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Microplastics in The Atmosphere and Their Interaction with Biological Systems Through Systematic Literature and Scoping Reviews

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Abstract

Microplastics in the biosphere have emerged as a pressing environmental and public health concern owing to their widespread occurrence and interactions with biological systems. This systematic review investigates the occurrence, transmission mechanisms, and health implications of airborne microplastics. The study applies the PRISMA framework and advanced search strategies in Scopus and Web of Science, resulting in the selection of 35 primary studies. These studies were synthesised into three thematic categories: (i) Characterisation of Microplastics in Various Environments, (ii) Airborne Transmission and Aerosolisation Mechanisms, and (iii) Health Implications and Biological Interactions. The first theme highlights the widespread distribution and diversity of microplastics, particularly fibres and fragments, across indoor and outdoor environments. The second theme examines the pathways through which microplastics become airborne, with a focus on the influence of environmental factors such as wind, humidity, and human activities on their dispersion. The third theme explores the potential health consequences of inhaled microplastics, including respiratory complications and their interactions with microbial communities. This review underscores the critical need for robust monitoring systems, stricter regulatory measures, and heightened public awareness to address the escalating risks posed by airborne microplastic pollution. The findings call for interdisciplinary research to better understand the dynamics of microplastics in the atmosphere and to develop effective mitigation strategies to safeguard ecosystems and human health.

1. Introduction

Microplastics (MPs) have emerged as a significant environmental pollutant, posing potential risks to ecosystems and human health. These small plastic particles, often less than 5 mm in size, have been detected in various environmental matrices, including water, soil, sediment, and even the atmosphere [1]-[4]. While much of the early research focused on their abundance in marine and freshwater environments, the atmosphere has recently become a significant pathway for MP transport, sinks, and exposure. The pervasive nature of MPs necessitates the development of robust and standardised methods for their extraction and analysis across diverse filter matrices. The extraction of MPs from complex environmental matrices presents several challenges due to the heterogeneous nature of these samples. Various methods have been developed and optimised to address these challenges, including density separation, chemical digestion, and filtration techniques [4]-[7]. For instance, Fenton's reagent has been identified as an effective protocol for removing organic material from complex matrices without degrading the MPs, thereby enhancing the accuracy of subsequent analyses. Similarly, optimised density-based approaches have been shown to improve the extraction efficiency of MPs from soil and sediment samples. In addition to the extraction methods, the identification and quantification of MPs require precise analytical techniques. Pyrolysis-gas chromatography-mass spectrometry (Py-GC/MS) and Raman spectrometry are commonly used to characterise the polymer types and morphologies of extracted MPs [8]. Compelling evidence highlights the prevalence of MPs indoors and outdoors, with concentrations often exceeding those outdoors. Factors such as human occupancy, furnishings and air ventilation act as reservoirs and secondary sources of MPs indoors. Thus, this raises concerns about prolonged human exposure, particularly through inhalation and digestion. Due to their smaller size, they can bypass the body's primary defence mechanisms and reach the lower respiratory tract, potentially serving as carriers of chemical additives or microbes that hitch rides on their surfaces [9]. Given their implications for human health, there is an urgent need for a comprehensive review that brings together current findings on MP sources and sinks, transport mechanisms, and environmental risks. This paper aims to review the presence of MPs in the biosphere, their sources and sink mechanisms, and to analyse methods for their detection and polymeric identification from diverse filter matrices. By addressing these, this study seeks to draw conclusions and recommendations for mitigating and controlling MP pollution, and for understanding the health implications and environmental risks it poses.

2. Literature Review

The extraction of atmospheric microplastics (MPs) from diverse filter matrices is a critical area of research due to the widespread presence of these pollutants and their potential ecological and health impacts. Various methods have been developed to isolate MPs from complex environmental matrices, each with its own set of advantages and limitations. For instance, a comprehensive review of extraction methods highlights the need for simple, rapid, low-cost, sensitive, and selective analytical techniques to effectively identify MPs in different environmental compartments [10]. The harmonisation of these methods is essential to ensure reproducibility and comparability of data across studies, as emphasised by the need for standardised protocols [11]. Additionally, the use of specific reagents, such as Fenton's reagent, has been validated for its efficiency in removing organic material from complex matrices, such as sludge and soil, thereby facilitating the extraction of MPs. Various filter materials, such as polycarbonate, nylon, and glass fibre, have been employed for capturing airborne MPs. Polycarbonate filters, known for their smooth surface and durability, are commonly used but can exhibit high fluorescence backgrounds that complicate analysis. Innovations such as aluminium coating have been introduced to mitigate these issues, thereby enhancing the accuracy of subsequent analyses using techniques such as micro-Raman spectroscopy [7], [10], [12].

Comparative analyses of different extraction solutions and isolation methods have shown varying efficiencies depending on the polymer type and matrix. For instance, density separation using solutions like NaI has been identified as the most effective method for extracting dense polymers such as polyethene terephthalate (PET), polyethersulfone (PES), and polyamide (PA), achieving extraction efficiencies of up to 71% from sediment matrices, although no single protocol has proven robust for all types and forms of MPs [13]. Sequential isolation techniques, such as membrane filtration followed by cloud-point extraction, have also been developed to isolate MPs and nanoplastics (NPs) from environmental waters separately, demonstrating high recovery rates and low detection limits [6]. Optimised density-based approaches, which use saturated NaCl and NaI solutions, have further improved the accuracy and precision of MP extraction from soil and sediment samples [5].

The extraction of MPs from biological samples, such as seafood, requires protocols that efficiently digest organic matter without degrading the plastic polymers. Studies have shown that a 10% KOH solution, incubated at 60°C for 24 hours, is effective at digesting biological tissues while preserving the integrity of most plastic polymers [1]. The presence of MPs in the atmosphere, including urban and remote areas, underscores the need for standardised sampling and identification methods to better understand their distribution and potential health impacts [14]. Advanced methodologies, such as tetramethylammonium hydroxide digestion combined with dichloromethane dissolution, have been developed to extract small MPs and NPs embedded in solid matrices, offering promising approaches for evaluating MP pollution [15]. These diverse approaches collectively contribute to the ongoing efforts to mitigate MP pollution and enhance our understanding of their environmental and health implications. The extraction and identification of microplastics from air samples involve several methodologies, each with its own set of advantages and limitations. A critical aspect of these methodologies is the choice of filter media, which significantly impacts the efficiency and accuracy of microplastic detection. Various studies have evaluated filter media, including quartz, polytetrafluoroethylene (PTFE), alumina, cellulose, and silver membrane filters, for microplastic extraction from air samples.

Quartz and PTFE filters are commonly used in air quality monitoring due to their high thermal stability and chemical resistance. However, these filters present challenges in microplastic detection. For instance, microplastics are not visibly detectable against quartz filters and are spectroscopically undetectable against PTFE filters, making these media less effective for microplastic analysis [3]. Alumina-based filters also face similar issues, in which the detection of microplastics is hindered by the filter's properties. In contrast, cellulose filters, while enabling microplastic detection, tend to burn during analysis when contaminated with particulate matter, thereby complicating extraction. These limitations highlight the need to select appropriate filter media that enable accurate microplastic detection without compromising sample integrity. Silver membrane filters have shown the most promise in microplastic extraction from air samples. Studies have demonstrated that these filters achieve the highest detection intensities for microplastics, even in samples with high particulate matter contamination. The use of Raman spectral imaging (RSI) with silver membrane filters has been particularly effective, allowing for the identification of inhalable microplastics in ambient particulate matter samples. This method not only enhances the visibility of microplastics but also ensures their detection over extended sampling periods, making it a robust approach for air sample analysis. The effectiveness of silver membrane filters underscores the importance of selecting filter media that withstand analytical procedures and yield clear, reliable results.

In conclusion, the choice of filter media is crucial for the extraction and detection of microplastics from air samples. While quartz, PTFE, and alumina filters present significant challenges, cellulose filters offer some potential but are limited by their susceptibility to burning. Silver membrane filters, on the other hand, have proven highly effective, particularly when used in conjunction with advanced analytical techniques such as RSI. These findings suggest that future research and standardisation efforts should focus on optimising filter media selection to improve the accuracy and reliability of microplastic detection in air samples, thereby contributing to a better understanding of microplastic pollution and its potential health impacts.

3. Materials and Methods

3.1 Identification

This study employed essential stages of the systematic review process to compile a significant body of pertinent literature. The method commenced with the identification of keywords, succeeded by the exploration of associated terms through dictionaries, thesauri, encyclopedias, and previous research. All pertinent phrases were identified, and search strings were formulated for the Scopus and Web of Science (WoS) databases (see Table 1). The preliminary stage of the systematic review identified 187 relevant papers from the two databases related to the study issue.

Table 1 *The search string*

Scopus	TITLE-ABS-KEY (indoor AND (ambient OR atmospheric) AND microplastic*) AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2024)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (LANGUAGE , "English")) Date of Access: June 2024
WoS	indoor AND (ambient OR atmospheric) AND microplastic* (Topic) and Highly Cited Papers and 2024 or 2023 or 2022(Publication Years) and English (Languages) and Article (Document Types) Date of Access: June 2024

3.2 Screening

The screening process entails a meticulous evaluation of potentially relevant research items to identify those aligning with the predefined research question(s). The content-related criteria commonly applied during this phase focus on selecting studies based on the classification of ambient microplastics extraction across various filter matrices. Duplicate papers were systematically removed from the compiled list of publications retrieved through the search. Initially, 142 publications were excluded, and 43 papers were further analysed according to the specific inclusion and exclusion criteria outlined in this study (see Table 2). The primary focus was on research articles, as they provided the main source of practical insights. Other types of publications, including reviews, meta-syntheses, meta-analyses, books, book series, chapters, and conference proceedings, were excluded. The review was restricted to English-language publications and focused on studies published between 2022 and 2024. Ultimately, two publications were excluded due to duplication.

Table 2 *The selection criterion is searching*

Criterion	Inclusion	Exclusion
Language	English	Non-English
Time line	2022 – 2024	< 2022
Literature type	Journal (Article)	Conference, Book, Review
Publication Stage	Final	In Press
Subject	Environmental Science, Pharmacology, Toxicology and Pharmaceutics, Chemistry, Earth and Planetary Sciences, Medicine, Chemical Engineering, Biochemistry, Genetics and Molecular Biology, and Materials Science	Besides Environmental Science, Pharmacology, Toxicology and Pharmaceutics, Chemistry, Earth and Planetary Sciences, Medicine, Chemical Engineering, Biochemistry, Genetics and Molecular Biology, and Materials Science

3.3 Eligibility

In the systematic review process, the final sample of research articles is determined after a rigorous application of predefined inclusion and exclusion criteria. It is essential to provide a comprehensive list of the research items that form the basis of the review findings to ensure transparency and reproducibility for the readers. Without this, the foundations of the review's conclusions would be unclear. In the third stage of the review process, the eligibility phase, 43 articles were initially shortlisted. These articles were further scrutinised by reviewing their titles and key content to verify their relevance to the study's objectives and ensure that they met the inclusion criteria. Through this detailed examination, 8 publications were excluded for various reasons, including being outside the scope of the research, having titles or abstracts that did not align with the study objectives, and, in some cases, the unavailability of full texts. As a result, a refined sample of 35 articles was finalised for further assessment and analysis (see Fig. 1 for an overview of the selection process). This systematic approach ensures that only the most pertinent and high-quality studies are included, enhancing the reliability and validity of the review's findings.

3.4 Data Abstraction and Analysis

In this study, an integrative analysis was employed as a primary assessment strategy to examine and synthesise various research designs, particularly those using quantitative methods. The aim was to identify key topics and subtopics relevant to the research objectives. The first step in theme development was data collection, in which the authors meticulously analysed 35 publications (as shown in Fig. 1) for content or assertions pertinent to the study's focus areas. The key findings extracted from those publications are summarised in Appendix 1. Following this, the authors reviewed significant existing research on the extraction of indoor and atmospheric/ambient microplastics. Both the methodologies and the findings from these studies were critically examined. The theme development process involved collaboration among the authors, who worked together to create themes based on the evidence gathered. A log was maintained throughout the data analysis phase to document key analyses, reflections, questions, and insights that emerged during data interpretation. This facilitated ongoing reflection and refinement of the themes. To ensure consistency and resolve any discrepancies in the theme development process, the authors compared their findings and discussed any differing viewpoints. The final themes were refined to maintain coherence and validity.

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Any inconsistencies or disagreements in the theme creation were addressed collaboratively by the authors. Adjustments were made based on expert feedback to enhance the precision and relevance of the themes. The expert review phase was crucial in confirming the clarity, significance, and appropriateness of each subtheme, thus ensuring a robust and comprehensive analysis. The questions are as follows:

i) How do the characteristics and concentration levels of airborne microplastics differ between urban and rural environments, and what factors influence their distribution in indoor and outdoor air?

ii) What are the health implications of human exposure to airborne microplastics, and how do these particles interact with microbial communities to facilitate pathogen transmission or respiratory conditions?

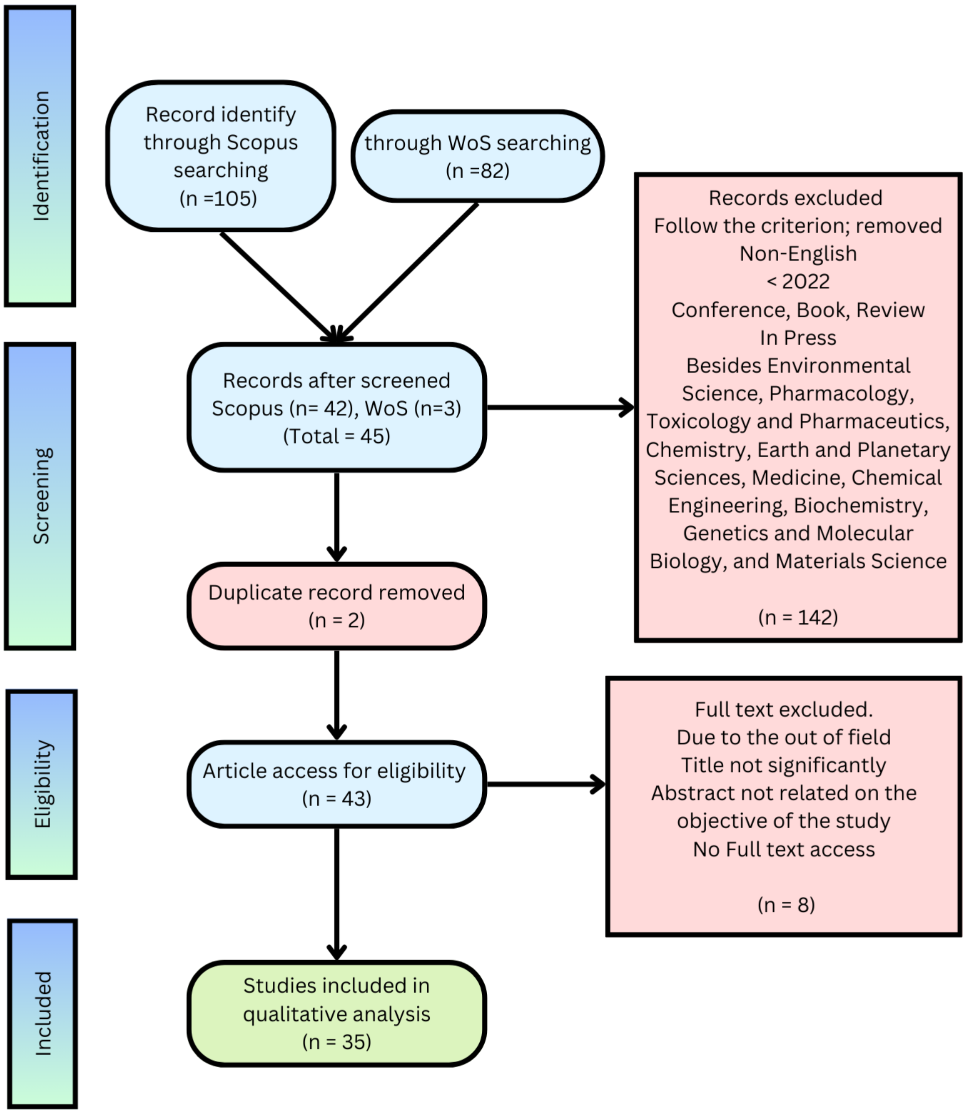

Fig. 1 *The PRISMA flow diagram of the entire procedure for selecting reviewed articles*

4. Result and Finding

The investigation into the presence, behaviour, and impact of microplastics in various environmental and biological systems has gained significant traction in recent years. With the growing recognition of the pervasiveness of microplastics, studies have focused on their characterisation, transport, and health implications. Research has consistently demonstrated that microplastics infiltrate air, water, and soil, with urban and industrial areas particularly affected. Indoor environments are emerging as significant reservoirs for microplastics, driven by human activity and ventilation systems. Understanding the pathways through which microplastics are generated, aerosolised, and transmitted is crucial for assessing their broader environmental and health impacts. This section provides a detailed analysis of the selected studies, categorised into three key themes, summarised from 35 publications listed in Appendix 1: (i) Characterisation of Microplastics in Various Environments, (ii) Airborne Transmission and Aerosolisation of Microplastics, and (iii) Health Implications [1]-[4]. While much of the early research focused on their abundance in marine and freshwater environments, the atmosphere has recently become a significant pathway for MP transport, sinks, and exposure. The pervasive nature of MPs necessitates the development of robust and standardised methods for their extraction and analysis across diverse filter matrices. The extraction of MPs from complex environmental matrices presents several challenges due to the heterogeneous nature of these samples. Various methods have been developed [16]-[19] with sizes often ranging from 10 to 75 μm, likely due to poor ventilation and the presence of synthetic materials. However, a few studies have found that the concentration of outdoor MP fallout is higher than that indoors, indicating a uniform vertical profile [20], [21]. This is possibly because lightweight MPs dominate indoor environments and are predominantly suspended and resuspended in the atmosphere. The deposition rates of MPs vary significantly across environments. In Barranquilla, Colombia, the MP deposition rates ranged from 1.2×10^3 to 1.1×10^4 MP/m²/day [22]. In homes, deposition rates ranged from 15.6 to 93.3 MP/m³, in public transportation from 5.8 to 17.3 MP/m², and in university rooms from 58 to 684 MP/m³. Choi et al. [23] conducted an extensive analysis of microplastics in urban and rural air samples, revealing marked variation in microplastic concentrations by geographic location. Urban areas consistently showed higher concentrations due to dense human activities, transportation, and industrialisation [8], [16], [20]-[22], [24]-[32], underscoring the anthropogenic influence on environmental pollution. Similarly, Yao et al. [25] reported comparable results, highlighting that population density and industrial zones contribute to elevated airborne microplastic levels.

Regarding the methodologies employed to characterise microplastics, several studies used advanced analytical techniques to identify microplastic particles by size, shape, and polymer type. Bhat [26] used high-resolution imaging to classify microplastics and noted a prevalence of smaller, inhalable particles in indoor environments. Indoor environments may serve as significant reservoirs for microplastics, particularly in densely populated regions, with contributions from household textiles, plastic-based furniture, flooring, electronic devices, and building materials [16], [27]. Moreover, the variation in polymer composition across different settings has been highlighted, with fibres and fragments being the most common forms of microplastics detected. The presence of MPs in indoor and outdoor samples, their ranges, the polymers identified, and proposed sources from the extracted literature searches are listed in Table 3.

A common thread in the discussion sections of the reviewed studies is the acknowledgement of microplastics as a persistent environmental contaminant. Researchers have noted that microplastics have infiltrated every layer of the environment, from air to soil and water systems. Choi et al. [23] emphasised the long-term implications of microplastic accumulation, suggesting that, unless mitigated, microplastic pollution could become increasingly difficult to control. Torres-Agullo et al. [24] supported this claim, stressing the importance of developing effective monitoring and mitigation strategies to reduce microplastic pollution in urbanised areas. The pervasive nature of microplastics across environments presents significant challenges for environmental management and public health, a conclusion also echoed by Yao et al. [25].

Table 4 *Polymers identified and possible sources of microplastics (MPs) in air from various studies*

References	PE	PP	PET	PS	PVC	PA	PES	PU	PV	PTFE	PMMA	Others	Possible Sources
[16]	X			X		X	X		X			Polyurethanes	synthetic textiles, packaging, furnishings, and home appliances.
[17]	X	X		X									synthetic materials, packaging, indoor consumer products, and the degradation of plastic debris.
[18]	X	X	X				X						textiles, packaging, and consumer plastic products
19]	X		X	X	X	X							carpets, flooring materials, synthetic textiles, and household consumer items.
[20]		X			X					X		HDPE, PVA	filters, lab reagents, and procedural contamination
[22]							X						synthetic textiles, abrasion of household items, and consumer product packaging.
[23]	X	X	X	X									common household and industrial materials, with textiles and packaging being significant indoor contributors.
[24]		X				X	X						synthetic textiles, personal care products, packaging, and abrasion of consumer goods and materials.

References	PE	PP	PET	PS	PVC	PA	PES	PU	PV	PTFE	PMMA	Others	Possible Sources
[25]	X	X	X	X	X								plastic packaging, films, and synthetic textiles
[28]	X	X			X		X	X				phenolic resin, rubber, cotton	plastic films, synthetic textiles, and consumer products.
[29]			X				X					Rayon, Cellophane	synthetic textiles, packaging, and cellulose-based materials accumulating on and released from air conditioner (AC) filters.
[31]	X		X			X		X					synthetic textiles, furniture, packaging, and consumer household materials.
[32]	X		X	X						X			bottled water, indoor air, and exhaled breath, representing films, textiles, and consumer packaging residues.
[33]		X	X									Nylon Acrylic Cellophane Rayon	synthetic textiles, packaging, and household materials, suspended in indoor fallout and AC filter dust.
[34]	X	X		X	X								packaging, textiles, and consumer plastic products.
[35]	X	X	X	X	X	X				X		HDPE, PLA, PMP, PEO, EP, EDPM	synthetic textiles, packaging, furniture, sealants, and household items
[36]	X	X	X		X	X	X					PCTFE	carpets, synthetic textiles, furniture, flooring, and household plastic products.
[37]	X	X	X	X									synthetic textiles, packaging, disposable plastics, and weathered consumer products.
[38]				X									synthetic polymers, consumer plastics, and packaging materials in indoor dust.
[39]	X	X	X			X							packaging, synthetic textiles, and consumer goods suspended in ambient air across urban zones.
[40]		X	X		X	X	X	X			X	EVA	synthetic clothing, containers, toys, carpets, and curtains found in everyday households.
[42]			X									Cellulose fibers Cotton	synthetic textiles and plastic-based household items, accumulated in air-conditioner and computer filters over six months of indoor operation.
[43]		X	X									Nylon	textiles and synthetic fabrics, consistent with local and long-range sources via atmospheric transport.
[48]	X	X	X									Nylon	surgical equipment, plastic packaging, and single-use medical supplies.
[49]			X				X						synthetic textiles and indoor consumer products, with additional input from industrial zones and urban waste sources.

Notes: PE = Polyethylene; PP = Polypropylene; PET = Polyethylene terephthalate; PS = Polystyrene; PVC = Polyvinyl chloride; PA = Polyamide; PES = Polyester, PU = Polyurethane; PV = Polyvinyls; PTFE = Polytetrafluoroethylene; PMMA = Polymethyl methacrylate

4.2 Airborne Transmission and Aerosolisation of Microplastics

"Microplastics and nanoplastics" (MNPs) have increasingly been identified in the atmosphere, raising concerns about their potential for aerosolisation and airborne transmission. Lambert et al. [27] explored the mechanism of microplastic aerosolisation via sea spray, revealing that factors such as polymer type, size, and environmental conditions significantly affect the aerosolisation rate. MPs are expelled into the atmosphere, particularly in coastal regions, where wind and wave action facilitate the process. Coastal seawater resulted in higher aerosolised MPs concentrations, with denser polymers easily aerosolised compared to the lighter polymer due to sea surface micro-layer content. In sea spray aerosols (SSA), smaller particles are more strongly enriched than larger ones. Similarly, Xie et al. [28] focused on inhalable microplastics in the air, emphasising their ubiquity and the health risks posed by their small size, which allows them to penetrate deeply into the respiratory system. Their study reinforced the understanding that microplastics smaller than 10 microns are especially hazardous due to their prolonged airborne suspension and inhalation potential.

Chen et al. [29] highlighted the role of air conditioning systems in both trapping and redistributing microplastics within indoor environments. These systems, which are intended to filter out airborne contaminants, may paradoxically become sources of airborne microplastics when fibres that accumulate in the filters are re-released into the indoor air. The authors identified human activities and indoor ventilation systems as key factors contributing to the continuous circulation of microplastics, particularly in high-traffic indoor spaces. This finding aligns with research by Liu et al. [30], who examined the shapes of airborne microplastics and noted that fibrous particles are particularly likely to remain suspended in the air for extended periods. These studies collectively underscore the importance of understanding how mechanical and environmental factors contribute to the persistence of airborne microplastics.

The dynamic behaviour of microplastics in the atmosphere was further analysed through simulation models by Li et al. [8], who examined the processes of suspension and deposition in both urban and natural environments. The simulation results demonstrated that microplastics can remain suspended in the air for extended durations under certain atmospheric conditions, such as low wind speeds and high humidity. This prolonged suspension increases the likelihood of human exposure and environmental contamination, particularly in densely populated or industrial areas where microplastic emissions are higher. The findings also emphasise that human activities, including industrial processes and transportation, exacerbate the resuspension of microplastics into the air.

The various studies reviewed consistently highlight the complexity of airborne transmission and aerosolisation of microplastics. Lambert et al. [27] and Xie et al. [28] emphasised the environmental and mechanical factors that facilitate the release and suspension of microplastics, while Chen et al. [29], [30] and Liu et al. [33] pointed to indoor sources of microplastic redistribution. These findings suggest that effective control of airborne microplastics will require a multifaceted approach that addresses both outdoor and indoor sources and understands the environmental conditions that enhance their transmission through the atmosphere.

4.3 Health Implications and Biological Interactions of Microplastics

The health implications of microplastics, especially their interaction with biological systems, have been extensively studied in recent years. Cui et al. [31] explored the exposure risks associated with airborne microplastics and their interaction with bacteria in urban environments. The study revealed that indoor environments, particularly in densely populated areas, are significant reservoirs of microplastics that may carry pathogenic bacteria. This association between microplastics and bacteria raises concerns about an increased risk of respiratory diseases from inhalation exposure. MPs can attract and retain metal particles, potentially increasing the risk of exposure to these metals when inhaled [34]. Similarly, Chen et al. reported that dense biofilms (containing pathogenic bacteria) formed on microfibers from air conditioner filters, indicating that MPs can serve as carriers for harmful microorganisms [33]. This can pose potential health risks through inhalation via airborne vectors [31].

In terms of detection techniques, Zhang et al. [32] developed a multi-spectroscopy method to enhance the detection of microplastics in environmental and biological samples. This method enables the identification of microplastic particles in smaller sizes, particularly in the respiratory system. The advanced detection techniques highlighted the pervasive presence of MPs in the air and their ability to reach deeper parts of the lungs, further increasing the risk of respiratory complications. The researchers noted that the majority of the particles detected in their study were smaller than 10 microns, which aligns with the findings of Sheng et al. [20], who quantified polystyrene nanoplastics in the atmosphere. These smaller particles pose an even greater health risk because they can bypass the body's natural filtration systems. Studies have shown that infants and toddlers are particularly vulnerable to higher exposure levels than adults. Additionally, certain indoor activities, such as vacuuming and using air conditioning filters, can significantly affect the concentration of MPs in the air.

Several studies addressed the potential for contamination during the analysis of airborne microplastics. Bhat et al. [21] discussed how laboratory contamination might interfere with the accurate measurement of microplastic levels, especially when samples are collected from indoor environments. The researchers highlighted the need for stringent contamination control during sampling and analysis to ensure reliable results. This concern aligns with earlier studies, which also emphasised the need for standardised methodologies to minimise the risk of contamination during microplastic analysis.

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These studies consistently highlight the health concerns linked to prolonged exposure to airborne microplastics, particularly in indoor settings where individuals predominantly reside. Thus, further investigation into the potential health effects of breathing microplastics, especially those smaller than 10 microns, is urgent [16], [20], [31]. The interaction between microplastics and microbial communities adds another layer of complexity, as these particles may act as carriers of pathogens, increasing the risk of respiratory infections.

5. Discussion and Conclusion

Microplastic contamination in various environments has become an emerging issue, pervasive and poses significant threats to ecosystems and human health. Based on the literature searches conducted, three subthemes are most commonly discussed in the literature on atmospheric microplastics. The subthemes are sources and sinks of MPs, mechanisms of transport and distribution of MPs in the indoor and outdoor atmospheres and the role of MPs in air as vectors to other metallic and biological elements, which pose health risks to human is illustrated in Fig. 2. Previous studies conclude that urban areas experience significantly higher concentrations of microplastics compared to rural areas, primarily influenced by human activities and industrialization. Population density and variety of indoor and outdoor human activities are key factors influencing the variation in microplastic levels. Advanced analytical techniques have been employed to study microplastics by size, shape, and polymer type, with findings indicating that most indoor MPs are concentrated in smaller size fractions. To make matters worse, some studies suggest that indoor spaces often act as reservoirs for microplastics, posing a significant risk of human exposure. Fibres and fragments are commonly the most detected forms of microplastics, with their composition varying across different environments and human activities.

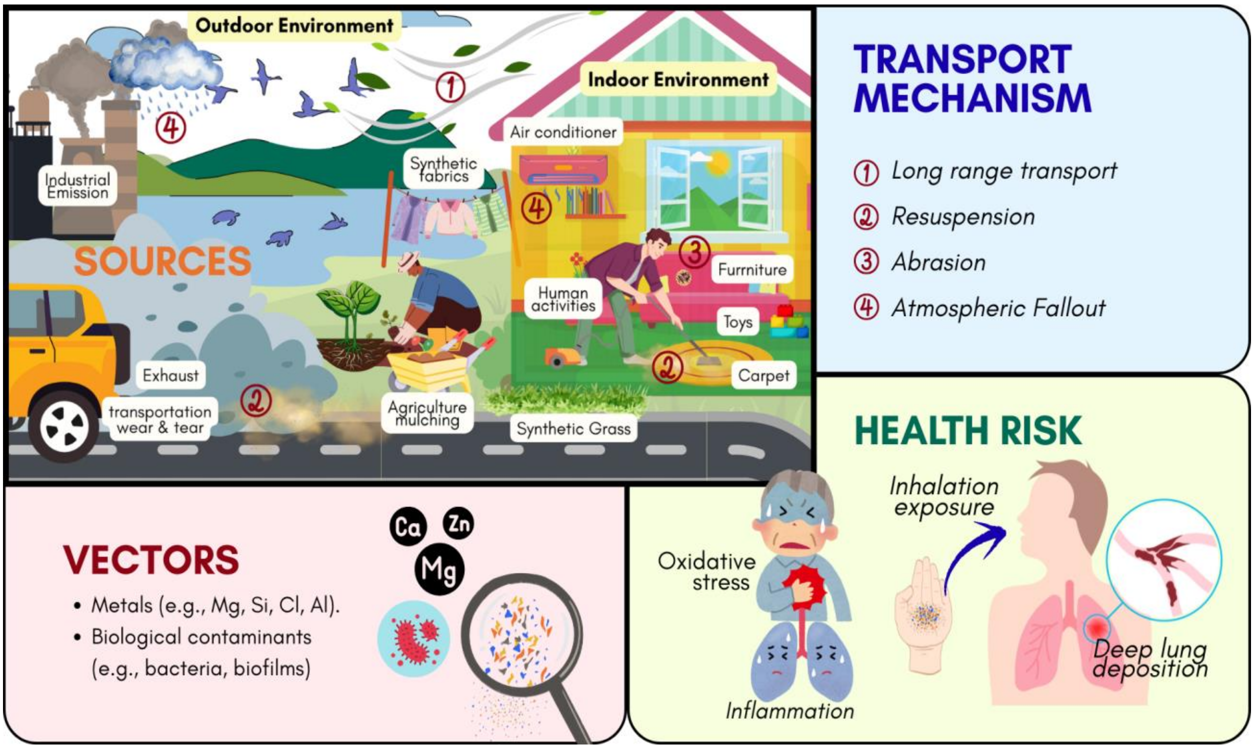

Fig. 2 *Sources, airborne transmission and health implications of microplastics in air*

Microplastics and nanoplastics have increasingly been detected in the atmosphere, raising concerns about their potential to become airborne and be transmitted through the air. Environmental factors such as wind, wave action, and atmospheric conditions significantly influence the aerosolisation of microplastics in coastal regions. Small particles, particularly those under 10 microns, pose notable health risks due to their prolonged airborne suspension and ability to penetrate deep into the respiratory system. Indoor environments also contribute to microplastic redistribution. Air conditioning systems, which are intended to filter contaminants, can inadvertently reintroduce fibres back into the air, particularly in high-traffic indoor spaces. Factors such as particle shape, especially fibrous forms, allow these microplastics to remain airborne for extended periods. Simulation models further show that microplastics can remain suspended in the atmosphere for extended periods under low-wind, high-humidity conditions, increasing the likelihood of human exposure, particularly in densely populated or industrial regions.

Recent studies have focused on the health implications of microplastics, particularly their interaction with biological systems. Airborne microplastics in urban environments, especially in densely populated indoor spaces, have been identified as significant reservoirs of these particles. The interaction between microplastics and bacteria poses a potential risk for respiratory diseases, as these particles may carry pathogens. The inhalation of fine particles, especially those smaller than 10 microns, poses serious health risks, as they can reach deep into the lungs and remain airborne for extended periods. Advanced detection techniques have revealed the widespread presence of microplastics in the air, with researchers emphasising the risks posed by smaller particles that bypass the body's natural defences.

The persistence of microplastics in air, soil, and water poses substantial long-term challenges for both environmental management and public health. To address these concerns, the studies reviewed have proposed various measures, including stricter regulatory frameworks to limit microplastic emissions from industrial sources and enhanced waste management practices. Bhat et al. [26] argued for increased public awareness regarding the sources of microplastics, especially within indoor environments, as common household activities may unknowingly contribute to microplastic contamination. This sentiment is shared by Abad-López et al. [22], who called for further research into the pathways through which microplastics are generated and dispersed within indoor environments. Reliable data collection through advanced, appropriate methodologies, as well as strict contamination control, is crucial to understanding microplastic behaviour. The health risks associated with long-term exposure, particularly regarding respiratory infections, emphasise the need for continued research to better understand and manage the impacts of microplastics. Based on the selected literature, a few key findings can be concluded:

- Indoor settings are the major exposure hotspots: Indoor air consistently exhibits higher concentrations of MPs as compared to outdoors, often by a factor of 1.5 to 8 times higher.
- Key indoor MPs polymers are PP, PET, PE and PS, mostly sourced from textiles, furniture, building materials, and air conditioning systems.
- Human activities and poor ventilation are often associated with indoor MPs, while resuspension is a common means of aerosolisation of outdoor MPs.
- Microplastic fibres, especially those under 100 μm and composed of polymers like PET, polyester, and polypropylene, are the most prevalent form detected in both indoor and outdoor air. These fibres primarily originate from synthetic fabrics and household items, and their small size increases the risk of deep-lung deposition and ingestion.
- Microplastics become airborne through textile shedding, abrasion, resuspension, and atmospheric fallout. Both local and long-range transport contribute to their widespread presence, with urban activities, synthetic grass, and even sea spray identified as sources. Microplastics persist in various environments, including remote and arid regions, and can be transported over long distances.
- Inhalation and ingestion of airborne microplastics pose potential health risks, including respiratory exposure, biofilm formation, and co-exposure to bacteria and chemical additives. Vulnerable groups such as children and the elderly may face higher risks. The presence of microplastics in clinical and educational settings further underscores the need for health impact assessments.

Thus, cross-contamination and standardisation remain challenges. Effective mitigation strategies include, but are not limited to, source management, improved ventilation, mask use, and regular cleaning. There is an urgent need for harmonised monitoring, risk assessment, and regulatory action to address this emerging environmental concern.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design***: Sara Yasina Yusuf, Nor Ruwaida Jamian, Dewika Naidu; ***Data collection***: Syazwaana Mohd Noor, Mohd Rosiskada Mohamed; ***Analysis and interpretation of results***: Sara Yasina Yusuf; ***Draft manuscript preparation***: Sara Yasina Yusuf, Dewika Naidu. All authors reviewed the results and approved the final version of the manuscript.

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Appendix 1 *Summary and key findings from 35 extracted publications*

No.	Reference	Year	Source title	Scopus	WOS	Summary/Key Findings
1	[8]	2024	Environmental Science and Pollution Research	/		Laboratory simulations revealed that hydrodynamic forces govern microplastic migration in lake sediment–water systems: PS, PET, and PA concentrations in the overlying water peaked and then declined (~1.07, 0.60, 0.83 particles/L), with suspension limited to the top 2 cm of sediment. Deposition increased to 313 particles/kg over time.
2	[16]	2024	Chemosphere	/		Raman micro-spectroscopy quantified indoor airborne microplastics (>1 µm) across four environments, yielding 58–684 MPs/m^3 (median: 212). Surgical masks removed 85.4% overall but only 57.6% of 1–5 µm MPs. The estimated human intake was 3,415 MPs/day, dropping to 283 MPs/day with a mask
3	[17]	2022	Journal of Hazardous Materials	/		The study reveals that during dining and drinking, people may ingest up to one million microplastic particles annually from atmospheric deposition—far exceeding direct food-based intake. Smaller fragments (<100 µm), especially indoors, dominate exposure. Simple actions like covering or rinsing dishware significantly reduce this overlooked yet substantial ingestion pathway.
4	[18]	2022	Science of the Total Environment	/		Microplastics were found in all samples, with indoor concentrations (~309 MPs/m^2/day) significantly exceeding outdoor (~123 MPs/m^2/day). Fibres, especially polyester, dominated across environments. Indoors, polyethene and polypropylene particles were also observed; fragments were the predominant particle morphology.
5	[19]	2023	Science of the Total Environment	/		The study analysed indoor air in various Australian environments and found microplastic fibres—mainly PET—in all locations. Concentrations were highest in childcare centres. The estimated annual inhalation exposure was highest among adult males. The findings highlight the persistent presence of indoor microplastics and call for improved exposure assessment and risk evaluation.
6	[20]	2023	Environmental Science and Technology	/		Active sampling with Py-GC/MS quantifies airborne polystyrene nanoplastics down to 15 pg/m^3. Ubiquitous PS NPs were detected indoors and outdoors, with outdoor levels surpassing indoor and uniform distribution up to 28.6 m. The method enables routine monitoring and assessment of exposure to atmospheric nanoplastics.
7	[21]	2024	Environmental Monitoring and Assessment	/	/	This study evaluates contamination sources in airborne microplastic analysis, finding that fibres (1–1000 µm) dominate blanks. Laminar-flow cabinets, pre-filtered solutions, and thermal-treating filters at 450 °C halve contamination. Authors urge harmonised QA/QC protocols to minimise cross-contamination and ensure reliable quantification of indoor/outdoor MP.
8	[22]	2024	Environmental Pollution	/		The article reviews indoor microplastic pollution, identifying key sources like synthetic fabrics, furniture, and building materials. Indoor concentrations often exceed outdoor levels, posing inhalation risks. It highlights bio-persistence, health effects, and the urgent need for better detection, mitigation strategies, and research to address this growing environmental concern.
9	[23]	2022	Water, Air, and Soil Pollution	/		The study found that indoor air contained about 1.5 times as many microplastics as outdoor air in South Korea. Poor ventilation increased indoor microplastic levels. The findings emphasise the need to manage microplastics at their source to reduce human exposure, especially in indoor environments.
10	[24]	2022	Environmental Pollution	/		The study found airborne microplastics in various indoor spaces in Barcelona, with the highest concentrations in buses. Most particles were fibres under 100 µm, primarily polyamide and polyester. Indoor activities and poor ventilation likely increase inhalation exposure risks.
11	[25]	2022	Environmental Research	/	/	Indoor air in Northern New Jersey contained up to 8 times as many microplastics as outdoor air. Polyethene fibres and fragments dominated indoors, while PVC fragments prevailed outdoors. Houses showed the highest fibre deposition, highlighting indoor environments as major sources of microplastic exposure.
12	[26]	2024	Air Quality, Atmosphere and Health	/		Urban areas typically have higher concentrations of MPs due to dense human activities and transportation. MPs become airborne through resuspension from land surfaces, urban abrasion, sea spray, and atmospheric fallout. MPs can be transported over long distances, reaching remote areas such as the Alps and the Arctic. Aerosolisation pathways include mechanical abrasion, textile shedding, and combustion processes.

No.	Reference	Year	Source title	Scopus	WOS	Summary/Key Findings
13	[27]	2024	Environmental Pollution	/		Lab experiments simulating sea spray showed that micro- and nanoplastics aerosolise more readily when particles are smaller, denser, or at lower concentrations (i.e., with less aggregation). While this uncovers a novel ocean-to-air transport route, human inhalation exposure via sea spray remains negligible compared to urban and indoor sources.
14	[28]	2022	Environment International	/		Using Raman microscopy to detect airborne microplastics down to 1 μm, this study reveals ubiquitous inhalable MPs (15.6–93.3 MPs/m^3) in indoor and outdoor settings in Shanghai. Predominantly small PE fragments, fibres, and beads are suspended via ventilation and human activity. Indoor concentrations exceed outdoor, highlighting health risks from deep-lung deposition.
15	[29]	2022	Environmental Pollution	/		AC filters accumulate and release microplastic fibres (mainly polyester, rayon, cellophane), with densities of 1.47–21.4×10^2 items/cm^2. Fibre loads increase after 35–42 days, and simulated filters emit PET fibres into the air. Estimated intake rises to ~11–44 items/kg-BW/day, highlighting AC filters as both sinks and sources of indoor MPFs.
16	[30]	2023	Environmental Science and Technology	/		This study establishes an unambiguous shape classification for hyperspectral-imaged microplastics—fibre, rod, ellipse, oval, sphere, quadrilateral, triangle, free-form and unidentifiable. Validated on 11,042 particles across indoor air, water and sediments, it enhances data comparability and notes that sub-30 μm indoor particles are often unidentifiable.
17	[31]	2022	Science of the Total Environment	/		Atmospheric deposition sampling in 20 urban homes identified 23,889 airborne microplastics (21 polymers, ~85% <50 μm) and 383 bacterial genera across five room types. MP abundance/composition varied with room use, cleanliness, and occupant age; elderly homes showed higher bacterial loads. MP–bacteria correlations highlight potential inhalation exposure risks.
18	[32]	2024	Science of the Total Environment	/		A novel one-stop μ-FTIR and μ-Raman method using reusable barium fluoride substrates enhances the detection of microplastics in indoor air, bottled water, and exhaled breath. It increases the number of identified MPs by 30%, 17%, and 38%, especially for coloured and <50 μm particles, while lowering costs and simplifying sample prep.
19	[33]	2023	Science of the Total Environment	/		Airborne microfibers collected from indoor fallout and air-conditioner filters across living rooms, dormitories, and offices carried dense biofilms. Fallout fibres hosted more bacteria, and AC filters harboured greater diversity of pathogenic species. Both natural and synthetic microfibers supported high biofilm formation and oxidative-stress tolerance, posing potential health risks through inhalation.
20	[34]	2024	Environmental Pollution	/		The study assessed indoor and outdoor air in Ranchi, India, revealing higher microplastic concentrations indoors. Fibres dominated all samples, with PE, PP, PS, and PVC identified. Seasonal variation influenced deposition rates, and elemental mapping showed contaminant adsorption on microplastics, highlighting potential health risks and environmental persistence.
21	[35]	2024	Air Quality, Atmosphere and Health	/		Active sampling in seven Turkish homes during COVID-19 detected 123 airborne microplastics (2.5–327 μm; 22 polymers) at 12–18 MPs/m^3 (156–240 MPs/day). Fibres, fragments, films and more bore additives/elements (C, O, F, Mg, Si, Cl, N, Al). Indoor levels varied with occupant activities and home characteristics.
22	[36]	2024	Environmental Pollution	/		Strong correlation was observed between airborne MPs and atmospheric fallout MPs. Carpets were identified as an important source of MPs to indoor air. Indoor airborne MPs were dominated by particles in the size range (10–25 μm). PET and PVC were the dominant MP polymer types in the UK indoor air. On a body-weight basis, UK toddlers inhale more MPs than adults, raising concern.
23	[37]	2024	Science of the Total Environment	/		The study investigates the presence of microplastics in indoor and outdoor air in Islamabad using advanced analytical techniques. It finds higher indoor contamination, mainly from fibres of PET, PE, PP, and PS. The results highlight potential inhalation risks and call for deeper research into the sources, transport, and health impacts of airborne microplastics.
24	[38]	2024	Aerosol and Air Quality Research	/		The study investigated indoor atmospheric particles at a Bangladeshi university using FTIR, SEM-EDS, and XRD. It identified microplastics, crystalline silica, and harmful functional groups, primarily from anthropogenic sources. The findings highlight potential health risks and the need for strategies to control indoor particulate pollution in academic environments.

No.	Reference	Year	Source title	Scopus	WOS	Summary/Key Findings
25	[39]	2024	Environmental Science and Technology	/		The study assessed ambient microplastic exposure in urban zones of a megacity. Annual exposure via inhalation, ingestion, and skin contact rivalled dietary intake. Microplastic characteristics correlated with airborne pathogens, especially Sphingomonas, suggesting potential health risks even in green spaces due to persistent airborne transmission.
26	[40]	2024	Science of the Total Environment	/		The study analysed microplastics in indoor dust from 60 homes across Lima, Peru. Polyester and polypropylene fibres dominated, originating mainly from household items and textiles. Concentrations varied by floor level and location, underscoring the influence of housing characteristics on indoor microplastic exposure and potential long-term health implications.
27	[41]	2024	Journal of Hazardous Materials	/		The study shows that mangrove leaves can effectively trap atmospheric microplastics (MPs), with retention varying with leaf texture and structure. Dominant MPs were fibrous, colored, and composed mostly of cellulose and rayon, highlighting mangrove plants as promising bioindicators of airborne MP pollution in coastal environments.
28	[42]	2024	Journal of Hazardous Materials	/		The study used Raman imaging to analyse indoor air filters from an air conditioner and a computer, revealing 73–88,000 microplastic fibres over a six-month period. Polyethene terephthalate (PET) was the dominant synthetic polymer. The findings highlight widespread indoor microplastic exposure and demonstrate Raman imaging's potential for accurate microplastic detection and environmental monitoring.
29	[43]	2023	Journal of Environmental Sciences (China)	/		The study examined airborne microplastics in Ahvaz, Iran, and found only fibrous particles—mainly PET, nylon, and polypropylene—with concentrations up to 0.017 MP/m^3. No seasonal or locational trends emerged. Results suggest both local and long-range sources, emphasising the persistence and potential for dispersal of airborne microplastics in arid urban environments.
30	[44]	2023	Environmental Science and Pollution Research	/		The study used hourly sampling to monitor airborne microplastics indoors and outdoors at urban and rural sites in the UK. Concentrations were highest indoors, especially in residential settings. Fibres dominated all samples, peaking during human activity. The research highlights diurnal variability and the need for improved methods to confirm microplastic identity.
31	[45]	2022	Toxics	/		The study examined indoor air in Kuwait using a six-stage cascade impactor and found 3.2–27.1 microplastic particles per m^3, mainly fibres. Concentrations varied by location and air conditioning type, with smaller particles more abundant. Findings highlight the need for standardised monitoring of inhalable microplastics due to potential health risks.
32	[46]	2022	Gondwana Research	/		The study analysed indoor airborne microplastics across educational settings and found fibres <0.5 mm to be the dominant form. Concentrations varied by room type, with the highest in high schools and the lowest in kindergartens. Abundance correlated with human activity and density, highlighting classrooms as key environments for microplastic exposure and potential health risk.
33	[47]	2022	Journal of Hazardous Materials	/		The article highlights polyethene scaffold netting and synthetic grass as emerging sources of airborne microplastics. Due to their poor quality, outdoor exposure, and widespread urban use, these materials fragment easily and contribute significantly to atmospheric pollution, raising concerns over inhalation risks and the urgent need for better monitoring and regulation.
34	[48]	2022	Environment International	/		The study found significant levels of airborne microplastics in surgical environments, especially during working hours. Polyethene terephthalate fragments were most common. Particle size and abundance suggest potential clinical exposure risks, highlighting the need to assess human health implications of microplastics generated by medical equipment and practices in operating theatres.
35	[49]	2022	Environmental Science and Technology	/		The study investigated airborne microplastics in indoor and outdoor environments across Sri Lanka. Indoor concentrations were notably higher, dominated by PET and polyester fibres linked to textiles. Industrial zones showed elevated outdoor levels. The findings emphasise airborne microplastic exposure in developing countries and highlight the need for further health research.