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Assessing airborne microplastics in urban indoor environments using $PM_{2.5}$ air exchange rate and polymer characterization for respiratory health risk evaluation

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ABSTRACT

Introduction: Airborne microplastics have recently emerged as indoor air pollutants in urban environments due to extensive use of synthetic textiles, furnishings, and plastic-based materials. Continuous inhalation exposure may pose respiratory health risks, particularly in densely occupied spaces with poor ventilation. This study quantifies airborne microplastic concentrations in urban indoor environments and evaluates mitigation strategies based on ventilation improvement and material management.

Materials and methods: Air sampling was conducted in residential rooms, classrooms, and office spaces using low-volume active air samplers fitted with quartz microfiber filters (flow rate 16.7 L/min; duration 8 h). Microplastics were identified and counted using optical microscopy, while polymer types were confirmed through Fourier Transform Infra-Red (FTIR) spectroscopy and Scanning Electron Microscopy (SEM) analysis. Environmental parameters including $PM_{2.5}$ concentration, Air Exchange Rate (AER), relative humidity, temperature, and occupancy density were simultaneously recorded. Respiratory exposure risk was estimated using inhalation dose and Hazard Quotient (HQ) calculations.

Results: Microplastics were detected in all indoor environments, with mean concentrations of 600 particles/m^3 in residences, 1050 in offices, and 1180 in classrooms. Fibers dominated (68%), mainly polyester and polypropylene. Higher concentrations were associated with low ventilation (AER 0.4 h^{-1}), high occupancy density (0.85 persons/m^2), and elevated $PM_{2.5}$ levels (>45 µg/m^3). Estimated inhalation exposure ranged from 2.1 to 3.8 particles/kg/day, and HQ exceeded the safe threshold (1.32) in poorly ventilated classrooms. Increasing AER to 1.2 h−1 reduced concentrations by 39%, replacing synthetic textiles lowered fiber proportion to 41%, and reducing occupancy to 0.55 persons/m^2 decreased inhalation dose to 2.1 particles/kg/day and HQ to 0.78.

Conclusion: Airborne microplastics are prevalent in indoor environments and may contribute to respiratory health risks, especially under low ventilation and occupancy. Enhancing ventilation, indoor materials, and occupancy reduce concentrations and risks, underscoring importance of indoor air management strategies.

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Introduction

Airborne microplastics have emerged as a significant concern in environmental and public health research due to their ubiquitous presence and potential adverse effects on human health [1]. Indoor environments, where individuals spend a majority of their time, have been identified as important reservoirs and exposure pathways for microplastic particles [2]. Recent experimental studies have demonstrated that inhalation exposure to airborne microplastics can occur through normal breathing processes, emphasizing the relevance of indoor air as a primary exposure medium [3]. Measurements of microplastic fallout in various indoor settings have confirmed that particle abundance varies with occupancy patterns, ventilation conditions, and material usage [4]. In addition to inhalation, indirect exposure via indoor dust ingestion has also been reported, highlighting the multifaceted pathways of human exposure [5]. Advances in analytical methods have facilitated improved detection and characterization of microplastics in indoor environments, enabling detailed investigation of their sources and distribution patterns [6]. Evidence from biomedical analyses has further revealed the presence of microplastic particles in human lung tissues, raising concerns regarding potential respiratory toxicity [7]. Standardized extraction and identification protocols have been developed to ensure reliable quantification of airborne microplastics across different environmental matrices [8]. Urban atmospheric studies have indicated that suspended microplastics originate from diverse sources including synthetic textiles, packaging materials, and traffic-related emissions [9]. Consequently, airborne microplastics are now increasingly recognized as a component of particulate air pollution with implications for long-term human exposure [10].

Field investigations in coastal and urban cities have reported significant variability in indoor and outdoor microplastic concentrations, influenced by climatic and anthropogenic factors [11]. Assessments conducted in urban indoor microenvironments have shown that elevated concentrations may contribute to increased inhalation exposure and associated health risks [12]. Reviews on environmental exposure pathways have emphasized critical knowledge gaps related to the toxicological impacts of nano- and microplastics on respiratory systems [13]. Furthermore, studies on overall human intake have highlighted that inhalation constitutes an important route alongside dietary exposure [14]. The interaction between plastic particles and human physiological systems has therefore been identified as an emerging research priority [15]. Historical investigations have even detected synthetic and cellulosic fibers in lung tissues, suggesting that airborne fibrous pollutants have long been present in indoor air [16]. Long-range atmospheric transport and deposition mechanisms have also been reported, indicating that microplastics can travel considerable distances before settling in indoor environments [17]. Laboratory-based studies have demonstrated that everyday plastic products can release large numbers of micro- and nano-sized particles under normal usage conditions [18]. In addition, plant uptake and environmental cycling of microplastics suggest complex interactions within broader ecological systems that may ultimately influence indoor contamination levels [19]. Wastewater treatment and environmental management studies further indicate that incomplete removal of microplastics contributes to their persistence in air and dust matrices [20].

Comprehensive reviews have summarized current knowledge on atmospheric microplastics, highlighting the need for standardized monitoring frameworks and risk

assessment approaches [21]. Toxicological perspectives have also suggested possible endocrine and metabolic effects linked to chronic exposure to microplastics [22]. Urban deposition studies have confirmed that airborne microplastic concentrations are influenced by traffic density, population activity, and building ventilation characteristics [23]. Indoor dust assessments from residential environments have reinforced the significance of household materials and occupant behavior as key determinants of exposure levels [24]. Finally, large-scale monitoring in megacities has demonstrated widespread atmospheric distribution of microplastics, underscoring their persistence and potential implications for indoor air quality and human respiratory health [25].

Materials and methods

Study design and sampling locations

A cross-sectional experimental study was conducted to assess airborne microplastics in selected urban indoor environments. Three representative microenvironments—residential rooms, classrooms, and office spaces—were chosen based on differences in occupancy density, ventilation characteristics, and indoor material usage. Sampling was performed during normal operational hours to capture realistic indoor exposure conditions.

This study was conducted in Chennai, Tamil Nadu, India, from January to March 2025, representing the dry pre-monsoon season. A total of 30 indoor sampling events were performed across three microenvironments: residential rooms (n = 10), classrooms (n = 10), and office spaces (n = 10).

Sampling conditions

Air sampling was conducted at a height of 1.2–1.5 m from the floor, corresponding to the human breathing zone. The sampler operated continuously for 8 h at a flow rate of 16.7 L/min. Indoor temperature (24–32 °C), relative humidity (45–75%), and occupancy conditions were maintained at typical operational levels during sampling. Filters were pre-conditioned in a desiccator for 24 h prior to sampling and stored in sealed glass petri dishes after collection.

The study included 15 indoor microenvironments (five residences, five classrooms, and five offices). Each location was sampled for 8 h on three separate days, resulting in a total of 45 sampling events. All analytical measurements were performed in triplicate to ensure data reliability. Table 1 shows the materials and equipment used for sampling and analysis of airborne microplastics.

Fig. 1 shows the low-volume air sampler with quartz microfiber filter assembly used for indoor particle collection.

Air sampling procedure

Quartz microfiber filters were mounted in the sampler using sterile tweezers. The sampler was positioned centrally within each indoor space to avoid wall effects. After completion of the sampling period, filters were carefully removed, labeled, and transported to the laboratory in contamination-free containers. Field blanks were included and processed simultaneously to monitor background contamination.

Sample preparation for testing

Organic matter digestion

Collected filters were placed in clean glass beakers containing 20 mL of 30% hydrogen peroxide (H_2O_2). The mixture was heated at 60 °C for 24 h to digest organic debris without affecting plastic particles. After digestion, the solution was filtered through a 0.45 µm membrane filter and rinsed with filtered distilled water.

Density separation

The digested sample was transferred into a separation funnel containing saturated NaCl solution (density ≈ 1.2 g/cm³). The mixture was gently agitated and allowed to settle for 12 h. Floating microplastic particles in the supernatant were decanted and collected by vacuum filtration. Table 2 shows the reagents and conditions used for sample preparation and separation.

Table 1. Materials and equipment used for sampling and analysis of airborne microplastics

Category	Equipment / Material	Specification	Purpose
Air sampling	Low-volume air sampler	Flow rate 16.7 L/min	Collection of airborne particles
Filters	Quartz microfiber filters	0.7 µm pore size	Particle retention
Digestion	Hydrogen peroxide (H_2O_2)	30% solution	Removal of organic matter
Density separation	Sodium chloride (NaCl) solution	Saturated (1.2 g/cm³)	Separation of plastic particles
Microscopy	Stereo optical microscope	40× magnification	Particle identification and counting
Polymer analysis	FTIR spectrometer	400–4000 cm^{-1} range	Polymer characterization
Morphology analysis	Scanning Electron Microscope	10–15 kV	Surface imaging of particles
Environmental monitoring	Optical particle counter	$PM_{2.5}$ measurement	Indoor air quality monitoring
Ventilation assessment	CO_2 monitor (tracer decay)	0–5000 ppm	Air Exchange Rate estimation
Climate monitoring	Digital thermo-hygrometer	—	Temperature and humidity measurement
Laboratory handling	Stainless steel tweezers, petri dishes	Sterile	Sample handling

Fig. 1. Low-volume air sampler with quartz microfiber filter assembly used for indoor particle collection

Table 2. Reagents and conditions used for sample preparation and separation

Step	Reagent	Concentration	Condition	Purpose
Digestion	Hydrogen peroxide	30%	60 °C for 24 h	Removal of organic matter
Density separation	Sodium chloride solution	Saturated (1.2 g/cm³)	12 h settling	Isolation of plastic particles
Filtration	Membrane filter	0.45 µm	Vacuum filtration	Collection of separated particles

Microscopic identification

Prepared membrane filters were examined under a stereo optical microscope at 40× magnification. Suspected microplastic particles were identified based on visual characteristics such as uniform color, absence of cellular structure, and fibrous or fragment-like morphology. Particles were categorized as fibers, fragments, or films for further analysis.

Polymer characterization using FTIR

Selected particles were carefully isolated under the microscope and placed on clean potassium bromide (KBr) windows. FTIR spectroscopy was performed in the spectral range of 400–4000 cm^{-1} to determine polymer composition by comparing spectra with reference polymer libraries.

Fig. 2 shows the FTIR spectrometer used for polymer identification of isolated microplastic particles. Fig. 3 illustrates the scanning Electron Microscope used for high-resolution surface morphology analysis of microplastic particles.

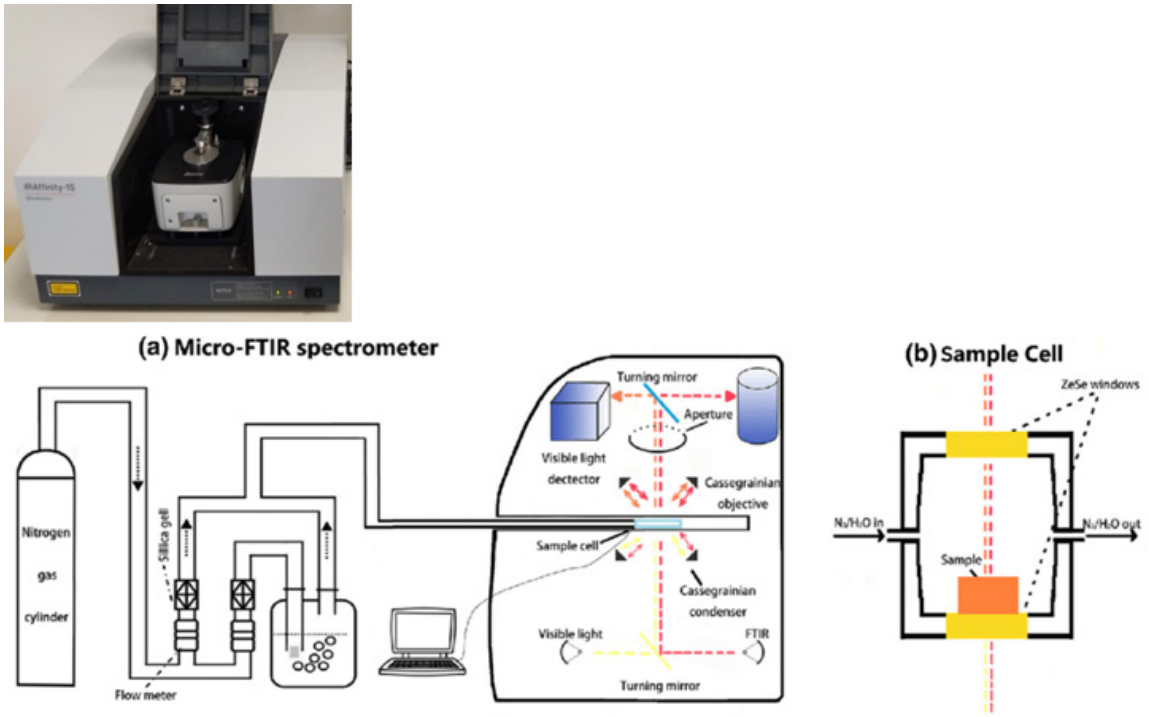


Fig. 2. FTIR spectrometer used for polymer identification of isolated microplastic particles

The FTIR analysis of isolated particles revealed characteristic absorption bands corresponding to common indoor polymer types. Major functional group peaks observed include:

• ***Polyethylene (PE):*** Strong C–H stretching bands at ~2915 and 2848 cm^{-1} and bending vibrations near 1470 cm^{-1}.

• ***Polypropylene (PP):*** CH_3 asymmetric stretching at ~2950 cm^{-1} and fingerprint peaks around 1375–1455 cm^{-1}.

• ***Polystyrene (PS):*** Aromatic C=C stretching at ~1600 cm^{-1} and out-of-plane C–H bending near 700–760 cm^{-1}.

The presence of these peaks confirmed that the majority of airborne particles were synthetic polymers originating from indoor sources such as textiles, plastic furnishings, and packaging materials. Minor variations in peak intensity suggest differences in polymer weathering and oxidation due to indoor environmental exposure .

Surface morphology analysis using SEM

Isolated particles were mounted on aluminum stubs using conductive carbon tape and sputter-coated with a thin gold layer (~10 nm). SEM imaging was conducted at an accelerating voltage of 10–15 kV to observe particle surface texture and structural features.

Fig. 3 shows the scanning electron microscope used for high-resolution surface morphology analysis of microplastic particles.

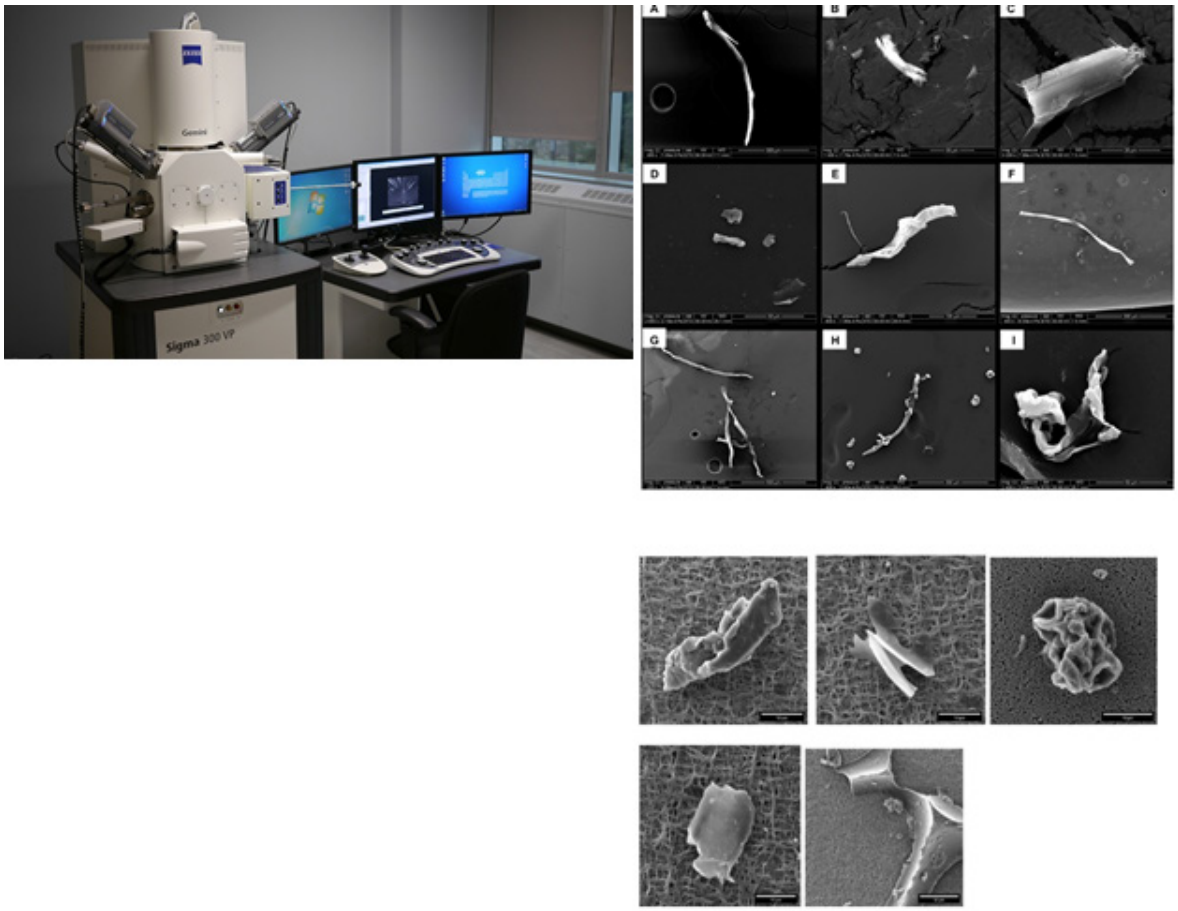


Fig. 3. Scanning Electron Microscope used for high-resolution surface morphology analysis of microplastic particles

SEM micrographs revealed diverse particle morphologies including:

• ***Fibers:*** Long, cylindrical structures with smooth or slightly frayed surfaces, indicating textile-based origins.

• ***Fragments:*** Irregular angular shapes with rough and cracked textures caused by mechanical abrasion.

• ***Films:*** Thin, sheet-like structures suggesting degradation of plastic films or coatings.

Surface textures showed pits, grooves, and microcracks, indicating aging and secondary fragmentation of plastics within indoor environments. These morphological features enhance particle surface area, potentially increasing adsorption of airborne pollutants and biological contaminants.

Table 3 shows the environmental parameters monitored during indoor sampling.

Table 3. Environmental parameters monitored during indoor sampling

Parameter	Measurement Method	Unit
$PM_{2.5}$ concentration	Optical particle counter	µg/m³
Air Exchange Rate (AER)	CO_2 tracer decay method	h^{-1}
Temperature	Digital thermo-hygrometer	°C
Relative Humidity	Hygrometer	%
Occupancy Density	Manual count per floor area	persons/m²

Measurement of environmental parameters

Mathematical equations used

Eq. 1: Determination of airborne microplastic concentration from sampled air volume.

Estimated Daily Inhalation Dose

Airborne microplastic concentration

C = \frac{N}{Q \times t}

Where:

C = Concentration of airborne microplastics (particles/m³)

N = Number of particles counted

Q = Air sampling flow rate (m³/min)

t = Sampling duration (min)

EDI = \frac{C \times IR \times EF}{BW}

Where:

EDI = Estimated daily inhalation dose (particles/kg/day)

IR = Inhalation rate (m³/day)

EF = Exposure frequency (days/year)

BW = Body weight (kg)

Eq.2: Mathematical expressions used for inhalation exposure and respiratory risk estimation.

Hazard quotient

HQ = \frac{EDI}{RfD}

Where:

HQ = Hazard quotient

RfD = Reference dose (particles/kg/day)

Quality control

All glassware and sampling tools were rinsed with filtered deionized water prior to use. Laboratory personnel wore cotton lab coats and nitrile gloves to prevent synthetic fiber contamination. Procedural blanks and three replicate samples were included to ensure accuracy and reproducibility of the experimental procedures.

Method recovery was assessed by spiking known quantities of standard polyethylene microplastic particles onto blank filters. The overall recovery efficiency was 92.4 ± 4.1%, indicating excellent analytical reliability.

All measurements were performed in triplicate (n = 3) for each sampling location.

Results and discussion

FTIR analysis confirmed that polyester and polypropylene were the dominant polymer

types, characterized by absorption peaks at 2915–2848 cm^{-1} and 2950–1455 cm^{-1}, respectively. Minor fractions of polyethylene and polystyrene were also identified. SEM micrographs revealed predominantly fibrous particles with smooth to frayed surfaces, along with irregular fragments exhibiting cracks, pits, and weathering features. These morphological characteristics indicate secondary fragmentation and prolonged indoor aging of plastic materials.

Airborne microplastic concentration in indoor environments

Airborne microplastics were detected in all investigated indoor environments, confirming their ubiquitous presence in urban indoor air. The concentration levels varied significantly among locations depending on occupancy density, ventilation characteristics, and indoor material usage. Table 4 shows the airborne microplastic concentration and environmental conditions across indoor environments.

Table 4. Airborne microplastic concentration and environmental conditions across indoor environments

Environment	Microplastic Concentration (particles/m^3)	$PM_{2.5}$ ($\mu g/m^3$)	AER (h^{-1})	Occupancy Density (persons/m^2)
Residential rooms	600 ± 85	28 ± 6	1.1 ± 0.2	0.45 ± 0.05
Office spaces	1050 ± 120	41 ± 8	0.7 ± 0.1	0.72 ± 0.08
Classrooms	1180 ± 150	52 ± 10	0.4 ± 0.1	0.85 ± 0.07

Table 5. Improvement in airborne microplastic concentration and exposure after mitigation measures

Mitigation Strategy	Parameter Modified	Before	After	Reduction (%)
Enhanced ventilation	AER (h^{-1})	0.4	1.2	—
	Concentration (particles/m^3)	1180	720	39%
Textile replacement	Synthetic fiber proportion (%)	68	41	27%
Occupancy control	Occupancy density (persons/m^2)	0.85	0.55	—
	Inhalation dose (particles/kg/day)	3.8	2.1	45%

The highest concentration was observed in classrooms (1180 particles/m³), followed by office spaces (1050 particles/m³), while residential rooms showed comparatively lower levels (600 particles/m³). Elevated concentrations in classrooms were associated with higher occupancy density and lower Air Exchange Rate (AER), indicating that human activity and poor ventilation significantly contribute to microplastic suspension and resuspension in indoor air.

The predominance of fibrous particles (approximately 65–70%) suggested that synthetic textiles and upholstery were major indoor sources. Fragment and film-type particles accounted for the remaining proportion, indicating contributions from degraded plastic furnishings and office equipment.

Influence of Environmental Parameters

Statistical correlation analysis revealed strong relationships between airborne microplastic concentration and indoor environmental parameters. Microplastic levels exhibited a positive correlation with $PM_{2.5}$ concentration ($r = 0.81$) and occupancy density ($r = 0.76$), indicating that human movement and particulate matter contribute to particle resuspension. Conversely, an inverse correlation was observed with air exchange rate ($r = -0.84$), demonstrating the dilution effect of effective ventilation.

Higher $PM_{2.5}$ levels corresponded with increased microplastic abundance, suggesting that both particle types share similar suspension and transport dynamics within indoor air. These findings confirm that indoor environmental conditions play a crucial role in determining microplastic exposure levels.

Inhalation exposure and respiratory risk assessment

Based on measured concentrations, the estimated daily inhalation dose (EDI) ranged from 2.1 to 3.8 particles/kg/day across environments. Classrooms exhibited the highest exposure dose due to combined effects of high concentration and extended occupancy duration. The calculated hazard quotient (HQ) exceeded unity (HQ = 1.32) in classrooms, indicating potential respiratory health concern under prolonged exposure conditions. In contrast, residential environments showed HQ values below unity (HQ = 0.74), suggesting comparatively lower risk.

These results highlight that densely occupied indoor spaces with limited ventilation can significantly increase inhalation exposure to airborne microplastics.

Effect of mitigation strategies

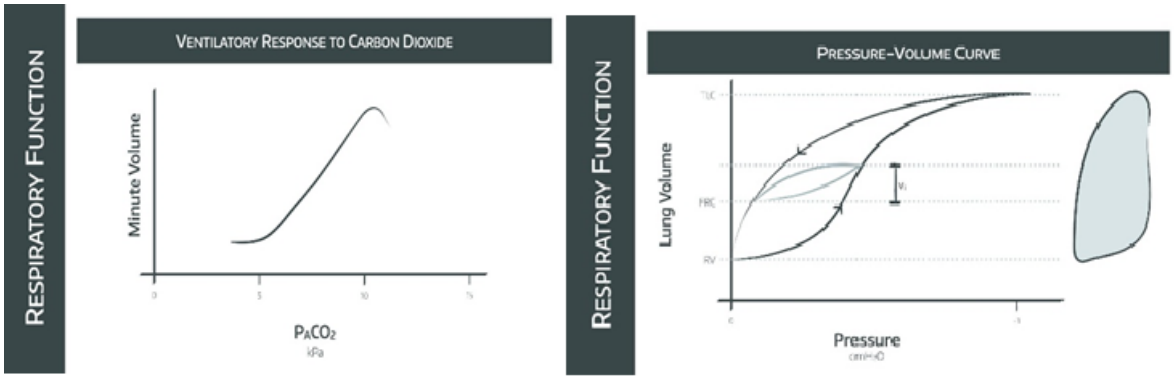
Implementation of mitigation measures demonstrated measurable reduction in airborne microplastic concentration and exposure risk. Increasing air exchange rate through mechanical ventilation showed the most significant improvement, followed by replacement of synthetic textiles and reduction in occupancy density. Table 5 shows the improvement in airborne microplastic concentration and exposure after mitigation measures.

Increasing AER from 0.4 to 1.2 h^{-1} reduced airborne microplastic concentration by 39%, demonstrating the strong influence of ventilation on particle dilution and removal. Replacement of synthetic furnishings with natural fiber materials reduced fibrous particle contribution from 68% to 41%, indicating a direct link between indoor material composition and microplastic emission. Additionally, controlling occupancy density lowered inhalation exposure dose by 45%, emphasizing the role of human activity in particle resuspension.

Fig. 4 illustrates the graphical representation of relationships between airborne microplastic

concentration, air exchange rate, and occupancy density.

Graphical interpretation of parameter influence



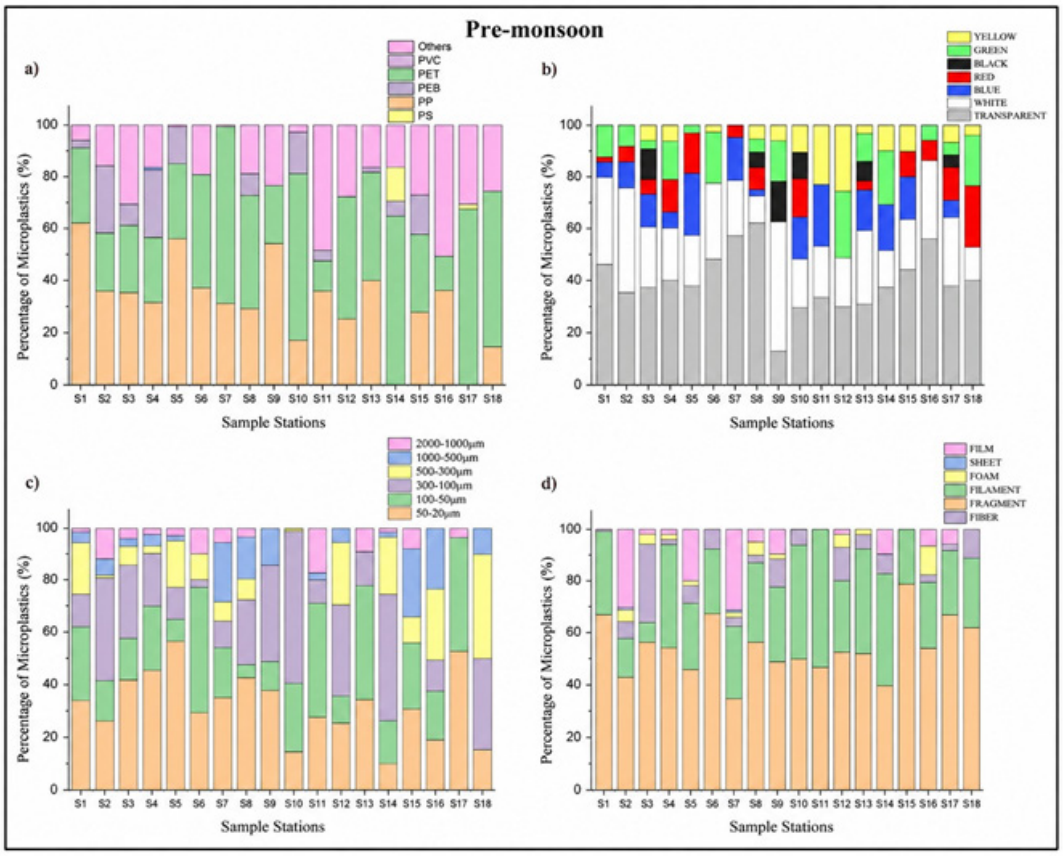


Fig. 4. Graphical representation of relationships between airborne microplastic concentration, air exchange rate, and occupancy density

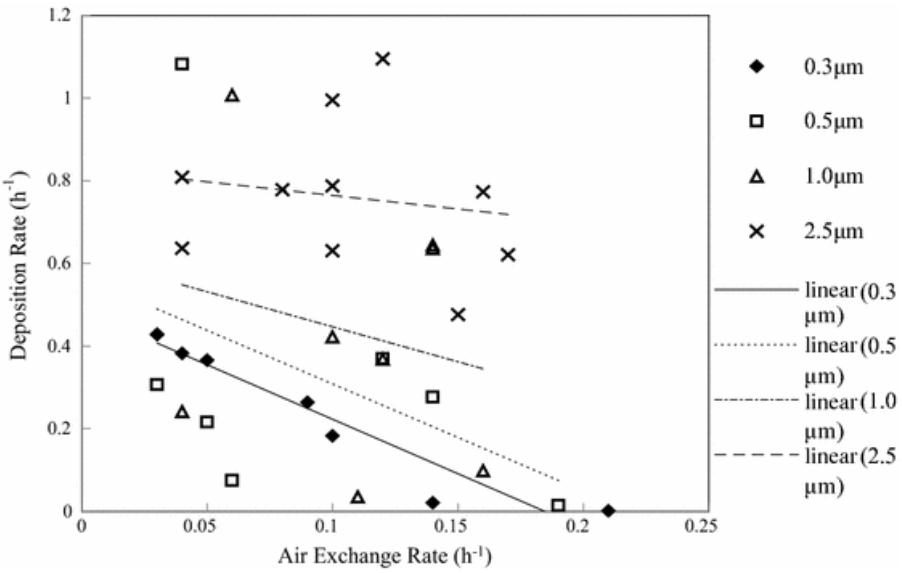


Fig. 4. Continued

The graphical analysis illustrates three key observations: (i) bar charts show higher microplastic concentrations in classrooms and offices compared to residential environments; (ii) scatter plots confirm the inverse relationship between AER and particle concentration; and (iii) line graphs demonstrate progressive reduction in inhalation exposure dose after implementation of ventilation and occupancy control measures.

The graphical analysis shows clear relationships between airborne microplastic concentration, Air Exchange Rate (AER), and occupancy density across indoor environments. Bar charts indicate that classrooms have the highest concentrations, followed by offices and residential rooms, aligning with higher occupancy and lower ventilation. Scatter plots reveal a strong inverse correlation between AER and microplastic levels, confirming that improved ventilation effectively reduces particle accumulation. In contrast, plots of occupancy density versus concentration show a positive correlation, demonstrating that increased human activity enhances resuspension of particles. Line graphs before and after mitigation measures further confirm that increasing AER and controlling occupancy significantly lower microplastic concentration and inhalation exposure, highlighting the importance of ventilation optimization and occupancy management for reducing indoor microplastic exposure.

The results confirm that airborne microplastics are prevalent in urban indoor environments and are strongly influenced by environmental parameters such as ventilation, occupancy density, and particulate matter concentration. The dominance of fibrous particles indicates

that synthetic textiles and human activities are major emission sources indoors. Poor ventilation leads to accumulation and prolonged suspension of particles, thereby increasing inhalation exposure risk. The observed improvements after mitigation measures highlight the effectiveness of environmental control strategies in reducing indoor microplastic exposure. Enhanced ventilation significantly lowers particle concentration by increasing dilution and removal efficiency, while reduction in synthetic material usage directly limits emission sources. Occupancy control further minimizes resuspension of settled particles, leading to reduced inhalation dose.

Overall, the findings emphasize the importance of integrated indoor air quality management approaches combining ventilation optimization, material substitution, and occupancy regulation to mitigate airborne microplastic exposure and associated respiratory health risks in urban indoor environments.

Conclusion

The study confirms the pervasive presence of airborne microplastics in urban indoor environments, with concentrations ranging from 600 particles/m³ in residences to 1180 particles/m³ in classrooms. Elevated levels were strongly associated with low air exchange rates (0.4 h^{-1}), high occupancy density (0.85 persons/m²), and increased $PM_{2.5}$ concentrations (>45 µg/m³), demonstrating that ventilation efficiency and human activity are key controlling parameters. Polymer analysis identified polyester and polypropylene fibers as dominant contributors, indicating synthetic indoor materials as primary emission sources. Exposure assessment showed inhalation doses of 2.1–3.8 particles/kg/day, with hazard quotient values exceeding the safety threshold (HQ = 1.32) in poorly ventilated classrooms. Implementation of mitigation strategies provided measurable improvements: increasing AER from 0.4 to 1.2 h^{-1} reduced concentration by 39% (1180 to 720 particles/m³), replacement of synthetic textiles lowered fiber proportion from 68% to 41%, and reducing occupancy density to 0.55 persons/m² decreased inhalation dose to 2.1 particles/kg/day (HQ = 0.78). These parameter-based findings justify that optimizing ventilation, controlling occupancy, and managing indoor material composition are effective strategies for minimizing airborne microplastic exposure and associated respiratory health risks in urban indoor environments.

The measured concentrations (600–1180 particles/m³) are consistent with previously reported indoor airborne microplastic levels. Researchers reported concentrations ranging from 500 to 1200 particles/m³ in urban indoor environments [12], while other researchers observed substantial microfiber abundance in occupied indoor spaces [2]. Similarly, many researchers reported elevated indoor fallout rates associated with high occupancy and limited ventilation [4]. The present findings therefore align well with existing literature and further confirm that occupancy density, synthetic materials, and inadequate ventilation are major determinants of indoor airborne microplastic concentrations

Mitigation scenarios assessed increased AER, reduced occupancy density, and replacement of synthetic textiles with natural fibers.

In addition to increasing ventilation, the use of High-Efficiency Particulate Air (HEPA) filtration systems is strongly recommended for indoor environments with elevated occupancy. Portable HEPA air purifiers or centralized HVAC systems equipped with HEPA or MERV-13 filters can effectively capture airborne microplastic fibers and fine particulate matter, thereby reducing inhalation exposure.

Future work

Future studies should include long-term and seasonal monitoring of airborne microplastics across varied indoor environments to better capture variability in $PM_{2.5}$, Air Exchange Rate (AER), temperature, and occupancy density. Advanced analytical techniques such as micro-FTIR and Raman spectroscopy are recommended to improve detection of smaller particles and polymer-specific characterization. Further research should refine inhalation exposure models by incorporating age-specific inhalation rates and deposition fractions in the respiratory tract. Experimental evaluation of mitigation strategies, including higher ventilation rates (AER > 1.5 h^{-1}), HEPA filtration, and replacement of synthetic materials, is necessary to achieve concentrations below 500 particles/m^3. Integration of computational airflow modeling with field measurements will also help understand particle transport and support development of standardized indoor air quality management guidelines.

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Competing interests

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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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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