PM_{2.5-10}$ fractions. This can be explained by high penetration and low deposition rates of PM_1 compared to other fractions, which provide longer suspension inside indoor microenvironments [14, 20].

PM deposition fractions (DF)

The DF of different PM sizes ($PM_{2.5-10}$, $PM_{1-2.5}$ and PM_1) in the head, TB and pulmonary regions and variation of DFs with generation numbers are presented in Figure 3. The DFs ranged between 61.7 - 96% during heavy exercise, 46 - 95.5 % during light exercise and 31 - 94.2% during sitting. The DF variation was due to different breathing rates related to that activity and changes in particle size. The order of DF for different regions of HRT under different activity patterns is- Pulmonary: heavy exercise < light exercise < sitting; TB: heavy < light < sitting; Head: sitting < light < heavy. The results concluded that greater physical exertion led to higher DF in the head region, whereas an opposite trend was observed in the pulmonary and TB regions. Similar outcomes are also visible from DF vs generation plots, where the sitting activity level has maximum DF for the pulmonary region (17-23 generations).

The total and head DF increases with the size of PM particles (head: PM_1=70%, $PM_{1-2.5}$ = 82% and $PM_{2.5-10}$=98.6%), whereas a reverse trend was observed for the TB region (PM_1 = 9.7%, $PM_{1-2.5}$=4.8% and $PM_{2.5-10}$=1.1%). In the pulmonary region, maximum DF was found for $PM_{1-2.5}$ in sitting and light exercise and for PM_1 during heavy exercise. The generations plot also verified this outcome, which showed that the peak of $PM_{1-2.5}$ during sitting and light exercises was higher than

PM_1. Whereas for heavy exercise, PM_1 dominates over $PM_{1-2.5}$. These results match previous studies where the head region DF increases with PM size [9, 18, 21, 22]. Another study reported that when the breathing rates are high, the deposition of coarse particles is significant in the extrathoracic region, and during low breathing rate, the deposition of finer particles is held in the deeper airways [23]. This can be illustrated by a combined action of impaction and sedimentation of coarse particles on the upper respiratory zone [5, 22]. Further, the deposition pattern of PM_1 and $PM_{1-2.5}$ was the same for all the activities, being higher DFs in pulmonary than in the TB regions, unlike $PM_{2.5-10}$ where DF follows the order: head>TB>pulmonary. Similar outcomes were also illustrated by generation diagrams where the peak of fine fraction and coarse fraction deposition lies in the pulmonary (18-21 generation) and TB region (6-10 generation), respectively. It is to be noted that generation numbers start from 0 (trachea) and continue till 23 (alveolar sacs), thereby incorporating only TB (generation 0-16) and pulmonary region (generation 17-23). Therefore, head deposition results cannot be verified from the generation plots.

In Budapest (Hungary), it was estimated PM_1 deposition during different activities in diverse microenvironments [24]. They observed that DF in the head decreases from 26% during sleep to 9.5% in heavy activity levels, and for the pulmonary region, it increases from 14.6 % during sleep to 34% while exercising heavily. In contrast, our study found that heavy and light exercises experienced their highest DF in the head, while in the pulmonary region, the maximum DF occurred during sitting. Such variation may be due to oral breathing assumed by Salma et al. [24] under light and heavy exercises, causing lesser deposition in the head region. A recent study by researchers reported that nasal breathing might be better than oronasal breathing from the perspective of regional deposition [5]. Hence, inhalation mode influences particle deposition and should be considered while estimating potential health risk. Furthermore, URT and FRC also influence DF values. An earlier study showed that 40% increase in URT value might lead to a 3 - 12% decrease in DF, while 65% FRC increase could trigger a reduction in DF by 25% in the pulmonary region [25]. Further, in previous studies, deposition fractions were estimated mainly by taking a single value of breathing frequency and tidal volume for different activity patterns. Such an approach may produce biased results [9].

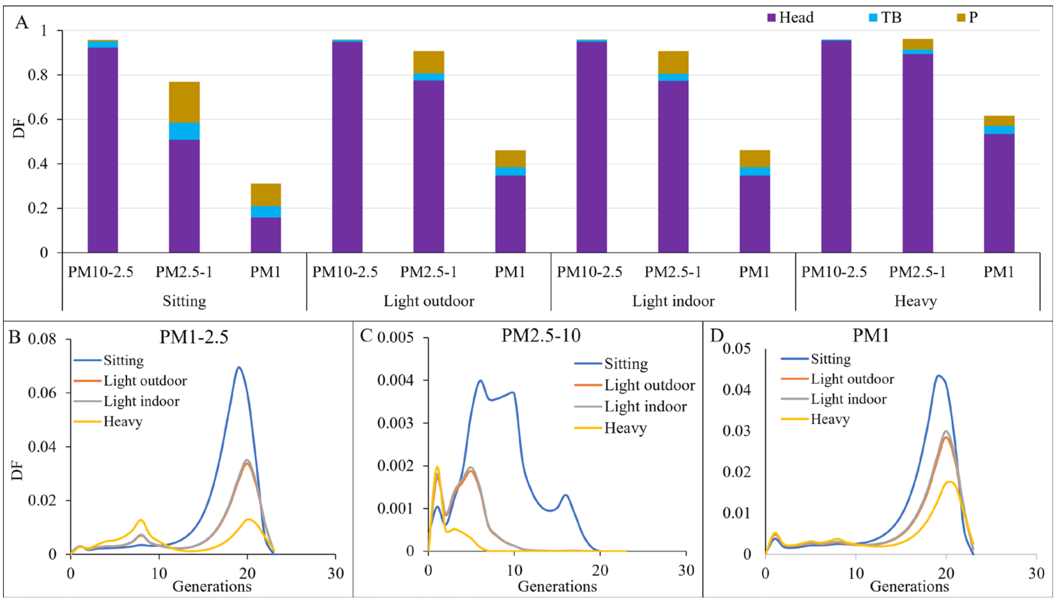

Fig. 3. Total and regional deposition fraction (A) and deposition fraction as a function of Generation numbers (B) for different activity patterns

Deposition fraction in the lobar region

There are five lobes in the human lung; two Lobes (Upper (LU) and Lower (LL)) in the left lung and three lobes (upper (RU), middle (RM) and lower (RL)) in the right lung. The lobe-wise DF of different PM sizes during different activity levels are presented in Fig. 4. For all the activities, $PM_{1-2.5}$ had maximum lobar deposition fraction compared to $PM_{2.5-10}$ and PM_1. Since coarse fraction is mainly deposited in the head region, its deposition in the lobar region is almost negligible. The DF of $PM_{2.5-1}$ in different lobes is - LU (0.03), LL (0.08), RU (0.03), RM (0.02) and RL (0.06). It was found that lobar deposition decreases with increased physical activity levels like TB and pulmonary regions. Also, it was observed that left lung had slightly higher deposition (PM_1 (52%), $PM_{1-2.5}$ (53%) and $PM_{2.5-10}$ (50.6%)) than the right lung (PM_1 (48%), $PM_{1-2.5}$ (47%) and $PM_{2.5-10}$ (49.4%)) for all PM sizes. Among the five lobes, the maximum deposition was received by the LL (30-44%), followed by RL (23-37%) and the least was found in RM (6-11%). Earlier studies also obtained a similar trend [18, 19, 26]. Further, the lower lobes contained two times greater deposition than the upper and seven times of middle lobes. This variation is because lower lobes have a larger volume, whereas middle lobes are the smallest. The overall results concluded that sitting activity level is critical for the lobar deposition of $PM_{1-2.5}$ particles. As per recent studies, higher deposition of fine fraction in the lobar region may cause decreased lung functioning and a higher risk of pulmonary diseases [26, 27]. Moreover, recent studies also stated that most of the lung cancers have a specific location. For example, pulmonary adenocarcinoma mainly occurs in the outer area of the upper lobe, while squamous cell carcinoma is often found in the central lung region [28]. Other researchers have observed that the lower lobes of the lung are more likely to develop cancer associated with idiopathic pulmonary fibrosis [29]. Thus, in predicting cancer and other respiratory diseases and performing targeted drug delivery, site-specific lung deposition analysis is important.

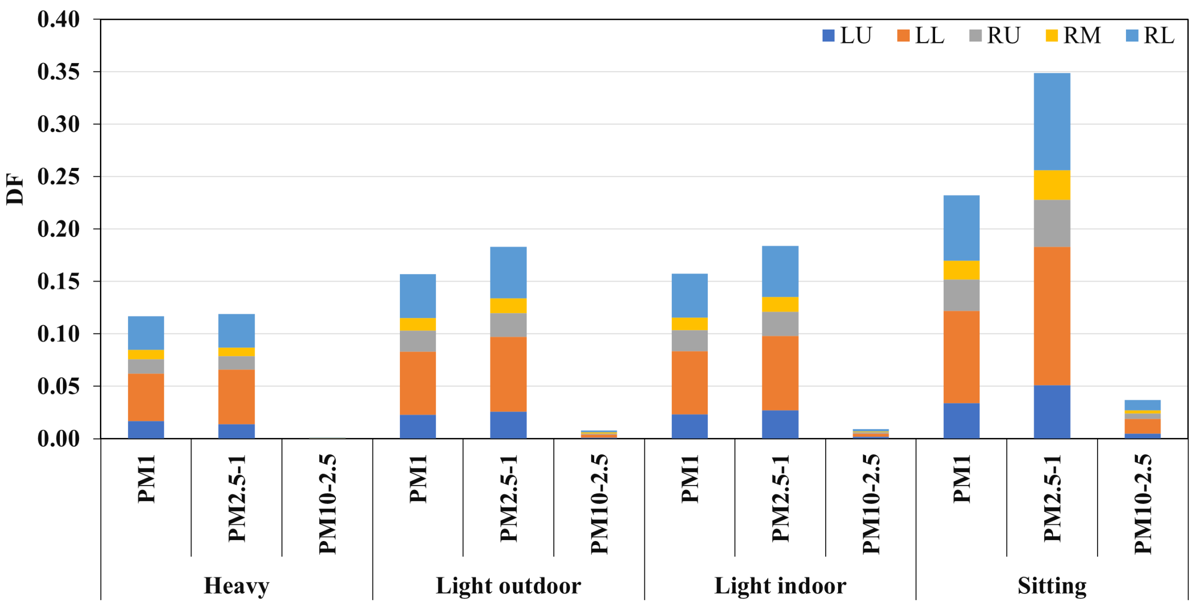

Fig. 4. Lobar deposition fraction of different activity patterns

Deposited mass of PM in the HRT

The deposited mass of PM in the HRT of students during different activities at various microenvironments is presented in Fig. 5. Notable variations were witnessed among the different seasons and these were in accordance with the PM levels monitored at various microenvironments i.e., winter>summer>monsoon. The difference in winter and monsoon deposition was 100% for $PM_{2.5\text{-}10}$, 75% for $PM_{1\text{-}2.5}$ and 126% for PM_1, whereas 5.5%, 9.4% and 61%, respectively between the winter and summer season. Considering all activity patterns, the deposited mass of coarse fraction ($PM_{2.5\text{-}10}$) follows the trend: pulmonary (0.5%)<TB (2%) <head (97.5%). Whereas a different trend TB (9%)<pulmonary (23%)<head (67%) was observed for the fine fraction (PM_1 and $PM_{1\text{-}2.5}$).

A study performed recently in Xian, China to quantify the deposition in pedestrian teenagers using the MPPD model stated following deposition: pulmonary (PM_{10} = 2%, $PM_{2.5}$ = 34% and PM_1 = 41%), TB (19%, 11.2% and 16%) and head (81%, 54.5 and 25%) [30]. Another study estimated deposition during physical exercise in the outdoor microenvironment using ICRP model and reported PM_{10}, $PM_{2.5}$ and PM_1 was maximum in the head (95%, 79%, and 68%) followed by pulmonary (2%, 13% and 24%) and tracheobronchial (2%, 7%, and 7%) regions [31]. Similarly, while modeling indoor PM deposition in a study was reported: PM_1, $PM_{2.5\text{-}1}$ and $PM_{10\text{-}2.5}$ in the head (42%, 58% and 71%), pulmonary (46%, 34% and 2.8%) [15]. Other researchers estimated $PM_{2.5}$ dose deposition using ExDoM model at the subway as pulmonary(10%), TB (4%) and head (68%) region [32]. Similar results were also reported in previous studies [14, 18, 21]. These studies are in strong correlation with our study. However, variability in deposition percent arises because of the inconsistency in lung physiological parameters and different PM concentration values.

Among different microenvironments, the mass deposition follows the same order for $PM_{2.5\text{-}10}$ and $PM_{1\text{-}2.5}$ i.e., outdoor>LHCs>labs>library, whereas for PM_1, the trend was: outdoor> labs>LHCs>library. The maximum outdoor deposition was due to its significantly higher PM concentrations than indoor, high minute ventilation (BF×TV) and high DF during heavy outdoor exercises. The results indicated that microenvironments had distinct orders for deposited mass and PM concentrations. It verifies that the microenvironment's criticality depends on multiple factors: PM concentrations, Activity levels, breathing pattern and exposure period. Since head region received maximum deposition in our study results, diseases like sinusitis, pharyngitis and rhinitis are most likely [19, 30]. Also, the substantial pulmonary deposition observed for fine fractions may cause cardiovascular mortality [4, 10]. Another important point to discuss is that respiratory illnesses like COPD, etc., influence regional ventilation, geometry of airways and breathing patterns, hence modifying the deposition pattern. Recent studies by researchers stated that obstruction in the airways, atelectasis and increased ventilation resulted in higher total deposition [33, 34]. These studies also revealed that airway obstruction leads to shifting particle deposition in the bronchial airways from distal to proximal, and uneven lung ventilation increases heterogeneity. Hence, future research on this aspect is crucial for a deeper understanding of respiratory diseases' effects on particle deposition.

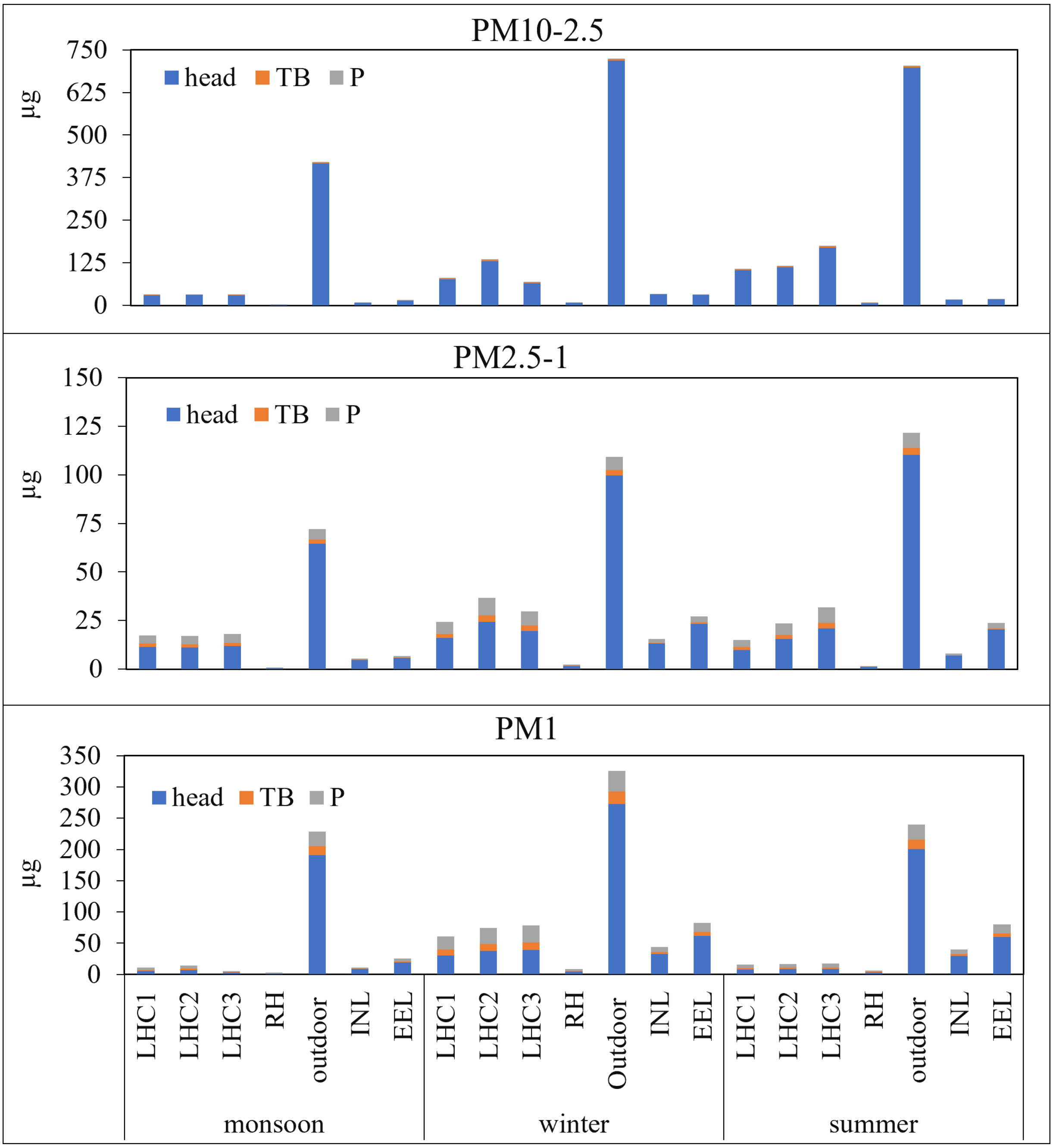

Fig. 5. Daily deposited mass of PM fractions ($PM_{2.5-10}$, $PM_{1-2.5}$ and PM_1) in different regions of HRT at various microenvironments

Clearance in tracheobronchial and pulmonary regions

The clearance rate in TB and pulmonary regions of students after PM_1 exposure is shown in Fig. 6. In TB region, the deposited mass during the exposure period cyclically rises and drops. The extremely fast clearance rate in the TB region compared to the pulmonary because both regions are governed by different mechanisms. The mucociliary action in the TB region is responsible for faster clearance, while the pulmonary region is held by absorption and non-absorption processes. In the absorption process, particles are removed by blood uptake or lymph circulation, and the non-absorption mechanisms involved phagocytosis by microphages. These mechanisms are quite slow and may take several months. Meanwhile, the deposited fractions translocate from the lungs to other organs and trigger many diseases [17, 35].

The rate of clearance is almost similar for different activity levels. However, the variation in retained mass was observed due to a distinction in the mass deposited during different activities. Considering all activities, the model predicted that around 1.5 % and 64% of the accumulated mass in the TB and pulmonary regions remained even after six months. A recent study by researchers also obtained similar results where, after five months, 68% of the ultrafine particles remained in the alveolar area [10]. It is to be noted that particle retention is not just dependent on the balance between alveolar clearance and exclusion via the lymphatic system to the blood flow. Based on the particles' compositions, they stimulate local inflammation and tumour formation while remaining inside the lungs within nodules and macules, predominantly in the middle of the pulmonary acinus. This leads to small airway diseases, the characteristics of urban dwellers, miners and smokers.

This study has some limitations. The lung deposition modeling was performed for adults of normal health status with nasal breathing. Literature-based lung morphological parameters were utilized for deposition calculations that require the subject's regional measurements in the future. Furthermore, the chemical characterization of PM particles was not performed, which can help identify the PAHs and metals dominating in a particular microenvironment and can be used to evaluate excess cancer risks and associated toxicity. Therefore, future studies should incorporate these factors.

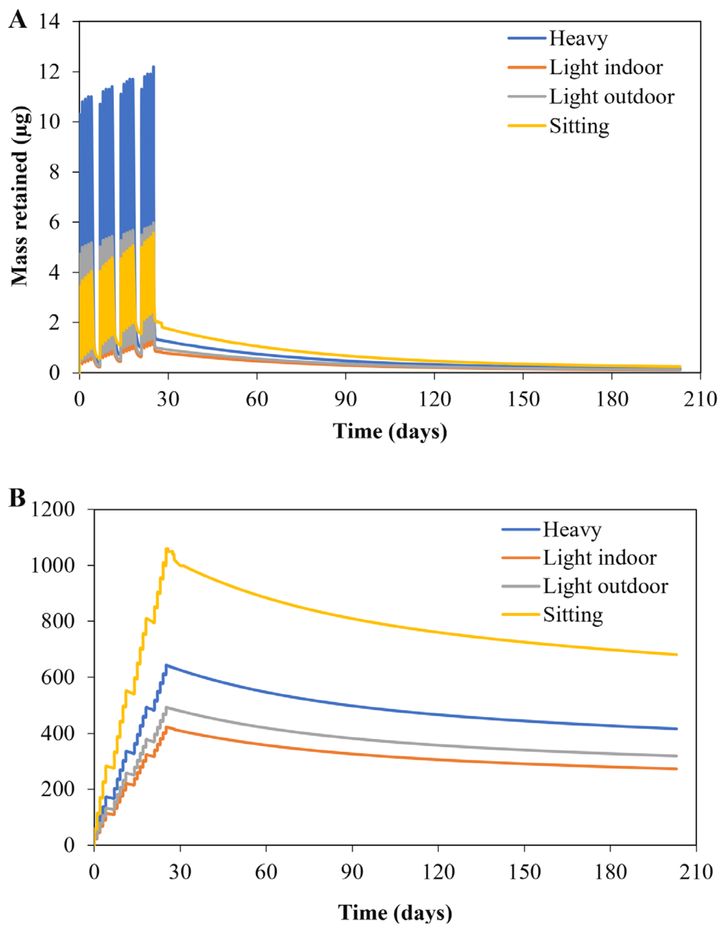

Fig. 6. Clearance in tracheobronchial (A) and pulmonary (B) regions for varied activity patterns when exposed to PM_1 emission for four weeks, followed by six months post exposure period

Conclusion

This study provides a preliminary idea of human health risks by quantifying mass deposition and its clearance due to exposure to PM particles in different microenvironments at a technical university in India. Among different microenvironments, PM_1 mass deposition follows the trend: outdoor>labs>LHCs>library, whereas for $PM_{2.5-10}$ and $PM_{1-2.5}$: outdoor>LHCs>labs>library. The study results concluded that microenvironment's criticality depends on PM concentrations, activity levels and exposure interval. In the lobar region, the left lung received a slightly greater deposition (PM_1 (52%), $PM_{1-2.5}$ (53%) and $PM_{2.5-10}$ (50.6%)). The extremely slow clearance rate of pulmonary region (64% PM_1 retained even after six months) poses risks of inflammation and tumour formation. The insights gained from this study will be helpful in the targeted drugs delivery and guide policymakers to alleviate PM pollution. Future studies should include individual variability, considering factors such as gender, age, and breathing patterns. Additionally, including particle chemical characterization will enhance the specificity of health risk and dose-response estimations. Furthermore, expanding the scope of this research to other comparable locations will allow for the investigation of the impact of meteorological and geographical factors on deposition doses.

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Competing interests

The authors declare no conflict of interest.

Authors Contributions

Salman Khan: Conceptualization, Methodology, Software, Writing – original draft, review & editing. Veerendra Sahu: Data curation, Methodology, Writing - review and editing.
N. Manoj Kumar: Software, Supervision, Writing - review and editing. Bhola Ram Gurjar: Conceptualization, Supervision, Writing - review & editing.

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Ethical considerations

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/ or falsification, double publication and/ or submission, redundancy, etc) have been completely observed by the authors.

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