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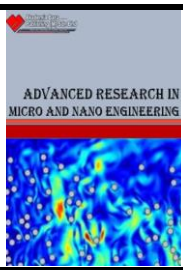


# Systematic Review on Indoor Microplastics: Unveiling Sources, Exposure Pathways, and Human Health Implications

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**ABSTRACT**

Indoor microplastics present a noteworthy and all-encompassing environmental issue that requires careful attention and contemplation. This comprehensive review navigates the intricate landscape of indoor microplastics, investigating their potential sources, pathways of exposure, and implications for human health. Commencing with an exploration of the origins and varieties of polymers within indoor environments, the review dissects commonplace products and manufacturing processes, identifying them as substantial contributors. Subsequent sections elucidate the diverse ways individuals encounter indoor microplastics, encompassing airborne dissemination, ingestion via dust and food, and skin contact with subsequent absorption. The critical evaluation of advancements in detection and measurement techniques addresses the complexities associated with accurately quantifying indoor microplastics. The review scrutinizes potential health risks linked to exposure, emphasizing cumulative effects and the vulnerability of specific populations. Prolonged contact with heightened concentrations of microplastics can bring about various consequences, including oxidative stress, DNA damage, organ dysfunction, metabolic disorders, immune responses, neurotoxicity, and reproductive and developmental toxicity. In the mitigation segment, strategies are outlined to curb microplastic presence at its source, manage indoor air quality, and advocate for policy and regulatory interventions. Identifying future directions and research gaps, the review serves as a roadmap for ongoing investigations. In summary, this study consolidates crucial discoveries, offers suggestions for future research initiatives, and emphasizes the critical need to understand and tackle the intricate network of indoor microplastics to safeguard both human health and environmental well-being.

## 1. Introduction

Over the last ten years, extensive research has been dedicated to investigating various aspects of indoor environments. These include studies on infection control through ventilation strategies [1-3],

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improvement of indoor air quality through small-scale botanical methods [4], facilitation of thermal comfort via air distribution [5-7], optimization of human comfort through air conditioning [8], consideration of thermal effects in diluting particle contaminants [9], enhancement of indoor air quality using natural ventilation [10,11], and mitigation of airborne infections through ventilation approaches [12-14], etc. However, the generation of plastic waste is escalating at a concerning pace, driven by population growth, rapid urbanization, and industrial expansion [15]. Hence, the widespread attention to the omnipresence of microplastics in environment has grown in recent years [16]. However, the past studies focus on their presence in oceans and terrestrial ecosystems. [17]. In this context, the relatively unexplored area of indoor microplastics becomes an interesting and crucial aspect of the larger microplastic landscape. These microplastics are imperceptible to the naked eye, presence in indoor spaces through various indoor sources, ranging from household products to building materials and manufacturing processes [18]. The indoor environment, often considered a sanctuary from external pollutants, becomes a dynamic arena where microplastics accumulate and posing potential risks to human health [19]. Generally, microplastics refers to the particles ranging from 1 µm to 1 mm in size [20]. Those plastic particles that exceeding 5 mm are categorized as mesoplastics (5 mm to 25 mm) and macroplastics (>25 mm) [21]. In some ecosystems studies, the microplastic could further divided into two categories: 1 mm to 5 mm and less than 1 mm [22]. Typically, microplastics stem from the degradation of larger plastic items/ plastic waste through diverse processes, including but not limited to biological degradation, chemical breakdown, abrasion, fragmentation, etc. [23].

Addressing indoor microplastics aligns with the principles of Sustainable Development Goals (SDG) 3: Good health and well-being [24] and SDG 11: Sustainable cities and communities [25]. Within the framework of SDG 3, it is crucial to acknowledge the potential health risks associated with indoor microplastics, underscoring the importance of ensuring good health and well-being of occupants [26]. On the other hand, creating awareness and implementing policies to manage indoor microplastics aligns with the sustainable and resilient urban environments promoted by SDG 11 [27]. Integrating efforts to address indoor microplastics into these broader sustainability goals reflects a holistic approach to creating healthier living environments within the framework of the SDGs. In alignment with the launch of the SDG 3 and SDG 11, legislative actions have been taken to address the prohibition of plastic bag sales, the imposition of charges on plastic bags, and the implementation of taxes on sellers of plastic bags [28]. Diverse regions, including Australia, North America, and the United Kingdom (UK), have implemented a variety of measures, such as local bans, partial bans, and fees for plastic bags. The UK actively advocates for the prohibition of plastic straws, cotton buds, and stirrers [29]. Certain European nations have implemented extensive measures, which involve the enforcement of charges for each bag [27], while Canada and South Australia both suggested the prohibition of single-use plastic bag [30]. Also, Bangladesh, India, and South Africa have progressively implemented bans on the consumption of plastic bags [31].

Scrutinizing the intricate network of indoor microplastics exposes a substantial gap in the current research landscape. While existing studies have shed light on the abundance of microplastics in outdoor settings, the distinct features of indoor environments, along with varied sources and exposure pathways, underscore the need for focused investigation in this area. This review seeks to address this gap by synthesizing existing knowledge, critically evaluating detection techniques, and exploring the potential health implications of indoor microplastics. This review paper focuses on highlighting the microplastic sources, pathways of exposure, and their impact on human health brings forth a unique contribution to the scientific literature. By synthesizing and critically evaluating the existing research in this research area, this review article aims to consolidate diverse findings and provide a comprehensive understanding of the intricate interplay between microplastics and human

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health. Also, it proposes potential avenues for future research, and offering a synthesized perspective on the collective impact of microplastic exposure on human well-being. This synthesis of information is crucial for policymakers, researchers, and stakeholders alike, as it facilitates the development of informed strategies to mitigate microplastic-related risks and underscores the significance of addressing this emerging environmental and health concern. The novelty of this review article lies in the holistic approach of integrating sources, pathways, and health impacts, thereby fostering a deeper comprehension of the complex dynamics surrounding microplastics in the context of human health.

## 2. Sources of Indoor Microplastics

Indoor microplastic pollution raises concerns for human health and environmental well-being, originating from various sources in residential and industrial settings. Everyday plastic products, such as packaging materials, synthetic textiles, and common household items, contribute to the release of microplastic particles within homes. Activities like cooking, cleaning, and indoor renovations further exacerbate the presence of microplastics in indoor air and water sources. In industrial environments, manufacturing processes in sectors like textiles, packaging, and electronics significantly contribute to indoor microplastic pollution. Specific industrial activities, such as 3D printing and certain waste management practices, also pose risks of introducing microplastics into indoor spaces. Addressing these diverse sources is imperative to mitigate the potential impacts of indoor microplastic pollution on human health and the environment. Figure 1 shows the overall idea of the indoor microplastic sources from the residential and industrial perspectives.

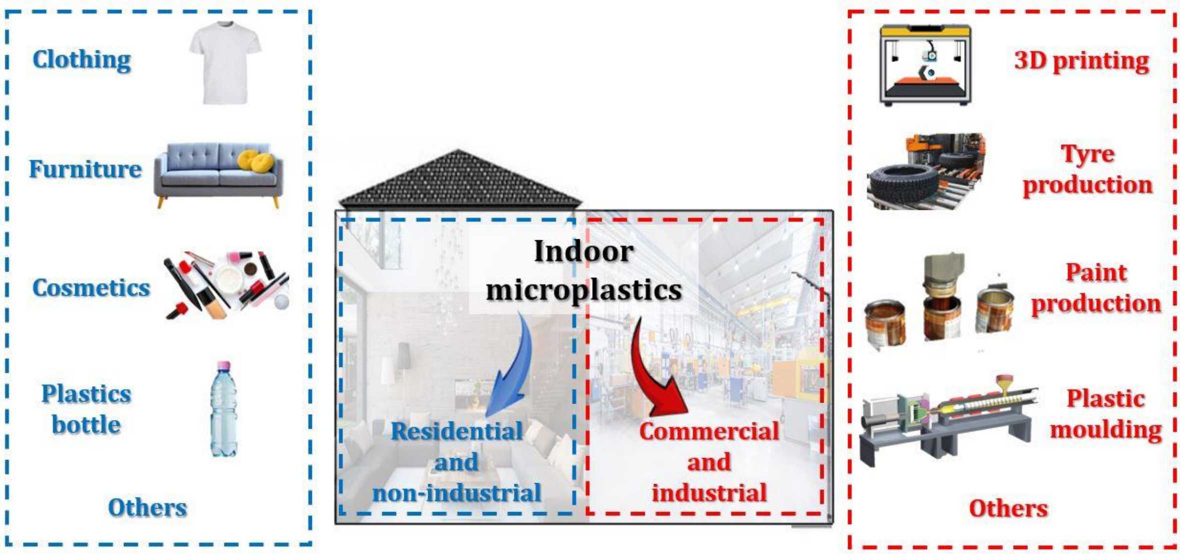


**Fig. 1.** Potential sources of indoor microplastics from residential and industrial perspectives

### *2.1 Residential and Non-Industrial Indoor Environment*

Indoor microplastics originate from a multitude of sources, each contributing to the complex indoor environment. Most of the microplastics are synthetic polymers which derived from petrochemical derivatives. A recent study reported that natural polymers were also presented in indoor environments [32]. Common consumer products, including clothes, furniture, cosmetics, and cleaning agents contain plastic composition for functional purposes. However, the microplastics were generated due to wear and tear of materials, after multiple usages [19]. Polymers such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) are prevalent in these products, releasing microplastics into indoor spaces. For instance, the synthetics grass sheet that covers the floor is made of PE, which commonly reproduced from lower quality or recycled materials [33]. Hence, this material is easily degraded and destructed into microplastics upon expose to sunlight or physical friction [34]. Textiles and synthetic fibers, pervasive in indoor settings as clothing and furnishings, shed microfibers composed of polymers like polyester, nylon, and acrylic [35]. Also, household materials such as paints contain polymers like ABS, contribute to indoor microplastics through degradation and wear [36]. Such a confirmation was performed using a Raman imaging, an effective approach to characterise microplastic and nanoplastic [36]. A recent study also identified that electronic devices as well as it's plastic casing release microplastics due to material lifetime [37]. The wide-ranging sources underscore the importance of considering specific polymer types and compositions to comprehensively address indoor microplastic contamination.

Understanding the polymer-based origins of indoor microplastics is crucial for developing effective strategies to mitigate their presence. Furniture and furnishings including synthetic leather, foam padding, and particleboard behave as the additional microplastics sources in indoor environment, which due to the materials degrade over time [38]. For instance, polymers such as polyurethane, vinyl ester, epoxy resins, phenol-formaldehyde and melamine formaldehyde that commonly used to make the plastic material rigid, contribute to the indoor microplastic load [39]. Identifying the varied origins of these microplastics sources establishes a basis for focused research and intervention strategies aimed at mitigating the influence of indoor microplastics on human health. These microscopic particles penetrate our living spaces via commonplace items, each infused with distinct polymers that collectively shape the intricate composition of indoor microplastics. Common consumer goods, such as personal care items like scrubs, toothpaste, and cosmetics, often contain microplastics as exfoliating agents or functional additives [40]. Table 1 tabulates the potential microplastics sources in various indoor environments.

**Table 1**
Potential sources of microplastics in different indoor environments

| Types of indoor environment | Sources | Continent/climate condition | References |
|---|---|---|---|
| Residential home | Clothing | Europe/ 4 seasons | Jenner, Sadofsky [41] |
| Bedroom/ living room | Bottle (PC) | Europe, South America, North America & Asia/ 4 seasons & single season (tropical) | Zhang, Wang [42] |
| Living room, dormitories, and offices (University) | Recycle plastic materials | Asia/ 4 seasons | Chen, Li [43] |
| Residential homes | Dust | Europe/ 4 seasons | Tian, Skoczynska [44] |
| Laboratories, library, and foyer (University) | Clothing | North America/ 4 seasons | Gaston, Woo [45] |
| Living room | Carpets | Oceania/ 4 seasons | Soltani, Taylor [46] |
| Offices and households | Textiles of PET and others | Asia/ 4 seasons | Xie, Li [47] |

***PC denotes Polycarbonate A-Bisphenol; PET denotes Polyester*

Referring to Table 1, the clothes made of synthetic fibers composed of polymers like polyester and nylon. These material will shed into microfibers and releasing them into the indoor environment after multiple wash (wear and tear) [48]. The process of washing degradation would be sped up low with low pH detergent, high spin-speed, longer duration of washing and drying process [48]. Also, types of washing machine could affect the microplastic release rate. For instance, top-loading washing machine could release microplastic approximately 9 times higher than the front-loading machine, due to the top-loading washing machine exert higher friction with metal perforated baskets

[49]. A recent study disclosed that in the washing process of 6kg clothing, 728789, 496030, and 137951 fiber fragments were emitted when the clothes are made with 100% acrylic (PAN), 100% PET and 65% PET/35% cotton, respectively [50]. Detergents used (powder type) also have positive correlation with the emission of microplastics. Interestingly, De Falco, Gullo [51] and Chiweshe and Crews [52] claimed that powder detergents contain zeolite, an inorganic compound that is insoluble in water and elevates the friction between clothing and the machine.

### *2.2 Commercial and Industrial Indoor Environment*

Microplastics presence in indoor environments through the intricate processes taking place within manufacturing facilities. Factories, hubs of production and innovation, inadvertently contribute to the release of microplastics during various stages of manufacturing. Plastic processing industries, involved in molding, cutting, and shaping raw materials, release microplastic particles into the indoor air as byproducts of these mechanical processes. Polymers commonly used in manufacturing, such as polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC), become sources of indoor microplastics as they undergo transformation within factory settings. The recycling process of electronic wastes in developing countries frequently includes the shredding and burning of plastics, leading to the local release of microplastics [37]. A recent study disclosed that the process of cleaning the 3D printers could release microplastics when the resin residues are dissolved in alcohol (10% ethanol) and expose to UV radiation (5 minutes) [53]. Apart from the cleaning process, fused filament fabrication (FFF), a 3D printing technique also emit noticeable microplastic into the indoor environment during the process of thermoplastic polymers. For instance, styrene is generated as a byproduct when using acrylonitrile butadiene styrene (ABS) filament [54].

The manufacturing factory or industry, such as coatings, paints, and adhesives industries containing polymers like acrylics, epoxies, and polyurethanes, also contributes to microplastic pollution. These substances, integral to the manufacturing process, may degrade over time, or leakage may occur during the waste management system, causing microplastics to be released into the indoor environment [55]. The microplastic released from paint to the environment is estimated to be ranging from 5.2 metric ton to 9.8 metric ton annually [55]. Also, microplastics were identified in the industry that manufacture plastic products, as a result of using plastic pellets [56]. As manufacturing facilities drive technological advancements, understanding the contribution of these processes to indoor microplastics becomes pivotal for adopting sustainable manufacturing practices and ensuring the overall environmental and occupational health of factory settings. Recognizing these sources within factory manufacturing provides a foundation for targeted interventions to mitigate microplastic pollution at its source.

## 3. Pathways of Exposure to Indoor Microplastics

In the exploration of indoor microplastics and their potential impact on human health, a key focus lies in understanding the pathways of exposure. Two predominant routes which are inhalation as well as ingestion. The dispersion of airborne microplastic influenced by various activities and materials, transforms into a dynamic channel for microplastics. Inhaling these tiny particles emerges as a significant means by which they enter the human body. At the same time, the deposition of microplastics on indoor surfaces adds to the composition of household dust, establishing an additional substantial route for ingestion during everyday activities. So far, the studies on the exposure of microplastic via human's skin contact are still limited. Figure 2 shows the pathways of human expose to microplastic through the two common pathways: inhalation exposure and ingestion exposure.

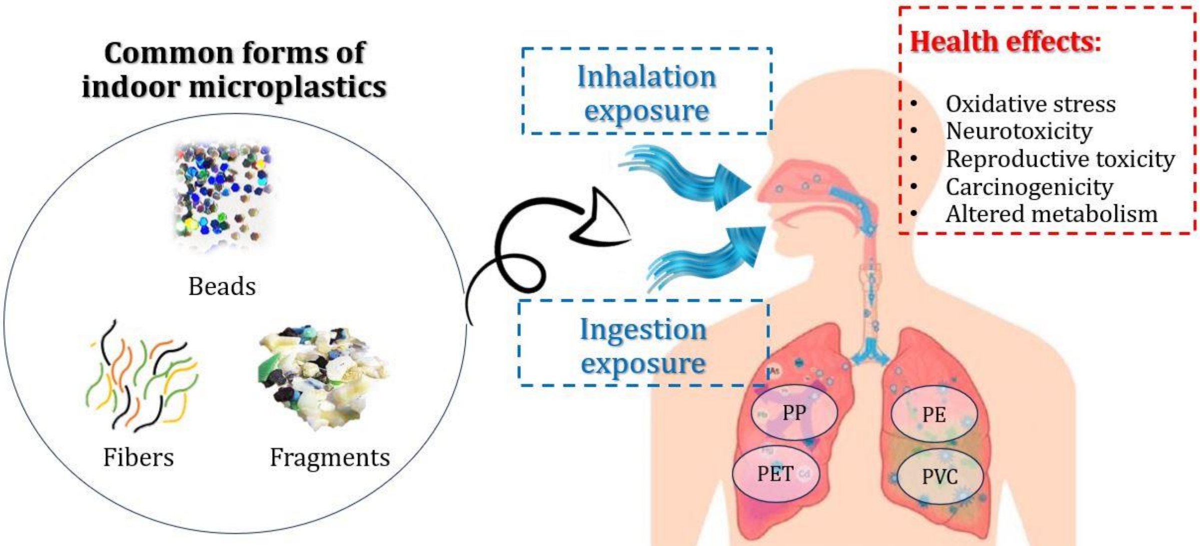


**Fig. 2.** Pathways of human expose to microplastic and its impacts on health (Adapted and revised from Lee, *et al.,* [57])

Referring to Figure 2, the most commonly identified indoor microplastic in indoor environments are fibers [19]. Other shapes such as fragments, films, beads and foams are also discovered in the indoor [41,43]. A recent study found that the average microplastic size found in various indoor environment is 66.15µm, by using a combination of microscope analysis, laser direct infrared imaging (LDIR) analysis, µ-Fourier transform infrared spectroscopy (FTIR) analysis and Raman analysis [57]. This finding is supported by another study, in which also disclosed that the indoor microplastic such as microplastic fibers are having the size ranging from 5m to 1mm [41]. As compared to the microplastic detected at non-indoor environments, the size could range from 50µm up to 2000µm [58].

*3.1 Airborne Transport and Inhalation*

The inhalation of airborne microplastics stands as a prominent pathway through which individuals are exposed to these minute particles within indoor environments. A recent study reported that microplastics found in indoor environments typically exhibited dark, elongated, and solid characteristics [57]. The concentration of airborne microplastic detected in various indoor environment ranging from 4308 particles/m$^3$ up to 14088 particles/m$^3$ [57]. Surprisingly, airborne microplastic detected in laboratory environment is finer in size, and more harmful towards human health [57]. As indoor air quality is influenced by various activities and factors (friction, heating, lighting) and materials, the degradation, wear and tear of plastics from different household items, textiles, and building materials contribute to the release of microplastics into the air [59]. Upon becoming airborne, these microplastics can endure for prolonged durations, constituting a dynamic element of indoor particulate matter. Human activities, such as sweeping, vacuuming, or even simple movements, can resuspend settled microplastics, ensuring a continuous presence in the indoor air [18]. Respiratory exposure becomes particularly noteworthy in spaces where ventilation may be limited, intensifying the potential health impact associated with the inhalation of microplastics. This occurrence gives rise to worries regarding potential long-term health effects, including the emergence of respiratory conditions and the likelihood of transfer to other organs [60]. This pathway underscores the intricate relationship between indoor microplastics and human health, emphasizing the importance of understanding airborne transport dynamics to develop effective strategies for exposure mitigation and risk management.

### *3.2 Ingestion Through Foods or Drinks Intake*

The ingestion of indoor microplastics through dust and food constitutes a significant exposure pathway. Routine activities, such as cleaning and handling objects, can resuspend these particles, leading to their ingestion through inhalation and direct contact. Also, microplastics present in the air can settle onto food surfaces during preparation and consumption [61]. Each individual is expected to consume 13731-68415 particles/Y/capita [62]. Contaminated food items, particularly those with high exposure potential, such as grains, fruits, and seafood, may introduce microplastics into the human digestive system [63]. A recent study identified that human could expose to polypropylene (PP) microplastics via diet (fish) and water, causing the oxidative stress in gill tissues and causes reduction in catalase levels, increment in malondialdehyde level and glutathione level [64]. The most concerning situation arose from the analysis of fish catches in the Northeast Atlantic Ocean. Out of the 150 fish examined (50 per species), 49% exhibited the presence of microplastics [65]. Microplastics were detected in the gastrointestinal tract, gills, and dorsal muscle of fish [65]. According to Barboza, Lopes [65], individuals adhering to the European Food Safety Authority's recommended fish intake may ingest an estimated 842 microplastics per year solely through fish consumption. In a practical clinical setting, microplastics (i.e., polyethylene, polypropylene, polystyrene, and polyurethane) were detected in both the human placenta and meconium (the newborn's initial stool) [66]. These results suggest a potential exposure to microplastics during pregnancy, potentially linked to Cesarean delivery [67]. This intricate interplay between indoor microplastics and daily activities accentuates the need for holistic approaches in assessing exposure risks, considering not only the airborne component but also the potential ingestion pathways that contribute to the overall indoor microplastic load.

### *3.3 Skin Contact and Absorption*

Skin contacts and absorption serves as another pathway for an individual to be exposed to microplastics. Microplastics present in textiles, clothing, and household items can come into direct contact with the skin during routine activities, i.e., washing or using scrubs and cosmetics that contain micro- and nanoplastic [68]. However, the penetration of microplastic into human skin is only limited to microplastics with the size of finer than 100nm [68]. Also, the friction and movement associated with daily tasks, such as sitting on furniture or handling objects, can release microplastics from these surfaces. Once in contact with the skin, these particles may adhere or be absorbed, potentially entering the body through the skin barrier. In 2022, researchers discovered the presence of microplastics in the bloodstream of humans [69]. The effects of microplastics in human blood are currently unknown and are being closely examined by researchers worldwide. Nevertheless, there is a growing concern among researchers that microplastics might have the potential to inflict damage on human cells [69]. Microplastics with a size of up to 40 nm were observed to penetrate into epidermal Langerhans cells surrounding hair follicles [70,71]. This is in contrast to the restricted uptake observed for larger counterparts, including particles measuring 750nm and 1500nm [70]. The presence of microplastics in personal care products, such as exfoliating scrubs and lotions, further heightens the likelihood of direct skin exposure. While the extent of absorption and potential health implications are areas of ongoing research, understanding the pathway of skin contact and absorption is crucial for comprehensively assessing the exposure routes of indoor microplastics. This route contributes to the intricacy of indoor microplastic exposure, underscoring the necessity for additional exploration into the potential effects on skin health and overall well-being.

## 4. Implications for Human Health

The implications of indoor microplastics for human health encompass several critical aspects, beginning with the potential health risks associated with exposure to these minute particles. As microplastics penetrate human body through pathways such as inhalation, ingestion, and skin contact, the absorbed chemicals and additives present on their surfaces may pose health risks. This includes concerns about inflammation, oxidative stress, and the release of toxic compounds, with the potential for adverse effects on various organ systems [40]. Considering cumulative effects and the long-term impact of exposure, the continuous and often unnoticed presence of indoor microplastics raises questions about the potential accumulation of health risks over time. Chronic exposure to microplastics, especially when coupled with other environmental stressors, may lead to persistent health effects that manifest gradually. The cumulative nature of this exposure underscores the importance of longitudinal studies to comprehensively assess the impact of indoor microplastics on human health. A recent study reported that direct exposure of human to microplastic could pose disease such as cancer, as well as cardiovascular toxicity, hepatotoxicity, and neurotoxicity [20]. A recent study reported a potential link between microplastics present in blood vessels and cardiovascular disease [72]. Furthermore, individuals with higher levels of microplastics in their plaque samples also showed elevated levels of biomarkers for inflammation [73], hinting at how these particles could contribute to poor health [73]. Surprisingly, a study revealed that the presence of microplastics in the plaque of patients' carotid arteries increased the likelihood of experiencing a heart attack, stroke, or death within 34 months [74]. Table 2 tabulates various types of microplastic in affecting the human experiences.

**Table 2**
Summary of various types of microplastics on human health

| Types of microplastics | Health impact | Particle size | References |
|---|---|---|---|
| Polyvinyl chloride | • Respiratory issues<br>• Reproductive issues | < 10 nm | [75,76] |
| Polystyrene | • Respiratory issue<br>• Hormone disruption<br>• Adverse neurological effects | 33 µm–190 µm | [77,78] |
| Polyurethane | • Respiratory issues<br>• Weaken immune system<br>• Skin irritation | < 5mm | [79,80] |
| Polyethylene | • Respiratory issues | 0.05 µm–11 µm | [81,82] |
| Polycarbonate | • Hormone disruption<br>• Adverse neurological effects | 5 nm–200 nm | [83,84] |
| Polyethylene terephthalate | • Respiratory issues | 12 µm–18 µm | [85] |

As indicated in Table 2, the majority of the microplastics have the potential to induce respiratory issues. Prolonged exposure to high concentrations of microplastics can result in various effects, including oxidative stress, DNA damage, organ dysfunction, metabolic disorders, immune responses, neurotoxicity, as well as reproductive and developmental toxicity [86]. Several recent studies highlight that microplastics in humans can lead to adverse health effects, including lethality, mental and reproductive issues, intestinal damage, and neurotoxicity [87-89]. Similar finding was also discovered by Wang, Tan [90], who claimed that accumulation of microplastics in tissues leads to swelling and blockage, contributing to adverse health effects. Also, certain populations may be more susceptible to the health implications of indoor microplastics. Vulnerable populations, such as infants, pregnant women, and individuals with pre-existing health conditions, may experience heightened risks due to their unique physiological conditions and increased sensitivity [91]. Understanding the specific vulnerabilities within these populations is crucial for targeted risk assessment and the development of protective measures. As research in this field progresses, unraveling the complex interplay between indoor microplastics and human health is essential to inform public health strategies and ensure the well-being of diverse populations.

## 5. Conclusion and Recommendation of Future Works

In conclusion, this systematic review provides a comprehensive synthesis of the current knowledge on indoor microplastics, highlighting the diverse indoor microplastic sources, exposure pathways, and potential human health implications associated with these microplastic contaminants. The collective findings underscore the various ways in which microplastics are being released into indoor environments, originating from commonplace items such as textiles, consumer goods, furniture, etc. Also, this review article illuminates the potential health risks posed by indoor microplastics, with a focus on respiratory concerns, ingestion, and the broader spectrum of physiological impacts. The compilation of current research serves as a valuable asset for researchers, policymakers, and healthcare professionals, providing guidance for upcoming inquiries and interventions designed to reduce the influence of indoor microplastics on human well-being.

In future work, more studies shall be conducted to reduce the concentration of indoor microplastics, by means of ventilation strategies or material choices. Also, it is suggested that researchers could explore other potential approaches to reduce the concentration of microplastic in indoor, as this proactive measure can enhance safety awareness and precautions for occupants. Exploring the effectiveness of public awareness campaigns in influencing individual behaviours related to plastic use within indoor spaces is another avenue that merits attention. Future study should strive to bridge existing knowledge gaps, offering practical solutions to mitigate the impact of indoor microplastics on both environmental health and human well-being.

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