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REVIEW ARTICLE

Indoor microplastics: a comprehensive review and bibliometric analysis

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Abstract
Indoor microplastic (MP) pollution is becoming a worldwide issue because people spend more time inside. Through dust and air, indoor MP pollution may harm human health. This review summarizes recent advancements in indoor MP research, covering pretreatments, quality control, filter membranes, and identification methods. Additionally, it conducts bibliometric analysis to examine the usage of keywords, publication records, and authors' contributions to the field. Comparatively, dust and deposition samples exhibit higher MP concentrations than indoor air samples. Fiber-shaped MPs are commonly detected indoors. The color and types of MPs display variability, with polypropylene, polyethylene, polyethylene terephthalate, and polystyrene identified as the dominant MPs. Indoor environments generally demonstrate higher concentrations of MPs than outdoor environments, and MPs in the lower size range (1–100 µm) are typically more abundant. Among the reviewed articles, 45.24% conducted pretreatment on their samples, while 16.67% did not undergo any pretreatment. The predominant filter utilized in most studies was the Whatman Glass microfiber filter (41.67%), and MPs were predominantly characterized using µ-FTIR (19.23%). In the literature, 17 papers used blank samples, and eight did not. Blank findings were not included in most research (23 articles). A significant increase in published articles has been observed since 2020, with an annual growth rate exceeding 10%. The keyword microplastics had the highest frequency, followed by fibers. This indoor MP study emphasizes the need for collaborative research, policymaking, and stakeholder involvement to reduce indoor MP pollution. As indoor MP research grows, so are opportunities to identify and minimize environmental and health impacts.

Keywords Pretreatment · Indoor Environments · Fibers · Human Health · Dust · Air

Abbreviations

Acr	Acrylic
ABS	Acrylonitrile Butadiene Styrene
ATR-FTIR	Attenuated total reflectance Fourier transform infrared spectroscopy
CL	Celloluse
CE	Cellophane
CA	Cellulose acetate
CTA	Cellulose triacetate
CO	Cotton
EDX	Energy Dispersive X-Ray Analysis
EP	Epoxy resin
EVA	Ethylene vinyl acetate
EPR	Ethylene-polypropylene
EPDM	Ethylene-propylene-diene-monomer
MPs	Microplastics
PF	Phenolic Resin
PR	Phenoxy resin
PEP	Poly (ethylene:propylene)
PTFE	Poly tetrafluoroethylene
PAN	Polyacrylonitrile
PA	Polyamide
PC	Polycarbonate

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Highlights
• Higher concentrations of MPs were seen indoors than outdoors, and fibers were the predominant shape of MPs (37.1% of studies) in indoor environments.
• Lower-size MPs (1—100 µm) mostly had a higher concentration.
• MPs were mainly characterized using a µ-FTIR (19.23%).
• The number of blank samples used in most research was not reported.
• Indoor MP analysis requires standardization.

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PES	Polyester
PE	Polyethylene
PET	Polyethylene terephthalate
PEI	Polyethylenimine
PLA	Polylactic acid
PP	Polypropylene
PS	Polystyrene
PSU	Polysulfone
PUR	Polyurethane
PVAc	Polyvinyl acetate
PVA	Polyvinyl alcohol
PVC	Polyvinyl chloride
QA	Quality assurance
QC	Quality control
RAY	Rayon
RC	Resin
RB	Rubber
SEM	Scanning electron microscope

Introduction

The issue of microplastics (MPs) and microscopic plastic particles, which are less than 5 mm in size, has become a substantial environmental concern due to their widespread pollution in natural ecosystems. Nevertheless, the issue of MP has expanded to encompass indoor environments, such as residential dwellings, commercial establishments, and public buildings (Bhat 2023). The indoor environment, which includes houses, businesses, markets, transportation, etc., is essential to contemporary human existence since people spend so much time inside (up to 90% or more) (Bhat et al. 2022a; Klepeis et al. 2001). MP expansion in these indoor environments is due to the widespread recognition of these spaces as potential sources of MP contamination (Bhat 2023; Bhat et al. 2021; Fang et al. 2022; Kashfi et al. 2022). MPs can exist in various shapes, such as pellets, films, foam, fragments, and microbeads. The most commonly manufactured plastics are polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), polystyrene (PS), polyurethane (PUR), polyvinyl chloride (PVC), polyamide (PA), and polycarbonate (PC). The presence of MPs in indoor environments is a matter of significant concern due to the potential risks they pose to human health and the environment.

One of the essential parts of studying MPs in the indoor environment is determining their sources. Although the literature on their sources is limited, some basic information is enough to analyze the problem. The primary sources of MPs in the indoor environment include synthetic textiles, the finishes used on household items, and cleaning materials (Bhat et al. 2021; Chen et al. 2020). Clothing, bedding, curtains, carpets, and other items made from synthetic or semi-synthetic fibers such as acrylic (Acr), PA, PES, polyolefin, elastane, or rayon (RAY) are some of the most common contributors to microfibres released into indoor air, typically through shedding during daily movement and use (Bhat et al. 2021; Zhang et al. 2020b). Release from the synthetic material happens in all indoor environments, whether homes or businesses. Its density depends on how many people live there and how much air moves through it. Another source of indoor MPs is the deterioration of all surface finishes, including wall and ceiling paints, PVC and PUR flooring, wallpapers, other plastic goods, kitchen plastic utensils like scouring pads, brushes, and towels, and basic multipurpose hygiene products. MPs are frequently released from these surfaces when used, cleaned, rubbed, cut, scratched, or maintained (Bhat 2023; Lassen et al. 2015). The density of MPs discharged into the indoor air is determined by the frequency with which they are used, maintained, and cleaned. MPs will be produced more significantly in residential kitchens than in comparable office facilities. Offices will produce more MP pollution associated with electronic equipment, printing, shredding etc. (Kacprzak and Tijing 2022). Indoor environments are also sensitive to outside MP sources, such as industrial or agricultural emissions specific to those industries' operations, and include MPs. The other typical external contaminant problem in many interior settings is traffic MPs from automobile tires (Tamis et al. 2021). Indoor spaces near busy highways are particularly prone to MP contamination from traffic. Although these sources are born externally, they may easily penetrate these spaces. These MPs can penetrate indoor environments through multiple entry points, including ventilation systems, interior activities such as cleaning and cooking, and the infiltration of outdoor air. MPs have the potential to accumulate on diverse indoor surfaces such as floors, carpets, and furniture, and can also be inhaled or ingested by individuals. The extent of indoor air pollution caused by MP within a building is influenced by various factors, such as the geographical and architectural characteristics of the building, the efficiency of its ventilation system, and the nature of activities conducted within its premises. The issue of MP contamination has frequently been attributed to indoor environments (Bhat 2023; Gaston et al. 2020; Ouyang et al. 2021).

The presence of MPs in indoor environments has been investigated by examining dust, air, and deposition samples. Dris et al. (2017) detected the presence of PA, PP, and PE MPs in apartments, offices, and house dust in France. The concentrations of these MPs ranged from 190—670 fibers mg^{-1}. In another study, Nematollahi et al. (2022) detected the presence of PET, PP, PS, and PA in dust samples collected from schools in Iran. The concentrations of these MPs ranged from 10—635 MPs g^{-1}. Gaston et al. (2020) identified the presence of PVC, PE, PS, PC, PA, and acrylonitrile butadiene styrene (ABS) in indoor air samples collected from university and hospital environments. The concentrations of these MPs were measured as fibers

(3.3 ± 2.9 fragments m^{-3}) and (12.6 ± 8.0 fragments m^{-3}). In a recent study conducted by Uddin et al. (2022), it was observed that the concentrations of PES and PA in air samples collected from various locations in Kuwait, including government buildings, residential dwellings, hospitals, and mosques, ranged from 3.24—27.13 MP m^3. Yao et al. (2021) conducted an indoor deposition study wherein they observed the presence of PS, PET, PE, PVC, and PP MPs. The concentrations of these fibers ranged from $(6.20 \pm 0.57) \times 10^3$ to $(1.96 \pm 1.09) \times 10^4$ fibers m^{-2} day^{-1} in various university environments (i.e., office, hallway, classroom) as well as in residential houses. In another indoor deposition study, Fang et al. (2022) discovered the presence of PET, PE, and PA MPs at a concentration of $(7.6 \pm 3.9) \times 10^5$ MPs m^{-2} day^{-1} in various indoor environments in China, including dining rooms in apartments, dining halls on campuses, restaurants, offices, and classrooms.

Despite a lack of empirical evidence concerning the adverse effects of MP pollution, it is crucial to recognize their potential as a significant concern, considering the continuous rise in their levels. Several studies have confirmed the presence of MPs in aquatic ecosystems. However, limited research has been conducted on airborne MPs in terrestrial environments, specifically indoor air environments (Bhat et al. 2023a, b; Kacprzak and Tijing 2022). A significant amount of studies, exceeding 96%, focus on examining MPs within marine and aquatic ecosystems. It is explicitly acknowledged that the primary source of these MPs in such environments is terrestrial. Nevertheless, there appears to be a lack of emphasis on research about MP within terrestrial ecosystems (Thacharodi et al. 2024; Xu et al. 2020). Although there is limited research and data on the assessment of MP prevalence and quantity in indoor environments, some studies have found significantly higher levels of MP content in air and dust samples collected from various indoor environments compared to outdoor environments (Kacprzak and Tijing 2022; O'Brien et al. 2023). A total of thirty-two research articles have been published on the subject of ambient air in outdoor environments. In comparison, a comparatively smaller number of eleven research articles have been published on indoor environments. Nine research studies have been conducted on indoor dust, whereas twenty-eight have been conducted on outdoor dust (O'Brien et al. 2023). The investigation of the impact of MPs on the human digestive system has primarily focused on exposure through contaminated food, particularly seafood, while inhalation exposure has received comparatively less attention in academic research (Bhat et al. 2022b; Prata et al. 2020b; Rahman et al. 2021). According to some researchers, people exposed to indoor MPs inhale an average of 26—130 airborne MPs daily (Prata 2018). Cox et al. (2019) identified an average concentration of 9.8 MPs per m^3; the results showed that males and females were exposed to 170 and 132 MPs per day, respectively, while male and female children were exposed to 110 and 97 MPs per day. Based on an average global airborne MP concentration of 0.685 particles/m^3 and a breathing rate of 8.64 m^3 per day, Domenech and Marcos calculated a relatively low global human daily inhalation intake of 5.9 MPs per day (Domenech and Marcos 2021). Other researchers have suggested that the number might reach as high as 272 MPs per day (Vianello et al. 2019). Different sampling techniques and environments may be the leading causes of the variability. Other factors such as how a space is used and occupied, the type of ventilation used, where the sampling equipment was placed, how much outside air entered the indoor environment, and the accumulation of primary and secondary MPs may also have impacted the results' variability.

Human reactions to inhaled MPs include chronic inflammation like bronchitis and allergic reactions like asthma or pneumonia (Kacprzak and Tijing 2022). Inhaled MPs in the body can be removed by clearing systems like sneezing, phagocytosis, lymphatic transport, and mucociliary escalator. Still, people with weak immune systems are more likely to experience chronic inflammation due to the accumulation of MPs in their bodies (Prata 2018). Even though the human body has clearing systems, removing MPs, especially fibers, is difficult because these particles have a large surface area. They are transporters of various contaminants because of their larger surface areas. They adsorb contaminants, such as pathogenic microorganisms, and release them, making them more hazardous (Bhat et al. 2023a, b; Prata 2018). The large surface area of airborne MPs makes them dangerous, regardless of whether or not they have oxidative organisms or other harmful compounds adsorbing to their surface. When the body's clearance system is compromised, MPs can be toxic through various mechanisms, including dust overload, oxidative stress, cytotoxicity, disruption of metabolism, and translocation. Furthermore, the MPs' persistent nature makes removal difficult, which in turn causes inflammatory responses. The presence of chronic inflammatory lesions may facilitate the onset of malignancy. Inflammation, followed by translocation or cancer, might result from any route of exposure, including the skin, inhalation, or digestion (Prata et al. 2020b). Studies document MPs in human intestinal tracts, placental tissue, blood, and lung tissue, though effects on humans remain largely unknown (Ibrahim et al. 2021; Leslie et al. 2022; Pauly et al. 1998; Ragusa et al. 2021). Despite limited knowledge of the effects of human exposure to airborne MPs, it is clear that exposure to MPs may be associated with an increased incidence of many diseases, such as immune disorders, neurodegenerative diseases, cardiovascular diseases, congenital disorders, or cancers, and due to their bioresistance and biopersistence characteristics, they may be difficult to remove from the bodies (Amato-Lourenço et al. 2020). Even evaluating the potential risks MPs pose to human health is a complicated procedure that requires an analysis of the toxicity, exposure, and classification of hazards. The potential adverse effects of MPs on human and environmental health are becoming an increasing source of worry and call for more study and regulatory action (Bhat et al. 2023a, b; Eraslan et al. 2023). The true potential of indoor MPs is still very unclear and inconsistent.

The present study involved the collection of literature that quantifies MPs in indoor environments. The collected data was organized based on publication year, synthesized, and subjected to statistical analysis. The study examined the macro trends or similarities by analyzing the varying sampling and analytical methods, concentrations, and morphological information of identified plastics, including their shape and size, as well as the diverse polymer compositions of MPs in indoor environments. Moreover, the presence of knowledge gaps was subsequently recognized, leading to the presentation of future research directions aimed at facilitating knowledge acquisition in this developing field.

Material and methods

The current investigation utilized a traditional search mechanism, Web of Science, to locate scientific research examining MPs in different indoor environment aspects, such as ambient air, fallout, and dust. The Web of Science database is widely utilized for empirical metrology. This database has been commonly employed across various disciplines in numerous bibliometric studies (Bhat et al. 2023a; Eraslan et al. 2021). The search strategy employed involved the utilization of pertinent keywords, specifically "Microplastics" and "Indoor," within the time frame spanning from 2004 to 18/04/2023. The study retrieved 123 articles, comprising 29 review articles, two editorial materials, one proceeding paper, and 91 research articles. The literature was peer-reviewed and published. The bibliometric analysis excluded review articles, editorial material, and proceeding papers. These research articles are indexed in Science Citation Index Expanded (85), Emerging Sources Citation Index (5), and Social Sciences Citation Index (1). Bibliometric analysis entails the categorization of an article based on specific characteristics.

- The phenomenon of coauthorship among authors. A total of 35 authors were found to have a minimum of two documents attributed to them.
- Co-occurrence of all keywords. The occurrence of keywords was greater or equal to 2.
- The minimum number of documents selected was 10, with a minimum of 10 citations, and the top 10 research articles were selected.
- The minimum number of articles per journal was two or more, and the top ten journals were selected.

A comprehensive review of all collected research articles was conducted to verify that each article pertained exclusively to indoor dust, fallout, and ambient samples. A total of 28 articles were subjected to statistical analysis, as certain articles focused on masks in indoor environments, aging of MPs in indoor environments, air conditioner filters, quality control (QC) and assurance(QA) of indoor MPs, indoor air quality, and the interaction of MPs with microorganisms in indoor environments or were reviewed papers and did not pertain to indoor dust, deposition, and ambient samples. The proportion of papers in the field of indoor MP studies was as follows: 11 articles (39.28%) focused on air, 11 articles (39.28%) examined dust, and six articles (21.42%) investigated deposition. The entirety of the articles were composed in the English language. The data analysis and graphical representations were conducted utilizing Microsoft Excel and Origin (2018). The bibliometric analysis was conducted using the VOSviewer software.

Review literature analysis

The literature analysis holds significant significance in indoor MP studies because it provides a comprehensive synthesis of existing research, offering valuable insights and facilitating the consolidation of knowledge. This tool enables researchers to discern deficiencies in knowledge, investigate patterns, and assess the general condition of the discipline. By examining existing scholarly literature, researchers can acquire a more comprehensive comprehension of the origins, routes, and possible health ramifications associated with MPs found indoors. It facilitates the identification of research gaps and guides future inquiries. Literature analysis in policymaking plays a crucial role by facilitating empirical evidence to inform decision-making processes and formulate impactful strategies to address indoor MP pollution and safeguard human well-being.

Sampling and pretreatment of samples

The sampling methodology adopted for indoor MPs varied between studies. MPs in the air can be collected using passive or active sampling. Active sampling uses a pumping sampler, whereas passive sampling entails a collection column or funnel, a receiving tube, and a final collection bottle. The active sampling technique can efficiently reduce the sample period and offer data on the MPs in the air mass that might not settle. The passive sampling method provides information about the MPs falling onto the surface. Dry and wet passive sampling have different applications and outcomes. Dry passive sampling uses samplers without liquid or moisture-absorbing material to detect airborne gaseous contaminants. In indoor and outdoor air quality monitoring, it detects volatile and semi-volatile organic compounds. Wet passive sampling uses liquid or gel-phase sorbents to capture dissolved or suspended contaminants in water. It measures pesticides, heavy metals, and organic pollutants in rivers and lakes. Dry samplers employ diffusion and adsorption onto solid sorbents, whereas wet samplers use liquid sorbents to absorb and retain analytes. Dry sampling is best for nonpolar and volatile chemicals, whereas wet sampling works for polar and nonpolar analytes. Hence, passive sampling to collect atmospheric deposition is recommended in conjunction with active sampling to gain a complete picture of air MP content. A sampling pump has been used for active sampling in many indoor environments like universities, hospitals, apartments, offices, classrooms, transit station waiting halls, living rooms, office rooms, nail salons, and mosques (Chen et al. 2022; Gaston et al. 2020; Liao et al. 2021; Uddin et al. 2022; Xie et al. 2022). Dust and deposition involved using vacuum cleaning, directly exposing filters, vacuum cleaner bags, glass petri dishes, and directly sweeping the floor with a nylon brush, horsetail brush, hog bristle brush, or steel dustpan (Dris et al. 2017; Kashfi et al. 2022; Liu et al. 2019a; Zhang et al. 2020a) in indoor environments like apartments, office, homes, bedrooms, living rooms, dining rooms in an apartment, the dining hall in campus, restaurant, and classrooms.

Various methods are employed for the pretreatment of indoor MPs, such as sieving, digestion, density separation, filtration, and drying. The objective of the pretreatment procedure is to segregate MPs from other contaminants, eradicate the pollutants adhered to MP, intensify the concentration of MPs, and facilitate the identification of MPs (Bhat et al. , 2021, 2023a, b; Luo et al. 2022). The analysis of the literature review on indoor articles (28) revealed that approximately 45.24% of these articles had conducted pretreatment on their samples. This pretreatment typically involves the utilization of chemicals for processes such as density separation or digestion. The works comprising 16.67% of the total have not undergone any pretreatment (Boakes et al. 2023; Field et al. 2022; Lim et al. 2022; Soltani et al. 2021; Torres-Agullo et al. 2022; Uddin et al. 2022; Zhang et al. 2020b). The experimental results indicate that a combination of density separation and acidic digestion was employed to treat the samples comprising 9.52% ($ZnCl_2 + H_2O_2$) (Abbasi et al. 2022; Chen et al. 2022; Nematollahi et al. 2022; Zhu et al. 2022), and 4.76% ($NaI + H_2O_2$) (Kashfi et al. 2022; Prata et al. 2020a). Nile red has also been employed in studies to characterize MPs (Abbasi et al. 2022; Cui et al. 2022; Soltani et al. 2021; Torres-Agullo et al. 2022) (Fig. 1). Nile Red is crucial in MP analysis as it is a fluorescent dye that selectively binds to plastic particles, enhancing their visibility under fluorescent microscopy. This enables efficient identification and quantification of MPs, aiding in understanding their distribution, impact, and environmental mitigation strategies.

To minimize losses in cases where the suspended aerosols concentrated on glass microfiber filters have fewer impurities, it is advisable to exclude density separation and digestion (Gaston et al. 2020; Liu et al. 2019b; Wang et al. 2020). While digestion and density separation are necessary, it is advised to concentrate the processed sample for visual inspection using gridded membrane filters with smooth surfaces (such as mixed cellulose ester membranes) (Luo et al. 2022). The sample can be identified and processed without pretreatment methods such as sieving, digestion, density separation, and filtration. This approach eliminates

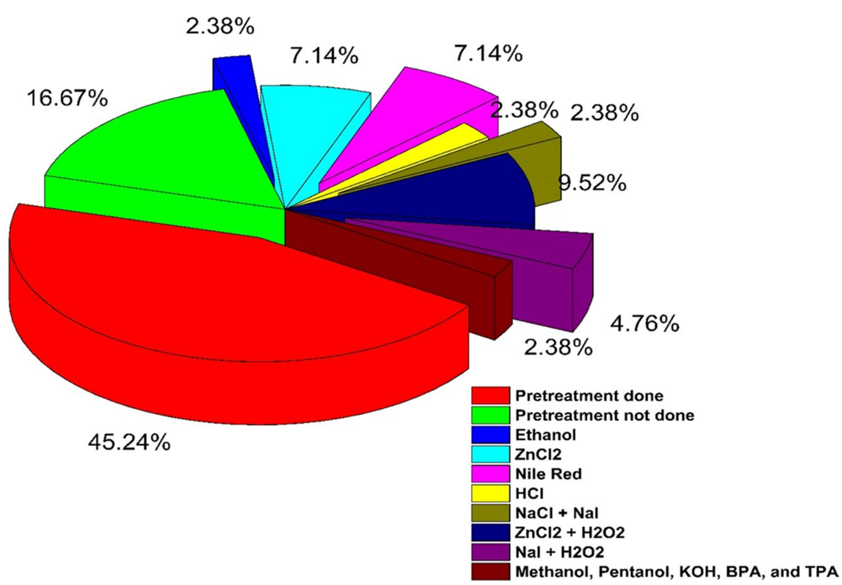


Fig. 1 Pretreatment of indoor microplastics summarized from the published literature

the potential for contamination caused by the pretreatment process. Notably, the surface characteristics of MPs may be modified by acidic digestion, which could conceivably impact their analysis or interpretation. However, Xie et al. (2022) highlight that the samples should be treated with dilute hydrochloric acid to remove the calcium carbonate, which may generate noise during Raman spectroscopy. Luo et al. (2022) reviewed the literature and found that in total suspended particulates (suspended aerosol), just four studies have done pretreatment steps like acidic digestion and one density separation. In dust deposition (atmospheric deposition) by using a brush and metallic pan, one study has done acidic digestion and two-density separation. By vacuum cleaning, one has done acidic digestion and three-density separation steps.

Filter membranes in indoor studies

The process of filtration can effectively concentrate MPs onto the filter membranes. Filters play a crucial and indispensable role in analyzing MPs as they facilitate the segregation and enrichment of plastic particles from samples obtained from the environment (Kundu et al. 2021). These entities function as a tangible obstruction, effectively entrapping larger particles while permitting the passage of smaller ones (Pandey et al. 2023; Rani et al. 2023). Filters play a crucial role in enhancing the effectiveness of the extraction and subsequent analysis of MPs, thereby enabling a precise evaluation and understanding of their prevalence, chemical makeup, and potential environmental consequences. Filters may influence the analysis of MPs when using instrumentation (Rani et al. 2023). The use of filters in MP analysis, especially in spectroscopic methods like FTIR or Raman spectroscopy, can introduce challenges such as background noise, sensitivity disruption, and spectral interference or exhibit peaks that coincide with microplastic spectra, affecting the accuracy of identification and quantification. To ensure the reliability of MP analysis results, it is crucial to carefully select filter materials and conduct thorough instrument calibration and validation to account for potential filter-related effects (Bhat 2023; Bhat et al. 2023b; Rani et al. 2023). Nine distinct types of filter membranes have been employed in indoor MP studies. Most studies have employed Whatman Glass microfiber filters (41.67%) (Dris et al. 2017; Gaston et al. 2020; Prata et al. 2020a; Soltani et al. 2021). Other frequently utilized filters include PTFE membranes (12.5%) (Choi et al. 2022; Fang et al. 2022; Liu et al. 2019a), Silver membranes (12.5%) (Boakes et al. 2023; Chen et al. 2022; Vianello et al. 2019), Cellulose ester membranes (8.33%) (Aslam et al. 2022; Jenner et al. 2021) etc. (Fig. 2).

Identifying MPs in environmental samples is essential, and selecting filter membrane materials is crucial in facilitating this procedure. Various materials, including PA, PES, glass fiber, and polyethersulfone, may influence the efficacy and precision of MP detection. PA and PES membranes are often used due to their robustness and ability to interact well with various solvents (Casino et al. 2023; Pandey et al. 2023; Rani et al. 2023). However, it is important to note that these membranes may retain some fibers, which might result in erroneous positive outcomes. Glass fiber filters are highly regarded due to their significant capacity for retaining particles and their little contamination from surrounding sources. On the other hand, polyethersulfone membranes, characterized by their hydrophilic nature, have a poor affinity for binding proteins, which can be advantageous for some MP sampling (Casino et al. 2023). The size of pores is critical in determining the spectrum of MP sizes that may be effectively collected. The size of the filter papers was mostly constant (47 mm) however, the differences were seen in pore size of filter membranes used for sampling in indoor MP literature like 0.8 μm (Vianello

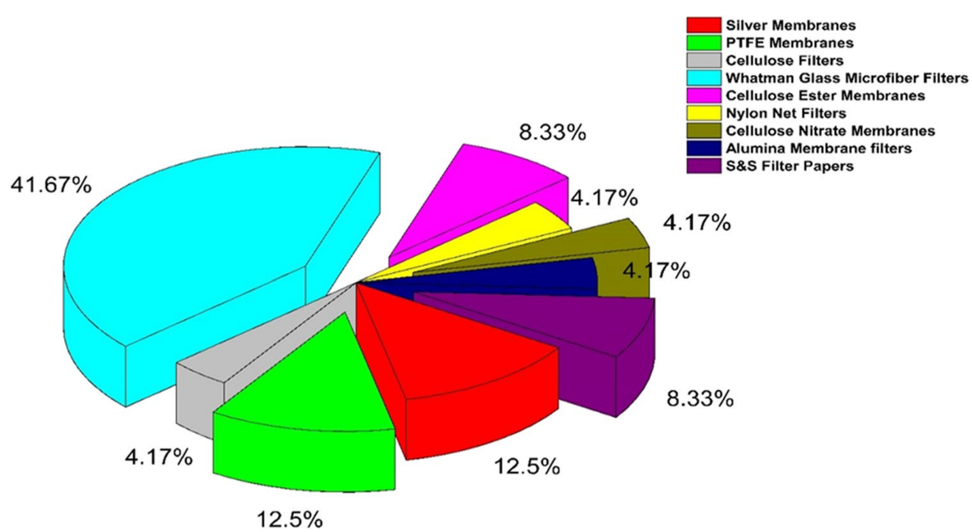


Fig. 2 Frequency of different filter membranes used in indoor microplastic studies

et al. 2019), 1.2 µm (Liu et al. 2019a), 5 µm (Jenner et al. 2021; Zhang et al. 2020b), 1.6 µm (Amato-Lourenço et al. 2022; Bahrina et al. 2020; Dris et al. 2017; Gaston et al. 2020), 0.7 µm (Liao et al. 2021), 0.6 µm (Boakes et al. 2023; Prata et al. 2020a), 20 µm (Choi et al. 2022; Torres-Agullo et al. 2022), 0.45 µm (Aslam et al. 2022; Chen et al. 2022; Cui et al. 2022; Fang et al. 2022), 0.22 µm (Xie et al. 2022), 2 µm (Abbasi et al. 2022; Kashfi et al. 2022; Nematollahi et al. 2022; Zhu et al. 2022) and 0.2 µm (Field et al. 2022).

Quality control and assurance

Implementing QC and QA measures is of utmost importance in analyzing MPs, as they play a critical role in ensuring the outcomes' dependability and precision. The QC/QA encompasses the implementation of standardized protocols, calibration of instruments, validation of sample handling, and verification of data. These measures serve to minimize variability and errors. Implementing appropriate QC/QA measures improves data integrity, comparability, and confidence, thereby facilitating rigorous evaluations and well-informed decision-making on MP pollution. The literature review analysis suggests that 17 articles incorporated blank samples in their research, while eight articles did not include blank samples. Notably, most studies (23) did not integrate blank results within their actual samples. In the samples of 16 studies, no MP was identified (Fig. 3). A total of 9 studies successfully detected MPs in their respective blank samples, while six studies incorporated the results from blank samples into their actual samples (Fig. 3). The variations were seen in the presence of MPs in blank samples, Vianello et al. (2019) identified 7.7 ± 3.8 MPs per blank sample, 1—5 fiber per liter (Zhang et al. 2020b), ≤ 3.4 MP fibers or fragments per liter (Gaston et al. 2020), 323 fiber and 319 particles in three field blanks (Prata et al. 2020a), 25 MPs ranging from 0—1 per sample (Jenner et al. 2021), 0—3 fibers per filter (Soltani et al. 2021), seven fibers and five fragments m^{-3} (Torres-Agullo et al. 2022), 1.9 ± 1.2 MPs $dish^{-1}$ (Fang et al. 2022), 1—5 MPs/g. Two studies have highlighted the type of MPs in their blank samples PES, PA, PS, PE, and PUR (Vianello et al. 2019) and PUR, PP, PVC, PET, and PP (Jenner et al. 2021).

The entire sample treatment procedure involved the omission of digestion and flotation techniques to minimize the loss of particles or contamination by MPs throughout multiple stages (Soltani et al. 2021; Zhang et al. 2020b). Some studies may have neglected to take blank samples, or if they did take them, they might not have accounted for contamination when analyzing the samples. Furthermore, there may be instances where such information was not disclosed in the study's results. Pretreatment can even contaminate the actual sample. Prata et al. (2020a) found sample treatment solely introduced 27 fibers from contamination, and pre-sampling introduced a mean of 106 fibers, being the primary source of contamination for air samples. Torres-Agullo et al. (2022) found fiber was the dominant type of MP in blanks with a concentration of 7 fibers/m^3.

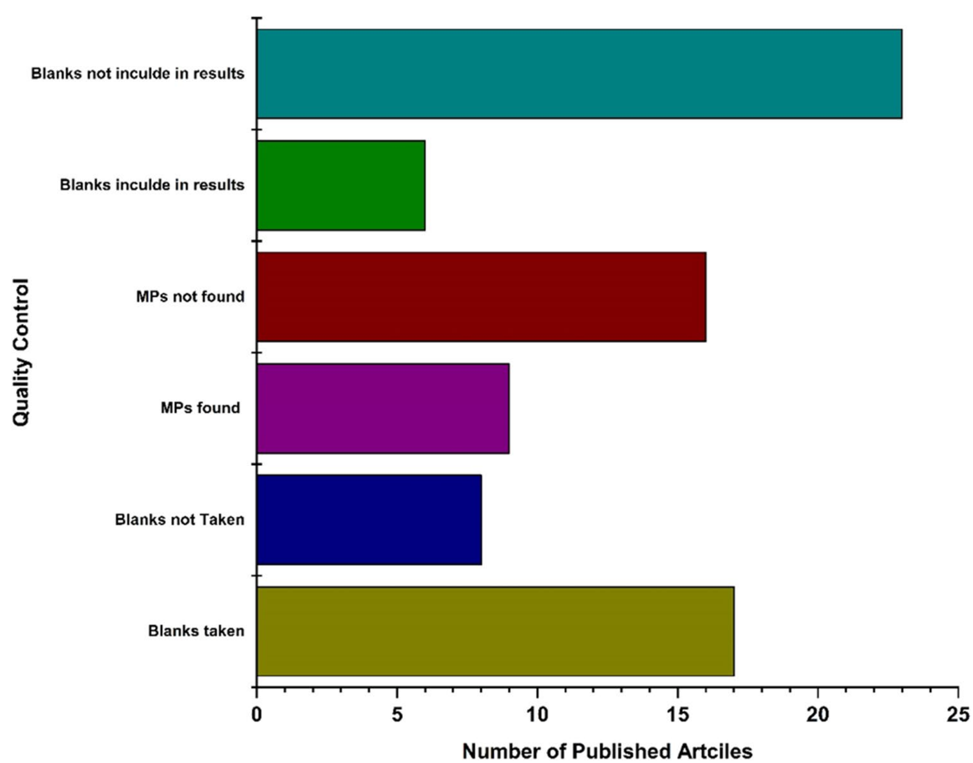


Fig. 3 Quality control procedures in indoor microplastics studies

Analyses of MPs demonstrate that field studies are challenging because of the wide variety of samples and analytical methods available to detect and quantify MPs. The wide variety of sampling approaches makes it difficult to meet the need for additional, higher-quality data. Due to the lack of standardization of methodologies for monitoring MPs in airborne and indoor environmnets, substantial difficulties in comparing results are caused (Thacharodi et al. 2024; Enst 2021). The approaches that are used can have a significant impact on the results that are obtained. MPs have been expressed using a wide range of different units, including particles per liter, spheres per liter, beads per liter, particles per square meter, particles per square meter per day, particles per liter, particles per kilogram, pieces per kilogram, items per kilogram, and kilograms per liter (liters can refer to water or sediment and kilogram can refer to dry or wet weight) (Bhat et al. 2023a, b). Also, various publications alter and convert the units they use for various purposes, and it is not always obvious which options are used throughout these transformations. In addition, there are many ways to categorize MPs depending on their morphology (fragments, pellets, beads, lines, fibers, films, and foams) and the kind of polymer they are made of (PP, PE, PS, etc.). While the latter is frequently capable of accurate determination, the criteria for characterizing the form are not always readily apparent. As a result, the procedures for collecting, processing, and evaluating samples and data are not standardized. MPs can be classified in a broad range of ways, including by shape, polymer type, and/or composition. This makes it difficult to compare the results of different studies directly and possibly leads to uncertainty between the findings of different investigations. A clear understanding of the dynamics and implications of MPs is also hampered, and stakeholders are prevented from taking the appropriate steps to address and (if required) alleviate the problem. In designing and implementing processes for collecting, analyzing, and characterizing MPs per suitable QC and QA standards, much work remains to be done. This is because MPs are a broad category of pollutants that significantly differ from one another in terms of their morphology, chemical characteristics, texture, color, density, and size. Contamination control techniques, which are an integral part of QC/QA, are one of the characteristics that differ from one study to the other studies.

Notwithstanding the critical nature of the issue, the capacity of many research organizations and laboratories to achieve comprehensive consistency heavily depends on their success in acquiring funding and infrastructure. There is no single method that is suitable for every laboratory, and not every laboratory is equipped to perform high-level and expensive treatments. As the field of study expands, new and innovative methods emerge in the scientific literature. One example of this is the ability of researchers and equipment to identify ever-smaller particles (Hermsen et al. 2018). Since MPs are present everywhere, even indoor air (Abbasi et al. 2022; Amato-Lourenço et al. 2022; Chen et al. 2022; Choi et al. 2022) and outdoor air (Abbasi et al. 2019; Allen et al. 2019; Amato-Lourenço et al. 2022; Choi et al. 2022). If adequate methods for controlling contamination are not followed, there is a risk that samples may be contaminated, which will lead to an inaccurate representation of the data. The presence of MPs in all matrices and environments, even under minor anthropogenic pressure (rural or virgin areas) (Allen et al. 2019; Bergmann et al. 2019; Ivar et al. 2013; Jiang et al. 2019; Lusher et al. 2015; Xiong et al. 2018) demonstrates the need for stringent controls not often applied to the management of other environmental contaminants when the risk of sample cross-contamination is low.

Yet, looking at quantitative contrasts of levels of MP contamination in the same or comparable species collected from diverse regions and of any trends over time remains very difficult. It is subject to considerable uncertainties because of procedural differences and problems in isolating, quantifying, and confirming the identity of MPs recovered from these sites. MP studies have shown that microfibers are prevalent in environmental samples. Fibers are the most often studied MP type in atmospheric deposition (Abbasi et al. 2019; Allen et al. 2019; Bergmann et al. 2019; Dris et al. 2016) and indoor environments (Catarino et al. 2018; Dris et al. 2017; Soltani et al. 2021). Later investigations have highlighted errors in analysis, such as improper spectroscopic measurements, which led to the incorrect identification of synthetic fibers as artificial or lignin fibers (Collard et al. 2015; Remy et al. 2015; Wesch et al. 2016). After sampling, microfibers in ambient samples might easily be mistaken for contamination in the laboratory. Because of this, detecting microfibers in environmental samples is still highly questionable since it is difficult to eliminate the possibility of background contamination. Abrasions on synthetic garments, incorrect cleaning of laboratory equipment, plastic tools used in treatment, inappropriate specimen sealing, and ambient air are all potential sources of background contamination with microfibers.

The correct QC/QA processes guarantee that the MP values reported on environmental samples are accurate and are not significantly impacted by the background laboratory contamination. Adding QC/QA measures also enables researchers to analyze differences in MP analysis, which enables them to decide whether the changes reported in the field are statistically significant or simply a reflection of variances in collecting and analyzing the data. It is necessary to collect QC/QA samples in the field and the laboratory to evaluate the procedure's effectiveness and ensure that MPs are quantified accurately. Assessments of QC/QA in the field and the laboratory include using field and laboratory blanks to measure procedural and background contamination during sampling and testing, field duplicates, standard practices for environmental chemical contaminant scanning, and variation measurements for sample collection and analysis. It is possible that increasing the number of replications at each location will result in more statistically accurate data, but it's essential to strike a balance when collecting replicates between time and resources. In the same manner that samples are collected and analyzed, fields, laboratory blanks, and duplicates should be gathered. Thus, designing and executing standard QC/QA processes will enable rigorous management activities to be reviewed to guarantee that they are appropriately implemented and in locations with the most impact.

Although most indoor MP studies did not adopt QC/QA parameters, few studies mentioned laboratory conditions and the laboratory's QC/QA experimental operations. Procedural blanks were prepared and analyzed to evaluate potential contamination during the sample preparation and scanning process (Liao et al. 2021; Vianello et al. 2019). Plastic tools and containers were excluded from the experiments. All glassware was rinsed twice with prefiltered high-profile liquid chromatography-grade methanol and dried on a clean bench. The extraction, filtration, and preparation of microscopical slides were conducted on a clean bench, and the depolymerization process was performed in a fume hood. The procedure blanks of all chemicals used were subjected to the same treatment as the samples (Liu et al. 2019a). All researchers handling samples or equipment wore natural fiber clothing at all times in the field and laboratory, with cotton lab coats donned for all sample processing and analysis. Glassware, including petri dishes, vacuum filtration funnels, and tweezers for handling filters, were triple rinsed with filtered deionized water immediately before use. All of the deionized water utilized for rinsing and sample processing was twice filtered through 1.6 μm filters to remove ambient fragments and plastics present in traditional research-grade deionized water generation systems, thereby reducing sample secondary contamination and filters were covered during analysis (Gaston et al. 2020; Jenner et al. 2021; Liao et al. 2021; Soltani et al. 2021). All procedures were conducted in the laminar flow hood in a clean room wearing a cotton lab coat and sterile gloves, using all glass and metal materials previously washed with nitric acid and distilled water covered with aluminum foil, and opened only when strictly necessary. All solutions were previously filtered, and the glass filtration system was washed with distilled water between samples (Liao et al. 2021; Prata et al. 2020a; Soltani et al. 2021). Ventilation from windows, doors, and airing devices was minimized, and work was conducted at times of low activity to minimize particle suspension. One researcher was responsible for all samples, ensuring standardized analyses throughout (Jenner et al. 2021).

Identification methods

Indoor MP studies have used different instruments to identify MPs for physical, chemical, and elemental characterization (Fig. 4). Most of the indoor studies have used μ-FTIR (19.23%), followed by Stereomicroscope (17.31%), fluorescent microscope (9.62%), FTIR (9.62%), μ-Raman (7.69%) etc. (Fig. 4). Analyzing airborne and indoor MPs is challenging. While no standard approach for their identification has been developed, numerous analytical methods have been used based on their features. Physical and chemical property-based approaches are often used among

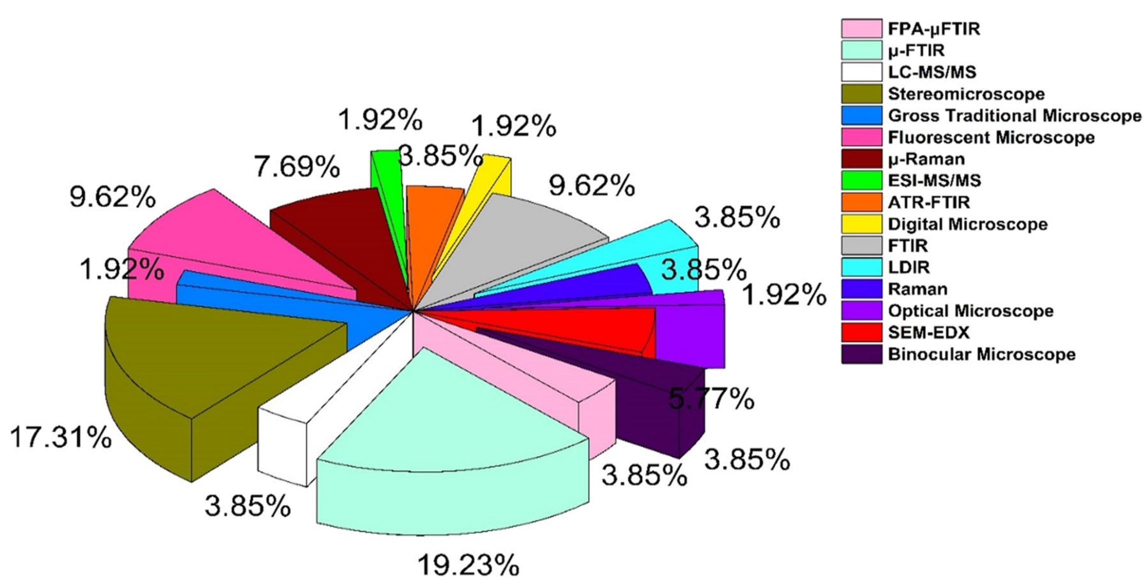


Fig. 4 Relative frequency of identification methods used in indoor microplastic studies

the many analytical techniques for MP identification (Bhat et al. 2023a, b; Rocha-santos and Duarte 2015; Shim et al. 2017). Physical characteristics are one of the most popular means of recognizing MPs. This often entails detecting MPs based on physical qualities such as elasticity, hardness, color, shininess, and structure, which are recognized using visual methods or by different microscopes like optical, binocular, stereo, and fluorescence (Abbasi et al. 2022; Aslam et al. 2022; Gaston et al. 2020; Hidalgo-ruz et al. 2012; Nematollahi et al. 2022). However, using visual inspection methods has considerable limitations, such as the visual variations of experimentalists influencing identification findings and the inability to recognize many MPs visually. The visual examination approach is less successful in detecting minute MPs or when there is interference (Shim et al. 2017). According to Dekiff et al. (2014), when the size of the MPs decreases, the inaccuracy of the visual examination technique rises. As a result, in the context of current MP detection, visual inspection is not advised as a stand-alone identification tool. The visual identification of MPs has significant shortcomings. Still, due to its low cost and ease of use, it is currently the most widely used method for MP analysis and identification.

Identifying the chemical composition of MPs is a crucial step in distinguishing plastic from other particle types. Different techniques have been used in indoor environments to characterize the MPs like Attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR) (Amato-Lourenço et al. 2022; Dris et al. 2017; Prata et al. 2020a), µ-Raman (Abbasi et al. 2022; Gaston et al. 2020; Kashfi et al. 2022; Uddin et al. 2022) and SEM–EDX (Abbasi et al. 2022; Kashfi et al. 2022; Nematollahi et al. 2021). FTIR and Raman spectroscopy are two complementary techniques often utilized to investigate the chemical composition of MPs. MPs are frequently identified using FTIR by ATR, transmission, and reflection. MPs with particle sizes greater than or equal to 300 µm are commonly found using ATR. The analysis is accurate and may be finished in one minute (Gong and Xie 2020). Each sample's FTIR spectroscopy can yield distinct spectra. Because various samples have different compositions, they produce varied spectral images. The kind of polymer forming the MPs may be readily recognized by comparing the spectrum of target particles to those of known materials in libraries. Besides FTIR, Raman spectroscopy only requires a minimal sample from various matrices and yields extremely trustworthy findings. MPs are subjected to Raman spectroscopy to get precise data on high molecular weight polymers, allowing further identification (Gong and Xie 2020). The µRaman (a combination of Raman spectrum imaging equipment and microscopy) can identify MPs as tiny as 1 µm, a spatial resolution that cannot be attained by any other technique (Lenz et al. 2015). Raman spectroscopy is also inappropriate for detecting fluorescent materials, and the MPs additives and pigments may make it challenging to identify the polymer. Additionally, a significant aspect that prevents the identification of the MPs is the fluorescence that some of the photosensitive components in the sample produced after being excited by the equipment (Song et al. 2015). Scanning electron microscope (SEM) is another tool frequently used to identify MPs. A powerful electron beam is produced and scans the sample's surface. The interaction of the electron beam with the material results in high-resolution photographs of the surface features (< 0.5 nm resolution) (Rocha-santos and Duarte 2015). By contrasting their surface characteristics, MPs may be distinguished from sample particles. By utilizing SEM to analyze the surface texture of the MPs, such as grooves, pits, fractures, and flakes, it is possible to determine the mechanical degradation patterns of MPs. For example, pits and grooves on the surface of airborne MPs may be attributed to collision and friction induced by atmospheric dynamics, whereas fractures could be caused by wind action (Cai et al. 2017). Furthermore, combining SEM with Energy Dispersive X-Ray Analysis (EDX) can offer information on particle elemental composition. Although SEM has been used effectively for MP detection, it is a time-consuming procedure in sample preparation and observation. As a result, SEM is ineffective for identifying a high number of MPs.

Most indoor MP studies did not mention the number of particles selected for qualitative and quantitative analysis in each study, which would have directly affected the balance between cost and accuracy. Studies either randomly selected the particles for analysis (Liao et al. 2021; Uddin et al. 2022) and cut the filters into different halves (up to 8) or read a few parts of the filters or a particular area under a microscope (Amato-Lourenço et al. 2022; Chen et al. 2022; Field et al. 2022; Gaston et al. 2020; Liao et al. 2021; Xie et al. 2022; Zhang et al. 2020b). However, few studies have mentioned the number of particles studied like 272 MPs (Vianello et al. 2019), 50 fibers, and 50 granules (Liu et al. 2019a), 28 fibers (Dris et al. 2017), 15 fibers (Aslam et al. 2022), 2,160 fibers (Soltani et al. 2022), 20 MPs (Fang et al. 2022), 21 MPs (Abbasi et al. 2022).

Concentration and morphological features

The analysis of indoor MP has been conducted in various indoor environments (schools, apartments, offices, buses, houses, hotels, subway cars, operation theatres, anesthetic rooms, dormitories, corridors, nail salons, classrooms, universities, hospitals, mosques, kindergartens, etc.) across multiple countries (Dris et al. 2017) France, (Vianello et al. 2019) Denmark, (Zhang et al. 2020b) China, (Gaston et al. 2020) California, (Prata et al. 2020a) Portugal, (Jenner et al. 2021) the United Kingdom, (Soltani et al. 2021) Australia, (Kashfi et al. 2022) Iran, (Lim et al. 2022) Japan etc. (Table 1) and have collected different types of samples (air, dust, and deposition). Indoor MP investigations have shown differences in sample sizes, counts, and blank sample numbers. Most of the studies did not report the number of blank samples in their studies. Four studies reported a blank count of 234 (Zhang et al. 2020b), 114 (Jenner et al. 2021), 4 (Torres-Agullo et al. 2022), and 30 (Field et al. 2022).

Concentration

Concentrations of MPs in the indoor air varied from concentrations of 5 MP fibers/m^3 to mean concentrations of 9 ± 6 MPs/m^3 (Vianello et al. 2019), 10 ± 6 MPs/m^3 (Uddin et al. 2022), 46 ± 55 MPs/m^3 (Chen et al. 2022) and 48 MPs/m^3 (Xie et al. 2022) to 1,583 ± 1,181 MPs/m^3 (Liao et al. 2021), primarily sampled from residential environments (Table 1).

Within indoor environments, MP fibers in an indoor deposition have been reported with concentrations ranging between 475—3,339 MP fibers/m^2/day (Dris et al. 2017) and 22—6,169 MP fibers/m^2/day (Soltani et al. 2021), or the mean concentration of 19,600 ± 900 MP fibers/m^2/day (Yao et al. 2021) in residential locations (Table 1). Film-shaped plastics have also been reported in an indoor deposition at concentrations of 5,990 ± 2,020 MP fibers/m^2/day (Yao et al. 2021). Undifferentiated by shape, total concentrations of MPs in deposition within indoor residential environments have been reported as 940,000 ± 500,000 MPs/m^2/day (Fang et al. 2022). Within office environments, the concentration of MP fibers in a deposition has been reported to vary between 307 ± 215 MP fibers/m^2/day (Amato-Lourenço et al. 2022) and 6,430 ± 2,540 MP fibers/m^2/day (Yao et al. 2021). Fragment-shaped MPs in deposition have also been reported at concentrations of 2.2 ± 2 MPs/ m^2/day (Amato-Lourenço et al. 2022) and 6,340 ± 2,540 MPs/ m^2/day (Yao et al. 2021; Zhang et al. 2020a). Undifferentiated by shape, the concentration of MPs in deposition within office locations has been reported as 890,000 ± 340,000 MPs/m^2/day (Fang et al. 2022). Indoor deposition of MP fibers in school environments was 1,404—5,844 MP fibers/m^2/day (Ouyang et al. 2021) and 6,200 ± 570 MP fibers/m^2/day (Yao et al. 2021). Film-shaped MPs have also been reported in schools at a concentration of 8,130 ± 2,170 MPs/m^2/day (Yao et al. 2021). Total MP concentrations within school-based deposition (irrespective of shape) have been reported to be 790,000 ± 350,000 MPs/m^2/day (Fang et al. 2022).

Based on particle count, mean concentrations of MPs in indoor dust have been reported to be 195 MPs/g (range: 10—635 MPs/g) (Nematollahi et al. 2022), 3,771 MPs/g (range: 81—55,830 MPs/g) (Abbasi et al. 2022) and 62—3,861 MPs/g (Zhu et al. 2022). MP fibers have been reported in concentrations varying from 19,000—67,000 MP fibres/g (Dris et al. 2017). Mean concentrations of PET have been reported as 0.43 mg/g in one student dormitory (Wang et al. 2017), 23 mg/g from 39 cities in China (Liu et al. 2019a) and 2 mg/g (India), 3.9 mg/g (Columbia), 4.4 mg/g (Pakistan), 9.2 mg/g (China), 10 mg/g (Kuwait), 11 mg/g (Vietnam), 14 mg/g (USA and Romania), 15 mg/g (Greece), 20 mg/g (Japan), 20 mg/g (Saudi Arabia) and 27 mg/g (South Korea) (Zhang et al. 2020a). Mean concentrations of PC were lower, reported as 240 μg/g in the one student dormitory (Wang et al. 2017), 1.8 μg/g (China) (Liu et al. 2019a), and 6 μg/g (Pakistan), 7 μg/g (Kuwait), 11 μg/ g (Columbia), 15 μg/g (Romania), 18 μg/g (China), 20 μg/g (India), 34 μg/g (Greece), 54 μg/g (South Korea), 58 μg/g (Saudi Arabia), 63 μg/g (Japan), 87 μg/g (USA), 120 μg/g (Vietnam) (Zhang et al. 2020a). The mass concentration of other polymers in indoor dust has not been reported to date (Table 1). Differences have been seen in the concentrations of MPs found in indoor environments in dust, deposition, and ambient samples. The concentration of MPs indoors was higher than outdoors (Amato-Lourenço et al. 2022; Dris et al. 2017; Yao et al. 2021) because of the many MP sources (such as synthetic textiles, clothes, and household items) and complex air dispersion processes (like ventilation rate, room partition, and weather conditions) (Bhat et al. 2021).

Size

The maximum reported length of indoor fibrous MPs varied from 2,181 μm (Xie et al. 2022), 2,800 μm (Uddin et al. 2022), 3,250 μm (Dris et al. 2017), 3,669 μm (Prata et al. 2020a), to > 5,000 μm (Gaston et al. 2020) in indoor air. The reported average length of indoor air MP fibers ranged between 177 and 237 μm, 250 μm (Prata et al. 2020a), 330, 383, and 641 ± 810 μm (Gaston et al. 2020). The mean diameter of MP fibers in indoor air has been reported to be 26—30 μm wide (with variability attributed to automatically versus manually calculated measurements) (Vianello et al. 2019). MP fragment sizes in indoor air were reported in two studies, being a mean of 68 μm in length and 37 μm in diameter (Vianello et al. 2019) and 58 ± 55 μm (predominantly 76—100 μm) (Gaston et al. 2020) (Table 1).

Within dustfall, MP fibers have typically occurred in larger sizes > 50 μm (Soltani et al. 2021) ranging between 50 and 510 μm (Amato-Lourenço et al. 2022), 50—2,000 μm (Zhang et al. 2020b) and 4,650—4,850 μm (Mandin et al. 2017). MP fiber diameters have been reported to be 11—20 μm (63%) (Jenner et al. 2021) and 19 ± 6 μm, larger compared to their natural counterparts at 17 ± 4 μm (Soltani et al. 2021). Fragments of MP have been detected between 50—200 μm (Soltani et al. 2021); however, they can range up to 50—989 μm (Amato-Lourenço et al. 2022). Proportionally, for each shape, the majority of plastics in

Table 1 Examples of some published literature on indoor microplastics

Country	Sample Vol	Sample NO	Blank NO	Concentration	Size	Color	Polymer Type	Reference
France	2—5 m^3 / 5.5 mg	2	Unreported	1586—11,130 fibers/day/m^2	50—4,850 µm	Unreported	PP, PA, and PE	(Dris et al. 2017)
Denmark	16.8 m^3 per sample	Unreported	Unreported	1.7 and 16.2 particles m^{-3}	37—177 µm	Unreported	PES, PE, PA, PP, PS, Acr, PUR, EPDM, PVAc, EVA, EP, PR, CA, CTA, PLA, and, PC	(Vianello et al. 2019)
China	10—15 mg	39	Unreported	4.6—26,800 mg g^{-1}	50 µm—2 mm	Unreported	PES, PUR, PA, PA, PP, PAN, Acr, PEI, and PEP	(Liu et al. 2019a)
Indonesia	Unreported	3	Unreported	95—351 particles	3—5 mm	Unreported	Unreported	(Bahrina et al. 2020)
China	Unreported	234	234	Dormitory (9.9×10^3 MPs/m^2/d), office (1.8×10^3 MPs/m^2/d) and corridor (1.5×10^3 MPs/m^2/d)	50—2,000 µm	Transparent, red, black, yellow, purple, and green	PES, RAY, Acr, CE, PP, PS, and PA	(Zhang et al. 2020b)
California	11.7 L min^{-1} for 8 h	21	Unreported	3.3 ± 2.9 fibers m^{-3} and 12.6 ± 8.0 fragments m^{-3}	58.6 ± 55 µm	Black, blue, red, and green	PVC, PE, RC, Acr, PC, and PS	(Gaston et al. 2020)
12 Countries	50 mg	286	Unreported	PET 38—120,000 µg/g and PC < 0.11—1,700 µg/g	Unreported	Unreported	PET and PC	(Zhang et al. 2020a)
Portugal	5 L m^{-1} 48 h	5	0	6 fibers m^{-3} and 5 SMPs m^{-3}	17—3,669 µm	Unreported	Unreported	(Prata et al. 2020a)
China	1 m^3 per sample	39	0	$1,583\pm1,180$ n/m^3	5—5,000 µm	Unreported	PES, PA, and PP	(Liao et al. 2021)
United Kingdom	Unreported	118	114	1,414 MP m^{-2} day^{-1} $\pm1,022$	5—5,000 µm	Unreported	PET, PA, and PP	(Jenner et al. 2021)
Australia	Unreported	32	Unreported	308—17,642 fibers/m^2/day	5—5,000 µm	Black, green, blue, red, grey, brown, and transparent	PE, PES, PET, and PA	(Soltani et al. 2021)
Kuwait	30 L min-1 for 360 mints	20	Unreported	3.2—27.1 particles m^{-3}	0.45—2,800 µm	Black, transparent, blue, red, grey	PES and PA	(Uddin et al. 2022)
Spain	10 L/min 1.5—3 h	15	4	4.2—17.3 MPs/m^3	< 5 mm—> 5 mm	Black, colorless, brown, red, purple, blue, grey, yellow, orange, green, pink, golden, and silver	PA, PES and PP	(Torres-Agullo et al. 2022)
Brazil	Unreported	14	Unreported	309.40 ± 214.71 MPs/m^2/day	51—511 µm	Unreported	PE, PP, PET, and PVAc	(Amato-Lourenço et al. 2022)
Taiwan	5.43 m^3	19	Unreported	46 ± 55 MPs/m3	< 50 µm	Unreported	Acr, RB, and PUR	(Chen et al. 2022)

Table 1 (continued)

Country	Sample Vol	Sample NO	Blank NO	Concentration	Size	Color	Polymer Type	Reference
Pakistan	Unreported	20	Unreported	Unreported	Unreported	Yellow, blue, green, red, white, purple, orange, transparent, and green	PET, EPR, PE, and PUR	(Aslam et al. 2022)
South Korea	7 L min^{-1} 48 h	5	Unreported	6 MPs m^3	20.1—6,801.2 µm	Unreported	PE, PP, PA, PES, Acr, and PS	(Choi et al. 2022)
China	2.5 m^3/h for 4 h	8	Unreported	15.56—93.32 N/m^3	2.40—2,181.48 µm	Black, blue, green, indigo, pink, purple, red, transparent, white, and yellow	PE, PES, PF, PVC, CO, PP, PUR, and RB	(Xie et al. 2022)
China	Unreported	21	Unreported	105 items m^{-2} d^{-1} dining/drinking venues	5.9—5,000 µm	Unreported	PET, PE, and PA	(Fang et al. 2022)
Iran	10 g	28	Unreported	195 MPs·g^{-1}	50—< 500 µm	Unreported	PET, PP, PS, and PA	(Nematollahi et al. 2022)
China	8 g	242	Unreported	1,174 MPs/g	50—> 1,000 µm	Black, yellow, blue, transparent, red, white, and green	PA, PS, PC, PES, PP, and PE	(Zhu et al. 2022)
Iran	1 g	50	Unreported	80—56,000 MP per g	≤ 5,000 µm	Black-grey, yellow-orange, white-transparent, red-pink, and blue-green	PET, PP, and PS	(Abbasi et al. 2022)
United Kingdom	Unreported	18	30	13,048 ± 14,283 particles m^{-2} day^{-1}	10—> 50 µm	Clean, brown, black, white, and blue	PET, PP, PE, and PTFE	(Field et al. 2022)
Japan	Unreported	10	Unreported	Unreported	45—< 5,600 µm	Unreported	PET, PE, PA, PVA, PSU, and CL	(Lim et al. 2022)
Iran	1 g	10	Unreported	48.6—139 items/mg	< 100—> 1,000 µm	White, transparent, orange, red, black, green, and purple	PE, PC, PP, PET, and PA	(Kashfi et al. 2022)
United Kingdom	Unreported	20	Unreported	93,772—311,040 particles/m^2/day	20—> 300 µm	Unreported	PA, PUR, PE, and PET	(Boakes et al. 2023)

*Actual units were taken from each specific article the 5—250 µm range were film (88%), fragment (99%), and sphere (98%) (Jenner et al. 2021).

The size range of MPs in indoor dust has been reported to be > 50—2,500 µm (Dris et al. 2017), with mode size ranges between 200 and 1,000 µm (45—63%) (Zhu et al. 2022) and 500—1,000 µm (32% (Nematollahi et al. 2022), 25% (Abbasi et al. 2022)).

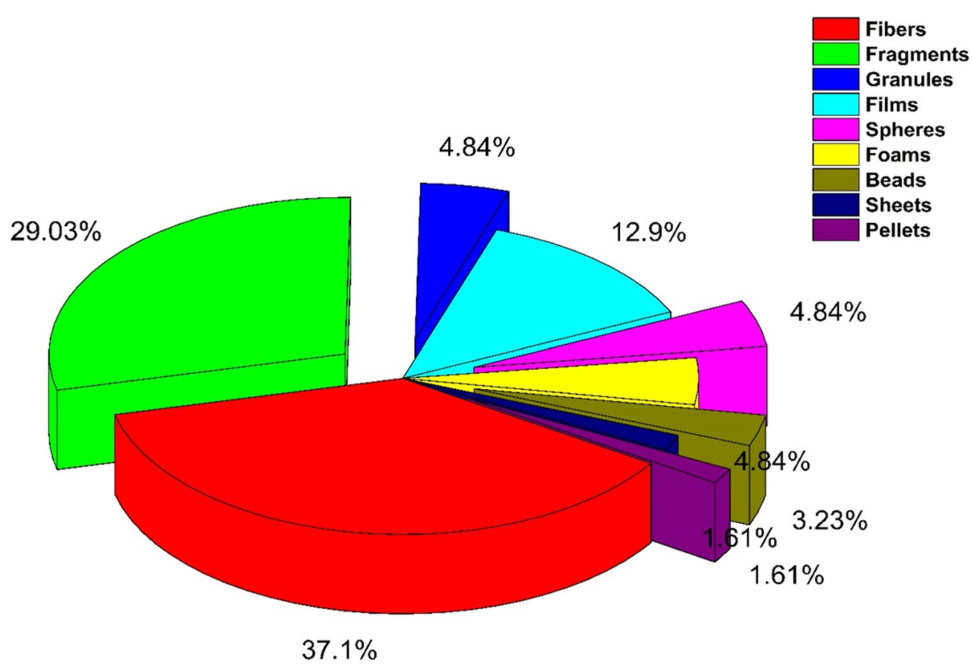
Color, type, and shape

Color, type, and shape are essential in identifying MPs. The color provides insights into their composition and origin, helping to determine potential sources and pathways. Different plastic types have distinct characteristics, influencing their behavior and environmental risks, and understanding the plastic-type aids in targeted mitigation. Shape reveals information about the origin and potential impacts, such as fibers from textiles or fragments from more oversized items. It affects mobility, interactions with organisms, and harm caused. By analyzing these characteristics, researchers can develop effective strategies for managing MP pollution, preventing its spread, and minimizing environmental consequences. Most of the indoor studies did not report the color in their results. Few studies reported the color of MPs like transparent, red, black, yellow, purple, and green (Zhang et al. 2020a), black, blue, red, and green (Gaston et al. 2020), black, transparent, blue, red, grey (Uddin et al. 2022), white, transparent, orange, red, black, green, and purple (Kashfi et al. 2022) etc. (Table 1). Transparent, red, black, green, blue, brown, orange, grey, and purple were the dominant type of MP colors. Various types of MPs have been identified through indoor studies like PP, PA, and PE (Dris et al. 2017), PVC, PE, RC, Acr, PC, and PS (Gaston et al. 2020); PET, PA, and PP (Jenner et al. 2021), PA, PES and PP (Torres-Agullo et al. 2022), PET, PE, and PA (Fang et al. 2022), PET, PP, PS, and PA (Nematollahi et al. 2022) and PA, PUR, PE, and PET (Boakes et al. 2023) etc. however Prata et al., (2020a) did not report the type of MP. The dominant MPs identified in indoor environments were PA, PP, PE, PS, PC, PUR, PET, PES, Acr, and PVC (Table 1). Indoor MPs have been classified into nine distinct shapes: fiber, fragments, granules, films, spheres, foams, beads, sheets, and pellets. Fiber has emerged as the predominant type of MP, accounting for 37.1% of the total, followed by fragments (29.03%), films (12.9%), and other categories (Fig. 5).

Bibliometric analysis

The utilization of bibliometric analysis is of utmost importance within the field of MP research, as it serves to delineate the research domain effectively, discern prevailing patterns, evaluate the influence of scholarly output, facilitate collaborative efforts, and bolster the foundation of decision-making processes grounded in empirical evidence. By examining scientific publications and relevant literature, a comprehensive assessment of research output is obtained, elucidating the countries, institutions, and authors exhibiting the highest productivity levels. This tool assists researchers in maintaining current knowledge regarding emerging trends and prominent subjects, thereby guiding their research endeavors and allocation of resources. The evaluation of research quality and the identification of influential researchers are facilitated by assessing impact and influence.

Fig. 5 Shapes of microplastics found in indoor environments of microplastics studies



Examining collaboration patterns facilitates the dissemination of knowledge and advancing interdisciplinary research. Bibliometric analysis is a valuable tool for policymakers, enabling them to make well-informed decisions in effectively addressing the issue of MPs. This is achieved through the implementation of regulations, policies, and interventions.

Research outcome in indoor environments

The bibliometric analysis conducted on indoor MPs revealed that researchers in 2017 exhibited significant interest in the occurrence of MPs within indoor environments (Fig. 6).

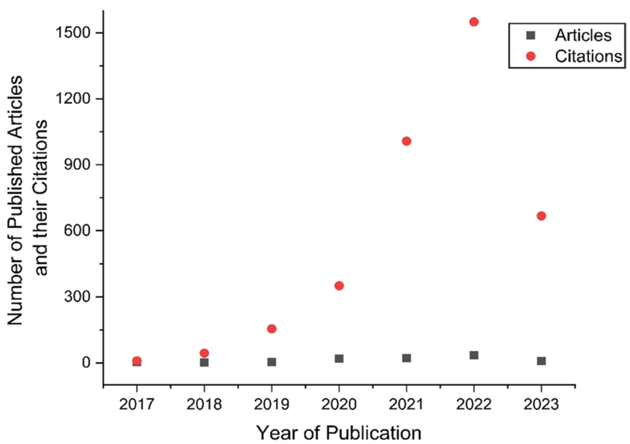


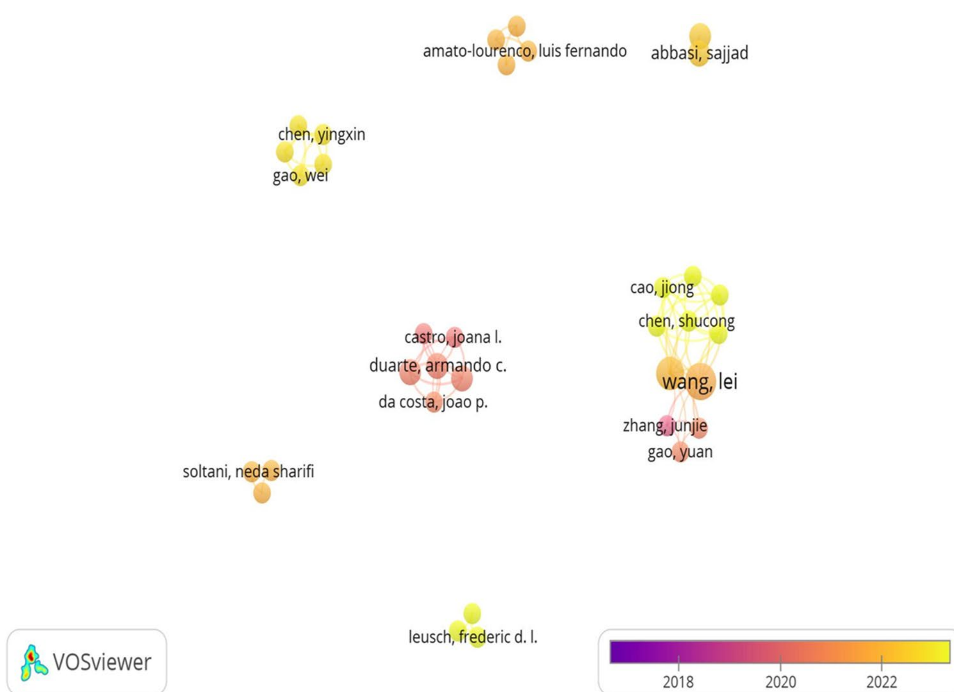
Fig. 6 The cumulative rate of publications in indoor environments with their citations

Between 2017 and 2019, the annual publication count remained below five articles. However, starting in 2020, there has been a notable increase in articles published, with an annual growth rate exceeding 10. In 2018, only a single article was published, whereas in 2022, 34 articles were published. The bibliometric analysis revealed that 91 articles have been published on indoor MPs, explicitly focusing on discussions related to this subject matter. The frequency of citations has notably increased over the years, with the lowest count recorded in 2017 (9 articles) and the highest count observed in 2022 (1,550). The indoor MP articles have 3,783 citations (Fig. 6). Given the topic's inherent novelty and the necessity for a further comprehensive investigation, it is anticipated that the number of articles and citations will rise within this domain in the upcoming years.

Coauthorship of authors

The inclusion of multiple authors in MP studies is of utmost importance due to its significant impact on collaborative expertise, the production of comprehensive research outcomes, the enhancement of credibility, the broader dissemination of findings, and the shared responsibility in addressing the complex problem of MP pollution. Bibliometric analysis of all literature in this review identified 35 authors who have published material relevant to indoor MPs, which were segregated by different clusters (Fig. 7). The minimum number of documents published by each author was 2. Of the 35 authors, 33 (94%) had published 2—3 articles; however, just two authors, "Sun, Hongwen"

Fig. 7 Bibliometric analysis showing the coauthorship of authors



and "Wang, Lei" have published 5 and 6 articles, respectively. In the coauthorship of authors, "Liu, Chunguang" had the highest number of citations (194). "Shi, Yumeng". Twenty-nine authors (82%) have a total link strength of ≤ 12, while six authors (17%) have a link strength of 14.

Cooccurrence of keywords

The identification of research themes, trends, and relationships within a field can be facilitated through the analysis of keyword cooccurrence in bibliometric studies. This tool facilitates the identification of shared research domains, interdisciplinary linkages, and emerging subjects, thereby offering valuable perspectives for researchers, policymakers, and stakeholders in influencing research trajectories and fostering collaborative efforts. Seventy-seven keywords were identified across all articles, with an occurrence of 2 or more (Fig. 8). The keyword microplastics frequency was the highest, appearing 29 times. It was followed by the keyword fibers, which appeared 21 times, deposition with 18 occurrences, atmospheric fallout with 12 occurrences, dust with 11 occurrences, pollution with 10 occurrences, China and exposure with nine occurrences each, indoor and ingestion with eight occurrences each, health with seven occurrences, airborne microplastics with seven occurrences, and indoor dust with six occurrences, among others. The microplastics keyword demonstrated the highest aggregate link strength, reaching a value of 167, followed by fibers at 155, deposition at 133, dust at 96, atmospheric fallout at 89, pollution at 79, china at 78, and ingestion at 72.

Highest cited articles in indoor environments

In bibliometric analysis, the most frequently cited papers show the significance, influence, and effect of research in an area. They act as standards for assessing the importance of academic work, aiding scholars in locating groundbreaking research, and offering perceptions of the developments and patterns that create the knowledge landscape. A minimum of 10 documents were selected, each containing at least ten citations. The top 10 research articles were chosen (Fig. 9). Dris et al. (2017) received the highest number of citations, totaling 533. This study examines fibers' characteristics and behavior in indoor and outdoor settings. The study also examined the rate at which fibers are deposited indoors and their concentration in dust samples collected from vacuum cleaner bags. Vianello et al. (2019) authored the second highly cited article, which has garnered 221 citations. In their study, the authors investigate the extent to which humans are exposed to indoor airborne MPs by employing a Breathing Thermal Manikin, followed by (Liu et al. 2019a) 182 citations, (Zhang et al. 2020b) 124 citations (Zhang et al. 2020a) 101 citations, Meanwhile, the remaining five articles exhibited citation counts below 100.

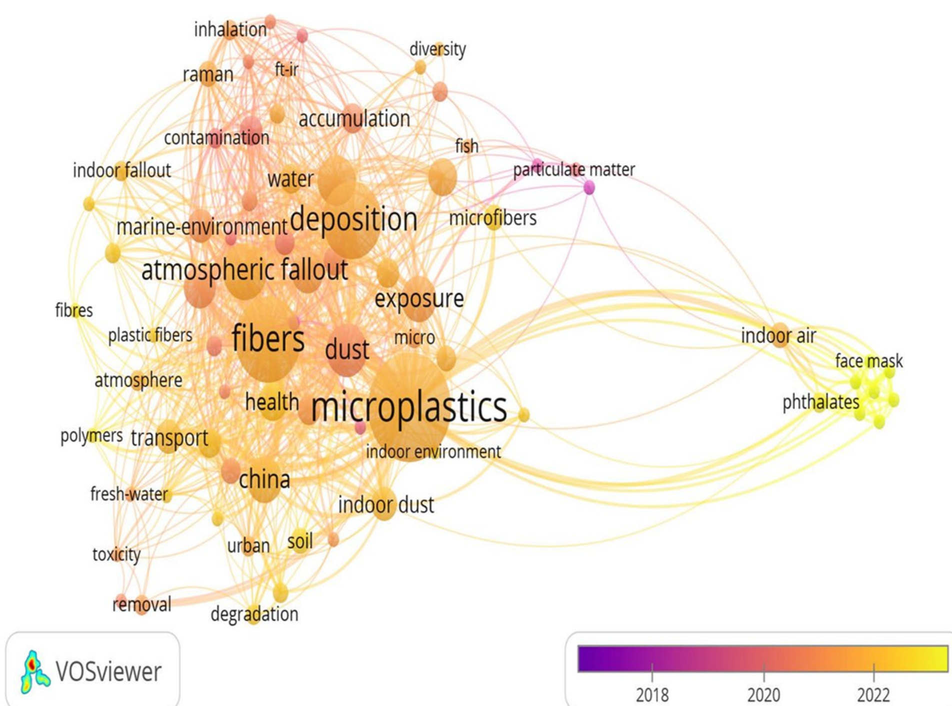


Fig. 8 Bibliometric analysis showing the co-occurrence of keywords

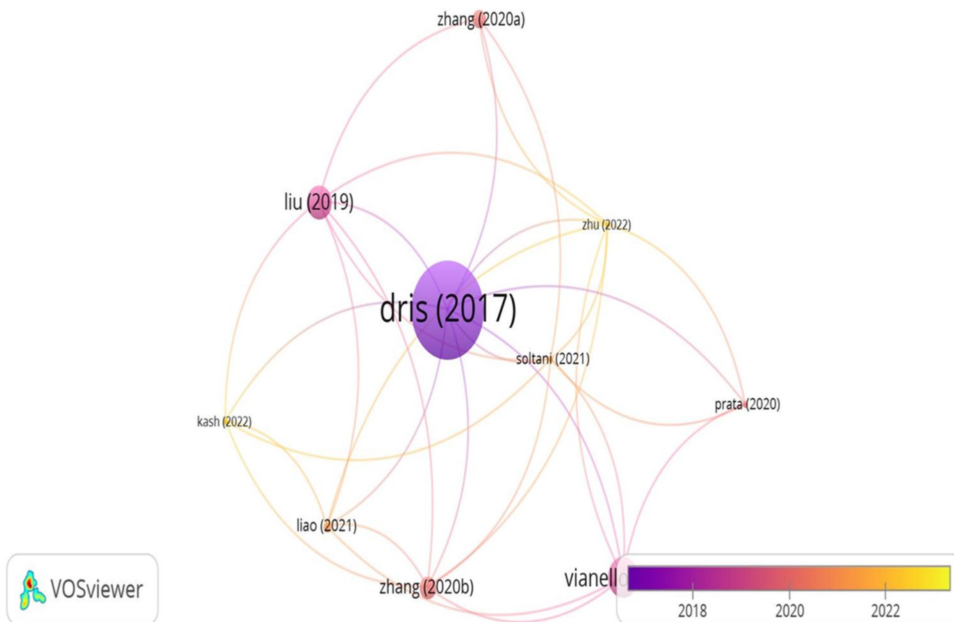


Fig. 9 Top 10 cited articles from indoor environments

Top affiliations, authors, countries, and funding agencies

The top affiliation, authors, countries, and funding agencies in bibliometric analysis are significant because they show how research output, partnership patterns, and financial support are spread out. They help find top universities, influential researchers, areas for research, and funding trends. This helps make decisions, allocate resources, and plan for the future in academics and research policy. A bibliometric analysis was conducted to examine the prominent affiliations, authors, countries, and funding agencies that make significant contributions to the field of indoor MPs. Among the top 10 affiliations, 40% (4 out of 10) were from China, while 30% (3 out of 10) were from Spain. Nankai University has published the highest number of articles, totaling nine. The authors Wang, Lan, and Sun, who emerged as the most prolific contributors in published articles, hailed from China. However, the remaining authors each published a maximum of three articles and hailed from various countries, including Korea, the United Kingdom, Portugal, Iran, and Brazil (Table 2).

China emerged as the foremost contributor in published articles (34) in indoor MPs, with the United States and England following closely behind with 11 articles each. Conversely, other countries such as Germany, South Korea, Australia, Iran, Italy, Netherlands, and France published fewer than ten articles in this domain. China appeared as the top country in terms of funding agencies, with a total of 32 published articles from 3 funding resources. In comparison, the United Kingdom secured the second position with ten articles from three funding sources. The remaining funding agencies comprised entities from Portugal, the European Commission, and Australia (Table 2). China was the leading country in terms of published articles. The reason can be that each China has a maximum of universities, authors, and funding agencies among the top ten leading published articles. In contrast, for the rest of the countries, their contribution from universities, authors, and funding agencies were less than China. The country's funding for scientific projects plays a vital role in the scientific world by increasing the university's scientific production by supporting scientific projects.

Top publishers and journals

The significance of top publishers and journals in bibliometric analysis is their ability to indicate research quality, visibility, and impact. Benchmarks are utilized to evaluate research productivity, influence, and collaboration and hold significant importance in shaping academic reputation, career progression, and decisions regarding research funding. Journals are essential in showing the number of articles published and their total citations. Elsevier emerged as the predominant publisher with the most published articles, totaling 53. The remaining nine top publishers have published fewer than nine articles. Most researchers have chosen to publish their work in journals affiliated with Elsevier. The preeminent scholarly publication in this field was the Science of the Total Environment, consisting of nine published articles. In contrast, the number of published articles in the other journals was equal to or less than five. Most of the journals

Table 2 Top affiliations, authors, countries, and funding agencies contributed to the field of indoor microplastics

NO	Affiliations	Published articles	Authors	Published articles	Countries	Published articles	Funding Agencies	Published articles
1	Nankai University (China)	9	Wang L (China)	9	Peoples of the Republic of China	34	National Natural Science Foundation of China Nsfc (China)	24
2	Shiraz University (Iran)	4	Sun H (China)	7	USA	11	UK Research Innovation Ukri (United Kingdom)	4
3	East China Normal University (China)	4	Kim H (Republic of Korea)	3	England	11	National Key Research and Development Program of China (China)	5
4	Chinese academic of science (China)	3	Kelly FJ (United Kingdom)	3	Germany	7	Natural Environment Research Council Nerc (United Kingdom)	3
5	University of Aveiro (Portugal)	3	Jenner LC (United Kingdom)	3	South Korea	6	Fundacao Para A Ciencia EA Tecnologia Fct (Portugal)	3
6	Ministry of natural resources of the People's Republic of China (China)	3	Duarte AC (Portugal)	3	Australia	6	Medical Research Council UK Mrc (United Kingdom)	3
7	Institute for Technological Research IPT (Brazil)	3	Da Costa JP (Portugal)	3	Iran	5	111 Program Ministry of Education China (China)	3
8	Spanish National Research Council (Spain)	3	Abbasi S (Iran)	3	Italy	5	European Commission	3
9	Centro de investigacon y Desarrollo pascual vila—CID CSIC (Spain)	3	Amato-Lourenco LF (Brazil)	3	Netherlands	5	European Social Fund Esf	3
10	Instituto de Diagnóstico Ambiental y Estudios del Agua—CSIC (Spain)	3	Carvalho-Oliveira R (Brazil)	3	France	4	Australian Government (Australia)	2

that featured articles on indoor MP were highly regarded, with a significant proportion falling within the top quartile (Q1) and possessing impact factors exceeding 5 (Table 3).

Conclusion and recommendations

This literature analysis highlights the critical aspects of indoor MP studies, including sampling methods, pretreatment procedures, QC measures, identification techniques, concentration characteristics, and bibliometric analysis of the published literature. It underscores the need for standardized protocols and comprehensive QC practices to ensure reliable and comparable study results. The presence of MPs in indoor environments is a concerning environmental issue, and further research is necessary to deepen our understanding of its implications and develop effective mitigation strategies. The analysis of the literature review on indoor articles revealed that approximately 45.24% of indoor articles had conducted pretreatment on their samples. The works comprising 16.67% of the total have not undergone any pretreatment. The experimental results indicate that a combination of density separation and acidic digestion was employed to treat the samples comprising 2.38% ($NaCl + NaI$), 9.52% ($ZnCl_2 + H_2O_2$), and 4.76% ($NaI + H_2O_2$). Nile red has also been employed in studies to characterize MPs. Nine distinct types of filter membranes have been employed in indoor MP studies. Most studies have employed Whatman Glass microfiber filters (41.67%). Other frequently utilized filters include PTFE membranes (12.5%), Silver membranes (12.5%), Cellulose ester membranes (8.33%) etc. The literature review analysis suggests that 17 articles incorporated blank samples in their research, while eight articles did not include blank samples. Notably, most studies (23) did not integrate blank

Table 3 Top publishers and journals which published articles on indoor microplastics

NO	Publishers	Published Articles	Journals (Quartiles-Impact factor/2022)	Published Articles
1	Elsevier	53	Science of the Total Environment (Q1-9.8)	9
2	Amer Chemical Soc	9	Environmental Pollution (Q1-8.9)	5
3	Springer Nature	9	Journal of Hazardous Materials (Q1-13.6)	5
4	Mdpi	6	Environment International (Q1-11.8)	3
5	Royal Soc Chemistry	2	Environmental Science & Technology (Q1-8.9)	3
6	Science Press	2	Toxics (Q1/Q2-4.6)	3
7	Wiley	2	Water Air and Soil Pollution (Q2/Q3-2.9)	2
8	Bangladesh Botanical Soc	1	Marine Pollution Bulletin (Q1-5.8)	2
9	Geomate Int Soc	1		
10	Polish Soc Ecological Engineering	1		

results within their actual samples. In the samples of 16 studies, no MP was identified. A total of 9 studies successfully detected MPs in their respective blank samples, while six studies incorporated the results from blank samples into their actual samples. Indoor MP studies have used different instruments to identify MPs for physical, chemical, and elemental characterization. Most of the indoor studies have used μ-FTIR (19.23%), followed by Stereomicroscope (17.31%), fluorescent microscope (9.62%), FTIR (9.62%), μ-Raman (7.69%), etc. Most of the indoor studies did not report the color in their results. Transparent, red, black, green, blue, brown, orange, grey, and purple were the dominant types of MP colors. The dominant MPs identified in indoor environments were PA, PP, PE, PS, PC, PUR, PET, PES, Acr, and PVC. Indoor MPs have been classified into nine distinct shapes: fiber, fragments, granules, films, spheres, foams, beads, sheets, and pellets. Fiber has emerged as the predominant type of MP, accounting for 37.1% of the total, followed by fragments (29.03%), films (12.9%), and other categories.

The bibliometric analysis conducted on indoor MPs provides valuable insights into this field's research landscape and trends. The analysis reveals a growing interest in indoor MPs, with a notable increase in publications since 2020. Researchers are actively exploring the occurrence of MPs in indoor environments and their impact. Collaboration among multiple authors is vital for comprehensive research outcomes and addressing the complex MP pollution issue. Coauthorship patterns highlight the importance of collaborative expertise in indoor MP research. It identifies key authors who have made significant contributions, with a few authors standing out for their high publication output. These findings emphasize the need for interdisciplinary collaboration and knowledge exchange among researchers in this field. The prevalence of keywords such as microplastics, fibers, deposition, and pollution underscores the focus on understanding indoor MPs' sources, behavior, and impacts. This analysis can guide researchers and policymakers in shaping research trajectories and fostering collaborative efforts. The identification of highly cited articles demonstrates the significance and influence of research in the field of indoor MPs. These articles are benchmarks for assessing research importance and can guide researchers in locating groundbreaking work. Researchers should focus on these highly cited articles and build upon their findings to advance knowledge in this field. The analysis of top affiliations, authors, countries, funding agencies, publishers, and journals provides insights into the key contributors to indoor MP research. China has emerged as a leading country regarding publications, affiliations, authors, and funding agencies. This suggests a strong emphasis on indoor MP research in China. Understanding the research output, partnership patterns, and financial support in this field can help with decision-making, resource allocation, and planning for future research and policy development.

Based on the findings presented in this review article, the following recommendations can be made:

1. Standardization of Protocols: There is a need for standardized protocols for sampling, pretreatment, and identification of MPs in indoor environments. Consistency in methodologies will facilitate better comparison and interpretation of results, allowing for a more comprehensive understanding of indoor MP pollution.
2. Enhanced Quality Control: Implementing rigorous QC measures, including blank samples, is crucial to identify and account for potential contamination. Researchers should incorporate blank samples to ensure accurate assessment and minimize false positives.
3. Comparative Studies: More comparative studies are required to investigate the variations in indoor MP concentrations across different environments and sample types. This will contribute to a broader understanding of the factors influencing MP presence indoors and guide targeted mitigation efforts.

4. Long-Term Monitoring: Long-term monitoring programs should be established to assess temporal variations in indoor MP pollution. Such programs will provide valuable insights into seasonal and annual trends, helping identify potential sources and develop effective management strategies.
5. Public Awareness and Education: Public awareness about indoor MP pollution is essential. Educating individuals about the sources, risks, and preventive measures associated with indoor MPs will promote responsible consumption, waste management, and behavior changes that can reduce MP contamination.

Based on the findings of the bibliometric analysis on indoor MPs, the following recommendations are suggested:

1. Encourage interdisciplinary collaboration: Given the complex nature of MP pollution, interdisciplinary collaboration should be fostered to leverage diverse expertise and address the multifaceted challenges associated with indoor MPs.
2. Foster knowledge exchange: Researchers and policymakers should actively engage in knowledge exchange platforms, conferences, and workshops to share findings, insights, and best practices related to indoor MP research. This will promote collaboration and the dissemination of knowledge in the field.
3. Support emerging research areas: As the number of publications on indoor MPs is expected to increase in the coming years, it is essential to support emerging research areas within this field. Funding agencies should allocate resources to support studies investigating emerging trends, innovative methodologies, and understudied aspects of indoor MP pollution.
4. Strengthen international collaborations: Given the global nature of MP pollution, international collaborations should be encouraged to facilitate data sharing, comparative studies, and harmonized approaches to addressing indoor MP pollution. This will contribute to a more comprehensive understanding of the issue and the development of effective mitigation strategies.
5. Promote open-access publishing: To ensure wider accessibility to research findings on indoor MPs, researchers and publishers should consider open-access publishing options. This will facilitate knowledge dissemination and allow policymakers, stakeholders, and the public to access the latest research on indoor MP pollution.

By implementing these recommendations, researchers, policymakers, and stakeholders can further advance knowledge, address gaps, and develop evidence-based strategies to effectively tackle the issue of indoor MP pollution, leading to healthier indoor environments and a more sustainable future.

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Declarations

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Consent to participate Not applicable.

Consent for publication Not applicable.

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References

Abbasi S, Keshavarzi B, Moore F, Turner A, Kelly FJ, Dominguez AO, Jaafarzadeh N (2019) Distribution and potential health impacts of microplastics and microrubbers in air and street dusts from Asaluyeh County, Iran. Environ Pollut 244:153–164. https://doi.org/10.1016/j.envpol.2018.10.039

Abbasi S, Turner A, Sharifi R, Nematollahi MJ, Keshavarzifard M, Moghtaderi T (2022) Microplastics in the school classrooms of Shiraz, Iran. Build Environ 207:108562. https://doi.org/10.1016/j.buildenv.2021.108562

Allen S, Allen D, Phoenix VR, Le Roux G, Durántez Jiménez P, Simonneau A, Binet S, Galop D (2019) Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nat Geosci 12:339–344. https://doi.org/10.1038/s41561-019-0335-5

Amato-Lourenço LF, dos Santos Galvão L, de Weger LA, Hiemstra PS, Vijver MG, Mauad T (2020) An emerging class of air pollutants: potential effects of microplastics to respiratory human health? Sci Total Environ 749:141676. https://doi.org/10.1016/j.scitotenv.2020.141676

Amato-Lourenço LF, dos Santos Galvão L, Wiebeck H, Carvalho-Oliveira R, Mauad T (2022) Atmospheric microplastic fallout in outdoor and indoor environments in São Paulo megacity. Sci Total Environ 821. https://doi.org/10.1016/j.scitotenv.2022.153450

Aslam I, Qadir A, Ahmad SR (2022) A preliminary assessment of microplastics in indoor dust of a developing country in South Asia. Environ Monit Assess 194. https://doi.org/10.1007/s10661-022-09928-3

Bahrina I, Syafei AD, Satoto R, Jiang J, Nurasrin NR, Assomadi AF, Boedisantoso R (2020) An occupant-based overview of microplastics in indoor environments in the city of Surabaya. Indonesia J Ecol Eng 21:236–242

Bergmann M, Mützel S, Primpke S, Tekman MB (2019) White and wonderful Microplastics prevail in snow from the Alps to the Arctic. Sci Adv 5:1–10

Bhat MA (2023) Identification and characterization of microplastics in indoor environments. Eskişehir Tech Univ Eskişehir Technical University. https://doi.org/10.13140/RG.2.2.2http://dx.doi.org/10.13140/RG.2.2.22164.889602164.88960

Bhat MA, Eraslan FN, Gedik K, Gaga EO (2021) Impact of textile product emissions: toxicological considerations in assessing indoor air quality and human health. In: Malik JA, Marathe S (eds) Ecological and health effects of building materials. Springer Nature Switzerland, pp 505–541. https://doi.org/10.1007/978-3-030-76073-1_27

Bhat MA, Eraslan FN, Awad A, Malkoç S, Üzmez OO, Döğeroğlu T, Gaga EO (2022a) Investigation of indoor and outdoor air quality in a university campus during COVID-19 lock down period. Build Environ J 219:109176. https://doi.org/10.1016/j.buildenv.2022.109176

Bhat MA, Gedik K, Gaga EO (2022b) Environmental toxicity of emerging micro and nanoplastics: a lesson learned from nanomaterials. In: Dar AH, Nayik GA (eds) Nanotechnology interventions in food packaging and shelf life. Taylor & Francis (CRC Press), pp 311–337. https://doi.org/10.1201/9781003207641-18

Bhat MA, Eraslan FN, Gaga EO, Gedik K (2023a) Scientometric analysis of microplastics across the globe. In: Vithanage M, Prasad MNV (eds) Microplastics in the ecosphere: air, water, soil, and food. Wiley, pp 3–13. https://doi.org/10.1002/9781119879534.ch1

Bhat MA, Gedik K, Gaga EO (2023b) Atmospheric micro (nano) plastics: future growing concerns for human health. Air Qual Atmos Heal 16:233–262. https://doi.org/10.1007/s11869-022-01272-2

Boakes LC, Patmore IR, Bancone CEP, Rose NL (2023) High temporal resolution records of outdoor and indoor airborne microplastics. Environ Sci Pollut Res 3:39246–39257. https://doi.org/10.1007/s11356-022-24935-0

Cai L, Wang J, Peng J, Tan Z, Zhan Z, Tan X, Chen Q (2017) Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: preliminary research and first evidence. Environ Sci Pollut Res 24:24928–24935. https://doi.org/10.1007/s11356-017-0116-x

Casino P, López A, Peiró S, Rios S, Porta A, Agustí G, Terlevich D, Asensio D, Marqués AM, Piqué N (2023) Polyethersulfone (PES) Filters Improve the Recovery of Legionella spp. and Enhance Selectivity against interfering microorganisms in water samples. Polymers (Basel) 15:2670. https://doi.org/10.3390/polym15122670

Catarino AI, Macchia V, Sanderson WG, Thompson RC, Henry TB (2018) Low levels of microplastics (MP) in wild mussels indicate that MP ingestion by humans is minimal compared to exposure via household fibres fallout during a meal. Environ Pollut 237:675–684. https://doi.org/10.1016/j.envpol.2018.02.069

Chen G, Feng Q, Wang J (2020) Mini-review of microplastics in the atmosphere and their risks to humans. Sci Total Environ 703:135504. https://doi.org/10.1016/j.scitotenv.2019.135504

Chen EY, Lin KT, Jung CC, Chang CL, Chen CY (2022) Characteristics and influencing factors of airborne microplastics in nail salons. Sci Total Environ 806:151472. https://doi.org/10.1016/j.scitotenv.2021.151472

Choi H, Lee I, Kim H, Park J, Cho S, Oh S, Lee M, Kim H (2022) Comparison of microplastic characteristics in the indoor and outdoor air of urban areas of South Korea. Water Air Soil Pollut 233:1–10. https://doi.org/10.1007/s11270-022-05650-5

Collard F, Gilbert B, Eppe G, Parmentier E, Das K (2015) Detection of anthropogenic particles in fish stomachs: an isolation method adapted to identification by raman spectroscopy. Arch Environ Contam Toxicol 69:331–339. https://doi.org/10.1007/s00244-015-0221-0

Cox KD, Covernton GA, Davies HL, Dower JF, Juanes F, Dudas SE (2019) Human consumption of microplastics. Environ Sci Technol 53:7068–7074. https://doi.org/10.1021/acs.est.9b01517

Cui J, Chen C, Gan Q, Wang T, Li W, Zeng W, Xu X, Chen G, Wang L, Lu Z, Li J, Jin B (2022) Indoor microplastics and bacteria in the atmospheric fallout in urban homes. Sci Total Environ 852:158233. https://doi.org/10.1016/j.scitotenv.2022.158233

Dekiff JH, Remy D, Klasmeier J, Fries E (2014) Occurrence and spatial distribution of microplastics in sediments from Norderney. Environ Pollut 186:248–256. https://doi.org/10.1016/j.envpol.2013.11.019

Domenech J, Marcos R (2021) Pathways of human exposure to microplastics, and estimation of the total burden. Curr Opin Food Sci 39:144–151. https://doi.org/10.1016/j.cofs.2021.01.004

Dris R, Gasperi J, Saad M, Mirande C, Tassin B (2016) Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? Mar Pollut Bull 104:290–293. https://doi.org/10.1016/j.marpolbul.2016.01.006

Dris R, Gasperi J, Mirande C, Mandin C, Guerrouache M, Langlois V, Tassin B (2017) A first overview of textile fibers, including microplastics, in indoor and outdoor environments. Environ Pollut 221:453–458. https://doi.org/10.1016/j.envpol.2016.12.013

Enst RKS (2021) Plastics - environmental aspects - state of knowledge and methodologies (ISO/TR 21960:2020)

Eraslan FN, Bhat MA, Gaga EO, Gedik K (2021) Comprehensive analysis of research trends in volatile organic compounds emitted from building materials: a bibliometric analysis. In: Malik JA, Marathe S (eds) Ecological and health effects of building materials. Springer Nature Switzerland, pp 87–109. https://doi.org/10.1007/978-3-030-76073-1_6

Eraslan FN, Bhat MA, Gedik K, Gaga EO (2023) The single-use plastic pandemic in the COVID-19 era. In: Vithanage M, Prasad MNV (eds) Microplastics in the ecosphere: air, water, soil, and food. Wiley, pp 65–75. https://doi.org/10.1002/9781119879534.ch4

Fang M, Liao Z, Ji X, Zhu X, Wang Z, Lu C, Shi C, Chen Z, Ge L, Zhang M, Dahlgren RA, Shang X (2022) Microplastic ingestion from atmospheric deposition during dining/drinking activities. J Hazard Mater 432:128674. https://doi.org/10.1016/j.jhazmat.2022.128674

Field DT, Green JL, Bennett R, Jenner LC, Sadofsky LR, Chapman E, Loubani M, Rotchell JM (2022) Microplastics in the surgical environment. Environ Int 170:107630. https://doi.org/10.1016/j.envint.2022.107630

Gaston E, Woo M, Steele C, Sukumaran S, Anderson S (2020) Microplastics differ between indoor and outdoor air masses: insights from multiple microscopy methodologies. Appl Spectrosc 74:1079–1098. https://doi.org/10.1177/0003702820920652

Gong J, Xie P (2020) Research progress in sources, analytical methods, eco-environmental effects, and control measures of microplastics. Chemosphere 254:126790. https://doi.org/10.1016/j.chemosphere.2020.126790

Hermsen E, Mintenig SM, Besseling E, Koelmans AA (2018) Quality criteria for the analysis of microplastic in biota samples: a critical review. Environ Sci Technol 52:10230–10240. https://doi.org/10.1021/acs.est.8b01611

Hidalgo-ruz V, Gutow L, Thompson RC, Thiel M (2012) Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ Sci Technol 3060–3075. https://doi.org/10.1021/es2031505

Ibrahim YS, Tuan Anuar S, Azmi AA, Khalik WMA, Lehata S, Hamzah SR, Ismail D, Ma ZF, Dzulkarnaen A, Zakaria Z, Mustaffa N, Tuan Sharif SE, Lee YY (2021) Detection of microplastics in human colectomy specimens. JGH Open 5(116):121. https://doi.org/10.1002/jgh3.12457

Ivar JA, Costa MF, Barletta M, José F, Cysneiros A (2013) Pelagic microplastics around an archipelago of the Equatorial Atlantic. Mar Pollut Bull 75:305–309. https://doi.org/10.1016/j.marpolbul.2013.07.040

Jenner LC, Sadofsky LR, Danopoulos E, Rotchell JM (2021) Household indoor microplastics within the Humber region (United Kingdom): quantification and chemical characterisation of particles present. Atmos Environ 259:118512. https://doi.org/10.1016/j.atmosenv.2021.118512

Jiang C, Yin L, Li Z, Wen X, Luo X (2019) Microplastic pollution in the rivers of the Tibet Plateau. Environ Pollut 249:91–98. https://doi.org/10.1016/j.envpol.2019.03.022

Kacprzak S, Tijing LD (2022) Microplastics in indoor environment: sources, mitigation and fate. J Environ Chem Eng 10:107359. https://doi.org/10.1016/j.jece.2022.107359

Kashfi FS, Ramavandi B, Arfaeinia H, Mohammadi A, Saeedi R, De-la-Torre GE, Dobaradaran S (2022) Occurrence and exposure assessment of microplastics in indoor dusts of buildings with different applications in Bushehr and Shiraz cities. Iran Sci Total Environ 829:154651. https://doi.org/10.1016/j.scitotenv.2022.154651

Klepeis NE, Nelson WC, Ott WR, Robinson JP, Tsang AM, Switzer P, Behar JV, Hern C, Engelmann WH (2001) The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. J Ofexposure Anal Environ Epidemiol 11:231–252

Kundu A, Shetti NP, Basu S, Raghava Reddy K, Nadagouda MN, Aminabhavi TM (2021) Identification and removal of micro- and nano-plastics: efficient and cost-effective methods. Chem Eng J 421:1–40. https://doi.org/10.1016/j.cej.2021.129816

Lassen C, Hansen SF, Magnusson K, Hartmann NB, Rehne Jensen P, Nielsen TG, Brinch A (2015) Microplastics occurrence, effects and sources of releases to the environment in Denmark, Danish Environmental Protection Agency

Lenz R, Enders K, Stedmon CA, MacKenzie DMA, Nielsen TG (2015) A critical assessment of visual identification of marine microplastic using Raman spectroscopy for analysis improvement. Mar Pollut Bull 100:82–91. https://doi.org/10.1016/j.marpolbul.2015.09.026

Leslie HA, van Velzen MJM, Brandsma SH, Vethaak AD, Garcia-Vallejo JJ, Lamoree MH (2022) Discovery and quantification of plastic particle pollution in human blood. Environ Int 163:107199. https://doi.org/10.1016/j.envint.2022.107199

Liao Z, Ji X, Ma Y, Lv B, Huang W, Zhu X, Fang M, Wang Q, Wang X, Dahlgren R, Shang X (2021) Airborne microplastics in indoor and outdoor environments of a coastal city in Eastern China. J Hazard Mater 417:126007

Lim E, Tanaka H, Ni Y, Bai Y, Ito K (2022) Microplastics/microfibers in settled indoor house dust—exploratory case study for 10 residential houses in the Kanto area of Japan. Japan Archit Rev 5:682–690. https://doi.org/10.1002/2475-8876.12298

Liu C, Li J, Zhang Y, Wang L, Deng J, Gao Y, Yu L, Zhang J, Sun H (2019a) Widespread distribution of PET and PC microplastics in dust in urban China and their estimated human exposure. Environ Int 128:116–124. https://doi.org/10.1016/j.envint.2019.04.024

Liu K, Wang X, Fang T, Xu P, Zhu L, Li D (2019b) Source and potential risk assessment of suspended atmospheric microplastics in Shanghai. Sci Total Environ 675:462–471. https://doi.org/10.1016/j.scitotenv.2019.04.110

Luo X, Wang Z, Yang L, Gao T, Zhang Y (2022) A review of analytical methods and models used in atmospheric microplastic research. Sci Total Environ 828:154487. https://doi.org/10.1016/j.scitotenv.2022.154487

Lusher AL, Tirelli V, Connor IO, Officer R (2015) Microplastics in Arctic polar waters: the first reported values of particles in surface and subsurface samples. Nat Publ Gr 5:1–9. https://doi.org/10.1038/srep14947

Mandin C, Dris R, Gasperi J, Guerrouache M (2017) A first overview of textile fibers, including microplastics, in indoor and outdoor environments. Environ Pollut 221:453–458. https://doi.org/10.1016/j.envpol.2016.12.013

Nematollahi MJ, Zarei F, Keshavarzi B, Zarei M, Moore F, Busquets R, Kelly FJ (2022) Microplastic occurrence in settled indoor dust in schools. Sci Total Environ 807:150984. https://doi.org/10.1016/j.scitotenv.2021.150984

O'Brien S, Rauert C, Ribeiro F, Okoffo ED, Burrows SD, O'Brien JW, Wang X, Wright SL, Thomas KV (2023) There's something in the air: a review of sources, prevalence and behaviour of microplastics in the atmosphere. Sci Total Environ 874:162193. https://doi.org/10.1016/j.scitotenv.2023.162193

Ouyang Z, Mao R, Hu E, Xiao C, Yang C, Guo X (2021) The indoor exposure of microplastics in different environments. Gondwana Res 108:193–199. https://doi.org/10.1016/j.gr.2021.10.023

Pandey B, Pathak J, Singh P, Kumar R, Kumar A, Kaushik S, Thakur TK (2023) Microplastics in the ecosystem: an overview on detection, removal, toxicity assessment, and control release. Water 15:51. https://doi.org/10.3390/w15010051

Pauly JL, Stegmeier J, Cheney T, Zhang PJ, Allaart A, Mayer G (1998) Inhaled cellulosic and plastic fibers found in human lung tissue. Cancer Epidemiol Biomarkers Prev 7:419–428

Prata JC (2018) Airborne microplastics: consequences to human health? Environ Pollut 234:115–126. https://doi.org/10.1016/j.envpol.2017.11.043

Prata JC, Castro JL, da Costa JP, Duarte AC, Rocha-Santos T, Cerqueira M (2020a) The importance of contamination control in airborne fibers and microplastic sampling: experiences from indoor and outdoor air sampling in Aveiro, Portugal. Mar Pollut Bull 159:111522. https://doi.org/10.1016/j.marpolbul.2020.111522

Prata JC, da Costa JP, Lopes I, Duarte AC, Rocha-Santos T (2020b) Environmental exposure to microplastics: an overview on possible human health effects. Sci Total Environ 702:134455. https://doi.org/10.1016/j.scitotenv.2019.134455

Ragusa A, Svelato A, Santacroce C, Catalano P, Notarstefano V, Carnevali O, Papa F, Rongioletti MCA, Baiocco F, Draghi S, D'Amore E, Rinaldo D, Matta M, Giorgini E (2021) Plasticenta: first evidence of microplastics in human placenta. Environ Int 146:106274. https://doi.org/10.1016/j.envint.2020.106274

Rahman A, Sarkar A, Yadav OP, Achari G, Slobodnik J (2021) Potential human health risks due to environmental exposure to nano- and microplastics and knowledge gaps: a scoping review. Sci Total Environ 757:143872. https://doi.org/10.1016/j.scitotenv.2020.143872

Rani M, Ducoli S, Depero LE, Prica M, Tubić A, Ademovic Z, Morrison L, Federici S (2023) A complete guide to extraction methods of microplastics from complex environmental matrices. Molecules 28:1–37. https://doi.org/10.3390/molecules28155710

Remy F, Collard F, Gilbert B, Compère P, Eppe G, Lepoint G (2015) When microplastic is not plastic: the ingestion of artificial cellulose fibers by macrofauna living in seagrass macrophytodetritus. Environ Sci Technol 49:11158–11166. https://doi.org/10.1021/acs.est.5b02005

Rocha-santos T, Duarte AC (2015) A critical overview of the analytical approaches to the occurrence, the fate and the behavior of microplastics in the environment. Trends Anal Chem 65:47–53. https://doi.org/10.1016/j.trac.2014.10.011

Shim WJ, Hong H, Eo S (2017) Identification methods in microplastic analysis: a review. Anal Method 9:1384–1391. https://doi.org/10.1039/c6ay02558g

Soltani NS, Taylor MP, Wilson SP (2021) Quantification and exposure assessment of microplastics in Australian indoor house dust. Environ Pollut 283. https://doi.org/10.1016/j.envpol.2021.117064

Soltani NS, Taylor MP, Wilson SP (2022) International quantification of microplastics in indoor dust: prevalence, exposure and risk assessment. Environ Pollut 312:119957. https://doi.org/10.1016/j.envpol.2022.119957

Song YK, Hong SH, Jang M, Han GM, Rani M, Lee J, Shim WJ (2015) A comparison of microscopic and spectroscopic identification methods for analysis of microplastics in environmental samples. Mar Pollut Bull 93:202–209. https://doi.org/10.1016/j.marpolbul.2015.01.015

Tamis JE, Koelmans AA, Dröge R, Kaag NHBM, Keur MC, Tromp PC, Jongbloed RH (2021) Environmental risks of car tire microplastic particles and other road runoff pollutants. Microplastics Nanoplastics 1:1–17. https://doi.org/10.1186/s43591-021-00008-w

Torres-Agullo A, Karanasiou A, Moreno T, Lacorte S (2022) Airborne microplastic particle concentrations and characterization in indoor urban microenvironments. Environ Pollut 308:119707. https://doi.org/10.1016/j.envpol.2022.119707

Thacharodi A, et al (2024) Microplastics in the environment: A critical overview on its fate toxicity implications management and bioremediation strategies. J Environ Manag 349:119433. https://doi.org/10.1016/j.jenvman.2023.119433

Uddin S, Fowler SW, Habibi N, Sajid S, Dupont S, Behbehani M (2022) A preliminary assessment of size-fractionated microplastics in indoor aerosol—Kuwait's baseline. Toxics 10:1–17. https://doi.org/10.3390/toxics10020071

Vianello A, Jensen RL, Liu L, Vollertsen J (2019) Simulating human exposure to indoor airborne microplastics using a breathing thermal manikin. Sci Rep 9:1–11. https://doi.org/10.1038/s41598-019-45054-w

Wang L, Zhang J, Hou S, Sun H (2017) A simple method for quantifying polycarbonate and polyethylene terephthalate microplastics in environmental samples by liquid chromatography-tandem mass spectrometry. Environ Sci Technol Lett 4:530–534. https://doi.org/10.1021/acs.estlett.7b00454

Wang X, Li C, Liu K, Zhu L, Song Z, Li D (2020) Atmospheric microplastic over the South China Sea and East Indian Ocean: abundance, distribution and source. J Hazard Mater 389:121846. https://doi.org/10.1016/j.jhazmat.2019.121846

Wesch C, Barthel AK, Braun U, Klein R, Paulus M (2016) No microplastics in benthic eelpout (Zoarces viviparus): an urgent need for spectroscopic analyses in microplastic detection. Environ Res 148:36–38. https://doi.org/10.1016/j.envres.2016.03.017

Xie Y, Li Y, Feng Y, Cheng W, Wang Y (2022) Inhalable microplastics prevails in air: exploring the size detection limit. Environ Int 162:107151. https://doi.org/10.1016/j.envint.2022.107151

Xiong X, Zhang K, Chen X, Shi H, Luo Z, Wu C (2018) Sources and distribution of microplastics in China ' s largest inland lake. Environ Pollut 235:899–906. https://doi.org/10.1016/j.envpol.2017.12.081

Xu C, Zhang B, Gu C, Shen C, Yin S, Aamir M, Li F (2020) Are we underestimating the sources of microplastic pollution in terrestrial environment? J Hazard Mater 400:123228. https://doi.org/10.1016/j.jhazmat.2020.123228

Yao Y, Glamoclija M, Murphy A, Gao Y (2021) Characterization of microplastics in indoor and ambient air in northern New Jersey. Environ Res 112142. https://doi.org/10.1016/j.envres.2021.112142

Zhang J, Wang L, Kannan K (2020a) Microplastics in house dust from 12 countries and associated human exposure. Environ Int 134:105314. https://doi.org/10.1016/j.envint.2019.105314

Zhang Q, Zhao Y, Du F, Cai H, Wang G, Shi H (2020b) Microplastic fallout in different indoor environments. Environ Sci Technol 54:6530–6539. https://doi.org/10.1021/acs.est.0c00087

Zhu J, Zhang X, Liao K, Wu P, Jin H (2022) Microplastics in dust from different indoor environments. Sci Total Environ 833:155256. https://doi.org/10.1016/j.scitotenv.2022.155256