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Airborne Microplastics In Indoor Environments: A Comprehensive Review Of Sources, Characterization Methods, And Health Implications

Nur Hazirah Md Zahir[1], Azman Azid[1*], Siti Noor Syuhada Muhamad Amin[2] and Mohd Saiful Samsudin[3]
[1]School of Animal Science, Aquatic Science and Environment, Faculty Bioresources and Food Industry, Universiti Sultan Zainal Abidin, Besut Campus, 22200 Besut, Terengganu, Malaysia
[2]Pusat Asasi Sains dan Perubatan UniSZA, Universiti Sultan Zainal Abidin, Kampus Gong Badak, 21300 Kuala Nerus, Terengganu, Malaysia
[3]Environmental Technology Division, School of Industrial Technology, Universiti Sains Malaysia, 11800 USM, Penang, Malaysia
***Corresponding author:** [1*]azmanazid@unisza.edu.my

ABSTRACT
This review highlights airborne microplastics (AMPs) in indoor environments as an emerging environmental and public health issue. As people spend most of their time indoors, exposure to AMPs - often at higher concentrations - is a growing concern. The paper compiles recent findings on their sources, distribution, detection methods, and health risks. Common indoor sources include synthetic textiles, dust, furniture, coatings, and plastic-based materials, with fibrous particles like polyester, polyamide, and polypropylene being most prevalent. Detection and characterization remain difficult due to the absence of standardized sampling and analytical methods. Inhalation of AMPs poses potential respiratory risks, though long-term health effects are still not well understood. Regulatory focus has largely remained on aquatic microplastics, leaving the indoor air largely unaddressed. This review underscores key research gaps, particularly in exposure assessment and harmonized methodologies, and calls for targeted approaches to reduce AMP exposure indoors. It provides a foundation for advancing future research and informing policy development.
Keywords *Airborne microplastics. Indoor environments. Microplastic exposure. Characterization methods. Health implications. Inhalation risk,*

INTRODUCTION
Recognising the significant amount of time individuals spend indoors, this review specifically focuses on airborne microplastics (AMPs) in indoor environments as a major environmental and public health concern. Since commercial production began around 1950, society has grown increasingly dependent on plastics due to their versatility, durability, lightweight nature, and low production costs, which have driven global demand. The widespread use and subsequent degradation of these petrochemical-based plastics within indoor environments contribute significantly to the presence of AMPs.
Studies have indicated that indoor concentrations of microplastics can be significantly elevated, often exceeding outdoor levels by up to eight times [1], underscoring the critical need to understand their sources, behaviour, and potential impacts within these frequently occupied spaces. Many plastics still end up as plastic garbage after being thrown away, even though many plastic products may be recycled and repurposed, leading to plastic debris and microplastics. Microplastics are defined as plastic particles smaller than 5 millimetres in size and can vary widely in shape and dimension [2]. Indoor environments are significant reservoirs of these microplastics due to the presence of various petrochemical-based materials.
This review synthesizes current knowledge on the primary sources of indoor AMPS, including synthetic textiles and fibres, household dust, furniture and home décor, various surface coatings such as paint and varnish, as well as plastic products and packaging materials. It addresses the considerable methodological challenges in their detection and characterization due to the lack of standardised operating procedures for atmospheric microplastics analysis. The review also examines the potential for inhalation of these particles, highlighting that airborne MPs pose a greater risk to human health than MPs found in other environments because they can enter the respiratory system [3]. Furthermore, this paper identifies key knowledge gaps specific to indoor environments, such as the need for standardised sampling and analytical techniques and further investigation into long-term health effects, to guide future research.

Studies have commonly reported fibrous forms in indoor environments, often originating from synthetic textiles, with polymers such as polyester, polyamide, and polypropylene being prevalent. The findings underscore the need for a more thorough and targeted strategy to understand and mitigate the specific challenges posed by indoor air borne microplastics and their potential health impact. A visual summary of the key topics addressed in this review, including sources, characterization methods, and health implications of AMPs, is presented in Figure 1.

Figure 1: Summary of the Airborne Microplastics in Indoor Environments: A Comprehensive Review of Sources, Characterization Methods, And Health Implications

TYPES OF MICROPLASTICS IN THE INDOOR ENVIRONMENT

Microplastics, typically less than 5 millimetres in diameter, encompass a broad range of shapes and sizes. They are primarily composed of synthetic polymers derived from petrochemical-based raw materials such as crude oil and natural gas. Plastics are synthetic polymer compounds with high molecular mass and flexibility, such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl. chloride (PVC), polyester (PES), and polyurethane, which are commonly used in everyday products. To enhance their functionality, durability, and efficiency, specific chemicals are often added to these compounds [4]. These chemical additives can be released along with the microplastics, adding to the complexity of potential health impacts.There are two main types of microplastics found in the environment which are primary and secondary microplastics [5]. Primary microplastics are intentionally manufactured particles smaller than 5 mm and include those directly added to products like exfoliating personal care items or as components in personal care and cosmetic products (PCCPs) [6]. However, the definition also extends to by-products generated during the use of plastic products, such as microfibres from clothing and tyre dust [7]. In the context of indoor AMPs, microfibres shed from synthetic textiles like polyester, nylon, acrylic, and spandex found in clothing, carpets, upholstery, and curtains are particularly significant primary sources.

Secondary microplastics are small plastic fragments that originate from the disintegration of larger plastic debris due to biotic and abiotic degradation in both marine and terrestrial environments [1]. Within indoor environments, the fragmentation of various petrochemical-based materials including furniture, home décor, surface coatings such as paint and varnish, and plastic packaging, contributes to the generation of secondary AMPs [8] [9] [10]. For instance, household plastics exposed to sunlight for extended periods can undergo photooxidation, leading to brittleness, cracking, and the release of microplastic particles into the indoor environment [11].

Microplastics exhibit various shapes, such as pellets, foam, fragments, and microbeads. In indoor air, fibrous shapes are often reported as the dominant form, likely originating from synthetic textiles and released through everyday activities such as wearing, washing, and drying synthetic garments [12]. For example, a study in Southeast Queensland, Australia, found that indoor dust from a school building was predominantly composed 98% of microfibers [13]. Other studies have also reported fragments as a common morphology in indoor environments. Another category is nanoplastics, which are plastic fragments smaller than 100 mm. These are created through the weathering and fragmentation processes of plastic waste. Due to their extremely small size, nanoplastics are of particular concern regarding potential inhalation and health effects [14].

The prevalence of certain polymer types also has implications for indoor AMPs. Studies have frequently identified polyethylene terephthalate (PET) and polypropylene (PP) as dominant polymers in indoor environments, likely due to their extensive use in textiles and packaging. Liao et al. [1] reported that the most prevalent polymer types in indoor AMPs were polyester (PES) at 28.4%, polyamide (PA) at 20.54%, and polypropylene (PP) at 16.3%, with fragments being the dominant shape. The properties of these polymers, such as their tendency to shed fibers (e.g., polyester and polyamide in textiles) or their degradation patterns leading to fragments (e.g., PE and PP in packaging), influence the types of AMPs found indoors.

The morphology of these particles, particularly the presence of sharp edges on fragments or the fine nature of fibers, can also influence their behavior in the air, such as suspension time and deposition rates, as well as their potential to interact with the respiratory system upon inhalation. A comparative summary of the key characteristics, origins, and examples of primary, secondary, and nanoplastics is presented in Table

Table 1. Comparison of Primary, Secondary, and Nanoplastics

Type	Size	Origin	Examples	Environment Found
Primary	< 5 mm	Intentionally manufactured or generated during product use	Microbeads in PCCPs, microfibres, tyre dust	Terrestrial & aquatic environments
Secondary	< 5 mm	Fragmentation of larger plastic waste through degradation processes	Broken plastic fragments, foam, pellet	Marine, freshwater, terrestrial
Nanoplastics	< 100 mm	Further breakdown of microplastics via weathering & chemical processes	Invisible plastic particles, degraded microbeads	Water, air, biological tissues

SOURCES OF INDOOR MICROPLASTIC

Indoor environments are significant reservoirs of microplastics due to the presence of various petrochemical-based materials. The major sources of indoor microplastics include synthetic textiles and fibers, household dust, furniture, home décor, surface coatings such as paint and varnish, as well as plastic products and packaging materials [9].

Synthetic Textiles and Fibers

One of the most significant sources of indoor microplastics is synthetic textiles, including polyester, nylon, acrylic, and spandex, which are commonly found in clothing, carpets, upholstery, and curtains. These fabrics shed microplastic fibers through multiple pathways such as washing clothes, which release microfibers into indoor air and wastewater. Daily wear and tear, where friction from movement causes fibers to detach. Vacuuming and air circulation, which further disperses microplastic fibers in household dust [16]. Studies have shown that synthetic fibers such as polyester and polyamide can shed microfibers during regular use and laundering. For instance, a study by Napper and Thompson [16] found that a single garment can release over 1,900 fibers per wash, contributing significantly to microplastic pollution.

Household Dust

Indoor dust serves as a major carrier of microplastics, containing fibers from textiles, degraded plastic particles, and residues from household products. These microplastics accumulate on surfaces and enter the human body through inhalation, ingestion via food contamination, and dermal contact [17].

Furniture, Home Décor, Paints, Varnishes, and Coatings

Many household items contain plastic-based materials, including polyurethane foam, polyester fabrics, and PVC coatings. These materials, commonly found in sofas, mattresses, carpets, curtains, and

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wallpapers, gradually degrade over time, releasing microplastics into the air and dust [18]. Similarly, indoor wall paints, furniture varnishes, and industrial coatings often contain synthetic polymers such as acrylics, polyurethanes, and epoxies, which degrade due to peeling, chipping, and dust accumulation also contribute to indoor microplastic contamination.

Plastic Products and Packaging

Common household plastics, including storage containers, food wrappers, plastic toys, and electronic casings, are also significant contributors. Any plastic product exposed to sunlight for an extended period is susceptible to photooxidation, a process in which ultraviolet (UV) radiation, oxygen, and heat break down the polymer structure [19]. This degradation leads to discoloration, brittleness, surface cracking, and fragmentation, ultimately releasing microplastic particles into the indoor environment.

Methodology for Assessing Airborne Microplastics

AMPs have become a recognized component of atmospheric pollution, however, their detection and characterization present considerable methodological challenges. The small particle size, diverse polymer composition, and typically low environmental concentrations of AMPs necessitate the use of comprehensive and carefully integrated approaches involving sampling, pre-treatment, identification, and quantification. At present, there are no standardized operating procedures (SOPs) for the analysis of microplastics in atmospheric environments. This is largely due to the limited number of studies focused specifically on AMPs. Consequently, this section provides a critical review of the methods currently reported in the literature for assessing AMPs in the atmosphere. The general workflow of sampling and analysis approaches used to assess AMPs is outlined in Figure 3.

The accurate detection and characterization of indoor AMPs are crucial for understanding their environmental distribution, exposure risks, and potential health effects. Various sampling and analytical techniques have been developed to identify, quantify, and classify microplastic particles in air samples. However, methodological inconsistencies and the lack of standardized protocols remain significant challenges in this field [20].

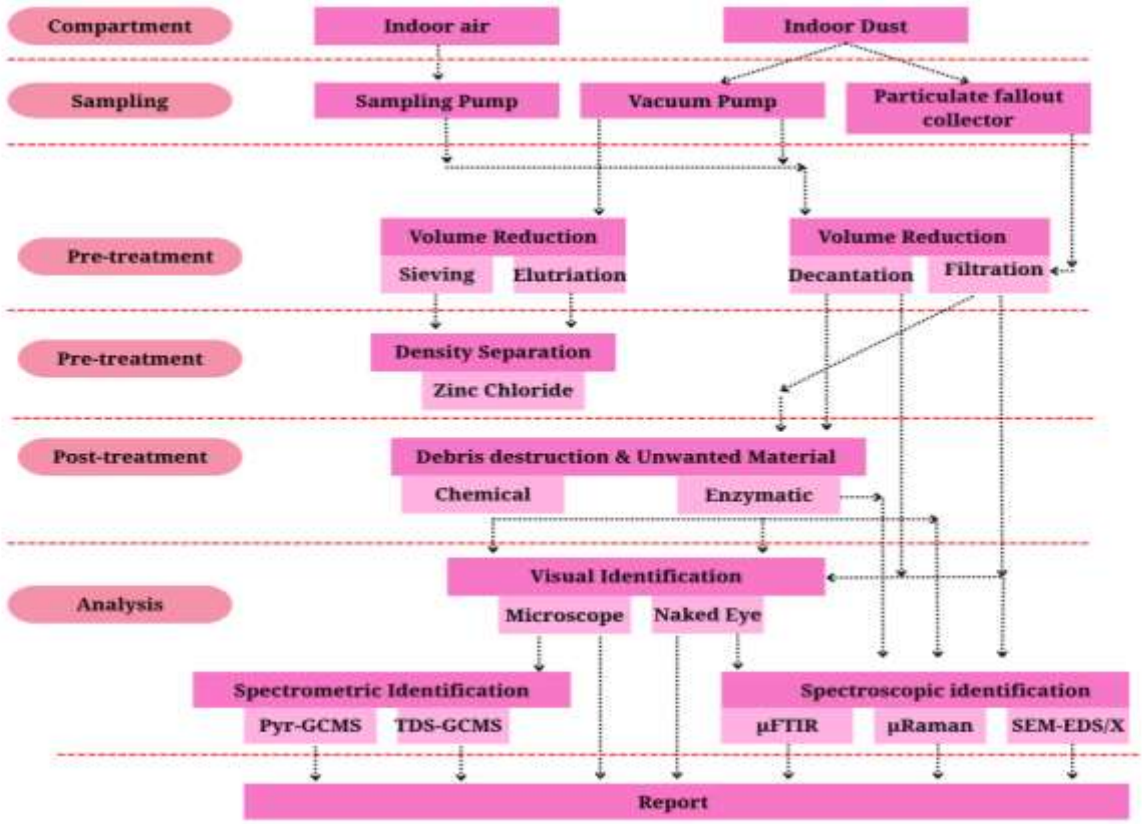

Figure 3: Possible Methodology

SAMPLE COLLECTION

There are several techniques to collect indoor microplastics samples which consist of active sample collection and passive sample collection each with its advantages and limitations.

ACTIVE SAMPLING

Active sampling involves the use of mechanical devices by drawing air through filtration systems to collect microplastic particles. This method allows for precise measurement of air volume, essential for calculating AMPs concentrations and assessing inhalation exposure [21]. Commonly, filters such as quartz, cellulose, glass fiber, alumina, or silver membranes are used to trap particles. Active sampling offers greater sensitivity and precision compared to passive methods, enabling the calculation of particle concentration per air volume [22].

1. **Filtration-based Air Samplers**

High-volume and low-volume air samplers are widely employed to collect airborne particles onto filters such as glass fiber, polytetrafluoroethylene (PTFE), or quartz. These collected samples are subsequently analyzed using techniques like spectroscopy or microscopy to detect and identify microplastics. The use of such samples facilitates precise control over airflow measurements, thereby enhancing the reliability of the data obtained.

2. **Cascade Impactors and Cyclones**

Cascade impactors and cyclones play a key role in separating particles based on their aerodynamic size, making them valuable tools for collecting microplastics in different size categories. This method is especially useful in aerosol studies, helping researchers understand how microplastics are distributed in the air and how they might be inhaled [23]. However, one limitation of these devices is that they are less effective at capturing the smallest microplastic particles, which could affect the accuracy of some studies.

PASSIVE SAMPLING

Passive sampling captures microplastics as they naturally settle onto surfaces over time. This method is straightforward, affordable, and ideal for long-term monitoring, particularly in locations without electricity access. Passive samplers, like glass containers with funnels, collect both wet and dry deposits without requiring power. Although passive sampling is less sensitive than active methods, it offers valuable insights into microplastic accumulation rates over extended periods [24].

1. **Deposition Samplers**

Deposition samplers passively collect airborne particles through dry or wet depositions, or a combination of both. They rely on natural forces, such as gravity for the settling of dry particles and precipitation for particle removal, rather than active mechanical sampling [25].

2. **Dust Collection and Analysis**

Dust collection is one of the most straightforward and commonly used methods for assessing AMPs, particularly in indoor environments. This approach relies on the natural gravitational settling of airborne particles over time, allowing for the accumulation of dust that may contain microplastic particles. The method is non-invasive, cost-effective, and suitable for long-term monitoring of indoor AMP depositions. For example, research by Chenappan et al. [26] used passive sampling for microplastics collection.

PRE-TREATMENT, POST-TREATMENT AND ANALYSIS OF AIRBORNE MICROPLASTICS

After sample collection, the volume is typically reduced to facilitate further processing. This can be achieved through sieving (e.g., using a 2.5 mm mesh), elutriation, decantation, or filtration, depending on the type of sampling equipment used [27].

Since microplastics embedded in dust often adhere to other particles, a density separation step is usually required. A zinc chloride solution is commonly used for this purpose, allowing microplastics to either float or sink based on their polymer density, thereby aiding in their separation from non-plastic materials. Following separation, chemical treatment is applied to remove organic matter and inorganic debris. This step typically involves reagents such as potassium hydroxide (KOH), hydrogen peroxide (H_2O_2), or nitric acid (HNO_3), which help to digest unwanted biological and natural residues without affecting the plastic particles.

For final analysis, a range of techniques is available to identify and quantify the isolated microplastics. Initial visual identification can be done using a microscope or even the naked eye in some cases. For more detailed compositional analysis, advanced methods such as pyrolysis-GCMS (Pyr-GCMS), thermal desorption GCMS (TDS-GCMS), micro-Fourier transform infrared spectroscopy (μFTIR), micro-Raman spectroscopy (μRaman), and scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS) are commonly employed.

AVAILABLE LITERATURE REVIEW ON AIRBORNE MICROPLASTICS

Literature Search Strategy and Selection Criteria

A comprehensive literature search was conducted using databases including Scopus, Web of Science, and Google Scholar, focusing on peer-reviewed articles published between 2015 and 2023. To ensure quality and reliability, only studies published in Scopus- or ISI-indexed journals were considered. Articles were

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selected based on their relevance to airborne microplastics (MPs), with a focus on those that provided empirical data, discussed sampling and analytical methods, or evaluated the environmental and health implications of airborne MPs. Studies that lacked methodological details, were opinion-based, or did not specifically focus on airborne MPs were excluded.

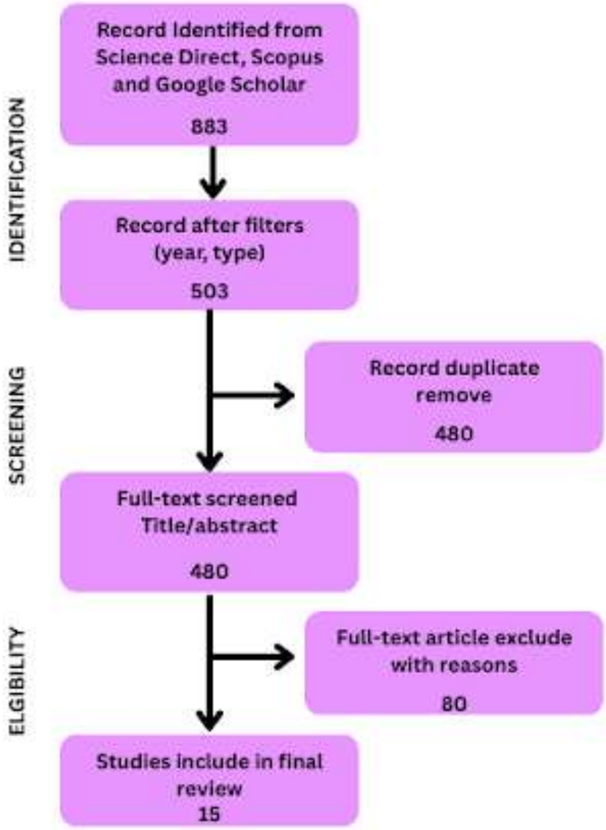

Figure 5: PRISMA Flowchart of Study Selection

Based on Figure 5, which presents the PRISMA flowchart, a systematic literature search was conducted using the ScienceDirect database to guide the identification and selection of relevant studies. The keyword "indoor airborne microplastics" was employed to retrieve pertinent publications. The initial search results were refined by publication year and research type to ensure both relevance and quality. Following the removal of duplicate records, a total of 380 articles were obtained. Subsequently, 15 articles were selected through a rigorous screening process based on their relevance, methodological robustness, and contribution to the research topic. These selected studies formed the core foundation of the literature reviewed in this paper.

TRENDS IN MICROPLASTICS RESEARCH

Research on microplastics has increased significantly over the past decade, particularly in the context of marine pollution. Between 2011 and 2022, over 1,300 studies focused on marine microplastics alone, reflecting the field's early emphasis on aquatic ecosystems [28]. However, research on AMPs began to emerge later, with only 147 related studies published between 2015 and 2021, according to bibliometric data.

The growing body of research on AMPs corresponds with rising concerns about indoor air quality and inhalation exposure. The COVID-19 pandemic further heightened this concern, as increased time spent indoors may have intensified exposure to indoor pollutants, including microplastics [29]. While early studies were largely exploring, recent publications have started addressing sources, concentration levels, polymer types, and potential health risks, signaling a shift toward more detailed, interdisciplinary investigations.

CONCENTRATIONS IN DIFFERENT INDOOR ENVIRONMENTS

Several review articles on AMPs have explored different aspects of this emerging issue. Some studies have focused on their identification and characterization in both indoor and outdoor air [27][30]. Others have examined human exposure, potential health effects, and toxicity, including their role in pathogenesis. Additionally, research has investigated the sources and fate of AMPs as well as the types of polymers and their distribution in urban and rural environments [31] [21][32].

However, further research is needed to determine the extent to which AMPs contribute to overall particulate matter (PM) pollution in indoor environments. To address this gap, we systematically review the existing literature and offer new insights into the current challenges in this field. Additionally, we examine studies that have documented AMPs in both indoor and outdoor settings, along with the characterization methods used for their analysis. Detailed information on microplastic forms, concentrations, sampling methods, and indoor settings from various global studies is summarized in Table 2

Table 2. Characteristics of indoor microplastics in different studies

Location	Form of MP	Concentration	Sampling Method	References
Australia	Predominantly microfibers (98%) and fragments (2%)	2.25 ± 0.38 MPs/m³	Active sampling using a stainless-steel air sampler with a 1 μm stainless-steel mesh filter	[13]
Turkiye	Predominantly Fragments	13.88 to 18.51 MPs/m³	Active sampling using PTFE filter by air sampling pump	[33]
Turkiye	Fibers, fragments, film, lines, foams, pellet	12.03 to 18.51 MPs/m³	Active sampling using PTFE filter by air sampling pump	[29]
Iran	Fibers, Fragments	48 MPs/m³	Active sampling using SKC pump with quartz microfilters	[34]
New Zealand	-	0.51 μg m−3 for the PM2.5 and 1.14 μg m−3 for the PM10	Active sampling using air pump with quartz filter	[35]

The presence of microplastics in indoor environments has become a growing concern, especially given that people now spend the majority of their time indoors. Indoor air quality plays a significant role in affecting human health. Recent studies have confirmed that microplastics are commonly found indoors, exhibiting a wide range of concentrations, shapes, sizes, and behaviors whether suspended in the air or settled on surfaces. A study by Din et al. [36] found that the concentration of microplastics in indoor air is significantly higher than outdoors. Indoor air samples contained around 4.34 ± 1.93 MPs/m³, while outdoor samples had only 0.93 ± 0.32MPs/m³. This difference highlights how indoor environments can be major sources of microplastic exposure.

Šaravanja et al. [37] pointed out that one of the main sources of indoor microplastics is clothing and textiles, especially those made from synthetic materials. These microfibers are often released during household activities like machine washing. In fact, many studies have confirmed that synthetic textiles shed a significant number of fibers during each wash, making them one of the leading contributors to microplastic pollution in indoor settings.

A study by Perera et al. [13], conducted over the course of one month across seven common indoor environments, revealed varying concentrations of AMPs depending on the location. The highest concentration was detected in a childcare facility, averaging 2.25 ± 0.38 MPs/m³, while the lowest was found inside a vehicle, with just 0.20 ± 0.14 MPs/m³. The microplastics identified were primarily in fibrous form, accounting for 98% of all particles, with the remainder being fragments. The length of the fibers ranged from 71 to 4,950 μm. PET was the most frequently detected polymer across the sampled locations.

Bhat [29] conducted an objective assessment of AMPs concentrations during the COVID-19 pandemic, a period when people spent most of their time indoors. The study found that residents in household settings were exposed to AMPs at concentrations ranging from 12.03 to 18.51 MPs/m³. Based on these findings, it was estimated that individuals could inhale between 156 and 240 microplastic particles per day while staying indoors.

Kaydi et al. [34] investigated the concentration and potential health risks of indoor AMPs across 30 different indoor environments, using active sampling methods during both winter and summer seasons. Their findings revealed that microplastic concentrations peaked in office settings during winter, reaching

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up to 48 MPs/m³. Spherical microplastics (spherules) were the dominant shape accounting for 67.2% of particles in winter and increasing slightly to 69.3% in summer. On average, microplastic levels were 4.703 MPs/m³ higher in winter than in summer, highlighting the influence of seasonal indoor activities and ventilation efficiency on microplastic accumulation. Additionally, the study found that building characteristics significantly influenced microplastic concentrations. Older buildings (over 10 years old) contained 3.284 MPs/m³ fewer particles compared to newer buildings. Likewise, the presence of a ventilation system was associated with a substantial reduction, buildings with ventilation had 18.496 MPs/m³ fewer AMPs than those without. These results emphasize the role of infrastructure and air circulation in shaping indoor air quality.

POLYMER TYPE AND MORPHOLOGY

Microplastics are made from different kinds of plastic polymers such as polyethylene, polypropylene, polystyrene, polyethylene terephthalate, and each type has unique properties. Research has identified several polymer types prevalent in indoor environments, with their concentrations varying across studies. Studies conducted in various countries have identified several dominant polymer types in indoor AMPs. Polyethylene terephthalate PET and PP are among the most frequently detected polymers, likely due to their widespread use in textiles and packaging materials According to Zhang et al. [38], the concentration of PET based microplastics in indoor samples ranged from 38 to 120,000 µg/g. PET is synthesized by esterifying terephthalic acid (TPA) with ethylene with glycol and is widely used in textile industry as well as in manufacturing bottles for food water, and soft drinks. The study also found that PET accounted for 62% of the microplastics detected and was present in 90% of the samples analyzed. A cross-study comparison of polymer types, morphologies, size ranges, and analytical techniques used for microplastic detection in indoor air is provided in Table 3

Table 3. Polymer type and morphology of microplastics

Location	Polymer	Morphology	Size Range	Detection Technique	References
Wenzhou City, China	PS, PA, PP, PE, PS	Fibers, fragments	5–30 µm	µ-FTIR spectroscopy	[1]
Barcelona, Spain	PS, PP, PA	Fibers, fragments	43 to 4436 µm	µ-FTIR spectroscopy	[40]
Turkiye	PA, PP, PTFE	Fibers	120–2222 µm	µRaman	[33]
Bangkok, Thailand	PP, PE, PET	Fragments, pellet, fiber	300–500 µm	micro-FTIR	[40]
Bangkok, Thailand	PE, PU, PP, PS	Fragments, Fibers	2.35 to 196.65 µm	FTIR	[41]

Liao et al. [1] reported that the most prevalent polymer types identified in indoor AMPs were PES at 28.4%, PA at 20.54%, and PP at 16.3%, with fragments being the dominant morphological form. Interestingly, a higher proportion of fibers was observed in samples collected from apartment environments, whereas office spaces exhibited a noticeably lower fiber content. This disparity is likely due to the greater presence of textile-based furnishings and more frequent human activity in residential settings, which contributes to the release and resuspension of microplastic fibers. In contrast, public and office buildings generally contain fewer textile materials and experience less fabric-related disturbance, leading to reduced fiber emissions.

Torres-Agulló et al. [39] reported that PA (51%) was the most frequently detected polymer in subway train air samples, closely followed by PES (48%), while PP was scarcely present, with only a single fiber (1%) identified in one of the trains examined. In the subway train environment, PA and PS were the dominant polymers identified, reflecting the extensive use of these materials in seat upholstery, carpets, and passenger clothing. The dynamic movement and constant occupancy within subway cars likely enhance the shedding of fibers from these textiles.

In contrast, PP was minimally detected (1%), likely due to its limited presence in fabrics and lower tendency to release fibers under mechanical stress.

A study by Bhat [33] reported that the majority of microplastics deposited in classrooms were composed of PA, PP, and PES, which are materials commonly used in the production of PA fibers for textiles, carpets, and packaging. While the surfaces of these fibers appeared relatively smooth, their edges were noticeably rough and irregular, indicating signs of abrasion and disintegration likely caused by friction during laundering, everyday wear, and mechanical stress.

Dahal and Babel [40] reported that in indoor air samples, fragments constituted the predominant microplastic morphology at 68%, followed by pellets (21%) and fibers (11%). The high prevalence of fragments is attributed to the prolonged exposure of plastic materials to environmental factors such as ultraviolet (UV) radiation, heat, moisture, and microbial activity, which facilitate the breakdown of larger plastic items into smaller fragments. Thailand's tropical climate, characterized by consistently high temperatures and humidity, along with an average UV index ranging between 11 and 12, creates conditions conducive to the photodegradation and fragmentation of plastics. The dominance of fragmented PE, PP, and PET in the study suggests that a significant portion of microplastics originates from sources beyond textiles. Specifically, PE is widely used in the production of plastic bottles, bags, and food containers, while PET is commonly employed in manufacturing single-use beverage bottles and food packaging materials.

Sarathana and Winijkul [41] reported that PE was the most prevalent polymer type in fragment-form AMPs, consistently detected across all sampling sites. In contrast, cellophane was the dominant polymer identified in fiber-form AMPs. Notably, a greater diversity of AMPs types was observed at the dumpsite compared to other locations, likely due to the collection of various waste materials in this area to produce refuse-derived fuel (RDF). The processes involved in RDF production (sorting and shredding) contribute to the generation of multiple AMP types. However, the study's use of FTIR was limited by its inability to detect particles smaller than 20 μm. To improve the detection and characterization of AMPs within the inhalable size range, more advanced techniques such as micro-FTIR, micro-Raman spectroscopy, and pyrolysis-GC/MS are recommended.

Different types of plastic polymers behave differently in indoor air, and these differences can affect how they impact our health. For instance, PET and PP are often found as fine fibers or small fragments. Because of their tiny size and lightweight, they can travel deep into the lungs when inhaled [42]. On the other hand, PA and polyester common materials in household textiles tend to shed easily during everyday activities like walking around or cleaning. This frequent release leads to higher exposure, especially in home environments [17]. Many of these fibers also show signs of wear and tear, like rough or jagged edges. These surface changes may make it easier for harmful substances like heavy metals and polycyclic aromatic hydrocarbons (PAHs) to stick to them [43]. To make matters worse, some plastics contain chemical additives like plasticizers, flame retardants, and stabilizers. These substances can be released into the air and inhaled, potentially causing hormone imbalances or triggering inflammation in the body [44].

Although fibre-shaped microplastics are often reported as the dominant form in indoor environments, variations in polymer types and morphologies across studies can largely be attributed to differences in sampling methods and analytical techniques. In many cases, limited access to advanced instrumentation has resulted in incomplete polymer identification, potentially leading to the underrepresentation of certain plastic types. Notably, studies that omitted digestion steps frequently reported a higher proportion of fibers, likely due to the presence of undigested natural fibers. In contrast, studies employing tagging techniques alongside chemical digestion tended to identify a greater abundance of fragments. This highlights the significant influence of methodological choices on the detection and classification of microplastic shapes.

HEALTH IMPLICATION OF MICROPLASTIC

Recent findings suggest that microplastics may pose significant health risks to living organisms. Plastics were once assumed to be biologically inactive due to their stable polymer structure, which consists of strong covalent bonds that contribute to their large molecular size, hydrophobic nature, and limited bioavailability. As a result, they were believed to pass through biological systems without significant absorption or alteration. However, plastics often contain various chemical additives, which can make up nearly 70% of their total composition, to enhance mechanical strength, color, flexibility, and resistance to fire. Some of these substances, such as phthalates, bisphenols, organophosphates, and biocides, have been associated with negative health effects, while others, including brominated flame retardants and chlorinated paraffins, exhibit bio-accumulative and persistent properties, raising concerns about their long-term presence in ecosystems and potential toxicity to humans and wildlife [45].

Humans are exposed to indoor microplastics primarily through inhalation, ingestion, and skin contact. It is estimated that individuals consume anywhere from tens of thousands to millions of these tiny particles each year, amounting to a daily intake of several milligrams [46]. Inhalation of these particles may cause oxidative stress and inflammation in the airways and lungs, potentially resulting in symptoms such as coughing, sneezing, and shortness of breath. Prolonged exposure could increase the risk of respiratory conditions, including chronic obstructive pulmonary disease [47].

Microplastics exist in various irregular shapes, including cubic, spherical, and rod-like forms, depending on their structural properties. These morphological differences are important when evaluating their potential risks to human health and the environment. Particles with sharp edges may cause physical damage to biological tissues, leading to toxicity through mechanical irritation [48]. Additionally, plastics are manufactured using a range of chemical additives, many of which function as endocrine disruptors which are chemicals that interfere with hormonal balance [49]. These substances, also known as hormonally active agents, have been linked to cancer and reproductive disorders. Microplastics may further contribute to endocrine disruption by acting as carriers that release these harmful compounds into the body. Moreover, microplastics have the ability to absorb toxic substances, including heavy metals and organic pollutants, which can be transported into human systems, potentially leading to adverse health effects [50].

Vasse and Melgert [51] estimate that humans inhale approximately 3,000 micro- and nanoplastic particles (MNPs) daily, assuming an average air intake of 15 m^3 per day. This exposure can stimulate an immune response, leading to the accumulation of inflammatory cells and macrophages in lung tissue, which may contribute to chronic inflammation and tissue damage. Additionally, research by Eberhard et al. [52] explores the neurotoxic potential of inhaled microplastics, demonstrating that these particles can translocate to the brain. Their findings suggest that such exposure may disrupt brain function and development, potentially leading to various neurological impairments.

In addition to nasal inhalation, oral ingestion is another significant route of microplastic exposure in humans. Key sources include drinking water, particularly from plastic bottles, as well as food items contaminated during processing and packaging [46]. Research by Catarino et al. [53] found that the ingestion risk from consuming mussels is relatively low compared to exposure to microplastic fibers from household dust settling on food during meals, with an estimated intake of 13,731–68,415 particles per person annually. This highlights the substantial role of indoor environments in microplastic exposure through the accumulation of airborne fibers on food.

EFFECT ON VULNERABLE POPULATIONS (CHILDREN & ELDERLY)

Some people, like children and the elderly, are more at risk from indoor AMPs because of their unique physical conditions and daily routines. For instance, children tend to breathe faster than adults and spend a lot of time indoors, especially playing on or near the floor, where microplastic fibers often settle in household dust [54]. Since their lungs and immune systems are still developing, they may be more prone to inflammation and oxidative stress caused by inhaling these tiny particles.

Older adults, on the other hand, often live with chronic respiratory or heart conditions that could be worsened by long-term exposure to AMPs [55]. As we age, our bodies become less efficient at detoxifying harmful substances and fighting off inflammation, which can make the health effects of microplastics more severe. Both children and the elderly also tend to spend more time indoors, sometimes in areas with poor ventilation, leading to greater long-term exposure. These realities highlight the importance of focused research and strategies to improve indoor air quality, especially for these more vulnerable groups.

Ecological Risks of Airborne Microplastics

The ecological risks associated with AMPs are an emerging concern, particularly due to their potential for wide environmental dispersion and their persistence in various ecosystems. Unlike aquatic microplastics, the impacts of AMPs are less understood, largely due to their recent recognition and the technical challenges associated with their detection and quantification in the atmosphere [56]. However, current evidence suggests that AMPs pose significant ecological risks through multiple exposure pathways and mechanisms.

Atmospheric Transport and Environmental Dispersion

Airborne microplastics can undergo long-range atmospheric transport, enabling their dispersal across vast distances from their original sources [57]. Studies have documented AMP deposition in pristine and remote ecosystems such as mountain ranges and polar regions, suggesting that no environment is exempt from microplastic pollution [58]. Upon deposition, AMPs can enter terrestrial and aquatic ecosystems, potentially alter environmental processes and contaminate food webs.

Wildlife Exposure: Inhalation and Ingestion

Wildlife, particularly birds, small mammals, and invertebrates, may be exposed to AMPs through inhalation or ingestion [59][60]. Although data on terrestrial exposure remain limited, the potential for respiratory deposition exists, especially for particles in the inhalable range (<10 µm) [44]. The inhalation

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of such particles may lead to respiratory irritation, inflammation, or oxidative stress in exposed organisms [61]. Ingestion, whether direct or trophic, may impair feeding behavior, induce gut blockage, or cause sub-lethal effects such as energy imbalance and growth retardation [62].

Soil Effects and Ecosystem Disruption

AMPs that settle onto terrestrial surfaces can become incorporated into soil, especially in agricultural and urban settings [63]. Their accumulation may affect soil physicochemical properties, including porosity, water retention, and aggregate stability [64]. Furthermore, microplastics have been shown to disrupt microbial communities and enzyme activities, thereby altering nutrient cycling and soil fertility [65]. These changes can cascade in affecting plant health and productivity, raising concerns about long-term soil ecosystem degradation.

Indoor-to-Outdoor Transition of Airborne Microplastics

Recent research has shown that AMPs are commonly found in both indoor and outdoor environments, but their levels indoors are often much higher. This is largely due to everyday indoor sources like textiles, furniture, and general human activity, combined with limited air circulation that allows these particles to build up.

For example, Gaston et al. [66] found that indoor air contained around 3.3 fibers and 12.6 fragments per cubic meter, much more than the 0.6 fibers and 5.6 fragments per cubic meter measured outdoors. Interestingly, the fragments found indoors were also smaller on average (about 58.6 µm) compared to those found outside (about 104.8 µm), which could mean a higher risk of inhalation indoors.

In another study, Boakes et al. [67] used high-resolution time-based sampling and discovered that, at peak times, AMP levels inside homes could be over 70 times higher than those outside. This stark contrast highlights how indoor spaces not only generate but also store AMPs, which can later be released into the outdoor environment through ventilation or everyday human movement.

Together, these studies highlight the ongoing exchange of microplastics between indoor and outdoor spaces and point to the need for more detailed research on how this transition happens and what factors influence it.

Gaps in Current Literature and Future direction

Although research on indoor AMPs has grown significantly in recent years, there are still many unanswered questions and areas that need further investigation. These knowledge gaps not only limit our understanding of indoor air quality but also hinder efforts to assess potential health risks linked to long-term exposure to microplastics indoors.

One major issue is the lack of standardization in sampling and analysis methods. Researchers use a variety of techniques such as different filter types, sampling durations, flow rates, and instruments, which makes it difficult to compare results across studies. Some rely on passive samples, while others use active pumps; some analyze samples with FTIR spectroscopy, while others use Raman or pyrolysis-GC/MS. These inconsistencies often result in data that can't be directly compared, which slows down progress in the field. Moving forward, developing consistent, standardized protocols would greatly improve the reliability and comparability of studies.

Another limitation is that not all studies identify polymers accurately. In many cases, microplastics are categorized based on their appearance under a microscope, without confirming the material using chemical analysis. This can lead to misidentification especially when natural fibers or dust particles resemble synthetic polymers. Incorporating spectroscopic confirmation techniques like μ-FTIR or Raman is essential to ensure that the particles being counted are indeed microplastics. There's also a clear bias toward reporting fiber-shaped microplastics, probably because fibers are easier to detect and are commonly shed from clothing and textiles. However, this focus may overlook other types like fragments, films, and foams, which could also be present in indoor air but go undetected due to the limitations of current sampling and detection methods. More balanced reporting on all shapes and forms of MPs is needed to understand the full picture.

In terms of where studies are conducted, most research so far has focused on homes and offices. But other important indoor environments like schools, hospitals, kindergartens, and public transportation are still understudied. These places often have high occupancy and vulnerable populations, such as children or patients, making them important areas for future research. A critical technical gap is the difficulty in detecting smaller particles, particularly those under 10 µm. These smaller MPs are especially concerning because they're more likely to be inhaled deeply into the lungs. However, many current instruments don't have the sensitivity to detect or identify these ultrafine particles, meaning we may be underestimating the true exposure risk.

Other than that, there's still very limited information on the potential health impacts of inhaling microplastics. While some laboratory studies have shown that MPs can cause inflammation or oxidative stress, real-world exposure data, especially long-term studies, are still lacking. Without this information, it's hard to draw firm conclusions about health risks. This highlights the need for more interdisciplinary work that brings together environmental scientists, toxicologists, and health researchers.

Lastly, addressing these gaps has important implications for both science and public health policy. Standardizing methods would allow regulatory agencies to establish exposure guidelines and improve indoor air quality monitoring. Expanding research to include vulnerable environments like schools and hospitals can inform building design standards and ventilation policies. Additionally, funding agencies should prioritize interdisciplinary research that connects environmental exposure with long-term health outcomes. This includes supporting the development of sensitive detection instruments and promoting collaboration between environmental scientists, toxicologists, and public health experts.

In the future, research on indoor AMPs should focus on improving and standardizing sampling and analysis methods to make studies easier to compare. There's also a need for better tools to detect smaller particles, especially those under 10 micrometers, as they can be easily inhaled. More studies should explore different indoor environments like schools, hospitals, and public transport, not just homes and offices. Researchers should also pay attention to all types of microplastics, not just fibers. Most importantly, more work is needed to understand the possible health effects of breathing in microplastics, especially over the long term. Collaboration between scientists and health experts will be key to addressing these gaps.

CONCLUSION

Indoor AMPs are an emerging concern, especially given the amount of time people spend indoors. This review highlights their widespread presence in indoor air, with fibers being the most commonly reported shape and polymers like polyester, polyamide, and polypropylene frequently detected. These particles are largely linked to everyday indoor sources such as textiles, carpets, and furnishings. Despite growing interest, major gaps remain. Inconsistent sampling methods, limited ability to detect smaller particles, and a narrow focus on certain environments hinder our full understanding. Most critically, the long-term health effects of inhaling microplastics remain largely unknown. To address these challenges, future research must prioritize standardized methods, broader sampling across diverse indoor settings, and interdisciplinary collaboration to assess real-world health impacts. Strengthening these efforts will be essential for shaping effective indoor air quality guidelines and protecting public health.

CONFLICTS OF INTEREST

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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