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A comprehensive characterization of indoor ambient microplastics in households during the COVID-19 pandemic

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Abstract

Airborne microplastics (MPs) can be easily inhaled by humans, impacting their health as they spend more than 80% of their time indoors, especially during the pandemic. Only a few research studies have examined indoor MPs in the micrometer size range using active sampling, and studies have mainly concentrated on MPs that are millimeters in size. This study investigated the composition of indoor airborne MPs by active sampling in seven houses in the city center of northwestern Turkey (Eskişehir) during the COVID-19 pandemic. The visual identification showed the presence of different colored MPs, white, red, orange, green, and yellow, with different shapes (fibers, fragments, films, lines, foam, and pellets). The size of the identified MPs was between 2.5 and 327.36 µm. The polymeric composition analysis showed the presence of 123 MPs in all the samples with 22 different polymeric compositions. Residents in these houses are exposed to airborne MPs, with inhalation estimates ranging from 12.03 to 18.51 MPs/m^3. However, it was also estimated that humans inhale 156–240 MPs daily in these houses. The dominant MPs were polyamide 6, polyvinyl chloride, polypropylene, ethylene propylene, polystyrene, and high-density polyethylene. Scanning electron microscopy energy dispersive x-ray elemental analysis revealed the presence of common structural elements, additives, or vectors that are added or adsorbed to MPs like carbon, oxygen, fluorine, magnesium, silicon, chlorine, nitrogen, and aluminum. These indoor environments are prone to MP pollution. Still, the MP level varies due to different characteristics of indoor environments, like activities and the number of occupants/people in the space, etc. The smaller MPs in all the samples highlight the necessity for standardized techniques of MP collection.

Highlights

- Indoor MPs have received very little attention until recently.
- The identified MPs ranged in size from 2.5 to 327.36 µm.
- The residents inhale 156–240 MPs every day.
- The inhalation of residents was from 12.03 to 18.51 MPs/m^3.
- Polyamide 6, polyvinyl chloride, polypropylene, and polystyrene were dominant identified MPs.
- Additives were found in MPs warranting further health effects.

Keywords Airborne microplastics · Micro Raman · MP$_{2.5}$ · Inhalation · Indoor environment · SEM-EDX

Introduction

Human exposure to indoor airborne microplastics (MPs) has received little attention. According to several researchers, the concentration of MPs in indoor air is significantly higher than in outside air (Chen et al. 2020; Gasperi et al. 2018; Jenner et al. 2021). MPs in indoor air differ from outside air because they come from various sources. They are caused by friction, heating, illumination, or wear and tear on anything made of or containing multiple types of plastics.

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This includes certain furniture, other domestic products such as carpets or curtains, and building materials such as wall paints or floor finishes (Bhat et al. 2021; Eraslan et al. 2021; Bhat 2024a). However, most MPs in indoor air specifically come from synthetic textiles used in clothes, such as acrylic (AR), polyamide (PA), or polyester (PL). They rip from clothing when worn, cleaned, and dried (Bhat et al. 2022b, 2023c). MPs < 5 µm in diameter, when breathed, are not filtered out by the nose but instead become trapped deep inside the lungs, producing a variety of health concerns ranging from a simple cough to lung infections such as pneumonia (OMEGA 2017). Particles < 2.5 µm in diameter can cause lifelong lung damage. They can also enter the bloodstream and cause significant health problems such as cardiovascular disease and cancer (Kevin 2018). On the other hand, MP properties can also affect human health by physical or chemical means (Bhat et al. 2022a; Gasperi et al. 2018; Rahman et al. 2021). The physical effect is associated with the MP particles' sizes, shapes, lengths, or concentration. The chemical effect is associated with chemicals added to plastics during manufacturing to improve their quality, strength, and performance; like plasticizers, antioxidants, UV stabilizers, lubricants, dyes, and flame retardants are some of the additives (Aurisano et al. 2021; Bhat et al. 2023a; Eraslan et al. 2023). Most of them do not bond chemically to plastics, and many of them are toxic, so during use and degradation, they can penetrate into the air. MP's can also serve as a vector for pollutants (Campanale et al. 2020; Bhat et al. 2022b, 2023c). MPs may also be susceptible to microbial biofilm growth. All these aspects are not yet fully understood and require more research to find sources and reasons for pollutants' presence in MPs.

Individuals spend more than 80–90% of their time inside (Bhat et al. 2022a; Bhat 2024b); the prevalence of MPs in the indoor environment, their influence on human health, and mitigation methods are critical. Many airborne pollutants are associated with the indoor environment as organic, inorganic, and biological contaminants. Different techniques have evolved in identifying and characterizing MPs (Thacharodi et al. 2024a, b). Indoor MPs have primarily been collected by passive samplings, like dust collection or fallout; however, few studies have used active sampling (Choi et al. 2022; Dris et al. 2017; Gaston et al. 2020; Liao et al. 2021; Uddin et al. 2022; Vianello et al. 2019). Indoor MP studies have employed nine distinct types of filter membranes (Bhat 2023a). Most studies have used Whatman Glass microfiber filters (Dris et al. 2017; Gaston et al. 2020; Prata et al. 2020; Soltani et al. 2021). Other frequently utilized filters include PTFE membranes (Choi et al. 2022; Fang et al. 2022; Liu et al., 2019), Silver membranes (Vianello et al. 2019; Chen et al. 2022; Boakes et al. 2023), Cellulose ester membranes (Jenner et al. 2021; Aslam et al. 2022). Different techniques have been used in indoor environments to characterize the MPs like ATR-FTIR (Attenuated total reflectance - Fourier transform infrared spectroscopy) (Amato-Lourenço et al. 2022; Dris et al. 2017; Prata et al. 2020), micro Raman (Abbasi et al. 2022; Gaston et al. 2020; Kashfi et al. 2022; Uddin et al. 2022) and SEM-EDX (Scanning electron microscopy with energy dispersive X-ray spectroscopy) (Abbasi et al. 2022; Kashfi et al. 2022; Nematollahi et al. 2021). Most indoor studies have used micro FTIR, followed by Stereomicroscope, fluorescent microscope, FTIR, micro Raman etc. (Bhat 2023a). Moreover, there is more work on outdoor ambient MPs than indoor MPs. Microscopes like optical ones are non-destructive techniques essential in morphologically identifying the MPs (2.5 µm) in the samples. The optical microscope should be used before other analytical techniques, as it is crucial to recognize whether a sample contains MPs. To adequately account for MPs in the lower size range, micro Raman investigations should be used. Like an optical microscope, Raman spectroscopy is non-destructive, requires a small sample quantity, allows for high throughput screening, and is environmentally friendly. However, higher laser power in the case of Raman spectroscopy can damage the sample. The intensity of laser power will depend on the sample. Compared to FTIR, Raman methods have a superior spatial resolution (down to 1 µm vs. 10–20 µm for micro FTIR) (Araujo et al. 2018). Analyzing hundreds of nanometer-sized particles with a SEM is also possible. Further information on the elemental composition of MPs can be obtained using an SEM equipped with an EDX spectroscope. Numerous unknowns exist regarding chemical composition, form, size, and any chemical leachate or adsorbed contaminants to indoor MPs. The prospect of MPs entering the human body and the consequences of such exposure on health is a growing worry.

This study aims to explore indoor house MPs by using active sampling. The size, shape, color, and type of MPs were identified by optical microscope, while their polymeric composition was determined by micro Raman microscope; however, SEM-EDX characterized the structural elements, additives present, or contaminants adsorbed in these MPs. As per the literature analysis, this is the first study where an optical microscope, micro Raman, and SEM-EDX instrument were used to characterize indoor MPs by active sampling in homes.

Materials and methods

Indoor MP samples were collected from seven houses in the city center of northwestern Turkey (Eskişehir) during the COVID-19 pandemic (December 2021). All the dwellings were located in the city center, ensuring convenient accessibility. They were designed as apartment-style units, with a minimum occupancy requirement of two individuals. Safety and the availability of power were prioritized. To better understand the origins of MPs in these indoor environments, the residents filled out a questionnaire that involved the building characteristics, textile contribution, electric and electronic device contribution, activities done at home, etc. Detailed information about the questionnaire is mentioned in the supplementary file (Table S1). The ambient samples were collected by active sampling on polytetrafluoroethylene (PTFE) filters with a 9 L/min Gilian 12 live flow air sampling pump for 8 h. Four thousand three hundred twenty liters of sample were collected on PTFE filters. Extensive preliminary testing showed that an eight-hour sample duration guaranteed a sufficient particulate load for MP analysis. The samples were collected at 1.2 m height because this is commonly used to equate to an adult's breathing height. Mostly, the pumps were placed in the center of the room (average 3 feet away from the wall). Filters were weighed before and after the analysis using a micro-analytical balance (AND BM-20) supported by an anti-vibrational table (AD 1671) in a laboratory at an indoor temperature of 17°C and 32% humidity (Table S2). Once the sampling was done, filters were stored in the fridge until the analysis. To find the chemical composition of MPs, it is essential first to identify whether the samples contain MPs or not and characterize them morphologically. These MPs were identified based on their source, type, shape, and color (Table 1) (Bhat 2023b, 2024c), and the Image J software was used in the optic microscope.

Plastic materials were excluded from the study to ensure quality control of MPs in the samples. Only glass material was used instead. Entry to the laboratory was restricted. To minimize the risk of contamination, we used cotton laboratory clothing and nitrile gloves (Bhat et al. 2024). The laboratory was regularly cleaned to prevent any contamination resulting from laboratory activity.

Table 1 Parameters used to describe the microplastics in this study

Source	Consumer products (e, g textiles, bottles, facial cleaners, plastic bags, wrappers, foam floats, styrofoam, cushioning, etc.)
Type	Fibers, Fragments, Films, Lines, Foam, and Pellets
Shape	*Fibers*: Equally thick through their entire length, should not be entirely straight- which indicates a biological origin and should not be tapered at the end *Fragments*: Flattened, shard-like, broken edges, rounded, subrounded, angular, and subangular *Films*: Transparent and thin (thinner than fragments) *Line*: Fibrous, thin, and straight *Foam*: Sponge-like texture *Pellets*: Tablet-like, oblong, cylindrical, spherical, flat, disk shapes, and mainly spherical to avoid rounded ends
Color	Transparent, crystalline, white, red, orange, blue, black, gray, brown, green, pink, tan, opaque, and yellow

For visual characterization of MPs, the Primotech Zeiss optical microscope with 5x objective (NA = 0.13), 10x objective (NA = 0.23), 20x objective (NA = 0.4), 50x objective (NA = 0.65), and 100x objective (NA = 0.8) was used. The optical microscope was operated by Axiovision SE64 Rel.4.9.1 software embedded with the AxiocamERc5s camera. Under the optical microscope, each filter was analyzed from left to right or right to left, then moved down slowly. Each filter should be analyzed at least three times to reduce the error while identifying the MPs and thus examined for almost 1–1.5 h. Counting all the MPs from the filters based on the morphological features was impossible because the sample content was very dense, and the chances of miscounting or mixing MPs with non-MP particles were always high. Hence, the main aim of using an optical microscope was to analyze whether these samples contained MPs or not. The general view of filters under the optical microscope is shown in the supplementary file (Fig. S1-S3). The samples were further analyzed for chemical and elemental characterization under micro Raman and SEM-EDX.

Micro Raman measurements of the samples were performed by an alpha 300R confocal Raman microscope (WITec), with a grating of G2:600 g/mm BLZ = 500 nm and a thermoelectrically cooled charge-coupled device (CCD) detector. The 532 nm radiation of a PS laser and a 10× objective (NA = 0.25; WD = 9.3 mm) and 50× objective (NA = 0.8; WD = 0.57 mm) EC Epiplan-Neofluar Disc Zeiss were used. Thorlabs GmbH laser intensity checker controlled the laser intensity. Raman spectra were recorded in the wavenumber range of 152–4287 cm^{-1}, with a spectral center of 2500, laser power of 9–10 mW, and an integration time of 15–20 s per scan. For each spectrum, 15–20 scans were accumulated. For each sample, 25–30% of the filter area was analyzed by micro Raman for about 4–5 h of quantification. The Raman system was operated by control five software (WITec). For better illustration, smoothing and baseline correction were also done. The spectra obtained in the micro Raman microscope were compared with reference spectra from the micro Raman polymer database using Open Specy (Cowger et al. 2021). The spectrums were also cross-checked with the polymer database book (Mark 2009). The highest matching score was considered as MPs. Very few studies have discussed the matching score, and given it, in their results, their scores varied from 27 to 97% (Cai et al. 2017; Tunahan Kaya et al. 2018; Liu et al. 2019b; Song et al. 2021).

Backscatter electron-scanning electron microscope (BSE-SEM) (FEG-SEM; Zeiss Supra 50 VP) coupled with an EDX micro analyzer (INCA Energy; Oxford Instruments) was used to characterize and identify the structural elements, additives present, and the contaminants adsorbed on the MPs. The working distance was 10, while the 20 kV was used for electron high tension. The BSE-SEM imaging mode is based on the principle that dark regions represent elements with low atomic numbers, and bright regions represent elements with high atomic numbers. All the samples were sprinkled over double-sided carbon tape and mounted on the SEM, and the surface morphology and micro and nano region elemental composition were determined. The surface morphology and element composition results were printed as black-and-white images and tables. The SEM-EDX measurements were taken after the optical and micro Raman microscope analysis. The advantage of doing this is that the carbon covering of filters for SEM-EDX measurements affects the filters and can not be used again if kept for a long time.

Results and discussion

It is challenging to identify MPs of different types of polymers and various sizes and shapes from the complex environmental matrix with only a single analytical technique. Therefore, this study used an optical microscope, micro Raman, and SEM-EDX combinations to characterize indoor ambient MPs. Before identifying polymer types of MP samples, it is essential to identify and characterize these polymeric particles based on their morphology. The visual identification of MPs is a crucial primary step in identifying the MPs. Still, there are high chances of human errors in determining the MPs, especially in complex matrices like air.

Visual identification of microplastics

The morphological characterization of ambient MPs (2.5 μm) in homes was done by optical microscope. The examples of some ambient MPs found in the homes are shown in Fig. 1. Fibers, fragments, films, lines, foam, and pellets were common MPs in these houses. Scanning samples under the optical microscope showed that fibers were the dominant type. This might be due to using textile products like clothes, carpets, sofas, and curtains in these indoor environments. Inhabitants of these homes reported having, on average, four curtains, four rugs, and three sofas in their dwellings. Sofas and carpets took up an average of 67.14% of the floor space. In addition, it was found that just 14.28% of homes dry their clothing indoors, while the remaining 71.42% do so both inside and outside the house. When grocery shopping, 85% of homes use plastic bags, and 71%

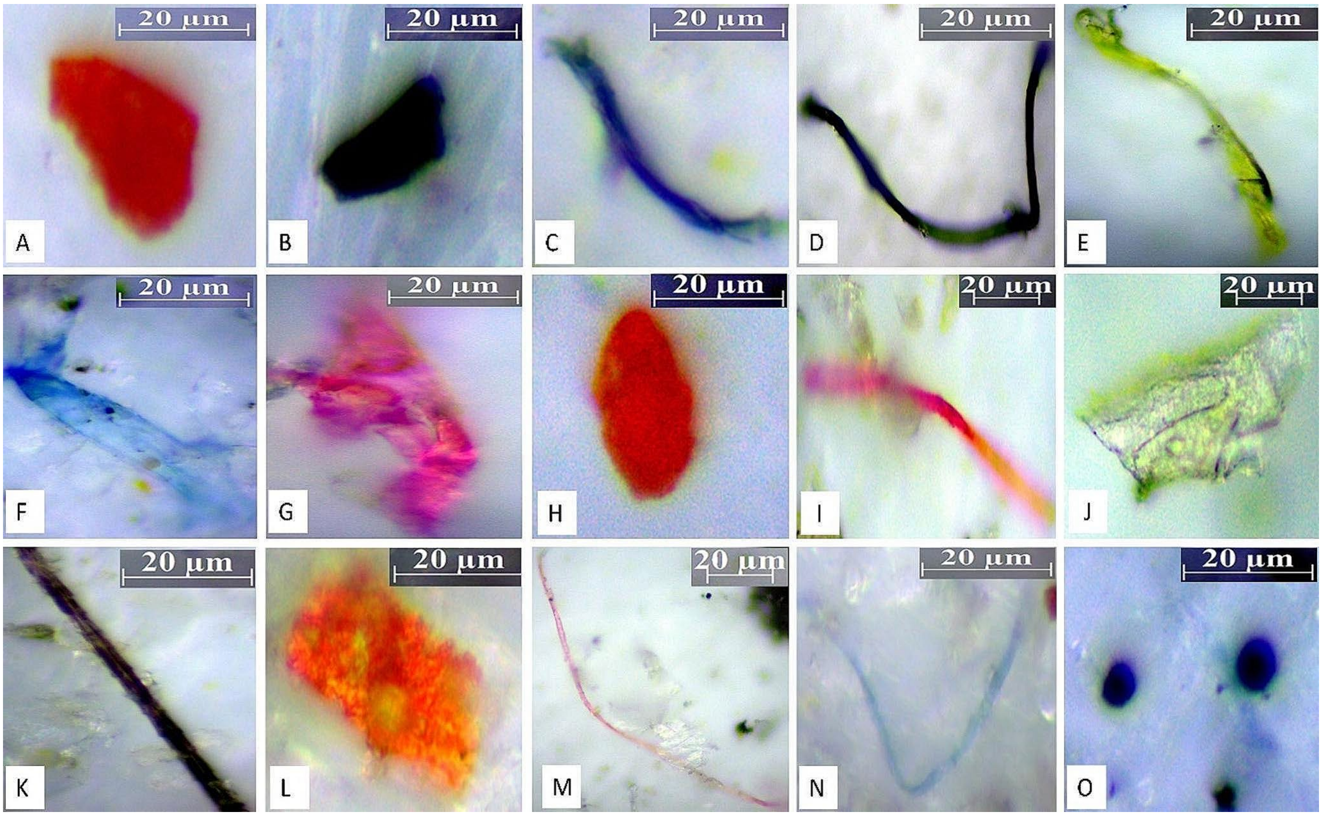


Fig. 1 Examples of some ambient microplastics found in the homes and classified by shape and color (**A**, **B**, **L**): Red and black fragments, (**C**, **D**, **I**, **M**, **N**): Blue, black, and red fibers, (**E**) Green foam, (**F**, **G**, **J**): Blue, magenta, and transparent films, (**K**): Black line

of households buy pre-packaged food. This suggests that houses are rich in MP resources. Electronic gadgets were present in every one of these indoor residences, with each home having an average of eight gadgets. Additionally, using these electronics increases the number of MPs in the home. Photographs and picture frames, which frequently have plastic parts like frames and protective coatings, may contribute to the spread of MPs across residential areas. According to the data analyzed from houses, the average number per residence was three. Notably, the percentage of residences without pictures varies widely, with 71.28% of all properties having no pictures. Nonetheless, photos were located in 28.57% of houses, which can be an extra source of MPs in these houses. The typical residence was only 79.28 m^2 (average) in size, which may make it harder to circulate fresh air and increase exposure to MPs. Natural ventilation was used for an average of 54.28 min daily, with no mechanical ventilation used in any of the homes. In addition to the indoor sources of MPs, the fact that all the houses were located in urban neighborhoods close to roadways (where road dust, including tire wear, is prevalent) raises the possibility of introducing MPs from outside the home via natural ventilation. Identifying these fibers, fragments, films, lines, foams, and pellets represents the presence of MPs in indoor environments. The difference in the maximum size of the identified MPs was seen among the ambient house samples. The size of MPs in ambient house samples one, two, three, four, five, six, and seven showed a range of 2.5–130.86, 2.5–392.02, 2.5–153.06, 2.5–1055.88, 2.5–258.42, 2.5–206.13 and 2.5–95.17 µm. However, the average range of MPs among all the samples was 2.5–327.36 µm. These MPs were in different colors (transparent, crystalline, white, red, orange, blue, black, gray, brown, green, pink, tan, magenta, opaque, and yellow). Moreover, considerable variations in size, shape, color, and type of MPs were seen. Their exposure level to the individual will differ depending on where participants live and other lifestyle factors. The last decade has shown a tremendous rise in MP studies; researchers are trying every possible way to identify and morphologically characterize these MPs. The results confirm the ubiquitous presence of MPs in indoor air environments demonstrated in studies using active sampling, like Dris et al. (2017) have also identified fiber as the dominant indoor MP type. All their samples contained fibers, probably due to the proximity of the sources and the fact that fibers might easily tear from clothes and some house furniture, carpets, curtains, textiles, etc. However, the size range of MPs (50 – 4,850 µm) was higher than the average size range of MPs (2.5–327.36 µm) seen in this study, and they did not quantify the MPs based on their color. Gaston et al. (2020), Liao et al. (2021), and Vianello et al. (2019) identified only fiber and fragment types of MPs. They did not identify other common types of MPs like film, pellet, foam, and line as identified in this study, and they also did not characterize the MPs based on their color. However, their identified size levels (58–641 µm), (5–5000 µm), and (68–237 µm) MPs were within the size range of MPs identified in this study (2.5–327.36 µm). Moreover, Uddin et al. (2022) and Xie et al. (2022) also identified the fiber, fragment, and bead-type MPs. Furthermore, they categorized the MPs based on their standard colors, as characterized in this study. Their lower size limit of MPs (0.45–2800 µm and 2.40–2181.48 µm) was either lesser than the lower size limit of MPs seen in this study or was almost equal (2.5–327.36 µm); however, their maximum size range of identified MPs was higher than the size of MPs identified in this study. Choi et al. (2022) characterized the indoor MPs as fibers and non-fibers, and they did not characterize MPs based on their color; however, their identified size range of MPs (20.1–6801.2 µm) was higher than the size range of MPs identified in this study (2.5–327.36 µm).

The results also showed the follow-up to passive sampling studies in indoor environments apart from active sampling studies indoors, like Dris et al. (2016) identified the smallest fibers with a size range of 200–400 and 400–600 µm. However, few fibers have been found in the 50–200 µm range. They also observed fibers smaller than 50 µm with the Stereomicroscope, but they could not correctly identify their nature and did not consider them. In another study in different indoor environments (Zhang et al. 2020), fibers were the prominent MPs seen with a size range of 50–2000 µm, and MPs less than 50 µm were undetectable. Liu et al. (2019) found the fiber, fragment, and granule shapes suspended atmospheric MPs with different size ranges from 23.07 to 9,555, 14 to 19, 47.70 to 2230, and 10 to 37 µm. Yao et al. (2021) found MP fibers, films, and fragments in indoor environments like offices, hallways, classrooms, and single-family houses. Nematollahi et al. (2021c) found fragments, sheets, and fiber in schools with a 500–1000 µm size range. Fiber, fragments, film, and debris in kindergarten classrooms, primary school, junior high school, senior high school, and the university's postgraduate study room were recently analyzed by Ouyang et al. (2021). The primary size of the indoor fibers was below 0.5 mm and 0.5–1 mm. From the literature mentioned above, it is clear that passive studies primarily focus on the millimeter size of MPs; however, active sampling has concentrated on the micrometer size of the MPs. Once we lower the size of MPs, it becomes difficult to count them and characterize them with non-MP particles, and even it would be more difficult for the nanosize range. Yet, counting is possible, as there might be high chances of human errors and creating a wrong MP count, which might develop extra uncertainties for risk assessment and modeling of ambient MPs. However, their polymeric identification is an essential step after morphological characterization as the chances of errors are significantly less or negligible.

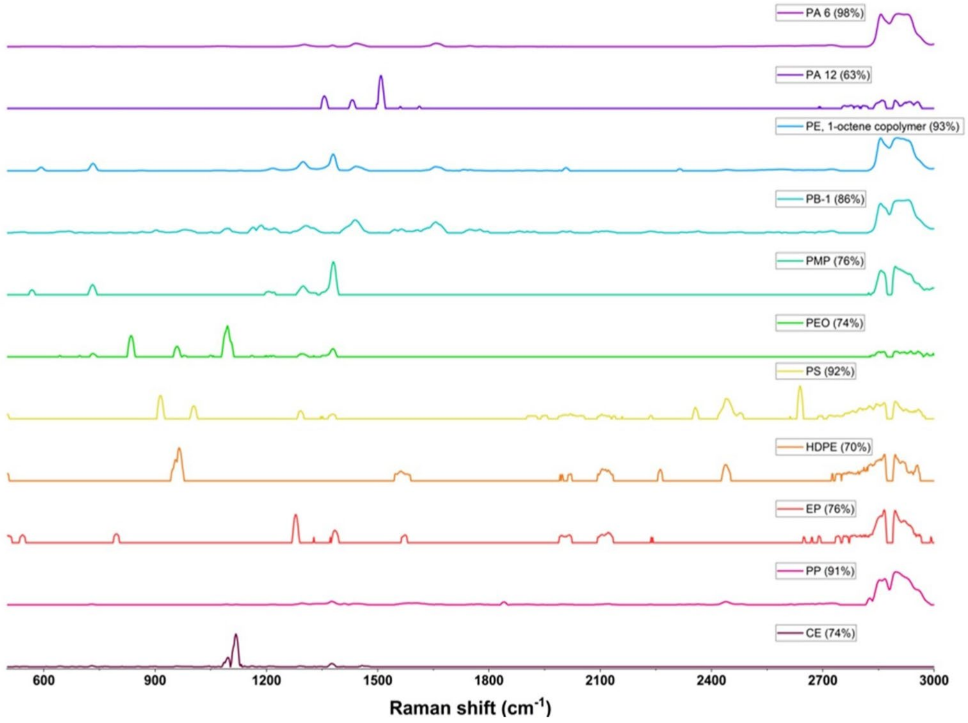
Polymeric identification

The micro Raman analysis of ambient indoor house samples showed the presence of different MPs. 25–30% of filters were scanned for the micro Raman analysis, which showed that 13, 16, 17, 19, 20, 20, and 18 MPs were identified in seven indoor house samples. Although only 25–30% of the filter area was scanned under the micro Raman, the filters' MPs were considered equally distributed. A total of 22 different types of MPs were identified. Their spectrums were plotted with the match degrees (Figs. 2 and 3). These identified MPs include ethylene vinyl acetate (EVA), polyamide 12 (PA 12), polyacrylamide (PAM) carboxy modified, polyethylene (PE) foamed, polyethylene terephthalate (PET), polylactic acid (PLA), polyamide 12 (PA 66), PTFE, sealing ring ethylene propylene diene monomer (EPDM), styrene ethylene butylene (SEBS), polyamide 6 (PA 6), PE 1-octene copolymer, poly(1 butene) isotactic (PB-1), polymethylpentene (PMP), poly(ethylene oxide) (PEO), polyvinyl chloride (PVC), polypropylene (PP), ethylene propylene (EP), polystyrene (PS), high-density polyethylene (HDPE), and cellulose (CE). These identified MPs have comprehensive sources and applications and are used daily in homes (Chanda and Roy 2008; Elias 2009; Mark 2009), and it was found that all the sources were present in these indoor houses like footwear, flooring, furniture, bottled beverages, food packaging, toys, electronics, insulation, pillows, non-stick utensils, films, seals, insulation, coatings, adhesive tapes, pipes, fittings, disposable plates, cutlery, biodegradable plastics, packagings, wires, plugs, photographs, and film coatings etc.

The distribution of ambient MPs varied among the house samples (Fig. 4). The MPs found in most house samples were sealing ring EPDM, SEBS, PA 6, PE 1-octene copolymer, PB-1, PMP, PEO, PVC, PP, EP, PS, and HDPE. MPs identified under microRaman were further characterized based on their type and color (Fig. 5). The fiber was the dominant type of MP seen under micro Raman. However, significant differences were seen in the colors. In ambient indoor house samples 1, 2, 3, 4, 5, 6, and 7, the concentrations of MPs were 12.03, 14.81, 15.74, 17.59, 18.51, 18.51, and 16.66 MPs/m^3. These concentration results represent the whole filter area and the total amount of air collected. Based on the micro Raman analysis, residents in these houses are exposed to airborne MPs (2.5–327.36 µm), with inhalation estimates ranging from 12.03 to 18.51 MPs/m^3 and 156–240 MPs daily.

In total, 123 particles were identified as MPs, consisting of 22 different types of MPs. As per the author's knowledge, this is the first indoor study where 22 different MPs were found in the indoor houses using the active sampling, while as in other indoor house air studies, only a standard or a limited number of MPs were seen and the findings agreed with them like Prata et al. (2020) found seven different types of MPs (polyester (PL), PA, Cotton (CO), wool (WO), linen (LI), viscose (VI), and rayon (CV) with a concentration of

Fig. 2 Micro Raman spectra of (1–11) ambient microplastics found in indoor houses (98%)* percentage of relevance



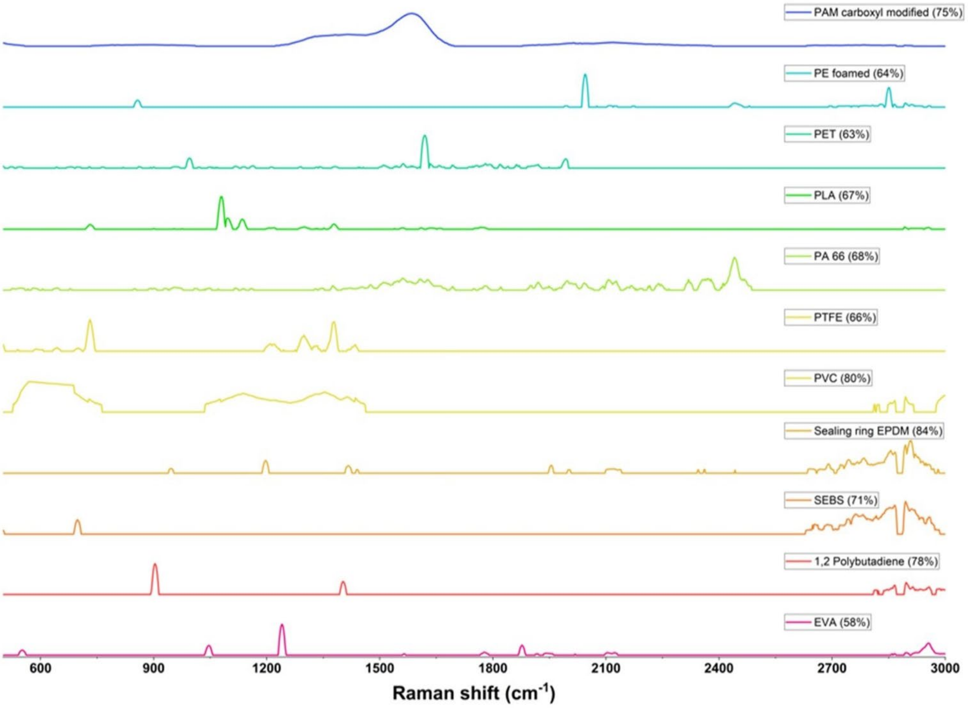


Fig. 3 Micro Raman spectra of (12–22) ambient microplastics found in indoor houses (75%)* percentage of relevance

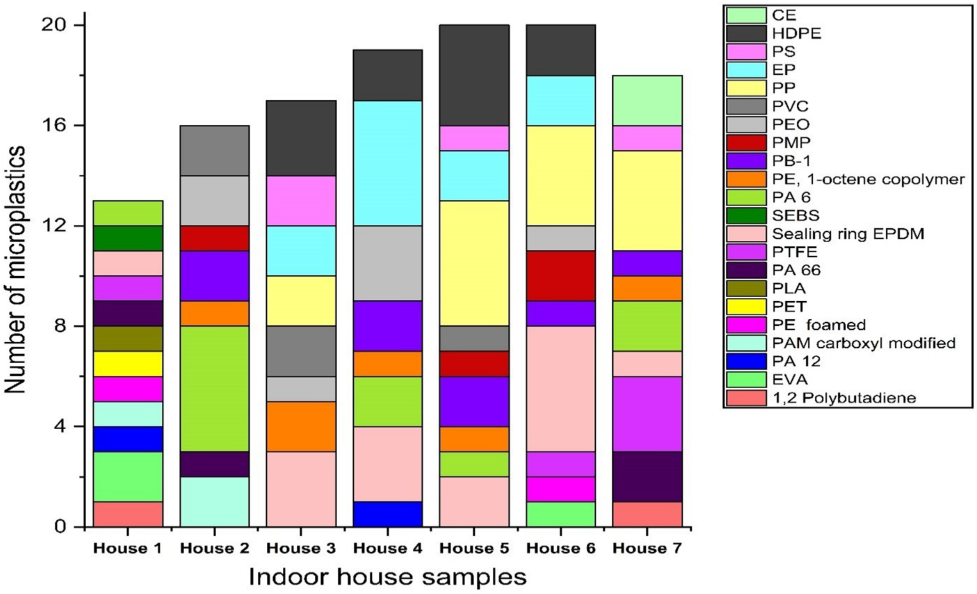


Fig. 4 Distribution of ambient microplastics found in each indoor houses

6 fibers m^{-3} in France by using ATR-FTIR. Xie et al. (2022) found eight MPs (PE, PL, resin (RC), PVC, CO, PP, polyurethane (PUR), and rubber (RB) with a concentration of 16–93 Nm^{-3} in China by using Raman. Choi et al. (2022) found ten different types of MPs (PP, PL, PS, PTFE, PVC, alkyd (ALK), AR, PA, PUR, and PE) with a concentration of 0.49–6.64 MPs m^{-3} in South Korea by using FTIR. However, differences were seen in the composition and concentration of MPs within these studies compared with the MPs found in this study; this might be due to the difference in the sampling locations, appropriate sources, sampling volume, and the type of instrument used. Only these three studies (Choi et al. 2022; Prata et al. 2020; Xie et al. 2022) have used active sampling to collect the MPs from houses. All these three studies have used different instruments (ATR-FTIR, Raman, and FTIR) to analyze MPs.

Passive sampling has also been done in different indoor environments apart from the active sampling, and the results showed the follow-up to these indoor passive sampling studies like four types of MPs were identified in indoor environments, including PET, PP, PS, and PA (Zhang et al. 2020). Recently, Yao et al. (2021) found that MPs like PS, PET, PE,

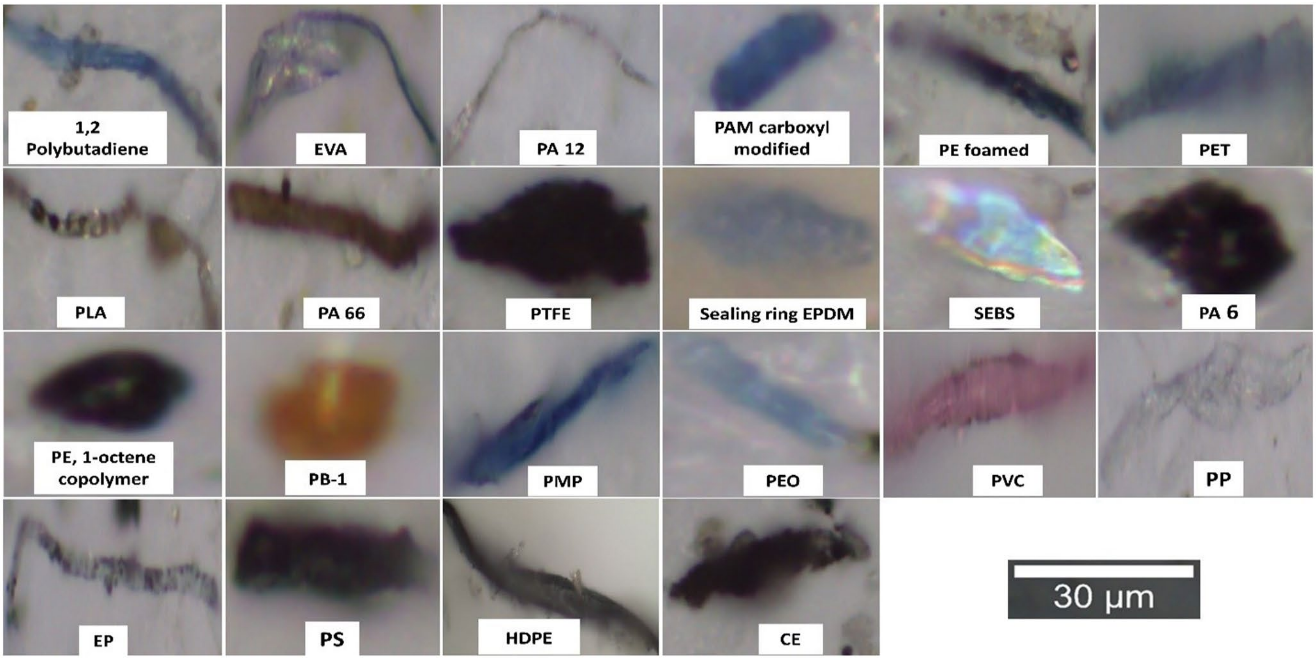


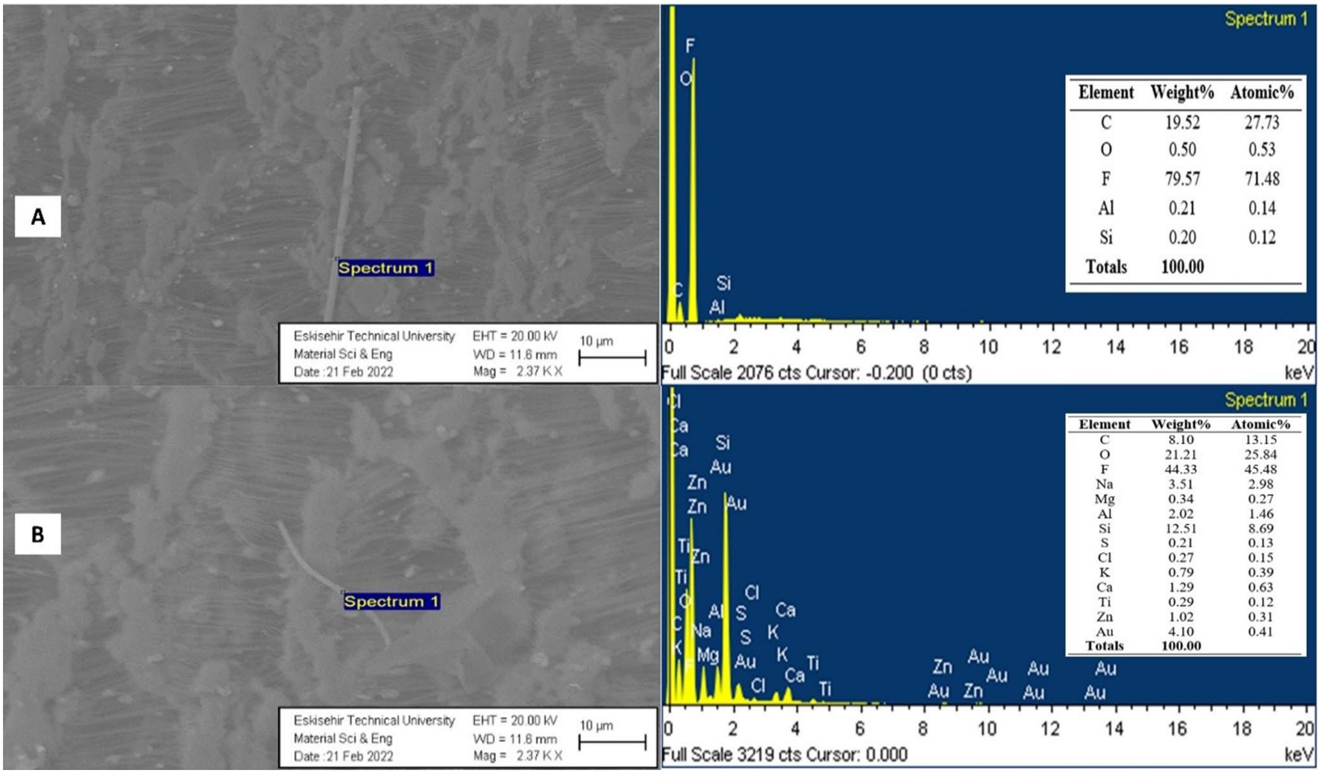
Fig. 5 Typical representation of ambient microplastics seen under micro Raman and are categorized by type and color (1,2 Polybutadiene, PAM carboxy modified, PET, PMP, and PEO); Blue fiber, (EVA, SEBS and PP); Transparent film, (PA 12 and EP); Transparent fiber, (PE foamed and HDPE); Black fiber, (PLA); Brown fiber, (PA 66); Maroon fiber, (PTFE, PA 6 and PS); Black fragment, (Sealing ring EPDM); Blue film, (PE,1-octene copolymer); Blcak pellet, (PB-1); Brown pellet, (PVC); Red fiber and (CE); Black foam

PVC, and PP were identified in indoor environments like offices, hallways, classrooms, and single-family houses. Nematollahi et al. (2021c) found PET, PP, and PS MPs in schools. The indoor exposure of MPs in different environments like kindergartens, primary schools, middle schools, high schools, and the university was conducted by Ouyang et al. (2021); five different MPs were found: PET, polyacrylonitrile (PAN), PVC, PP, and PA. Even MPs like PAN, polymethyl methacrylate (PMMA), PE, AR, PP, PA, and PET have been seen in households (Jenner et al. 2021). Like active sampling studies, slight differences were seen in the MPs in these passive sampling studies compared with the MPs in this study. Apart from the chemical characterization of MPs, it is noteworthy to identify the structural elements, additives added to them, or the additional contaminants they may carry because these pollutants make them extra toxic.

Identification of structural elements, additives, or adsorbed contaminants on microplastics

Besides the color, type, shape, and polymeric composition of the identified MPs, SEM-EDX analysis was done to determine the morphological changes, structural elements, and additives present or adsorbed contaminants in these MPs. Indoor ambient house sample 1 showed the presence of different structural elements, additives, or adsorbed contaminants on these MPs (Fig. 6). The carbon (C), oxygen (O), fluorine (F), aluminum (Al), and silicon (Si) were the common elements in the indoor MPs of house sample 1. The difference in their weight percentages was seen under the SEM-EDX analysis. C and F had the highest weight% in the line type of MP (Fig. 6-A). Meanwhile, in the fiber, MP C, O, F, and Si (Fig. 6-B) had the highest weight%.

Indoor ambient house sample 2 showed the presence of different structural elements, additives, or adsorbed contaminants on these MPs (Fig. S4). The C, O, magnesium (Mg), potassium (K), chlorine (Cl), and Si were the common elements in the indoor MPs of house sample 2. The difference in their weight percentages was seen under the SEM-EDX analysis. C and O had the highest weight% in both the MP fiber and fragment type. Indoor ambient house sample 3 showed the presence of different structural elements, additives, or adsorbed contaminants on these MPs (Fig. S5). The C, O, F, and gold (Au) were the common elements in the indoor MPs of house sample 3. The difference in their weight percentages was seen under the SEM-EDX analysis. C, O, F, and Si had the highest weight% in the pellet type of MP (Fig. S5). C, O, and F had the highest weight% in the fiber type of MP (Fig. S5). Indoor ambient house sample 4 showed the presence of different structural elements, additives, or adsorbed contaminants on these MPs (Fig. S6). The C, O, F, sodium (Na), Mg, Al, Si, Cl, K, calcium (Ca), iron (Fe), and Au were the common elements in the indoor MPs of house sample 4. The difference in their weight



Element	Weight%	Atomic%
C	19.52	27.73
O	0.50	0.53
F	79.57	71.48
Al	0.21	0.14
Si	0.20	0.12
Totals	100.00	

Element	Weight%	Atomic%
C	8.10	13.15
O	21.21	25.84
F	44.33	45.48
Na	3.51	2.98
Mg	0.34	0.27
Al	2.02	1.46
Si	12.51	8.69
S	0.21	0.13
Cl	0.27	0.15
K	0.79	0.39
Ca	1.29	0.63
Ti	0.29	0.12
Zn	1.02	0.31
Au	4.10	0.41
Totals	100.00	

Fig. 6 SEM-EDX examples of some ambient microplastics found in house one and classified by shape (**A**): Line, (**B**): Fiber

percentages was seen under the SEM-EDX analysis. C, O, F, and Si had the highest weight% in the foam type of MP (Fig. S6). C, O, and F had the highest weight% in the fragment type of MP (Fig. S6). Indoor ambient house sample 5 showed the presence of different structural elements, additives, or adsorbed contaminants on these MPs (Fig. S7). The C, O, F, Mg, Al, Si, Ca, Fe, and Au were the common elements in the indoor MPs of house sample 5. The difference in their weight percentages was seen under the SEM-EDX analysis. C, O, F, and Ca had the highest weight% in both fragments. Indoor ambient house sample 6 showed the presence of different structural elements, additives, or adsorbed contaminants on these MPs (Fig. S8). The O, F, Mg, Al, Si, sulfur (S), Cl, K, Ca, Fe, and Au were the common elements in the indoor MPs of house sample 6. The difference in their weight percentages was seen under the SEM-EDX analysis. O, F, Mg, and Si had the highest weight% in the pellet type of MP (Fig. S8). C, O, F, and Si had the highest weight% in the pellet type of MP (Fig. S8). Indoor ambient house sample 7 showed the presence of different structural elements, additives, or adsorbed contaminants on these MPs (Fig. S9). The O, F, S, and Cl were the common elements in the indoor MPs of house sample 7. The difference in their weight percentages was seen under the SEM-EDX analysis. F, Si, Cl, and zinc (Zn) had the highest weight% in the pellet type of MP (Fig. S9). C, nitrogen (N), and F had the highest weight% in the pellet type of MP (Fig. S9).

C, O, F, Mg, Si, Cl, K, Ca, Au, Na, S, Al, Fe, Zn, titanium (Ti), and N were the common elements seen in the identified MPs. The SEM-EDX showed the differences in the weight percentages among all ambient MPs identified. This can be due to the difference in the polymeric composition of identified MPs or the manufacturing process of plastic items when these additives were added. The additives or adsorbed contaminants make the MPs more toxic to human health. The surface of some MPs appears smooth, while irregular patterns were also seen on their surfaces, showing they have undergone degradation (Bhat et al. 2023b). Until now, none of the active indoor MP studies have done the SEM-EDX analysis, so the SEM-EDX results of this study were compared with the indoor passive sampling studies like the results followed the findings of Abbasi et al. (2022); they found C, N, O, Na, Al, Si, Cl, Ti, manganese (Mn), copper (Cu), Zn, antimon (Sb), and lead (Pb) while the C, N, O, Na, were the dominant elements. Furthermore, the results also agreed with the results of Kashfi et al. (2022), who found C and O as dominant elements in all MPs, while N, phosphorus, iodine, Cl, Al, Ca, Mg, Na, and Si were the other elements. Besides these two indoor dust studies, the results also agreed with the indoor dust samples of schools (Nematollahi et al. 2021). Nematollahi et al. (2021) found that MPs were composed of a high percentage of C and O with SEM-EDS, while the MPs had a minor percentage of other elements, including N, Na, Mg, Al, Si, Cl, Ti, Mn, Cu, Zn, tin, Sb, mercury (Hg), and Pb. Due to environmental exposure, MPs exhibited homogeneous surface texture and degradation patterns, such as grooves, pits, cracks, etc. Some particles have a linear fracture on the surfaces, which the physical action of wind may contribute to, and there are adhering particles on the surface (Cai et al. 2017). Mechanical and chemical deterioration, collisions and friction, or wind action may cause these imperfections in surface texture. Physical abrasion and chemical weathering against sunlight, air, and humidity increase the surface roughness of some MPs and enhance their contaminant adsorption (Abbasi 2021; Bhat et al. 2023b). The patterns aid in the adhesion of additional particles to the surface of MPs, increasing the toxicity and health risk of MPs to humans.

Although EDX cannot differentiate between different types of association, relatively high concentrations of certain metals in some samples (F, Si, Mg, and Ca) likely reflect the presence of contemporary and historical additives and catalytic residues in polymeric materials. On the other hand, lower and more uniform concentrations of elements that are not frequently added to plastics and/or are more indicative of geogenic material (such as Al, Mg, and Na) were found to have been captured from the environment. In addition, other components may be present in the plastic either as functional additives or reaction residues or as components of extraneous material that is stuck to or adsorbed onto the surface of the plastic. The presence of C indicates the existence of polymer components. High quantities of C, O, N, and plastic-specific chemical components demonstrate the correct identification of MPs (e.g., Cl in PVC) (Abbasi 2021). The presence of elements Al, Si, Na, and Mg on MPs are dominant constituents of silicate minerals (e.g., clays) and can likely be caused by silicates adsorbed onto the surface of these polymeric particles. Al, Ca, Si, and Mg mainly originated from natural materials such as soil or dust, and Cu and Zn from anthropogenic sources (such as burning fossil fuels and abrasing vehicles) (Ganesan et al. 2019; Abbasi 2021) adhere to the surface of plastic particles. Na, Mg, K, Al, Si, Ca, Cl, and O adhere to MPs' surface (Ganesan et al. 2019). Zn is a well-known urban element that likely originated from anthropogenic activities, including traffic and industrial activities (Ahmady-Birgani et al. 2015; Nematollahi et al. 2021). Fe is also widely used as an additive in plastic materials to achieve desired properties, such as colored plastic (Nematollahi et al. 2022). Al, Si, Na, and Mg are likely adsorbed onto the surface of MPs, and silicate minerals such as clays may cause their presence (Nematollahi et al. 2021). To achieve a wide range of colors, textures, and functionality, a wide variety of elements (Ti, Si, Zn, Al, and Fe) have been used in paints, which might be pigments, binders, or additives (Kowalczyk et al. 2012; Lopez et al. 2023; Pfaff 2021; Zuin et al. 2014). As these additives are not chemically bonded to the polymeric matrix, they can be released into the environment due to weathering (Hahladakis et al. 2018). The lower and more uniform concentrations of elements not commonly added to plastics and/or are more indicative of geogenic material, e.g., Si, Ca, K, Na, Mg, and Ti (Soltani-Gerdefaramarzi et al. 2021). F is used in toothpaste, mouthwash, and the manufacturing of PTFE, which is a nonstick coating for cookware (Vranic et al. 2004; McKeen 2012); there are chances that F might have been adsorbed on the surfaces of MPs. Minerals like gypsum contain S naturally (Kong et al. 2020), and these gypsums are used inside houses.

Sources and possible exposures to microplastics in homes

This study showed that humans in indoor houses are exposed to 12.03–18.51 MPs/m^3 and inhale 156–240 MPs daily. Vianello et al. (2019) formulated that a male person inhales 272 MPs per day. In another study, inhalation of airborne MPs, including microfibers (length > 5 μm, with diameter < 3 μm) via indoor air, has been estimated at 26–130 airborne MPs per day (Catarino et al. 2018). The primary reasons for the variability could be associated with different sampling methods (like sampling time and flow rate) and environments. Still, other factors such as space usage and occupancy, type of ventilation, location of sampling apparatus, level of outside air penetration of the indoor space, and accumulation of primary and secondary MPs can contribute to the differences. Synthetic fabrics, household item finishes, and cleaning chemicals are the primary sources of MPs in the interior environment. Clothing, bedding, curtains, carpets, and other items made from synthetic or semi-synthetic fibers such as PA, AR, PL, polyolefin, elastane, or CV are among the most common contributors to microfibres released into indoor air, typically through shedding during everyday movement and use (Bhat et al. 2021). Synthetic textile release occurs in all home and indoor business areas. The population determines its density, the intensity of people, and the amount of air movement. Another internal source of MPs is the wear and tear of all surface finishes such as wall/ceiling paints, floor finishes, wallpapers, other plastic items, kitchen plastic utensils such as scouring pads, brushes, etc. cloths, and general multipurpose cleaning products. MPs are typically released from these surfaces due to their use, cleaning, rubbing, cutting, scraping, or maintenance. Outdoor MPs, such as industrial or agricultural emissions containing MPs from their activities, can also enter the indoor environment. Traffic MP particles from automobile tires are another prevalent external contaminant impacting many indoor environments. Indoor facilities near busy highways are particularly prone to MP contamination from traffic. Although these sources are born outside, they can quickly enter indoor areas via windows, infiltration, or mechanical ventilation. The wind, open windows, and infiltration move many MP contaminants from the outside to the interior environment. Without adequate filtering systems, air conditioning and supply ventilation contribute to the passage of outside air contaminants into buildings via outside air components. Internally, pollutants from the outside and within the building settle or deposit on the floor and other surfaces, together with regular dust, and are redistributed back into the air by foot circulation and related air turbulence (Gaston et al. 2020). Similarly, when air conditioners are turned on, they enhance interior air turbulence, causing dust and MPs to fly around and be resuspended (Gaston et al. 2020). Natural air movement gradually replaces interior air with outside air, combining unfiltered outdoor and indoor air. The pollution particles from the floor and other surfaces are lifted into the air by the breeze from natural cross ventilation. The impact of ceiling fans is similar (Gaston et al. 2020).

Although research on MPs that collect in indoor spaces is minimal, several studies have indicated their high concentration (Chen et al. 2020; Gasperi et al. 2018; Jenner et al. 2021) in indoor air, raising serious concerns about human health owing to inhalation, skin contact, and ingestion. Although ingestion is typically caused by eating externally contaminated food, MPs in the interior air that settle on plates during meals can also be consumed. Exposure to MPs in contaminated food, particularly seafood, and its effects on the human digestive system appears to be the most investigated route, with inhalation exposure being the least examined (Prata et al. 2020; Rahman et al. 2021). Even in relatively low polluted areas, MPs less than 10 µm in size, including ultrafine particles less than 0.1 µm in size, are the most dangerous to human health because they easily penetrate respiratory systems, causing the development of severe diseases in susceptible individuals. Human responses to inhaled MPs generally include chronic inflammation, such as bronchitis, and allergic reactions, such as asthma and pneumonia (Prata 2018; Prata et al. 2020). 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 resistance and persistence characteristics, they may be difficult to remove from the bodies (Amato-Lourenço et al. 2020). Recent research found that some of the finest particles, less than 0.1 µm in size, can breach the alveolar-capillary barrier and enter the circulation, causing harm to numerous organs or systems in the body, including the cardiovascular and neurological systems (Facciolà et al. 2021). Despite cleaning mechanisms inside the human body, MPs, particularly fibers, are challenging to remove due to their large surface area or sticking nature. They are carriers of various contaminants due to their larger surface areas. They adsorb pollutants, such as harmful bacteria, and then release them, increasing their toxicity. Chemical additives such as bisphenol A or phthalates, esters of phthalic acid, various heavy metals such as Zn, Hg, or Pb, or chemical compounds such as flame retardants are commonly used to improve the quality of MPs (Campanale et al. 2020), as MPs by themselves are toxic by adding these activities make them more toxic. When MPs are subjected to UV radiation, weathering, or aging, their chemical makeup can be altered, making them even more harmful (Bhat et al. 2023b). MPs and their associated pollutants in the human body showed a need to investigate the source of indoor airborne low micro-range MPs and their reliable exposure assessments.

Airborne MPs may be breathed, which may result in respiratory problems. Microfibers, released from textiles and other items, can become suspended in the air and may be breathed into the respiratory system (Lim et al. 2022; Chen et al. 2023). Particles with non-uniform shapes may exhibit distinct interactions with biological systems in contrast to spherical particles with regular shapes (Wright and Kelly 2017; Bhat et al. 2023b). To assess the health hazards caused by inhaling MPs and understand the current pollution levels of inhalable MPs, it is essential to create innovative methods for analyzing tiny suspended atmospheric MPs. Particles smaller than five µm are capable of being deposited in the lung, as stated by Jabbal et al. (2017). Additionally, particles smaller than ten µm are more likely to be breathed by humans, according to Xie et al. (2022). Moreover, smaller particles may provide a higher health risk than bigger particles (Bhat 2024a, c). Prolonged PA particle exposure led to the increased release of Interleukin-8 and elicited modulation of the immunometabolism. (Alijagic et al. 2024). Asthma due to the thermal degradation products of PVC are well documented (Lee et al. 1989). The risk of respiratory symptoms increased 3.6-fold in PP flocking workers, and PP increased the chances of interstitial lung disease (Atis et al. 2005). PS are toxic to mammalian cells, which can induce apoptotic processes (Canesi et al. 2015) and affect physiology and behavior, potentially affecting organismal fitness in contaminated aquatic ecosystems (Pitt et al. 2018).

Comparison of results with indoor active sampling microplastic studies

MP research has attracted massive attention over the last decade; however, the work done on indoor MPs using active sampling is limited (Table 2). Only a few studies have been done in indoor environments using active sampling. Different researchers have adopted various methods for the characterization and optimization of MPs, from sampling flow rate to techniques (Table 2). Huge differences were seen in the usage of flow rate and sampling time in different studies. Still, the extensive preliminary testing in this study showed an eight-hour sample duration with 9 L/min, guaranteeing a sufficient particulate load for MP analysis. Although all the active indoor sampling studies focused on the micrometer size range, this might be due to the instruments used, whose size ranges are mainly in the micrometers. Still, this study's size range of MPs was relatively lower than the other active sampling studies (Table 2). Moreover, the MPs' colors and types identified in this study were higher than in the other active sampling indoor studies, as they mostly identified fiber and fragment types of MPs, and most of the studies did not characterize MPs based on their color. This shows the difficulty in characterizing indoor ambient MPs, as there is a vast gap in the methodology of ambient MPs research. However, differences were seen in the abundance of MPs with the other active sampling indoor MP studies (Table 2); this might be due to the difference in the flow rate and duration of sample collection. This is the first study where morphological characterization was done by optical microscope, polymeric composition by micro Raman, and structural elements or additives, or vectors that are added or adsorbed were done by SEM-EDX instrument simultaneously. None of the studies until now have used SEM-EDX or all three of these instruments simultaneously. Other indoor active sampling studies used Raman or FTIR or a combination of a stereomicroscope with Raman or FTIR (Table 2). To characterize the MPs adequately based on their morphology, polymeric composition, structural elements or additives, or vectors that are added or adsorbed, an optical microscope, FTIR or Raman, and SEM-EDX based on the size of MPs should be used simultaneously. The policy implications of indoor MPs are significant because people spend most of their time inside, and the indoor surroundings may harm human health.

The increased abundance of smaller MP particles seen in indoor environments may need the establishment or modification of indoor air quality regulations. Policymakers should consider establishing thresholds for MP concentrations to safeguard human health and overall welfare. Policies may restrict the manufacturing and use of consumer items that cause indoor MP pollution. This might mean banning particular plastics in home products or promoting eco-friendly alternatives. Policymakers may engage in public awareness and education efforts to alert families about indoor ambient MP sources and health risks. This may make individuals and communities use plastic more responsibly. The research revealed indoor MP knowledge gaps. Policymakers might finance research and monitoring to understand better indoor MP exposure's origins, routes, and long-term impacts. Another policy implication is that further knowledge of the exposure levels and their health effects is required to derive exposure guidelines that protect the population from potential health effects. Thus, funding agencies should invest in studies that conduct further research to provide that evidence.

Recommendations for research and mitigation strategies

- The human MP exposure level through inhalation and MP distribution pattern in indoor environments require more investigations in the future.
- To analyze all possible characteristics of MP presence in the indoor environment and determine the scope of the problem, it is essential to examine not only the forms but also the nature of the spaces in which they occur, methods of generation and dissemination, and physical and chemical properties.
- Before properly investigating and understanding the MP issue, specific urgent mitigation steps might be implemented to limit the human risk of exposure to this pollutant.
- There are currently two indirect and direct approaches for reducing MP presence in the indoor environment. The indirect technique is installing adequate filters in new or existing ventilation or air conditioning systems. The most straightforward strategy is to eliminate MP sources. Both approaches are sophisticated and might be challenging to apply at times. Both systems have advantages and disadvantages and would not be needed if we could replace bio-resistant plastics with biodegradable materials or develop a method to degrade plastics safely.
- Ist is crucial to examine multidisciplinary methods to tackle the difficulties presented by indoor MPs effectively.
- Researchers should also look at the long-term consequences of indoor MP exposure on humans, considering any possible health risks and creating focused intervention plans.

Table 2 Abundance and characteristics of indoor ambient microplastics collected by active sampling from different locations

Country	Sampling type	Flow rate	Period	No. of samples	Size	Microplastic type	Color	Abundance	Polymeric type	Techniques	Reference
Turkey	Active	9 L/min	8 h	7	2.5–327.36 µm	Film, fragment, fiber, pellet, foam, and line	transparent, crystalline, white, red, orange, blue, black, gray, brown, green, pink, tan, magenta, opaque, and yellow	12.03–18.51 MPs/m^3 and 156 - 240 MPs daily	1,2 Polybutadiene, PAM carboxy modified, PET, PMP, PEO, EVA, SEBS, PP, PA 12, EP, PE foamed, HDPE, PLA, PA 66, PTFE, PA 6, PS, Sealing ring EPDM, PE,1-octene copolymer, PB-1, PVC, and CE	Optical microscope, SEM-EDX, and micro Raman	This study
France	Active	8 L/min	4–7 h	3	50 – 4,850 µm	Fiber	Unreported	1.0 and 60.0 fibers/m^3	Cellulose fibers, CA, PA, and PP	Stereomicroscope and ATR-FTIR	(Dris et al. 2017)
Denmark	Active (Manikin)	0.82 L/min	24 h	3	68–237 µm	Fragments and fibers	Unreported	272 MPs inhale 24 h	PES, PE, PA, and PP	FPA- micro FTIR	(Vianello et al. 2019)
California	Active	11.7 L/min	8 h	4	58–641 µm	Fragments and fibers	Unreported	3.3 fibers and 12.6 fragments m^3	PS, PE, PET, Resin, ABS, PA, PC, and PVC	Stereoscope, fluorescence microscopy, micro FTIR, and micro Raman	(Gaston et al. 2020)
China	Active	100 L/min	2–3 days	13	5–5000 µm	Fragments and fibers	Unreported	1583 MPs /m^3	PL, PA, PP, PE, PS and PVC	Fluorescence stereo microscope and micro FTIR	(Liao et al. 2021)
Kuwait	Active	30 L/min	6 h	20	0.45–2800 µm	Fragments and fibers	Black, transparent, blue, red and grey	3.24 to 27.13 MP m^3	PES and PA	Fluorescence, UV stereomicroscope, and micro Raman	(Uddin et al. 2022)
China	Active	2.5 m^3/h	4 h	5	2.40–2181.48 µm	Fragments, beads, and fibers	Black, blue, green, indigo, pink, purple, red, transparent, white, and yellow	15.56 to 93.32 MPs /m^3	PE and PES Phenolic Resin, PVC, Cotton, PP, PU, and Rubber	Raman	(Xie et al. 2022)
Korea	Active	7 L/min	48 h	5	20.1–6801.2 µm	Fiber and nonfiber	Unreported	0.49–6.64 MPs/m^3	PP, PE, PES, PU, PS, PTFE, PVC, ALK, AR, PA, and PU	FTIR	(Choi et al. 2022)

Strengths and limitations

The research included different instruments to examine MP particles efficiently. This research provides a complete analysis of the different kinds and amounts of MPs found in indoor environments. The findings of this study will be valuable in developing standardized techniques for accurately characterizing indoor ambient MPs. Identifying the source of MPs was conducted via a questionnaire, which provided helpful information for developing tailored mitigation methods. According to the available sources, the study proposed innovative and effective methods to decrease the amount of MP particles that people are exposed to inside. This research contributes to the advancement of sustainable practices and regulations. The evidence of exposure to MP is valuable in characterizing the levels of MP that humans can potentially inhale or ingest through dust ingestion or dermal contact. Very few studies currently report indoor MP levels, and there is even less evidence for Eastern Mediterranean countries. The primary drawback of the study is the smaller sample size. Additionally, the sample material was very dense, making it hard to count all the MPs from the filters based on morphological traits and increasing the likelihood of miscounting or combining MPs with non-MP particles.

Conclusions

This study addresses the limited knowledge on indoor airborne MPs, specifically to outline what types and levels of MPs humans may be typically exposed to daily within the home.

- The morphological identification of MPs showed the presence of different colored MPs from transparent, crystalline, white, red, orange, blue, black, gray, etc.
- MPs in different shapes like film, fragment, fiber, line, foam, and pellet were seen in this study, and fiber was the dominant type of MP.
- Micro Raman analysis showed the presence of 123 MPs, consisting of 22 different types of MPs. The dominant MPs were sealing ring EPDM, SEBS, PA 6, PE 1-octene copolymer, PB-1, PMP, PEO, PVC, PP, EP, PS, and HDPE.
- Residents are exposed to airborne MPs (2.5–327.36 µm), with inhalation estimates ranging from 12.03 to 18.51 MPs/m^{3,} and it was also estimated that residents in these indoor environments inhale 156–240 MPs per day.
- SEM-EDX revealed the presence of common structural elements and additives, like C, O, F, Mg, Si, Cl, K, Ca, Au, Na, S, Al, Fe, Zn, Ti, and N.
- These indoor environments are prone to MP pollution. The exposure level of MPs differed among individuals, depending on where residents lived and other lifestyle factors.
- The critical factors determining MP abundance in indoor house air are the amount of textiles present and using plastic items in houses. Mostly synthetic textiles were present in these houses, from carpets, sofas, and curtains to armchairs.

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Author contributions Mansoor Ahmad Bhat: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Roles/Writing - original draft; and Writing - review & editing.

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Data availability The author confirms that the data supporting the findings of this study are available in the article.

Declarations

Ethical approval Not applicable.

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Conflict of interest The author has no conflicts of interest to declare.

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