



Original Research Paper

Indoor PM_{2.5} as a Reactive Carrier of PAHs and Heavy Metals: Seasonal Chemistry and Women focused Exposure in Urban Households of Northern India

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Abstract: Indoor PM_{2.5} is increasingly recognized as a chemically active aerosol capable of transporting toxic organic and inorganic constituents within household environments. The present study investigated seasonal indoor PM_{2.5}, particle bound 16 USEPA recommended PAHs, selected heavy metals, and respiratory deposition characteristics across Industrial, Commercial, and Residential microenvironments in the capital of the most polluted state of Northern India. The study emphasis on women-focused domestic exposure and therefore, 24-hour indoor PM_{2.5} monitoring was conducted in 18 different households between November 2023 and October 2024, with sampling positioned between the kitchen and living area to represent the dominant household exposure zone for women. PM_{2.5} mass was determined gravimetrically, PAHs were analysed using GC-MS, selected metals were quantified by ICP-OES, and respiratory deposition was estimated using the Multiple Path Particle Dosimetry (MPPD) model. Indoor PM_{2.5} exhibited a clear seasonal trend of winter > summer > monsoon across all studied houses, with Industrial house showing the highest winter concentration (235 µg m⁻³). The compositional profile of indoor PM_{2.5} was strongly dominated by high molecular weight (HMW) PAHs, particularly InP, B(a)P, Chr, Pyr, and B(a)A, indicating substantial particle-phase persistence of combustion-derived compounds. Industrial households showed the strongest HMW PAHs contribution, accounting for 94.2% and 90.4% of total PAHs during summer and winter, respectively, while Commercial households exhibited a winter HMW contribution of 91.2%. Carcinogenic PAHs constituted a major fraction of total indoor PAHs, particularly in Industrial summer (74.1%), Industrial winter (61.2%), and Commercial winter (61.3%), confirming substantial predominance of particle associated toxic organic compounds within indoor aerosols. Heavy metal analysis further demonstrated the presence of a reactive inorganic fraction within indoor PM_{2.5}, with Zn, Pb, Ni, Cu, Mn, Fe, and Cr showing distinct seasonal and microenvironmental variability. Respiratory deposition modelling indicated age-dependent differences in pulmonary deposition, with younger women showing comparatively greater deposited mass under elevated PM_{2.5} conditions. Winter Industrial households showed the highest deposited dose, reflecting enhanced accumulation and respiratory retention of the chemically elevated contribution of fine particles under stagnant atmospheric conditions. Collectively, the findings demonstrate that indoor PM_{2.5} in urban households functions not merely as suspended particulate matter, but as a chemically complex exposure medium carrying persistent PAHs and toxic metals. The study highlights the importance of integrating aerosol composition, seasonal behaviour, and respiratory deposition assessment for understanding indoor exposure dynamics among women living in rapidly urbanizing Northern India.

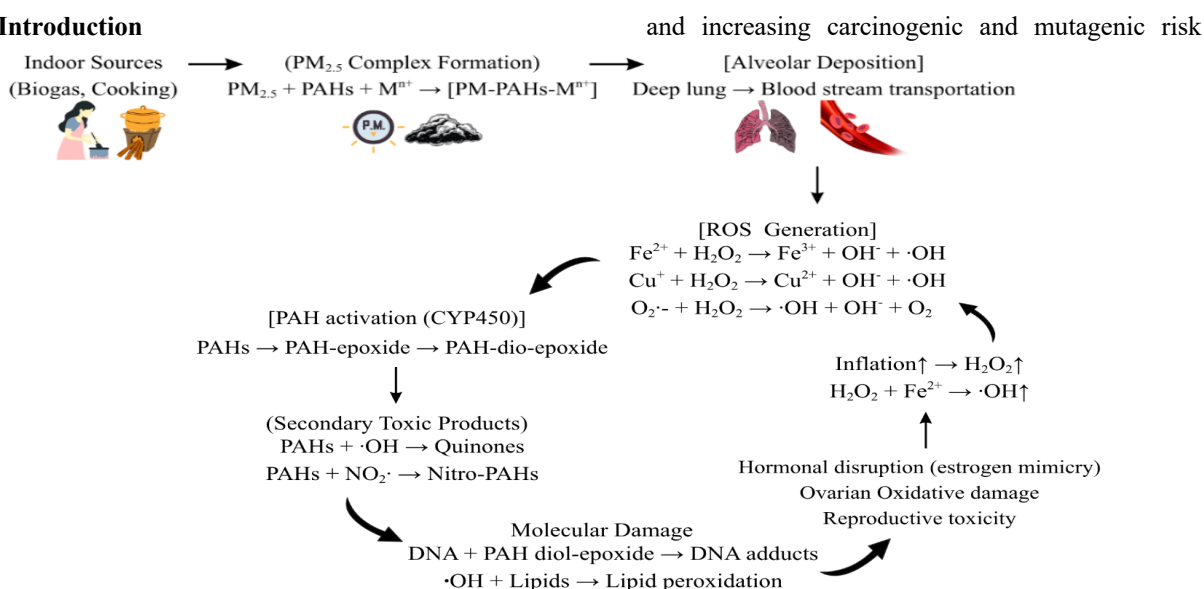
Keywords: Indoor PM_{2.5}, PAHs, Heavy metals, Respiratory deposition, women's exposure

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Introduction



Indoor air pollution in urban households represents a complex and evolving environmental health challenge, particularly in densely populated cities of developing countries where domestic emissions and outdoor infiltration coexist within confined residential microenvironments. Household activities such as cooking, heating, incense burning, mosquito repellent use, smoking, cleaning, and fuel combustion continuously release fine particulate matter (PM_{2.5}), volatile organic compounds, and combustion derived toxicants into indoor spaces, while additional pollutants infiltrate from traffic corridors, commercial activities, and industrial emissions (Feng et al. 2024, Koengkan et al., 2022, chen, k et al. 2022). Within confined and often poorly ventilated indoor spaces, these pollutants undergo adsorption, gas particle partitioning, heterogeneous oxidation, surface catalysis, and redox cycling, producing chemically transformed aerosols whose toxicity depends not only on PM_{2.5} mass but also on composition, reactivity, and interactions among coexisting contaminants. This chemistry based perspective is essential because household air pollution remains a major health concern, with women often experiencing higher domestic exposure due to time spent in cooking and household activities (Dida et al. 2022). In indoor environments, fine particles can transport particle-bound polycyclic aromatic hydrocarbons (PAHs), oxygenated/nitrated PAHs, and transition metals that undergo adsorption/absorption partitioning, heterogeneous oxidation, and surface-mediated reactions (Madaniyazi, L. et al. 2022, Flanagan et al. 2022). Recent studies have shown that combustion-related emissions strongly influence the gas particle partitioning behaviour of PAHs, particularly under indoor and urban atmospheric conditions (Yang et al. 2025). This distinction is important because high molecular weight PAHs preferentially associate with PM_{2.5}, allowing deeper respiratory deposition

through metabolic activation pathways (Hu et al.2022). In addition, PM_{2.5} bound metals such as Fe, Cu, Mn, Ni, Cr, Pb, and Zn may further enhance toxicity through redox cycling, Fenton like reactions, and antioxidant depletion (Xu et al. 2022, Wang et al. 2020). Figure 1 demonstrates that fine particles can transport chemically reactive PAHs and transition metals deep into the respiratory tract, where redox active metals may promote ROS (Reactive oxygen species) formation and oxidative stress. Simultaneously, particle bound PAHs can undergo metabolic activation and contribute to mutagenic and carcinogenic responses. These combined physicochemical interactions increase the toxicological relevance of indoor PM_{2.5} exposure, particularly in poorly ventilated residential microenvironments (Taushiba et al.2026).

Figure 1. Pathways of PM_{2.5} associated PAHs and trace metals leading to oxidative stress, inflammatory responses and genotoxicity in indoor environments

Thus, understanding indoor PM_{2.5} requires a compositional and mechanistic perspective that integrates both aerosol chemistry and human exposure. Polycyclic aromatic hydrocarbons (PAHs) are among the most important organic contaminants associated with indoor PM_{2.5}. These hydrophobic compounds are formed primarily during the incomplete combustion of biomass, coal, kerosene, liquefied petroleum gas, cooking oils, incense, candles, and tobacco products. Their distribution between gaseous and particulate phases depends strongly on molecular weight and vapor pressure, with higher molecular weight congeners such as benzo[a]pyrene preferentially adsorbing onto fine particles. Particle association increases atmospheric persistence, facilitates deep lung

deposition, and enhances biological uptake. Benzo[a]pyrene is of particular concern because it is a well established carcinogenic PAHs and is widely used as a toxicological marker of combustion related pollution as described in Figure 2. Following inhalation, benzo[a]pyrene undergoes cytochrome P450 mediated metabolic activation to epoxides, quinones, and diol epoxides capable of forming DNA adducts and initiating mutagenic and carcinogenic processes. In addition to direct genotoxicity, PAHs can disrupt endocrine signalling and interfere with placental and fetal development, thereby increasing concern for reproductive and developmental health. The metabolic activation of benzo (a) pyrene highlights the importance of particle bound carcinogenic PAHs in indoor aerosol toxicology, particularly under chronic residential exposure.

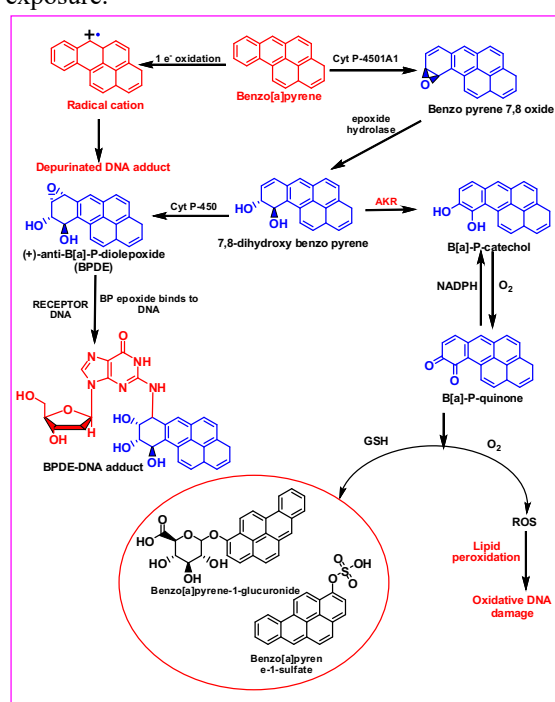


Figure 2. Plausible pathway of Benzo[a] pyrene Induced ROS Generation/ DNA Adduct Formation and DNA damage

Women's exposure to indoor PM_{2.5} deserves specific attention because household air pollution disproportionately affects women, particularly in homes. WHO reports that household air pollution contains fine particles capable of penetrating deep into the lungs and entering the bloodstream, and that exposure is especially high among women who spend more time near domestic emission sources (W.H.O 2025). PM_{2.5} exposure may be associated with adverse pregnancy outcomes, reduced birth weight, impaired fetal development, and anaemia related vulnerability among women of reproductive age (Jana et al. 2025, Ward et al. 2025, Acharya et al 2026). These effects are biologically plausible because PM_{2.5} bound PAHs and metals can induce

inflammation, endocrine disruption, and genotoxic pathways (Ellwanger et al 2025, Wu et al 2025). Therefore, in women focused indoor air studies, PM_{2.5} should be discussed not only as an inhalable pollutant but as a chemically active exposure mixture with reproductive, haematological, and long-term toxicological relevance. Although indoor PM_{2.5} exposure has been widely reported, most Indian residential studies still focus mainly on particulate mass concentration or isolated source categories (Aziz et al. 2025). Women's personal exposure during cooking has also been linked with PM_{2.5} bound PAHs derivatives and carbonaceous fractions, confirming that domestic microenvironments are chemically complex exposure zones rather than simple PM_{2.5} mass environments (Deepthi et al. 2025). Previous studies have investigated indoor PM_{2.5}, PAHs, or heavy metals independently, most residential exposure assessments in India remain largely concentration based and rarely integrate the combined chemistry of PM_{2.5}, associated organic and metallic toxicants within indoor microenvironments. In particular, limited studies have simultaneously examined seasonal indoor PM_{2.5} variability, particle bound PAHs, trace metal enrichment, and their mechanistic toxicological relevance from a women centered exposure perspective in densely populated Indo Gangetic urban households (Goel et al. 2024, Pandey et al. 2013). Previous investigations from Indian cities, including Lucknow, have primarily focused on ambient particulate pollution or isolated pollutant categories without adequately linking indoor aerosol chemistry, source related transformations, and biologically relevant exposure pathways. Therefore, the importance of the present study lies in developing an integrated chemistry based framework that combines seasonal indoor PM_{2.5} characterization, particle bound PAHs composition, trace metal interactions, and women specific residential exposure interpretation within urban household environments of Lucknow, India. Accordingly, the present study interprets women's exposure within a biologically plausible framework linking indoor PM_{2.5} chemistry, PAHs, metal interactions, and time activity related inhalation exposure.

2. Materials and Methodology

2.1 Study area and household microenvironment selection

The study was conducted in Lucknow, the capital city of Uttar Pradesh, India, located in the central Indo Gangetic Plain at approximately 26°51'N and 80°57'E, about 123 m above mean sea level (Dwivedi et al. 2022). Lucknow is a rapidly expanding northern Indian city where household air quality is influenced by mixed land use, increasing vehicular density, commercial activity, industrial emissions, domestic combustion, and seasonal

meteorological variability (Khan et al. 2025). Its location within a highly polluted urban airshed makes it suitable for investigating indoor PM_{2.5} as a chemically active carrier of particle bound polycyclic aromatic hydrocarbons (PAHs) and heavy metals (Mannan & Ghamdi 2021). Households were selected following a preliminary questionnaire based survey covering location, household structure, indoor activities, ventilation characteristics, surrounding emission sources, and reported health related discomforts. Based on land use and source influence, households were grouped into three microenvironmental categories, i.e., industrial, commercial, and residential. Industrial households were located near industrial activity, traffic movement, and dust intrusion. Commercial households were influenced by markets, roadside cooking, traffic corridors, and mixed use activity, and residential households were located in comparatively planned areas with lower direct industrial and traffic influence. A total of 18 households were selected, with six households from each microenvironmental category shown in Figure 3. Each household was monitored four times in each season, and each monitoring event consisted of 24 hour integrated sampling. Thus, every household underwent 12 monitoring days over the one year study period, yielding a total of 216 household level 24 hour monitoring events across all microenvironments.

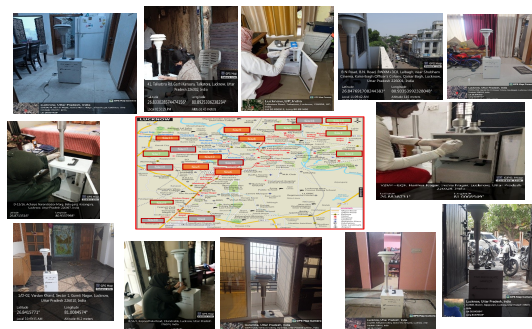


Figure 3. Selected microenvironments for monitoring of pollutants

2.2 Ethical approval and women relevant sampling locations

The study was approved by Integral University, Lucknow. The purpose of the study was explained to respondents or household guardians, and consent was obtained. Study information was provided in English and Hindi, and personal information was kept confidential. Indoor sampling was conducted between the living room and kitchen zone to capture the combined influence of cooking, living space occupancy, cleaning, resuspension of settled dust, incense use, mosquito repellents, household product emissions, and ventilation behaviour. This location was intentionally selected because it represents the transition area where both kitchen emissions and living room

exposure interact. Field observations indicated that women were commonly engaged for approximately 4-5 h in cooking and an additional 1-2 h in cleaning and other household chores, making this microenvironment highly related to repeated women's indoor exposure. The study therefore, interprets health relevance through measured PM_{2.5} bound chemistry rather than through direct clinical or biomarker outcomes.

2.3 PM_{2.5} sampling design and gravimetric determination

Indoor PM_{2.5} monitoring was conducted from 1 November 2023 to 30 October 2024 across the selected households. Twenty four hour integrated PM_{2.5} samples were collected using an Envirotech APM 550 fine particulate sampler operated at a calibrated flow rate of 17.57 L min⁻¹. Sampling was performed using GF/A 47 mm filters with 0.5 µm pore size. The sampler was positioned at least 2 m away from doors, walls, and direct obstructions to minimize localized disturbance and to obtain representative indoor particulate loading (Dwivedi et al. 2023)). Before and after sampling, filters were conditioned in a desiccator at 20-30 °C for 24 h and weighed three times using a Shimadzu ATX 224 analytical balance. PM_{2.5} mass concentration was calculated gravimetrically using the difference between post and pre sampling filter weights divided by the total sampled air volume (Zehra et al. 2025).

$$M = (M_f - M_i) \times 10^3$$

$$V = Q_{avg} \times t / 10^3$$

$$C = M/V$$

where M is collected PM_{2.5} mass (µg), M_f and M_i are post and pre sampling filter masses (mg), V is sampled air volume (m³), Q_{avg} is average flow rate (L min⁻¹), t is sampling duration (min), and C is PM_{2.5} concentration (µg m⁻³).

2.4 Extraction and GC MS analysis of 16 USEPA PAHs

After gravimetric analysis, each filter was divided into two portions, one for 16 USEPA priority PAHs and the other for heavy metals. For PAHs analysis, filters were extracted using n hexane dichloromethane (1:1, v/v). Samples were spiked with pyrene d₁₀ for recovery assessment and ultrasonicated in three sequential extraction steps of 30 min each. Extracts were filtered through 0.22 µm Millex syringe filters, cleaned using a silica gel column, eluted with n hexane dichloromethane (3:1, v/v), concentrated using a rotary evaporator, and reduced to approximately 1 ml under nitrogen. The analyzed PAHs were Nap, AcY, AcP, Flu, Phe, Ant, Flth, Pyr, BaA, Chr, BbF, BkF, BaP, InP, DahA, and BghiP. Quantification was performed using GC-MS (Clarus 600 MS, PerkinElmer, USA) equipped with an Elite 5MS capillary column (30 m × 0.25 mm × 0.25 µm). Helium was used as carrier gas at 1 mL min⁻¹, the injector temperature was 280 °C, and detection was performed in selected ion monitoring

(SIM) mode. Calibration was conducted using PAHs standards and pyrene d_{10} internal standard (Lee et al. 2025).

2.5 Acid digestion and ICP-OES analysis of PM_{2.5} bound heavy metals

The second filter portion was digested for heavy metal analysis using 5 mL concentrated HNO₃ on a hot plate at 40-60 °C for 90 min. After cooling, digests were filtered through 0.22 µm filters and diluted to 10 mL with Milli Q water. Procedural blanks were prepared using the same method. Seven PM_{2.5} bound metals Cr, Cu, Fe, Mn, Ni, Pb, and Zn, were quantified using ICP-OES (iCAP 6300 Duo, Thermo Scientific). Glassware was soaked overnight in 2% HNO₃ and rinsed with deionized water before use (Aziz et al. 2025). The selected metals were interpreted not only as elemental contaminants but also according to their chemical relevance. Fe and Cu were considered redox active metals capable of contributing to Fenton type ROS generation, while Cr, Ni, Pb, Zn, and Mn were interpreted in relation to oxidative stress, inflammatory relevance, systemic toxicity, and household dust or combustion linked sources.

2.6 Chemical characterization, exposure interpretation, and QA/QC

Chemical interpretation was based on seasonal variation, microenvironmental concentration patterns, PAHs congener profiles, ring number distribution, and PM_{2.5} bound metal composition. PAHs source interpretation considered the dominance of combustion derived congeners and diagnostic ratios, including Flth/(Flth+Pyr) and BaA/(BaA+Chr).

These ratios were used only as supporting evidence because PAHs profiles may be altered by indoor partitioning, degradation, and atmospheric ageing. Metals were interpreted in terms of both source relevance and redox/toxicological significance. The overall framework treated PM_{2.5} as a reactive carrier matrix in which PAHs and metals coexist and may jointly influence indoor aerosol toxicity. Quality assurance included sampler inspection before and after relocation, monitoring of flow rate and sampling volume, monthly calibration, field blanks, laboratory blanks, recovery checks, and instrumental detection limit assessment. For PAHs, recovery based on pyrene d_{10} (240 ng) was approximately 70 ± 10%. Field blanks (n = 2) and laboratory blanks (n = 2) were analyzed. Instrumental detection limits were determined at signal to noise ratio ≥3, and method detection limits were calculated from blanks as mean blank plus three standard deviations. Peaks with signal to noise ratio below 3 were treated as not detected. No target PAHs were detected in field or method blanks, therefore, blank correction was not required. PAHs detection limits and recoveries are summarized in Table 1. For metals, method detection limits were calculated as three times the standard deviation of

blank measurements, and recovery, wavelength, instrumental detection limit, and spike concentration are summarized in Table 2.

Table 1. Detection limits and recovery percentage for PAHs analysis by GC-MS

PAHs	Detection limit (ng m ⁻³)	Recovery % ± RSD	Mean analyzed concentration (ng m ⁻³)
Nap	0.007	78 ± 2	0.39
AcY	0.007	66 ± 6	0.42
Ace	0.007	59 ± 7	0.04
Flu	0.006	80 ± 9	1.02
Phe	0.003	79 ± 6	2.06
Ant	0.006	68 ± 9	0.87
Flth	0.003	82 ± 3	4.23
Pyr	0.004	91 ± 1	5.11
BaA	0.004	79 ± 6	2.22
Chr	0.006	77 ± 3	3.60
BbF	0.007	76 ± 9	5.98
BkF	0.006	110 ± 3	3.26
BaP	0.006	81 ± 2	1.12
InP	0.003	84 ± 6	2.37
DahA	0.006	62 ± 3	1.02
BghiP	0.007	71 ± 9	0.96

Table 2. Detection limits and recovery percentage for heavy metal analysis by ICP-OES

Met al	Wavelength (nm)	Recovery % ± RSD	Instrument detection limit (µg L ⁻¹)	Spike concentration for MDL (µg L ⁻¹)
Pb	220.35	79 ± 1.2	1.20	3.00
Cu	324.74	85 ± 0.8	0.48	1.00
Fe	259.33	89 ± 1.6	0.16	0.40
Zn	213.80	91 ± 0.9	0.10	0.40
Mn	257.60	81 ± 0.5	0.02	0.05
Ni	231.60	79 ± 1.8	0.21	1.00
Cr	205.50	82 ± 1.2	0.12	0.40

3. HRA of pollutants/ Exposure assessment

3.1 Multiple path particle dosimetry model [MPPD Model] (Human Respiratory Tract Deposition Model)

The Multiple-Path Particle Dosimetry (MPPD) model is a widely used computational dosimetry tool designed for in silico assessment of particulate matter deposition in the respiratory systems of humans and experimental animals, including rats, mice, rhesus monkeys, pigs, and rabbits. For human respiratory deposition analysis, the MPPD model

incorporates several airway morphometry models representing different lung geometries and physiological conditions. These include the Yeh-Schum Single-Path model, Yeh-Schum 5-Lobe model, Stochastic model, Age-Specific Symmetric model, Age-Specific 5-Lobe model, Weibel Symmetric model, Pacific Northwest National Laboratory (PNNL) Symmetric model, and PNNL Asymmetric model. These morphometric frameworks enable detailed simulation of particle transport and deposition across different regions of the respiratory tract under varying exposure and breathing conditions (Deepthi et al. 2019, Rajouriya & Taneja 2023).

The Yeh-Schum 5-Lobe is a five lobe human lung model developed by Yeh and Schum (Yeh & Schum 1980) for computing the deposition of PM in the different lobes. This lung geometric model assumes uniform lung ventilation. It was chosen for this study because it characterizes the unique features of individual air passages down to the segmental bronchi level while illustrating the air passages within each lobe through a single path approach. It allows for the analysis of PM deposition within each lobe, providing insight into regional differences in deposition patterns.

The MPPD model calculates, at both regional and overall levels, pulmonary deposition fractions and clearance through diffusion, impaction, and sedimentation at various places in the respiratory system. In the head (H), tracheobronchial (TB), and pulmonary (P) areas of the respiratory tract, the multiple path particle dosimetry model (MPPD, v3.04) was used to calculate the deposition fractions of PM_{2.5} particles (Mahalingam et al. 2024, Ababio et al. 2025).

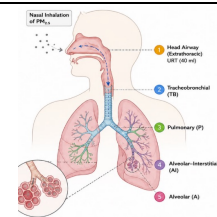
Deposited dose was calculated by using Equation 1:

$$D_{\text{Total}} = C \times IR \times (DF_H + DF_{TB} + DF_{PU}) \quad (1)$$

Where, D_{Total} Total deposited dose, C = Concentration, IR = Inhalation rate, DF_H = Deposition fraction in the head region, DF_{TB} = Deposition fraction in the tracheobronchial region, DF_{PU} = Deposition fraction in the pulmonary region (Londahl et al. 2014).

Further details of the specific input parameters including functional residual capacity (FRC) (mL), Upper Respiratory Tract (URT) volume (mL), density (g cm^{-3}), exposure condition, aerosol concentration, aspect ratio, inhalability adjustment, breathing frequency (breaths per minute [bpm]), tidal volume (mL), inspiratory fraction, body orientation and breathing scenario and these parameter values in figure 4 for the Yeh-Schum 5-Lobe lung geometric model employed in this study (Neder et al. 1999, Brown et al. 2013, Gao et al. 2018)

Parameters	Age groups				
	20-29	30-39	40-49	50-59	≥60
Species	Human				
Model	Yeh-Schum 5 lobe				
FRC (ml)	2380	2540	2490	2540	2930
URT (ml)	40				
Exposure Condition	Constant exposure				
Aerosol Concentration	PM _{2.5}				
Breathing frequency (n/min)	17.87	18.85	18.90	19.70	21.10
Tidal Volume	566.67	550	550	500	500
Breathing Scenario	Nasal				



Species= Human
Model= Yeh-schum 5 lobe
Exposure= PM_{2.5}
Scenario= Nasal

FRC= Functional Residual Capacity
URT= Upper Respiratory Tract
N/min= Breaths per minute
ML= Millilitre
Acenaphthylene

Breathing parameters by age groups
Breathing frequency (N/min): 17.87-21.10
Tidal Volume (ml): 566.67-500

Figure 4. Age Dependent Respiratory Parameters Applied in the Yeh Schum 5 Lobe Model for Indoor PM_{2.5} Deposition

3.2 HRA for the Heavy metals

In this study, the health risk assessment model developed by the Environmental Protection Agency (EPA) of the United States was used to evaluate the health risks posed by transition metals in PM_{2.5} (Xie et al. 2020). The present study principally targeted

women, therefore, the subject group was divided into seven categories according to age group and the body weight taken during the evaluation and the average value obtained during the survey.

The exposure to PM_{2.5} can occur via ingestion, inhalation and dermal pathways. Dose exposure due to ingestion Chronic daily intake (CDI, mg kg⁻¹ day⁻¹), and the dermal contact, dermal absorbed dose (DAD, mg kg⁻¹ day⁻¹) was calculated to assess the total exposure dose of metals associated with PM_{2.5}. The calculation was done in accordance with the Human Health Evaluation Manual and Supplemental Guidance for Dermal Risk Assessment (Part E) (U.S.E.P.A. 2000) Following equations were employed.

$$DAD = C \times SA \times AF \times ABS \times EF \times ED \times CF / BW \times AT \dots\dots\dots (2)$$

$$CDI = C \times IngR \times EF \times ED \times CF / BW \times AT \dots\dots\dots (3)$$

Where,

DAD= Dermal absorbed dose (mg kg⁻¹ day⁻¹), C=Concentration, SA= Exposed skin surface area (cm²), AF=skin adherence factor (mg/cm²), ABS=dermal absorption factor, EF= exposure frequency (days/year), ED= exposure duration (years), CF=Conversion factor, BW= body weight (kg), AT= average time (days)

CDI= Chronic daily intake (mg kg⁻¹ day⁻¹), C= Concentration, IngR = Ingestion rate (mg/day), EF= exposure frequency (days/year), ED= exposure duration (years), CF=Conversion factor, BW= body weight (kg), AT= average time (days) (Abdulaziz et al. 2022).

In addition to individual PAH concentrations, compositional indices including Σ LMW PAHs, Σ HMW PAHs, HMW/LMW ratio, and carcinogenic PAH fraction were calculated to support interpretation of indoor aerosol composition and particle phase dominance across seasons and microenvironments. Σ LMW PAHs included 2-3 ring compounds (Nap, AcY, Ace, Flu, Phe, and Ant), whereas Σ HMW PAHs included 4-6 ring PAHs (Flth, Pyr, BaA, Chr, BbF, BkF, BaP, InP, DahA, and BghiP). The HMW/LMW ratio was calculated as the ratio of total HMW PAHs to total LMW PAHs. The carcinogenic PAH fraction was estimated from the summed contribution of BaA, Chr, BbF, BkF, BaP, InP, and DahA relative to total measured PAHs. These indices were calculated using reported seasonal mean indoor PAH concentrations and were interpreted as descriptive indicators of indoor aerosol characteristics.

4. Results and Discussion

4.1 Indoor PM_{2.5} across seasons and microenvironments

Indoor PM_{2.5} concentrations showed a clear seasonal and microenvironmental rise across the monitored households, with the total pattern following winter >

summer > monsoon and Industrial > Commercial > Residential microenvironments. As shown in Table 3, Industrial households obtained the highest PM_{2.5} concentrations, of 235 µg m⁻³ in winter, 148.2 µg m⁻³ in summer, and 58.0 µg m⁻³ in monsoon. Whereas Residential households recorded the lowest concentration, but still above the standard limits. All the houses were at least 2-3 times higher than the WHO limits.

Table 3. Seasonal indoor PM_{2.5} concentration range across microenvironments

Microenvironme nt	Winte r PM _{2.5} (µg m ⁻³)	Summe r PM _{2.5} (µg m ⁻³)	Monsoo n PM _{2.5} (µg m ⁻³)
Industrial	142- 235	82.6- 148.2	33.6- 58.0
Commercial	102- 197	77.0- 186.0	27.0- 61.3
Residential	74- 144	39.3- 78.9	16.2- 46.5

The winter season heightening was most pronounced in Industrial and Commercial households, indicating that reduced ventilation, lower temperature, atmospheric stagnation, and weaker dispersion increased indoor particle residence time. Under these conditions, PM_{2.5} behaves not only as a suspended particulate pollutant but also as a condensed phase carrier that can retain semi volatile organic compounds and particle bound metals. Higher PM_{2.5} mass during winter provides a larger surface matrix for adsorption of PAHs and trace metals, thus increasing the chemical and toxicological significance of indoor aerosols beyond mass concentration alone. The Industrial microenvironment showed the highest concentration range in all seasons, reflecting the combined influence of nearby industrial activity, road dust intrusion, combustion emissions, poor ventilation, and indoor resuspension. Commercial households also showed elevated PM_{2.5} concentration, particularly during winter and summer, and this may be due to combined contributions from traffic infiltration, market related activity, cooking, cleaning, and household consumer products. Residential households showed comparatively lower concentrations, however, the winter remained high enough to indicate meaningful chronic indoor exposure. Therefore, residential microenvironments should not be interpreted as low risk environments, especially because women may spend several hours daily in kitchens and doing various household chores. The positioning of the sampler between the kitchen and living area is scientifically relevant because this zone represents the most active household exposure corridor for women. Questionnaire survey done by household women reveals that women commonly spend approximately 4-5 hours in cooking and an

additional 1-2 hours in cleaning and household chores. Thus, even when PM_{2.5} concentrations were lower in Residential households than in Industrial or Commercial households, the repeated daily exposure duration may substantially increase the influenced inhalation burden.

4.2 Microenvironmental distribution and compositional characteristics of indoor PM_{2.5} bound PAHs

Commercial, and Residential households, indicating strong influence of combustion intensity, atmospheric conditions, particle-phase partitioning, and indoor retention processes. The quantitative compositional indicators presented in Table 4 demonstrated that high molecular weight (HMW) PAHs consistently dominated the indoor aerosol fraction across all studied microenvironments. Industrial households showed the highest total PAH burden during both summer and winter, with Σ Total PAHs reaching 164.872 and 188.030 ng m⁻³, respectively. Similarly, Commercial households also showed substantial winter dominance, whereas Residential households maintained comparatively lower but persistent indoor PAH concentrations across all seasons. A major observation from Table 4 reveals predominance of HMW PAHs over low molecular weight (LMW) compounds. Industrial households showed HMW contributions exceeding 90% during summer and winter, accompanied by elevated HMW/LMW ratios of 16.21 and 9.46, respectively. Commercial households also showed strong HMW dominance, particularly during winter where the HMW fraction accounted for more than 91% of the total PAH burden. In comparison, Residential households exhibited lower HMW/LMW ratios, although HMW compounds still remained the dominant fraction across all seasons. This compositional behaviour indicates that the indoor particulate phase was strongly enriched with combustion derived PAHs possessing lower volatility, stronger hydrophobicity, and greater affinity for PM_{2.5} surfaces, thereby favouring prolonged particle phase persistence within indoor aerosols. The compositional pattern further revealed that carcinogenic PAHs constituted a substantial fraction of the total indoor PAH burden. As indicated in Table 4, carcinogenic PAH contributions reached 74.1% and 61.2% in Industrial households during summer and winter, respectively, while Commercial households showed a comparable winter carcinogenic fraction of 61.3%. These findings are environmentally important because carcinogenic HMW PAHs such as B(a)P, InP, Chr, and B(a)A are strongly associated with fine particles capable of deeper respiratory penetration and prolonged indoor suspension. The observed seasonal variability further demonstrated that winter conditions promoted stronger accumulation of particle associated PAHs within indoor environments. Reduced atmospheric dispersion,

lower ventilation, and enhanced gas to particle partitioning during colder conditions likely intensified the retention of combustion derived aerosols indoors. Although monsoon conditions substantially reduced the total PAH burden across all households due to rainfall washout and lower outdoor to indoor infiltration, detectable HMW and carcinogenic PAHs persisted even during monsoon, indicating continued contribution from indoor activities and residual particle retention. Despite comparatively lower PAH concentrations in Residential households, the continued presence of carcinogenic PAHs remains important from a women-focused exposure perspective because of prolonged occupancy.

Within kitchen and living spaces may lead to repeated low inhalation exposure over extended periods. Collectively, the compositional indicators summarized in Table 4 show that indoor PAH behaviour across the studied households was governed by the interaction of combustion-derived aerosol generation, particle-phase persistence, seasonal atmospheric behaviour, and indoor retention processes.

Table 4. Total percentage of low and high molecular weight PAHs and their carcinogenic fraction in different seasons

Micro environment	Season	Σ Total PAHs	Σ LMW PAHs	Σ HMW PAHs	HMW contribution (%)	HMW/LMW ratio	Carcinogenic PAH fraction (%)
Industrial	Summer	164.872	9.581	155.291	94.2	16.21	74.1
	Winter	188.030	17.908	170.122	90.4	9.46	61.2
	Monsoon	33.075	9.843	23.231	70.2	2.36	53
Commercial	Summer	89.768	12.777	76.991	85.8	6.03	55.6
	Winter	181.28	15.93	165.35	91.2	10.38	61.3
	Monsoon	15.45	4.097	11.353	73.5	2.77	43.8

Residential	Summer	43.41	12.906	30.504	70.3	2.36	57.6
	Winter	39.192	10.161	29.031	74.1	2.86	40
	Monsoon	8.482	3.571	4.911	57.9	1.38	36.1

4.3 Seasonal variation of indoor PM_{2.5} bound PAHs across microenvironments

The seasonal behaviour of indoor PM_{2.5} bound PAHs showed a clear shift in both concentration and chemical composition across Industrial, Commercial, and Residential households. As illustrated in Figure 5, PAHs concentrations were highest during winter, followed by summer, while monsoon levels declined substantially. This reduction during monsoon is consistent with rainfall mediated wet scavenging, reduced resuspension, and lower outdoor to indoor particle infiltration, however, the persistence of detectable PAHs indicates that indoor sources and particle retention continued to influence household exposure. Especially, the seasonal response was not uniform across PAHs species. High molecular weight PAHs, including B(a)P, InP, B(ghi)P, B(a)A, Chr, and Pyr, consistently dominated the indoor particulate phase, particularly in Industrial and Commercial households. Their predominance reflects their lower volatility, stronger hydrophobicity, and greater affinity for PM_{2.5} surfaces, which favour particle phase retention under cooler and poorly ventilated winter conditions. In comparison, several low molecular weight PAHs showed weaker particle association and lower seasonal persistence, indicating that the observed pattern was governed not only by emission strength but also by compound specific partitioning behaviour within the indoor aerosol composition. A key finding from Figure 5 is that winter did not merely increase total PAHs concentration, it selectively intensified the particle bound fraction of persistent and carcinogenic HMW PAHs. This indicates a seasonal transition toward a more chemically complex and potentially more toxic indoor aerosol profile. Industrial households showed the highest seasonal PAHs concentration, followed by Commercial and Residential households, confirming the influence of source proximity, indoor particle retention, and microenvironmental conditions. Although Residential households showed comparatively lower concentrations, the continued presence of carcinogenic PAHs remains important because women may experience repeated, long-duration exposure in kitchen and living areas through cooking, cleaning, household product use, and occupancy-related resuspension. Therefore,

even low PAHs concentrations may become cumulatively relevant over time. To further support the source-related interpretation of indoor PM_{2.5}-bound PAHs, we evaluated selected diagnostic ratios, including Flth/(Flth+Pyr), BaA/(BaA+Chr), and InP/(InP+BghiP) (Supplementary Table S1). The observed ratio pattern predominantly suggested pyrogenic and combustion-related influence, particularly within Industrial and Commercial households. However, the ratios were interpreted cautiously because indoor aerosol transformation, gas-particle partitioning, and mixed indoor-outdoor contributions may alter conventional source characteristics under household conditions. Despite these limitations, the diagnostic ratio pattern remained consistent with the predominance of combustion derived high molecular weight PAHs observed across the studied households.

4.4 Indoor PM_{2.5} bound heavy metals and women focused exposure relevance

Indoor PM_{2.5} contained measurable concentrations of Cr, Mn, Fe, Ni, Cu, Zn, and Pb across Industrial, Commercial, and Residential households, confirming that the indoor aerosol load was not limited to particulate mass or PAHs composition but also included a metal bearing reactive portion. As summarized in Table 5, the metal profile showed clear seasonal and microenvironmental differences, with the strongest elevation generally observed during winter in Industrial and Commercial households. This pattern is consistent with the PM_{2.5} mass trend reported previously, indicating that winter indoor particles may provide a larger surface matrix for simultaneous retention of organic and inorganic toxicants.

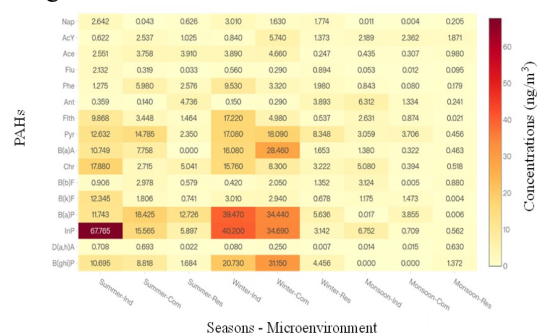


Figure 5. Seasonal heatmap of indoor PM_{2.5} bound 16 USEPA priority PAHs across Industrial, Commercial, and Residential households.

Table 5. Indoor PM_{2.5} bound heavy metals across microenvironments and seasons

Seasons	Microenvironment	Highest reported indoor metal peaks in PM _{2.5}
Winter	Industrial	Zn 3.6, Pb 3.1, Ni 2.3, Cu 1.6, Mn 1.3 $\mu\text{g m}^{-3}$

	Commercial	Ni 3.1, Zn 1.9, Cu 1.6, Pb 1.3, Mn 1.3 $\mu\text{g m}^{-3}$
	Residential	Pb 2.3, Cu >1.0, Zn >1.0 $\mu\text{g m}^{-3}$
Summer	Industrial	Zn 2.06, Fe 1.5, Cu 1.02, Ni 0.81, Pb 0.70 $\mu\text{g m}^{-3}$
	Commercial	Mn 1.2, Zn 1.1, Fe 1.01, Pb 0.91, Ni 0.70 $\mu\text{g m}^{-3}$
	Residential	Pb 0.87, Ni 0.78, Zn 0.72, Cu 0.48, Mn 0.48 $\mu\text{g m}^{-3}$
Monsoon	Industrial	Ni 1.6, Zn 1.01, Pb 0.64, Fe 0.40, Mn 0.30 $\mu\text{g m}^{-3}$
	Commercial	Ni 1.9, Pb 1.9, Zn 1.3, Cu 0.60 $\mu\text{g m}^{-3}$
	Residential	Cu 1.9, Zn 1.6, Ni 0.55, Fe 0.30 $\mu\text{g m}^{-3}$

The Industrial microenvironment showed the strongest metal concentration, particularly during winter, where the dominant pattern was Zn,Pb,Ni, Cu, Mn. This reflects the likely combined influence may be of industrial dust, metal containing particles, combustion of fossil fuel, waste disposal, combustion emissions, road dust intrusion, renovation activity, indoor resuspension, and reduced ventilation. During summer, the Industrial profile shifted toward Zn, Fe, Cu, Ni, while in monsoon Ni, Zn, Pb remained dominant despite the washout effect due to rain. The persistence of Ni and Zn across seasons suggests that Industrial households experience continuous indoor penetration and retention of metal bearing PM_{2.5}. Chemically, Fe and Cu are important because they can participate in redox cycling and Fenton type reactions, increasing reactive oxygen species (ROS) generation, while Ni, Cr, and Pb contribute to inflammatory, genotoxic, systemic, and reproductive health concerns. The Commercial microenvironment showed a mixed metal profile, with winter dominated by Ni,Zn,Cu,Pb and monsoon by Ni,Pb,Zn. The persistence of Ni and Pb in Commercial households is particularly important because these metals are associated with combustion derived and traffic related fine particles and may remain indoors under low ventilation or closed window conditions. Thus, Commercial microenvironments should not be interpreted only as

outdoor influenced, but also be represented chemically mixed residential spaces where indoor activities and infiltrated urban emissions overlap. The Residential microenvironment showed comparatively lower concentrations, but the results remain exposure relevant because women may spend longer daily durations within houses. Residential households showed Pb,Cu,Zn dominance in winter, Pb,Ni, Zn in summer, and Cu,Zn,Ni in monsoon. This seasonal shift suggests that indoor household activities, settled dust resuspension, cooking, cleaning, room fresheners, mosquito repellents, incense use, tobacco smoke exposure, plumbing materials, batteries/appliances, and outdoor infiltration may all contribute to metal bearing PM_{2.5}. Although concentrations in Residential households were generally lower than Industrial and Commercial households, repeated daily exposure in the kitchen living transition zone can increase cumulative inhalation burden, especially among women engaged in cooking, cleaning, and household chores. From a women focused health perspective, the concern is not limited to peak concentration but extends to duration, frequency, particle size, and chemical reactivity. PM_{2.5} bound metals can penetrate deep into the respiratory tract and may contribute to oxidative stress, airway inflammation, systemic circulation of toxicants, endocrine disturbance, reproductive vulnerability, and pregnancy related risk pathways. Pb is of particular concern because of its systemic and reproductive toxicity, Ni and Cr are relevant for inflammatory and genotoxic responses, Fe and Cu can amplify oxidative potential through redox cycling, and Zn and Mn, although essential elements, may become toxicologically relevant when repeatedly inhaled in particle bound form (Jomoya et al. 2025). Therefore, even low metal concentrations in Residential households is critical because long duration domestic exposure may convert low concentrations into a meaningful cumulative dose.

4.5 Regional deposition fraction and deposited dose of PM_{2.5} using the MPPD model

The Multiple Path Particle Dosimetry (MPPD) model was applied to assess indoor PM_{2.5} exposure into biologically relevant respiratory deposition among women of different age groups. This modelling step is important because PM_{2.5} concentration alone does not fully represent health relevance (Kim 2009, IARC 2016, ICRP 1994), the fraction of inhaled particles retained in the head (H), tracheobronchial (TB), and pulmonary regions (PU) determines the potential site of biological interaction. The regional deposition fractions obtained from the model are presented in above Figure 4. PM_{2.5} deposition showed a clear age related redistribution within the respiratory tract. Head region deposition increased from 0.5552 in the

20-29 year group to 0.5852 in women aged ≥ 60 years, whereas pulmonary deposition decreased from 0.1677 to 0.1189 across the same age range, as summarized in Table 6. This shift suggests that younger women experience relatively greater distal lung penetration of PM_{2.5}, while older women show greater proximal airway retention. The pattern is physiologically plausible because age related changes in breathing frequency, tidal volume, airway geometry, and lung ventilation can alter airflow distribution and particle deposition behaviour.

Table 6. Regional deposition fraction of PM_{2.5} across age groups using the MPPD model

Age group	Head region	Tracheobronchial region	Pulmonary region	Total deposition fraction
20-29 years	0.5552	0.0462	0.1677	0.7691
30-39 years	0.5670	0.0456	0.1528	0.7654
40-49 years	0.5671	0.0454	0.1542	0.7667
50-59 years	0.5582	0.0467	0.1431	0.7479
≥ 60 years	0.5852	0.0451	0.1189	0.7492

An important finding is that deposition fraction remained nearly unchanged across microenvironments and seasons despite large variation in measured indoor PM_{2.5} concentrations. This is expected because deposition fraction is primarily controlled by physiological and particle size parameters, including breathing pattern, airway geometry, functional residual capacity, and assumed aerosol size, rather than by pollutant concentration itself. Therefore, deposition fraction alone cannot explain seasonal or microenvironmental differences in exposure burden. For this reason, deposited dose provides a more informative exposure metric because it incorporates both inhaled concentration and deposition probability. Deposited dose varied strongly across microenvironments and seasons, following the same exposure increase observed for indoor PM_{2.5} mass. Industrial households showed the highest deposited dose across seasons, ranging from 27.506 to 112.375 μg , followed by Commercial households (28.640 to 94.204 μg) and Residential households (20.553 to 68.859 μg). This

confirms that women living in Industrial and Commercial microenvironments receive a greater inhaled and retained PM_{2.5} burden, particularly when household exposure occurs repeatedly during cooking, cleaning, and routine indoor activities. Although Residential households showed the lowest deposited dose, the exposure remains health relevant because daily occupancy duration in kitchens and living areas may convert lower concentrations into meaningful cumulative inhalation burden (Zhou et al. 2018, Alves et al. 2013, McDuffie et al. 2021, Karahulian et al. 2015). Seasonally, winter produced the highest deposited dose across microenvironments and age groups, ranging from 67.277 to 112.375 μg . Summer deposited dose decreased to 34.875-88.943 μg , likely due to stronger atmospheric mixing and improved dispersion (Zheng et al. 2026, Fang et al. 2026, Tran & Molders 2011) as summarized in [Supplementary Table S2]. The lowest deposited dose occurred during the monsoon period (20.553-29.313 μg), which can be attributed to rainfall-mediated wet scavenging and washout of suspended particulate matter (Li et al. 2022). Thus, the deposited dose results provide the biological exposure link between measured indoor PM_{2.5} concentration and potential respiratory burden in women. Therefore, MPPD modelling strengthens the interpretation that indoor PM_{2.5} exposure should not be assessed only by measured concentration. The model shows that age specific respiratory physiology influences where particles deposit, while measured concentration determines how much particle mass is ultimately retained.

4.6 Deposited mass visualization and age dependent respiratory deposition of indoor PM_{2.5} across seasons and microenvironments

The deposited mass visualization generated using the Yeh-Schum 5-Lobe MPPD model demonstrated distinct seasonal and age related differences in the regional retention of indoor PM_{2.5} within the respiratory tract. Figure 6 (a-c) illustrates the deposited mass distribution patterns across Industrial, Commercial, and Residential households during winter, summer, and monsoon seasons. The visualization results showed that deposited PM_{2.5} mass was strongly influenced by both indoor PM_{2.5} concentration and age dependent respiratory physiology. Across all seasons, younger women consistently showed higher deposited mass compared with older age groups, following the general trend 20-29 > 30-39 > 40-49 > 50-59 > ≥ 60 years. This behaviour is physiologically relevant because younger individuals generally possess higher tidal volume, stronger inhalation dynamics, and greater pulmonary penetration efficiency, which collectively favour deeper transport and retention of fine particles within distal lung regions. The highest deposited mass visualization was observed under winter Industrial household conditions, where

elevated indoor PM_{2.5} concentrations combined with stagnant ventilation conditions promoted enhanced respiratory retention of fine particles. In contrast, monsoon conditions showed substantially lower deposited mass across all age groups and microenvironments due to rainfall mediated atmospheric washout, reduced suspended particle loading, and lower outdoor to indoor infiltration. Summer conditions showed intermediate deposition behaviour, reflecting moderate atmospheric mixing and comparatively lower indoor PM_{2.5} accumulation than winter. An important observation from Figure 6 (a-c) is that the deposited mass distribution was not restricted only to upper airway regions, but extended into pulmonary regions where PM_{2.5} associated PAHs and heavy metals may become biologically more relevant. The deposited mass visualization provides a physiologically relevant extension of the measured indoor PM_{2.5} data by showing how inhaled particles may be regionally retained within the respiratory tract under different seasonal and microenvironmental exposure conditions. This interpretation is especially important in the present study because PM_{2.5} was not chemically inert but carried particle-bound PAHs and heavy metals. Therefore, higher deposited mass under winter and industrial conditions indicates greater potential delivery of chemically enriched particles to respiratory surfaces, rather than simply higher airborne concentration. Age-wise differences in deposited mass should be taken as model derived deposition behaviour based on respiratory parameters, not as direct evidence of clinical risk. Thus, the visualization strengthens the exposure assessment by linking indoor PM_{2.5} concentration, aerosol chemistry, and regional respiratory deposition while avoiding unsupported health outcome claims.

Figure 6 (a). Deposited Mass visualization at different concentrations across different age groups in winter season

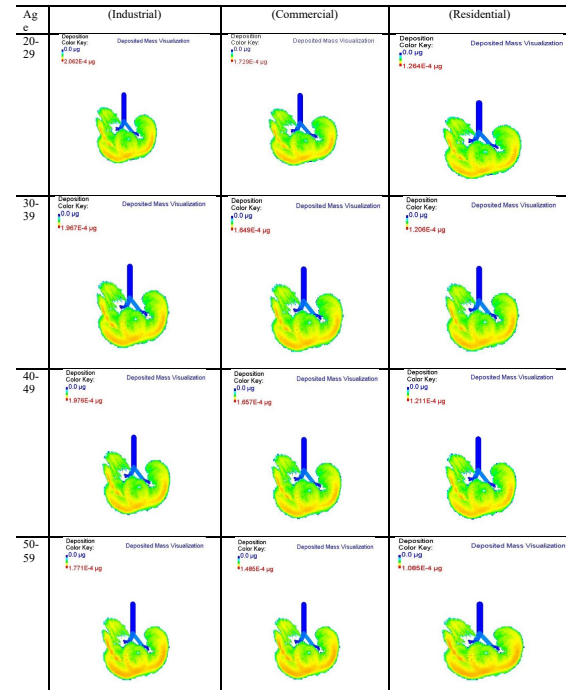


Figure 6 (b). Deposited Mass visualization at different concentrations across different age groups in the summer season

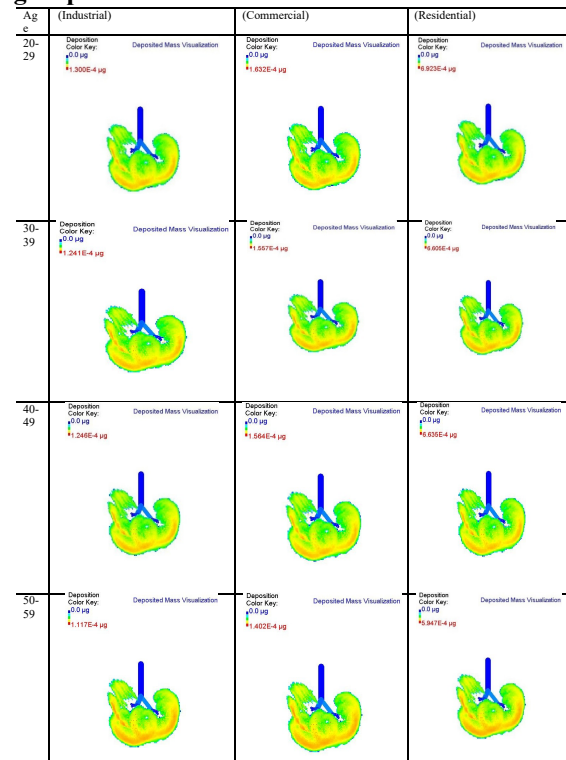
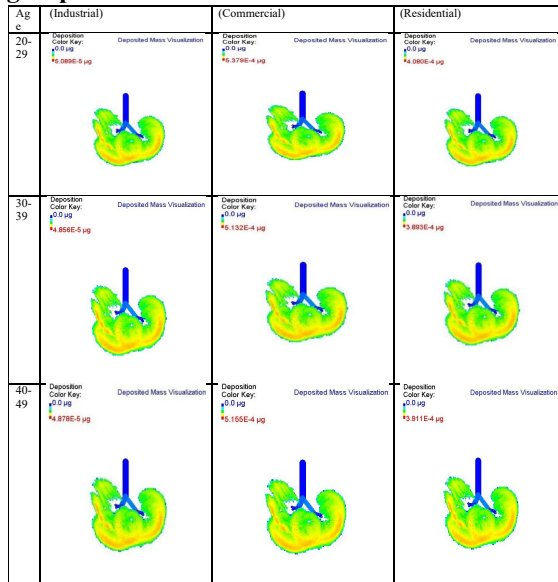


Figure 6 (c). Deposited Mass visualization at different concentrations across different age groups in the Monsoon Season**4.7. DAD and CDI of PM_{2.5} bound heavy metals in women**

The dermal absorbed dose (DAD, mg kg⁻¹ day⁻¹) and chronic daily intake (CDI, mg kg⁻¹ day⁻¹) of PM_{2.5} bound heavy metals were estimated for women under the highest exposure setting, represented by Industrial households during winter. This was selected because the preceding sections identified winter as the season with the highest PM_{2.5} burden, strongest PAHs predominance, and greatest heavy metal fingerprint intensity. Therefore, the DAD and CDI assessment provides a focused interpretation of internal exposure potential under the most critical indoor condition observed in this study. The estimated values across age groups are summarized in Table 7.

Table 7. DAD and CDI values of PM_{2.5} bound heavy metals in women under the highest exposure scenario

Age group	Risk metric	Cr	Mn	Fe	Ni	Cu	Zn	Pb
20-29 years	D	12	6.8	1.	16.	11.	24.	19.
	A	8.2	36	74	69	32	11	13
	D	4		0	3	6	0	0
30-39 years	C	49	19.	5.	61.	38.	86.	75.
	DI	3.4	95	99	57	72	11	18
		2	0	8	0	2	2	0
40-49 years	D	72.	3.9	1.	12.	6.4	16.	13.
	A	20	42	09	46	75	24	14
	D			2	1		0	4

ars								
	C	29	11.	3.	41.	23.	57.	50.
	DI	4.6	53	58	34	89	39	04
		3	0	9	0	9	0	6
40-49 years	D	58.	2.8	0.	8.3	5.1	12.	9.8
	A	65	09	92	90	37	14	99
	D			1			0	
	C	21	10.	2.	29.	18.	42.	35.
	DI	8.9	73	94	60	67	69	12
		2	6	7	0	4	1	7
50-59 years	D	46.	1.7	0.	8.8	4.8	8.9	8.3
	A	89	84	96	40	74	26	28
	D			6				
	C	16	10.	2.	28.	14.	33.	29.
	DI	4.6	98	14	82	88	24	67
		1	0	9	0	2	0	0
≥60 years	D	41.	1.9	0.	7.2	3.7	7.4	6.7
	A	18	95	61	70	56	31	94
	D			0				
	C	14	7.6	1.	23.	12.	27.	24.
	DI	7.8	40	98	75	67	33	95
		1		4	1	1	1	0

The results reveals that the 20-29 year age group had the highest estimated exposure problem for nearly all metals, with DAD values of Cr (128.24), Zn (24.11), Pb (19.13), Ni (16.69), Cu (11.33), Mn (6.84), and Fe (1.74) and CDI values of Cr (493.42), Zn (86.11), Pb (75.18), Ni (61.57), Cu (38.72), Mn (19.95), and Fe (5.99). A progressive decline was observed with increasing age, indicating that age dependent exposure parameters, intake assumptions, body weight normalization, and activity patterns strongly influence dose estimates. The consistently higher CDI compared with DAD indicates that chronic intake represents the more important exposure pathway than dermal absorption under the modelled condition. Among the measured metals, Cr and Pb showed the highest toxicological concern. Chromium showed the highest DAD and CDI values, suggesting its dominant contribution to estimated internal dose. This is important because Cr, particularly in more toxic oxidation states may be associated with oxidative stress, inflammatory response, and genotoxic effects. Pb also remained consistently elevated across age groups and is relevant for women's health because of its systemic toxicity, endocrine disruption potential, reproductive relevance, and possible pregnancy

related implications. Although Ni, Cu, Zn, Mn, and Fe showed lower values than Cr and Pb, their repeated intake remains important because these metals can contribute to, inflammatory signalling, neurological effects, and redox cycling when inhaled or absorbed in particle bound form. The age-wise decline in DAD and CDI should not be interpreted as absence of risk among older women. Rather, it indicates relative reduction in estimated dose under the applied exposure assumptions. Women of all age groups remained exposed to multiple metals simultaneously, and the combined presence of Cr, Ni, Cu, Zn, and Pb suggests a mixed-metal exposure scenario rather than isolated metal toxicity. This is particularly important in indoor households where women may spend long hours cooking, doing various household chores.

5. Conclusion

The present study demonstrates that indoor PM_{2.5} within urban households of Northern India represents a chemically complex aerosol system influenced by combustion derived emissions, seasonal atmospheric conditions, indoor particle persistence, and household activities. Across Industrial, Commercial, and Residential microenvironments, indoor PM_{2.5} consistently followed a seasonal pattern of winter > summer > monsoon, with Industrial households recording the highest pollutant accumulation under winter conditions. The compositional assessment revealed strong dominance of high molecular weight PAHs, particularly InP, B(a)P, Chr, Pyr, and B(a)A, indicating persistent particle phase association of combustion derived organic compounds within indoor aerosols. The elevated carcinogenic PAH contribution observed in Industrial and Commercial households further confirms that indoor PM_{2.5} acted as an important carrier of toxic organic constituents with substantial inhalation relevance. The simultaneous presence of Cr, Mn, Fe, Ni, Cu, Zn, and Pb demonstrated that indoor PM_{2.5} also contained a reactive inorganic component capable of contributing to cumulative respiratory exposure. Essentially, the integration of chemical characterization with MPPD modelling strengthened the exposure interpretation by demonstrating that elevated indoor PM_{2.5} concentrations translated into greater respiratory deposition under winter and Industrial household conditions (Lawrence et al. 2017). Younger women showed comparatively higher pulmonary deposition because of age dependent respiratory parameters incorporated within the model, whereas prolonged indoor occupancy and repeated daily exposure increased the overall exposure significance across all age groups. These findings are environmentally important because women spend substantial durations within kitchen and living environments during cooking, cleaning, and other domestic

activities, thereby increasing repeated interaction with chemically active indoor aerosols. The study provides significant baseline evidence for understanding indoor aerosol behaviour in urban households of Northern India, where indoor environments are continuously influenced by mixed combustion emissions, urban aerosol transport, and limited ventilation conditions. From a public health and policy perspective, the findings also highlights that indoor air quality assessment should extend beyond PM_{2.5} mass concentration alone and incorporate aerosol composition, particle-associated toxicants, seasonal behaviour, exposure duration, and respiratory deposition characteristics (Taushiba et al. 2023). The generated data may assist environmental regulators, urban planners, and public health authorities in identifying high risk indoor microenvironments, improving household ventilation strategies, reducing combustion related indoor emissions, and developing India specific indoor air quality guidelines that consider PAHs and trace metals alongside PM_{2.5} mass concentration (Khan et al. 2024). Thus, the study establishes a chemistry driven framework linking indoor aerosol composition, respiratory deposition, and women focused household exposure, thereby providing scientifically relevant evidence for future indoor air quality management and exposure mitigation strategies in rapidly urbanizing regions of Northern India.

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Author contributions

Anam Taushiba: Data analysis, writing of the original draft.

Alfred Lawrence: Supervision, Conceptualization, review and editing Review

Rahila Rahman Khan: Ph.D. Supervisor

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Data availability

Not Applicable

Declarations

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The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

Human ethical approval and Consent to participate

Not applicable

Consent for publication

All the participants were informed about publishing their results and consent was taken from all the survey participants.

Competing interests

The authors declare that they do not possess any identifiable conflicting financial interests or personal relationships that may have potentially influenced the research presented in this manuscript.

Abbreviations

The following abbreviations are used in this manuscript:

PM_{2.5} =Particulate matter with an aerodynamic diameter ≤ 2.5 μm

PAHs =Polycyclic aromatic hydrocarbons

Cr =Chromium

Mn =Manganese

Fe =Iron

Ni =Nickel

Cu =Copper

Zn =Zinc

Pb =Lead

ROS =Reactive Oxygen Species

WHO =World Health Organization

MPPD =Multiple Path Particle Dosimetry Model

CDI =Chronic daily intake

DAD =Dermal absorbed dose

HMW =High molecular weight

NaP = Naphthalene

Acy =Acenaphthylene

AcP =Acenaphthylene

Flu = fluoranthene

Phe = Phenanthrene

Ant = Anthracene

Flth = Fluoranthene

Pyr = Pyrene

BaA =benz(a)anthracene

Chr = chrysene

BbF= benzo(b)fluoranthene

BkF = benzo(k)fluoranthene

BaP =benzo(a)pyrene

InP= Indeno pyrene

DahA = dibenz(a,h)anthracene

BghiP= benzo(ghi)perylene

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