National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

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a literature review

RIVM letter report 2021-0059
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Synopsis

Microplastics in indoor air

In recent years, the problem of tiny plastic particles, or microplastics, in the environment has attracted considerable attention. Microplastics degrade slowly, if at all, and are found everywhere around us. Not much is known about microplastics in air inside homes. The Ministry of Infrastructure and Water Management (IenW) would very much like to know more about this because small particles of certain substances are detrimental to air quality and consequently to public health.

RIVM has therefore looked into the possible presence of microplastics in indoor air and has summarised the knowledge found in scientific literature on this topic. This knowledge will enable IenW to take any measures that may be necessary. It can also be used to assess whether these substances entail health risks and the data needed to make such assessments.

Generally speaking, the concentrations appear to be low. On average, there are between 1.6 and 9.3 microplastic particles per cubic metre. The particles measured are fairly large, i.e. more than 11 micrometres in diameter. This makes them larger than the ultrafine particles normally measured to assess air quality (PM2.5 and PM10 or smaller than 2.5 and 10 micrometres in diameter). It is possible that much smaller microplastics are also present in the investigated homes. But it is currently difficult to measure the smaller types of microplastic particles in air. It is precisely smaller particles that are not good for air quality (e.g. PM2.5 and PM10).

The most significant sources of microplastics in homes are textiles, such as clothing, carpets and curtains. Besides fibres, many fragments of microplastics are found in indoor air. Further research is needed to determine whether these particles also originate from textile fibres or from other sources. Besides this, information is needed on the smallest type of microplastic particles. With this knowledge more effective measures can be taken to improve air quality.

Keywords: microplastics, air pollution

Publiekssamenvatting

Microplastics in binnenlucht

De laatste jaren is er veel aandacht voor hele kleine plastic deeltjes, microplastics, in het milieu. Ze breken heel langzaam of niet af en worden overal in het milieu gevonden. Er is nog niet zoveel bekend over microplastics in de lucht in huis (binnenlucht). Het ministerie van Infrastructuur en Waterstaat (IenW) wil daar graag meer over weten. Van sommige stoffen zijn kleine deeltjes namelijk niet goed voor de luchtkwaliteit, en daarmee voor de volksgezondheid.

Het RIVM heeft daarom verkend of microplastics in de binnenlucht voorkomen. Het heeft hiervoor een overzicht gemaakt van de kennis in de wetenschappelijke literatuur over microplastics binnenshuis. Met die kennis kan IenW zo nodig maatregelen nemen. De informatie kan ook worden gebruikt om te beoordelen of er risico's voor de gezondheid zijn en welke gegevens daarvoor nodig zijn.

Over het algemeen lijken de concentraties laag te zijn. Gemiddeld zijn het er tussen de 1,6 en 9,3 microplastic deeltjes per kubieke meter. De gemeten deeltjes zijn vrij groot, groter dan 11 micrometer. Ze zijn daarmee groter dan de veel kleinere deeltjes fijnstof die standaard voor de luchtkwaliteit worden gemeten (PM2.5 en PM10, oftewel kleiner dan 2,5 en 10 micrometer). Het is mogelijk dat er ook veel kleinere microplastics in de onderzochte binnenlucht zitten. Maar het is nu nog moeilijk om de kleinere microplastics in de lucht te meten. Juist de kleinere deeltjes zijn niet goed voor de luchtkwaliteit (PM2.5 en PM10).

De belangrijkste bronnen van microplastics in huis zijn textiel, zoals kleding, tapijt en gordijnen. Naast vezels worden veel fragmenten van microplastics in binnenlucht gevonden. Uitgezocht moet worden of deze deeltjes ook van de vezels van textiel komen of van andere bronnen. Daarnaast is informatie nodig over aanwezigheid van de kleinste microplastic deeltjes. Met deze kennis kunnen effectievere maatregelen worden genomen om de luchtkwaliteit te verbeteren.

Kernwoorden: microplastics, luchtvervuiling

Contents

Summary

Microplastics are currently receiving a great deal of interest, primarily due to their persistence and widespread presence in the environment. The air compartment plays an important role in their long range transport, with microplastics being detected even in remote areas. At the same time, we have a limited understanding of microplastics in air. This is especially true in indoor air, an important compartment for human exposure to volatile or particulate contaminants and which acts as a source to outdoor air for microplastics. In this report, we have compiled the limited available literature on microplastics in indoor air. The aim is to increase our understanding of the sources which release microplastics to indoor air and describe their concentration and fate. This will be helpful when deciding on the direction of future research and ultimately for reducing microplastic pollution in indoor air.

In the current literature the release and emission of microplastics to indoor air is considered to mainly occur due to wear and tear of clothing. Several studies have demonstrated and quantified microplastic fibre release from clothing. Only very limited information is available on other sources of microplastics in indoor air, although several potential other sources have been described in the literature, such as from construction, e.g. sanding of polymer containing paints, from wear of household plastic items, and 3D-printing using polymer-based filaments. The data on release rates is too limited to accurately estimate these emissions to indoor air.

Measurements of deposition and concentration are important for assessing the degree of microplastic pollution in indoor air. Results from three studies from Australia, Denmark and France, show an average range of microplastic concentrations in indoor air from 1.6 - 9.3 microplastics/m^3, with a maximum of 20 microplastics/m^3. This comprises 4 - 36% of the total particles detected, which are mainly particles from a natural origin (e.g. cotton fibres or skin flakes). The microplastic concentrations measured in indoor air are commonly for relatively large particles, (> 11 um), compared to often measured particle size ranges relevant for indoor air quality (<2.5 um (PM2.5) and < 10 um (PM10)). Although smaller microplastics may occur at higher concentrations (microplastics/m3), currently observed concentrations in indoor air can be considered low and in line with existing health and safety limits for exposure to particulate matter.

Though in several studies we found data on the concentration of microplastics in indoor air, only a few discuss the sources. These point towards several key areas for further research:

- Develop methods capable of measuring microplastics at lower size scales, down to a nanometre.
- Develop widely accepted guidance, e.g. through OECD or ISO, aimed at applying new or existing measurement guidelines to the robust sampling, analytics and data analysis of microplastics.
- Increase our knowledge on the sources of microplastic fragments found in indoor air samples by studying their release from clothes

and textiles, while considering other potential sources and relevant indoor activities.
- Increase our understanding of adverse effects from microplastics in indoor air to support hazard and risk assessment.
- Improving our understanding of microplastics in indoor air will contribute to taking more effective measures for improving air quality.

1 Introduction

Several public health and environmental protection agencies have reported on plastics pollution in general, and more specifically on pollution from microplastics (SAPEA, 2018). Plastic products that end up in the environment tend to break down into smaller pieces over decades to hundreds of years, these are so-called micro and nanoplastics. Additionally, microplastics, such as microbeads and microfibres are also intentionally applied in different products, e.g. as a binder in paint or in capsulated forms to control the release of fertilizers or pharmaceuticals (Scudo *et al.*, 2017). Environmental pollution from microplastics is a great cause for concern due to their persistence against (bio)degradation, their small size, and their tendency to fragment into increasingly smaller (nano)particles. Due to the latter's' size, they are more prone to digestion and are liable to transfer within food chains, potentially causing adverse biological effects (ECHA, 2020a). For this reason, it is important to control and minimize the release and emission of microplastics to the environment. To achieve this, there is an urgent need to understand microplastic sources, emission pathways, transport, behaviour, and fate in the environment (Figure 1). Although not further addressed in detail in this report, there is also a clear need to understand the potential adverse effects that microplastics can have on human health and the environment in order to fully understand their impact on pollution.

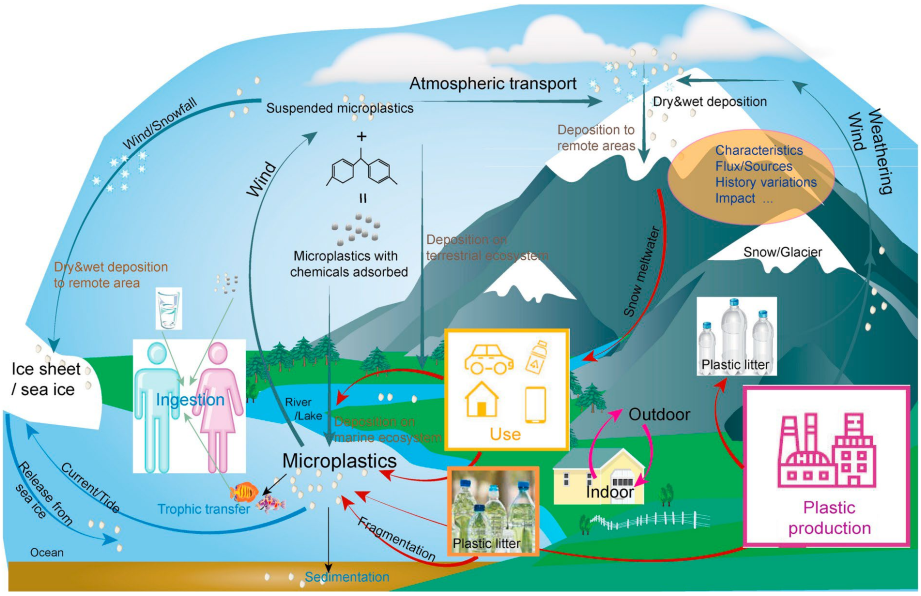

Figure 1 Illustration of global flow of microplastic pollution. Figure from (Zhang et al., 2020b).

In the past decade, most studies focussed on microplastic pollution of the aquatic and more specifically, the marine environment, the final destination of many plastics (Eriksen *et al.*, 2014; Lassen *et al.*, 2015; ECHA, 2019). Less attention has been paid in recent literature to the air compartment, however in recent years this aspect has gained increasing attention due to its role in the transport of microplastics and exposure to microplastics through inhalation (Gasperi *et al.*, 2018; Huang *et al.*, 2020; Mbachu *et al.*, 2020; Zhang *et al.*, 2020b) (Evangeliou *et al.*, 2020). Moreover, regulatory agencies are increasingly looking at the air compartment in relation to microplastics. In a recent report on microplastics in the environment, the German Environment Agency (2020) includes the abundance of microplastics in the atmosphere. and highlights tire wear as an important source. In a draft science report on plastic pollution by Environment and Climate Change Canada and Health Canada (2020), the presence of microplastics in outdoor and indoor air compartments is also considered, and the main microplastics sources are identified as fibres from textiles and wear particles from tires.

Overall, these studies indicate the widespread occurrence of microplastics in air, which emphasises the need for a better understanding of the degree of exposure and consequently of the potential health risks, including options to reduce them(Evangeliou *et al.*, 2020). It is expected that human exposure through inhalation of airborne microplastics (Gasperi *et al.*, 2018) and potential ingestion after deposition are important exposure routes. These routes are mainly of concern due to microplastics' biopersistence and their potential to carry pollutants (Gasperi *et al.*, 2018). A distinction is often made between indoor air and outdoor air. Given that tire wear particles are released in outdoor air and textiles are used and applied in both indoor and outdoor environments, the interchange of air between these two is also important in order to fully understand exposure to microplastics in the air compartment (Figure 1).

To increase our understanding of the fate of microplastics and to be able to act on microplastic presence in the environment, we need to increase our understanding of the sources, emissions and subsequent transport of these particles; that is the focus of this report._In this literature review, we gathered information relevant to assessing microplastic exposure in indoor air. We describe existing knowledge on the sources which release microplastics to indoor air and describe their fate and concentration (Figure 2).

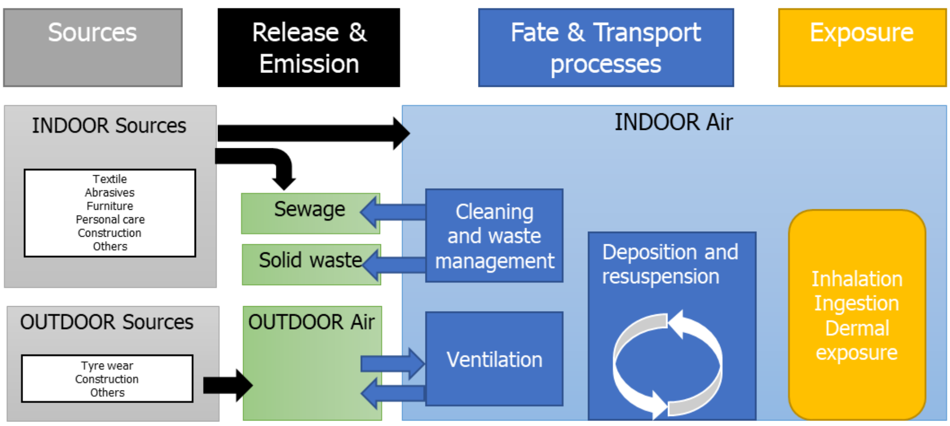

Figure 2 Diagram illustrating the scope of this study highlighting the Sources, Release and Emission, Fate, and Transport that lead to exposure to microplastics in indoor air.

1.1 Scope and approach

In this literature study, we focused on gaining a better understanding of the sources, release and emission, and exposure to microplastics in indoor air. This study should help policy makers define further steps on how to address the issue of microplastic pollution. For this reason, the study discusses studies on the sources and release rates of microplastics to indoor air. This is followed by reviewing all the available data on concentrations and composition of microplastics in indoor air.

Based on this, we discuss the relationship with other sources of particulate matter in indoor air, such as wood smoke. This in order to better understand the contribution of microplastics to overall indoor air quality. Furthermore, to be able to understand the contribution of indoor air to overall microplastic pollution, the concentration of microplastics in indoor air will be compared to their concentration in outdoor air.

Although this inventory is aimed to be at screening level, it is a first step in revealing data gaps and identifying which knowledge can help prioritise future policy measures for reducing microplastic pollution and improving indoor air quality. Potential human health or ecological effects of exposure to microplastics through air are not included, although this information is needed for assessing the impact microplastics have on human health and the environment. For any human or environmental health impact assessment, data on exposure concentrations is needed. This report is a first step to gathering the knowledge needed to move from studies on sources, emissions, and concentration measurements of microplastics, to exposure estimates.

Microplastics
Microplastics are not primarily defined by their origin or by their composition; they can be manufactured as a microplastic (e.g. microbeads) or be the degradation product of larger plastic items (Velimirovic *et al.*, 2020). We used the ECHA working definition. In summary this states that microplastics are defined as particles containing solid polymer, to which additives or other substances may have been added, and where ≥ 1% w/w of particles have: (i) all dimensions ≤ 5 mm, or (ii) a length of ≤ 15 mm and length to diameter ratio of > 3, with some exceptions for biodegradable, water soluble or naturally occurring polymers. Further details on the current working definition of microplastics can be found in (ECHA, 2020b) and (Faber *et al.*, 2021).

No lower size limit has been defined for microplastics so with plastic particle sizes observed at a nanometre scale, these nanoplastics should also be considered part of this group of materials, microplastics. In this study there is no specific focus on nanoplastics, but as size and shape play an important role in fate and exposure to particles, size ranges are reported where possible.

Literature search
As the basis for this review Scopus and Google Scholar were used to find the relevant scientific literature on microplastics in indoor air and air in general. Search terms were used related to two main topics: microplastics and air. The search was performed between 1 July 2020

and 21 Aug. 2020. This resulted in 41 papers and reports from the search results as well as from our network of experts at RIVM and other research institutes. These papers varied from literature reviews to monitoring and experimental studies related to indoor air, and other studies with relevant links such as those aimed at outdoor air and microplastics in general. Data were extracted from the different studies. Where data were only reported in figures, they were extracted using WebPlotDigitizer v4.3 (https://automeris.io/WebPlotDigitizer/).

2 Sources and emission of microplastics to indoor air

In this chapter, the sources of microplastics are briefly described with a focus on studies that estimate the release and emission of microplastics to indoor air. Specific information was found on microplastic release from textiles, PET (Polyethylene terephthalate) bottles, and 3D printing.

2.1 Sources of microplastics to air

The current literature highlights that the primary source of microplastics to indoor air is the shedding of polymeric textile fibres from clothing, furniture, carpeting and household goods (Parker-Jurd *et al.*, 2019; O'Brien *et al.*, 2020; Wagterveld *et al.*, 2020).

Textiles are indicated as a major source to air alongside tyre wear particles (Parker-Jurd *et al.*, 2019; Wagterveld *et al.*, 2020), but of these two sources, only the shedding of fibres from textiles contributes directly to microplastics in indoor air. The ubiquitous use of synthetic fibre-based textiles makes it a widespread source with a high chance of release in almost every home. In addition to textiles, other sources of microplastics to indoor air may be relevant. Some studies have shown the release of nanoplastics from 3D-printing (Stephens *et al.*, 2013; Azimi *et al.*, 2016; Katz *et al.*, 2020). Others have indicated that microplastic fragments, potentially unrelated to fibres, are also found in air samples (Klein and Fischer, 2019; Liu *et al.*, 2019; Vianello *et al.*, 2019). This suggests other sources of microplastics in (indoor) air, e.g. from construction materials, packaging, and other plastic household items.

Furthermore, outdoor air could contribute to indoor microplastics as a result of contaminated air being sucked into buildings. However, indoor air is mainly considered to be a source of microplastics to outdoor air. For instance, in a Swiss study (Kawecki and Nowack, 2020) on mass flows of microplastics to the environment, the indoor air was solely considered an additional source of emissions to outdoor air, contributing 37%, on average, to the total outdoor air microplastic emissions. Sources of microplastics to indoor air considered by Kawecki and Nowack (2020) were broader than textiles alone, although wear from clothes and other textiles was the main source (75%) and the only one for which specific data were used. Other sources include other household plastics (16%) and construction coverings (9%). This is in line with observations in a study by Parker-Jurd *et al.* (2019), where the deposition of synthetic fibres (and tyre wear particles) was measured in outdoor air at an urban location, a rural location, and a location near a motorway. They found an increased deposition of synthetic fibres in the urban location compared to the rural location or the motorway. This can be linked to the higher population density and the resulting release from clothes in urban areas, either directly or through indoor air.

2.2 Microplastic release and emission

2.2.1 *Textiles*

Several studies have reported on microplastic release to surface waters from textiles as a result of washing clothes (Pirc *et al.*, 2016; De Falco *et al.*, 2018; Yang *et al.*, 2019; Napper *et al.*, 2020)). However, only a few report on the *release* from textiles to air (indoor or outdoor); two studies quantified release from textiles to indoor air (De Falco *et al.*, 2020; O'Brien *et al.*, 2020). Further data on microfibres in air are based on measurements of deposition or concentration (see chapter 3).

In the study by De Falco *et al.* (2020), the release of microfibres from different textile fabric types to air and water was studied during everyday use. The release to air was studied by letting a person wearing the textile perform a set of movements in a 4 m^2 room for 20 minutes. Microfibres were collected on a petri dish with filter paper. The results indicated that the release rate of microplastic fibres is dependent on the textile type. They found that a continuous woven polyester blouse showed the lowest release, while a mixed 50% polyester, 50% cotton knitted sweatshirt, consisting of short staple fibres with moderate twist and high hairiness, released the most. No fleece clothing was included in this study, although this type of textile was shown to release the most fibres during washing (Carney Almroth *et al.*, 2018). This indicates that the types of fibres (e.g. long/short) and fabric structure (e.g. woven/knitted) used can influence the release of microplastics, similar to studies on release to water during washing (Yang *et al.*, 2019).

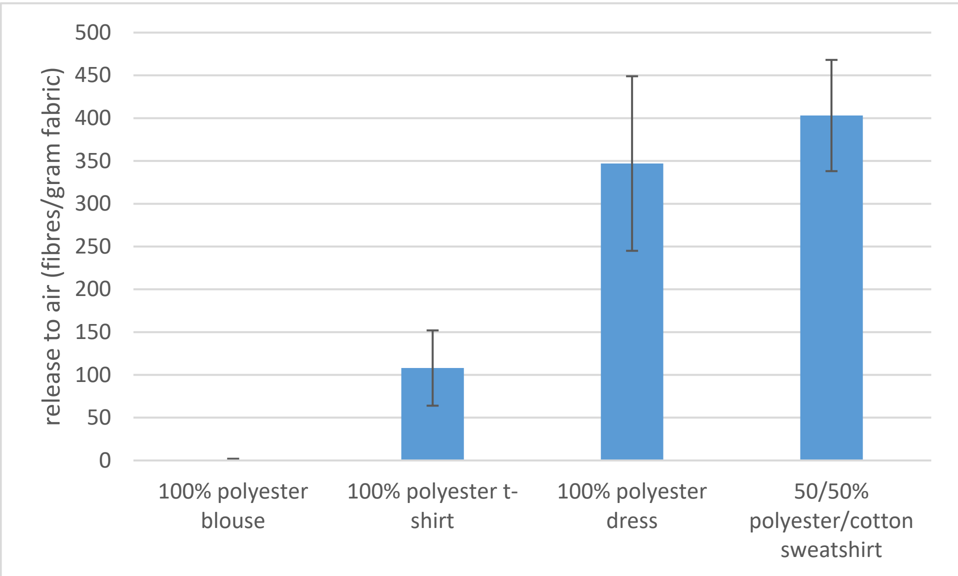

Figure 3 Microfibre release to air from four different clothing articles with varying fabric structure from wearing during specific activities for 20 minutes. Data from De Falco et al. (2020).

In addition to fibre release from clothing use, fibres are also released to air when using a dryer for drying clothes after washing (O'Brien *et al.*, 2020). In the study by O'Brien *et al.* (2020) in Australia the release of fibres due to machine drying of a fleece blanket was measured using a high volume total suspended particle air sampler, though only 1 blanket was tested with a single washing machine and dryer (n=1). The results provide evidence that microfibres can be released to the ambient air during a drying cycle, e.g. by escaping through the dryers filters. The filter retains most of the mass in the form of lint collected in the filter, 77 ± 22 mg of lint which equates to ~$1.1 \pm 0.3 \times 10^6$ fibres compared to only 58 ± 60 fibres released to air. This release to air equates to about 2 fibres/m^3 added to indoor air every washing/drying cycle.

In an earlier study by Pirc *et al.* (2016), the release from a fleece blanket was also measured, but not to the ambient air. Here it was observed that in consecutive washing and drying cycles, the amount of fibres released to water was reduced by as much as 75% compared to the first washing/drying cycle. In the study by O'Brien *et al.* (2020), the opposite was observed, where the most fibres were found to be released after the last washing/drying cycle.

Given the release of microfibres from different clothing types to air measured by De Falco *et al.* (2020), it remains unclear how much fibre would be released from other types of textiles. However, for release to water, Carney Almroth *et al.* (2018) show that PET fleece or microfleece fabrics gave an almost 100-fold higher release of microfibres compared to any of the other tested fabric types based on knitted polyester-based fabrics or acrylic and nylon-based fabrics. Assuming similar relative releases to air compared to water, this finding would indicate that the observed release rates estimated by De Falco *et al.* (2020) for clothing use would likely be higher for fleece fabrics. This would also mean that the release rates to air due to machine drying observed by (O'Brien *et al.*, 2020) are likely to be lower for some other textile types, e.g. woven or knitted fabrics with lower hairiness.

During washing, the release of microfibres to water can be mitigated by using filters or other systems to catch microplastic fibres. The efficiency of these devices intended to reduce microfibre release during clothes washing, has recently been tested by Napper *et al.* (2020). Although this helps to reduce the release of microplastics to wastewater, in terms of release to indoor air the effects remain unknown. On the one hand, the release may increase due to handling and emptying filters. On the other hand, release to air may be reduced due to the lower amount of loose fibres available for release during subsequent drying and use.

Overall, the amount of microplastic release from clothing that results in emission to indoor and outdoor air is dependent on the distribution between indoor and outdoor locations and the time and type of clothes used there. This in turn depends on climate and behavioural habits. For example it can be assumed that the release due to the use of textiles and washing/drying largely takes place in indoor spaces in moderate and arctic climate zones. This also makes it more likely that the indoor air might, via ventilation, be a source of microplastics to the outdoor air causing them to end up elsewhere in the environment. The release to outdoor air might be mitigated by filtration, for instance with air recirculation systems (heat recovery units) currently applied in newly built homes and other buildings (Jacobs and Borsboom, 2019). Older air ventilation systems often do not apply any type of filter, for example buildings with mechanical or natural ventilation.

Overall, there is only limited quantitative data on the release of microplastics from textiles to indoor air from specific products. But it should be clear that clothes are not the only sources of microfibres; any textile use, such as curtains or rugs are also potential sources.

2.2.2 *Other sources*

In addition to textiles, there are numerous other potential sources of microplastics mentioned in literature such as packaging, toys, construction products, and personal care products (Verschoor *et al.*, 2014). It remains unclear, however, what types of other sources significantly contribute to airborne microplastics in the indoor environment. There is evidence that other non-fibre microplastics comprise a significant part of the microplastics in indoor air (87%) (Vianello *et al.*, 2019) and outdoor air (88-95%) (Allen *et al.*, 2019; Klein and Fischer, 2019). But very little research reports on the release of microplastic fragments to the indoor air related to specific product types. The focus on microfibres and textiles can have several reasons, but it is clear that only recently, detection methods have improved, e.g. through automated image analysis of particle shape combined with detection of polymer type. These types of improvements will improve accuracy and reduce bias when detecting specific microplastic types (e.g. microfibres versus fragments).

In one study, the release of microplastics from plastic water bottles into drinking water was studied (Winkler *et al.*, 2019) by opening and closing the bottles, and by physical deformation, based on daily use and reuse. This only resulted in a significant release of microplastics from the caps made from HDPE (High Density Poly Ethylene) and no increase in microplastic release from the bottle itself, made from PET. It is not clear whether the microplastics released from the caps were emitted into the air, as this was not assessed in this study.

A less common source of microplastics is the use of plastics in fuse filament fabrication three-dimension (3D) printers (Stephens *et al.*, 2013; Azimi *et al.*, 2016; Katz *et al.*, 2020). With particle emission rates ranging from 10^{10} to 10^{12} particles per hour, this indicates a much higher particle release per use of a 3D printer (3 hours) compared to those observed for textiles. The particles released during 3D printing are much smaller than those released from textiles; around 100 nm (40-600 nm) in size for use of an ABS (Acrylonitril-Butadieen-Styreen) filament, and around 300 nm (100-600 nm) using a PLA (Poly Lactic Acid) filament (Katz *et al.*, 2020). Part of the particles released due to 3D printing fall within the category of nanoplastics.

Although no quantitative data was found for other microplastic sources to indoor air, several sources are specifically mentioned in the literature. For instance, one would expect release of polymer-based paint particles during sanding or drilling and possibly due to abrasion from everyday use (Faber *et al.*, 2021). Although it is understood that high impact or high energy activities will release the most and smaller particles (Ekvall *et al.*, 2019), release from every day use of plastic-based products is also expected. Releases may range from the housing or cases of our everyday electronics (e.g. mouse pad, phone case) to toys and furniture (e.g. laminated compressed wood).

Although many release rates are unknown, specific types of activities are relevant for estimating indoor emissions of microplastics and consequently, exposure. Some relevant exposures may occur. For instance, during specific activities such as drilling and sanding which are known to produce suspended particulates. However, many other activities induce some degree of abrasion, although it is not considered that they result in the release of significant amounts of plastic abrasion products to air, e.g. sports induce abrasion of shoes and other sporting equipment (balls etc), also indoor, extensive child play with plastic toys, etc. These types of activities normally exert relatively low force abrasion, probably resulting in larger particles not easily suspended in air. Furthermore, an important factor, as shown from the study on plastic bottles (Winkler *et al.*, 2019), is the polymer type used and product design. This can have a significant effect on the release of microplastics from abrasion or shear stress. The PET bottles seem to be relatively hard and resist abrasion in normal use compared to the HDPE bottle caps, which seem to release most of the microplastics. Moreover, there was a large difference in release rate ascribed to differences in bottle design.

Currently only a few studies were found that quantify the release of microplastics from indoor use of specific products or when conducting indoor activities. The release rates observed for clothes and 3D printing are reported for a single activity or for textile, per gram of textile. This means that the release rates still need to be converted to emission rates based on an activity scenario for a specific indoor area (e.g. based on number of people wearing synthetic clothes in a room per day). Furthermore, there seems to be too little data to estimate a realistic emission rate, as release rates from many other sources are absent. Further research should specifically include quantification of release of microplastic fragments from clothes and other textiles, while it should also consider other potential sources.

3 Microplastic deposition and concentration in indoor air

In contrast to measuring the release or emission of microplastics to air from a specific activity (wash dryer) or product (clothes) reported in the previous section, others have measured the resulting concentration in indoor air or the deposition of all types of microplastic sources relevant to a specific location, for example a room in an apartment or office building. The measurements resulting from these studies of indoor air are briefly discussed in this chapter. We found two studies on deposition (3.1) from indoor air and two studies reporting concentrations of microplastics in indoor air (3.2). A second aspect is the relationship of microplastics as a fraction of indoor air dust composition(3.3).

3.1 Microplastic deposition from indoor air

Deposition is the process of particles settling out of the air onto a surface, or of particles attaching or depositing on a surface after a collision, e.g. due to air flow. Most studies on particle deposition measure the deposition rate as the number count or mass of dust which settles on a certain area (m^2) within a specific timeframe (e.g. days). This type of measurement mainly captures larger particles which settle/deposit faster than smaller ones.

In a study by Zhang *et al.* (2020a) three different indoor areas were monitored for microplastic deposition. They observed a much higher deposition of microplastics at desk level (1.2 m) in a student dormitory (2100 – 29000 microplastics/m^2/day) compared to an office (600 – 4500 microplastics/m^2/day) or corridor (500 – 6000 microplastics/m^2/day) where the students studied or worked. They hypothesized that this was due to differences in the number of sources in these locations and the activities that play a role in suspension of microplastics in air. For instance, the deposition rates were significantly higher on weekends in the dormitory compared to weekdays, with an opposite effect for the office where weekdays showed higher deposition rates. Moreover, in a separate test they showed that the deposition rates increased with increasing power of the air conditioning unit in the dormitory (Table 1). This was due to the increased air flow and resuspension of settled dust. It is important to realise that different types of activities affect the overall exposure to microplastics in air.

From the dust deposited in their samples, 35%-37.5 % was composed of microplastics. These consisted largely of Polyester and Rayon fibres, with other polymer types constituting less than 8% of the collected microplastics.

Table 1 Deposition rates in a student dormitory based on the airconditioning (A/C) power mode affecting air flow (from (Zhang et al., 2020a).

A/C modes	***Deposition rates (in microplastics/m^2/day)***
off	58
sleep	179
low	350
medium	333
high	383

In a study by Dris *et al.* (2017), the deposition and abundance (see section 3.2) of fibres in two apartments and one office building in Paris, France, were measured. They found deposition rates ranging from 1600 to 11000 fibres/m^2/day, of which 33% consisted of microplastic fibres resulting in a deposition of 533 to 3666 microplastic fibres/m^2/day. The remaining 67% were fibres from natural materials. The variation in deposition rates could not be clearly explained but varied across the three locations and four measurement times spread out over the four seasons of a year (no significant differences). The authors state that some of the differences can be explained by the different building materials, furniture, cleaning habits, and activities that take place in the apartments. Furthermore, these deposition rates were about 1 - 2 orders of magnitude larger than previously observed outdoor deposition rates.

No other studies have reported deposition rates of microplastics from indoor air, although one did measure microplastics (PET/PC (PolyCarbonate)) in dust samples taken in 39 major Chinese cities (Liu *et al.*, 2019). They found that the concentration of PET in indoor dust (23000 mg/kg dust (1550–120,000 mg/kg dust)) was considerably higher than outdoor (1650 mg/kg dust (212–9020 mg/kg dust)) concentrations found on balconies, whereas PC did not have significantly different concentrations between indoor (4.6 mg/kg) and outdoor (2.0 mg/kg) samples. This may indicate that the PET sources are more likely to be indoors, whereas the PC sources could also be outdoors. The applied method makes it difficult to interpret and compare the observed data with others, e.g. the time period in which dust could accumulate was unclear. This period is needed to calculate deposition rates, which would have been beneficial for a more straightforward comparison as it is currently unknown what the deposition time or kinetics are of the indoor and outdoor dust collected. In this study, 40% of collected granules was found to consist of microplastics, and 38-46% of collected fibres was composed of microplastics.

3.2 Microplastic concentration in indoor air

Microplastic concentration or abundance is a measure for the amount of particles suspended in the air and can be used to calculate human exposure through breathing. Microplastic concentration in air is most commonly reported as the number (e.g. of microplastic) or mass (e.g. kg) of particles per volume (e.g. m^3) of air. It is mostly measured by actively pumping a known volume of air through a filter or other device which catches the particles for counting or weighing. In principle, the measurement height can affect the size distribution of particles captured, with smaller particles remaining suspended higher in the air compared to larger ones being found predominantly closer to the ground due to settling. Three studies were found which reported indoor air microplastic abundance; these are discussed briefly below (see Figure 4).

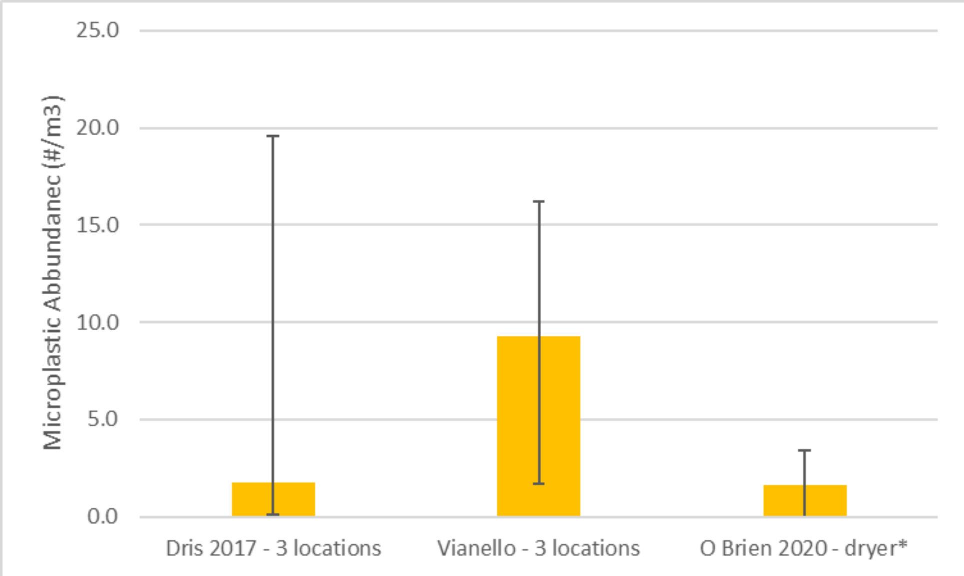

*Figure 4 Microplastic abundance/concentration in indoor air (number of particles (#) per cubic meter air). *estimate based on release from using a dryer.*

Dris *et al.* (2017) sampled indoor air, measuring abundance as well as the deposition rate (see section 3.1) in two apartments and an office building, using a microplastic proxy to estimate the contribution of microplastics in each sample. This proxy means they did not actually measure the microplastics present in each sample, but identified a fraction of microplastics present in the overall particle counts and used that fraction to calculate microplastic content in each sample using the total fibre abundance. This resulted in an average of 1.8 microplastic fibres/m^3 in all the samples, ranging from 0.13 to 20 microplastic fibres/m^3 depending on the location.

In another study, Vianello *et al.* (2019) used a breathing thermal manikin in three apartments in Aarhus, Denmark to sample indoor air. This breathing thermal manakin is a human-like puppet sat at a table in which also skin temperature and breathing is simulated. From these measurements, the microplastic concentration was estimated to be an average of 9.3+/-5.8 microplastic particles/m^3. Depending on the apartment, microplastic abundance ranged from 1.7 - 16.2 microplastic particles/m^3 in indoor air. Microplastics made up about 4% of the total particles inhaled and captured using the manikin method, with the remainder consisting of other types of particles. The microplastic mainly consisted of polyester (81%), polyethylene (5%) and nylon (3%). Several other polymer types were detected, but only in low quantities.

Overall only these two studies attempted to measure indoor air concentration of microplastics (Figure 4), with the highest particle numbers detected using the thermal manikin (Vianello *et al.*, 2019). This might be due to the detection limit of their quantification method being

11 µm compared to the 50 µm lower size limit for the Dris *et al.* (2017) study. Additionally, Dris *et al.* (2017) focused on fibres using a manual approach, by counting particles based on visual inspection, whereas the Vianello *et al.* (2019) study applied an automated system based on Fourier-Transformed Infrared Spectroscopy (FTIR) spectra and the MPhunter software.

In addition to these measurements, O'Brien *et al.* (2020) calculated an average concentration of 1.6+/-1.8 fibres/m^3 in the surrounding air (21 m^3 room) based on the release of microfibres from fleece during use of a mechanical dryer (see section 2.2.1).

3.3 Indoor air dust and microplastic composition

Three articles were found reporting analytical measurements of microplastics deposition from, or concentrations in, indoor air. During determination of microplastics in indoor air, the distinction between artificial and natural particles and between polymer-based and inorganic man-made particles was made after sampling.

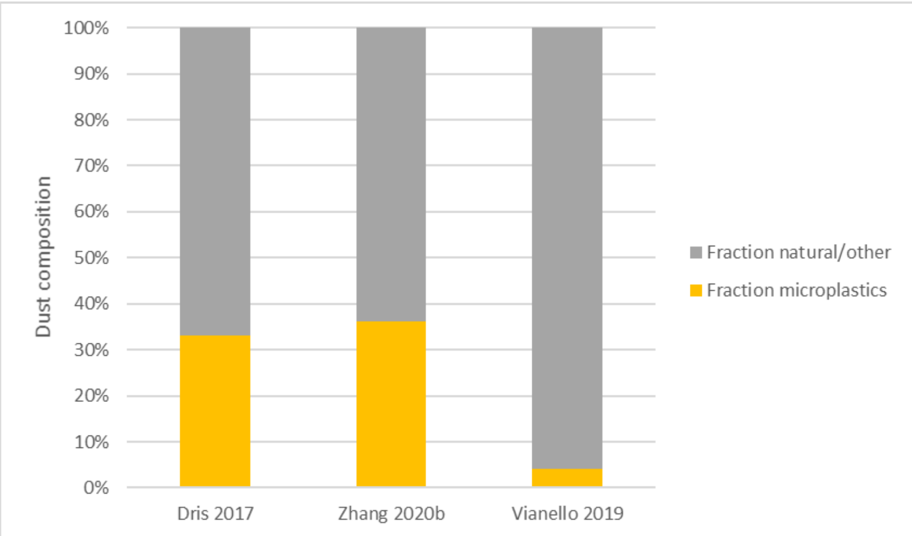

Figure 5 Composition of particles found in indoor air divided in fossil-based materials and other natural materials such as protein or cellulose-based.

The fraction of synthetic plastics in the total of particles detected ranged between 4 and 36% (Figure 5) as analysed in three studies. Vianello *et al.* (2019) found the lowest fraction of synthetic fossil-based polymers compared to the other two studies (Dris *et al.*, 2017; Zhang *et al.*, 2020a) which found similar fractions of synthetic polymers in their samples. Additionally, similar fractions were reported for outdoor air. In one study (Parker-Jurd *et al.*, 2019) measuring atmospheric fallout (including through rain) of fibres, about 10% of total collected fibres was considered synthetic. Whereas in a study by Li *et al.* (2020) on urban outdoor air at a university campus in Beijing, 35% of synthetic polymers was detected, similar to that in the studies by (Dris *et al.*, 2017) and Zhang *et al.* (2020a). It is remarkable that a 40% fraction of man-made mineral fibres (e.g. rock wool or glass fibre) and 7.8% asbestos was detected, with only 4.5% natural organic fibres. The study by (Li *et al.*,

2020) shows that there are several other potential sources of fibres in outdoor air, for instance from building materials. Specific ones such as asbestos are already regulated because of their adverse effect on human health. These three studies took place in two cities in Europe (Paris and Aarhus) and several cities in China, so any comparison of results is hampered be the large range of uncertainties related to the sources (e.g. types of furniture and clothes), the measurement methods (e.g. focused on fibres or automated including fragments), and location-specific factors (e.g. ventilation or weather conditions).

An interesting observation was made by Dris *et al.* (2017) relating to particle size and long range transport of microplastics. The smallest sized particles were measured using active pump sampling (abundance measurement) in outdoor air above the roof of an apartment building (maximum size 1650 µm). The maximum particle size (3250 µm) in the apartments using active pump sampling was lower compared to the maximum size (4850 µm) using passive sampling in dust fall (deposition). This is logical as larger particles deposit faster after release or resuspension, so measurement height plays a role. This study indicates that the height at which particles are resuspended is dependent on their size, but also indicates that the smallest particles are also more prone to long range transport.

In the studies on releases to indoor air discussed in section 2.2 and on abundance in indoor air itself, the microplastics were mostly in the form of microfibres (Dris *et al.*, 2017; De Falco *et al.*, 2020; O'Brien *et al.*, 2020; Zhang *et al.*, 2020a). However, Vianello *et al.* (2019) found only 5% - 22% fibres, with an average of 87% being classified as fragments. This was also reported in two studies on outdoor air in which much larger number-based fractions of microplastic fragments were found (Allen *et al.*, 2019; Klein and Fischer, 2019), which can be partly explained by the measurement method applied. Another explanation could be the fragmentation over time during transport (Huang *et al.*, 2020), but this remains uncertain. Nevertheless, it is important to realize that most studies until now have focussed on identifying the sources and release rates of microplastic fibres instead of fragments. This is an area that needs further research, e.g. on the release of fragments from textiles and the formation of secondary microplastics from the abrasion or degradation of larger plastic items.

A general overview of exposure to microplastics in indoor air is hampered by the fact that only a few studies report data relevant for indoor air. One study stands out due to its use of a sophisticated sampling and promising automated detection method without a predetermined focus on a specific particle type. Nevertheless, from the three studies, the average microplastic abundance in indoor air ranged from 1.6 - 9.3 particles/m^3, with a maximum of 20 particles/m^3.

4 Discussion

Only a few, mostly recent studies provide some insights into the release to, deposition from, and concentrations of microplastics in indoor air. Unfortunately, the measurement methods are mostly unique in each study presented, making comparison difficult. For this reason, it is important to understand some of the differences and discuss implications in relation to risk assessment and future studies on microplastic pollution (section 4.1). Indoor air quality has been studied in relation to particle matter for much longer. Therefore, in section 4.2 we will compare the results found here with existing work on PM2.5 and PM10 indoor air concentrations Furthermore, in section 4.3, the limited data available for indoor air is briefly reviewed in the perspective of outdoor air and the link to other compartments Finally, in section 4.4, we summarize the main conclusions and identify knowledge gaps.

4.1 Factors affecting measurements

The measurement techniques used for microplastics in indoor air are one of the causes of uncertainty and variability in the estimates of the exposure to particles in air. Foremost, there is a clear difference between exposure estimates based on either deposition or concentration measurements. Deposition measurements relate to the rate particles are deposited on a certain surface area (particle per m^2 per day), which can be used to estimate exposure to children through ingestion or dermal uptake, if found to be relevant for microplastics. Potentially an indirect link can be made with exposure through inhalation because the deposition rate is also related to the concentration and size of particles in the air; small particles deposit more slowly or not at all compared to larger particles. Concentration measurements relate to the amount of particles present in a specific volume of air (particles per m^3), which can be used to estimate exposure through inhalation.

In relation to this, the measurement height is an important parameter for consideration. A low height, on or close to the floor, will result in accumulation of more and larger particles, compared to measurements at common human respiratory height (HRH), between 1 - 2 meters, or even higher in the atmosphere in outdoor air. This means that the type of particles measured close to the ground are more relevant for relating exposure to activities undertaken by children and babies, and measurements at HRH are more relevant to activities common to all humans, such as sleeping, sitting or standing/walking. Measurements higher than HRH are more relevant for understanding long range transport than for measuring direct exposure of humans. The most advanced methods currently available to measure exposure are devices like the “Breathing Thermal Manikin” which simulates the normal breathing activity of a person, e.g. sitting at a table (Vianello et al., 2019).

Another important factor influencing measurements is the differences in detection techniques. It is possible that some techniques potentially overestimate microplastic fibres in comparison to other types of microplastic fragments, for instance due to limitations in visual selection and potential bias. In some experiments in which colouring and automated detection methods were applied, significant contributions of microplastic fragments (Klein and Fischer, 2019) and natural particles (Vianello *et al.*, 2019) were found compared to other studies.

Finally, it is common knowledge, for instance from forensic studies, that in post-sampling, contamination with fibres is known to occur, although this is not specifically focused on microplastics (Henry *et al.*, 2019). For this reason, it is good to pay attention to including proper controls in order to avoid measurement artefacts (Prata *et al.*, 2020). Several studies state explicitly that they do this, e.g. (O'Brien *et al.*, 2020), while for others it is unclear, e.g. (Dris *et al.*, 2017).

Variability and uncertainty can be reduced by applying widely accepted measurement standards such as by OECD or ISO, with specific attention for microplastics. This will make reuse of measured data more feasible as comparison between studies is then more straight forward, and any variability and uncertainty from technical and analytical approaches is minimized.

4.2 Indoor air PM2.5 and PM10

In general, indoor and outdoor air quality is often based on the concentration of particulate matter (PM) and volatile organic compounds. Microplastics are a type of particulate matter and we briefly discuss some other PM sources in the most common size ranges, those below 10 μm in size (PM10) and 2.5 μm in size (PM2.5).

Based on the results of the limited number of studies on microplastic concentrations and deposition in/from indoor air, the particle sizes measured are all larger than 10 μm, thus they fall outside the typically considered exposure to PM2.5 or PM10 in air quality assessments (Mathijssen *et al.*, 2019). For instance, only Vianello *et al.* (2019) were able to detect particle diameters close to 10 μm, the others had a lowest size detection limit of 50 μm, which is also a common detection limit in outdoor air microplastic studies (Huang *et al.*, 2020; Mbachu *et al.*, 2020; Zhang *et al.*, 2020b).

The concentration of measured microplastics in indoor air seems to be low compared to other sources of PM in indoor air. For instance, a study on the effects of woodburning in households in Norway detected an average PM2.5 concentration of 15.6 $\mu g/m^3$ in households using wood burning stoves, and 12.6 $\mu g/m^3$ in households without wood burning stoves (Wyss *et al.*, 2016). These concentrations were reported in mass based units, therefore a conservative conversion of these PM2.5 concentrations to number based units is performed. This is done by taking the max diameter of 2.5 μm and a relatively high particle density of 2500 kg/m^3 resulting in ~95.000 and ~77.000 particles per m^3 for households with and without woodstoves, respectively. Microplastic abundance was measured at a maximum of 20 particles per m^3, however this was with the lowest size of detection being 10 μm instead of 2.5 μm.

In the study by (Dris *et al.*, 2017) on microplastic abundance in indoor air, it was observed that airborne microplastic concentration increases with decreasing particle size, down to the 50 µm detection limit. In the study by Vianello *et al.* (2019), the most abundant particle size class was above the 10 µm detection limit at 20 µm, but with a logarithmic size distribution. It thus remains unclear if microplastics also make up part of the indoor PM10 and PM2.5 indoor fine dust category; this should be clarified in further studies. This would also help with assessing the potential contribution of microplastic pollution on negative effects on health caused by exposure to PM2.5 and PM10, the health standards set for indoor and outdoor air. The advised long term health-based guideline values, derived by RIVM and similar to the outdoor levels set by the WHO (WHO, 2006) are 20 µg/m^3 and 10 µg/m^3 for PM10[1] and PM2.5[2], respectively (Dusseldorp and van Bruggen, 2007). These concentrations cannot directly be compared to findings in this study, as these size ranges were not measured. Please note that this excludes any risk limits related to specific substances that might be present in indoor aerosols.

One of the most strictly regulated types of particles is asbestos because of its long-term health effects. We use asbestos as a worst-case base line for comparison using the particle specific limits: negligible risk level (*verwaarloosbaar risiconiveau, VR*) and maximum permissible risk level (*maximaal toelaatbaar risiconiveau, MTR*). Depending on the asbestos fibre type, the negligible risk levels are 3 and 28 fibres per m^3 air for Amphibole and Chrysotile, respectively (Hegger *et al.*, 2014). The maximum acceptable risk levels are 300 fibres Amfibole per m^3 and 2800 fibres Chrysotile per m^3. Although there is no evidence to suggest that certain microplastic fibres have the same hazard potential as asbestos, particle toxicity can also not be entirely dismissed. Such particle toxicity is related to knowledge about the particle characteristics, such as fibre aspect ratio, dimensions, and rigidity. Overall however, the measured concentration in indoor and outdoor air for microplastic fibres (20 fibres/m^3) can be considered low in comparison to these limits, as concluded by Kooter *et al.* (2020). Please note that there are no data reported for the smaller particle range.

Occupational exposure and exposure during specific activities of consumers may result in temporary higher exposures to microplastics, similar to non-microplastic fibres and particle exposures (Mathijssen *et al.*, 2019; Kooter *et al.*, 2020). In one study on PM2.5 in general (not microplastics) (Lévesque *et al.*, 2001), the highest PM2.5 exposures were linked to the presence of a bronze workshop, home renovations, and cleaning of a wood burner ashtray. Given this observation for other particle types, it is conceivable that home renovations could result in added release of microplastics, as PVC and other plastics are common in different building materials. There is currently no study or data available specific to microplastics that quantifies these type of releases. Another specific source is the release of microplastics and nanoplastics from 3D printing, which could potentially lead to relevant exposures based on the observed 10^{10} to 10^{12} particles released per hour. A comparison with existing limits for PM2.5 and PM10 requires conversion of this release rate to a concentration in the respective indoor space. Further research

[1] 20 µg/m^3 PM10 corresponds to ~1900 particles/m^3, assuming spherical particles with density of 2500 kg/m^3 and diameter of 10 µm.
[2] 10 µg/m^3 PM2.5 corresponds to ~61000 particles/m3, assuming spherical particles with density of 2500 kg/m^3 and diameter of 2.5 µm.

is needed on the link between indoor activities and microplastics release to air.

Overall, it is advisable to specifically include measurement methods that can detect microplastics between 100 nm (PM0.1) and 10 µm (PM10) in future studies on microplastics in indoor air. None of the existing studies (excluding 3D printing) are able to detect particles smaller than 10 µm. Yet, these are commonly considered the most relevant for assessing effects on human health. The smaller particles are much more prone to suspension in air than larger ones, in particular for fragments. Of the larger particles, fibres are more prone to suspension in air due to their shape and small diameter. Given the lack of measurements of microplastics in the size classes PM10 and PM2.5 and the low overall abundance of the larger particles, the significance of the microplastic contribution to a reduction of the overall indoor air quality remains uncertain.

4.3 Indoor air versus other routes of exposure

The indoor air and similarly the outdoor air compartments are mainly where emissions take place and are redistributed over other compartments; air is not a microplastic sink such as soil or sediment or water. Microplastics in indoor air eventually either end up in outdoor air or are deposited and removed from indoor surfaces. where their further fate is dependent on cleaning and waste treatment steps. Microplastics in outdoor air are mainly deposited in the water or soil compartments where they can accumulate (Kawecki and Nowack, 2019; Sieber *et al.*, 2020).

A Swiss study of seven commodity plastics (Kawecki and Nowack, 2019) reports that overall, the indoor air emissions to outdoor air are estimated to account for 6% of the total emissions to air, soil and surface water together. This means that mitigation options aimed solely at indoor air will be unlikely to contribute much to a reduction in overall microplastic environmental pollution. However, air quality can still be adversely affected by release of indoor microplastics, depending on their hazard potential. Given the limited data available, it is too early to formulate potential specific mitigation options. For instance, more insights are needed in the specific characteristics of microplastics released to indoor air. Information is needed on the smaller particle sizes, from PM10 to PM2.5 and smaller, and their abundance, sources and contribution to overall indoor air quality. Furthermore, information is needed on the possible health effects caused by microplastics.

Nevertheless, as textiles are considered a major source of microplastics to indoor air (Parker-Jurd *et al.*, 2019; Kawecki and Nowack, 2020), mitigation of these can potentially also prevent or reduce the release to indoor air. For instance, mitigation options aimed at the source, e.g. using material alternatives to synthetic fibres. is also likely to reduce indoor air microplastic emissions. Similarly, when reducing microplastic release to water, limiting their release by altering weaving techniques or fibre strength or length could potentially also reduce their release to air. Nevertheless, such measures should be considered in light of the expected reduction in overall human and environmental risk from exposure to microplastics. Moreover, it is essential to look at potential environmental and health impacts of any alternatives products or solutions to prevent any regrettable substitution.

4.4 Conclusions and recommendations

This desktop study reviews the currently available literature on microplastic sources, concentrations and deposition in indoor air. Overall, there is a high level of uncertainty in assessing and quantifying any potential human exposure to microplastics via indoor air. Additionally, as a consequence, microplastic-specific health safety levels are not yet available, and information on hazard needs to be considered, however this was outside the scope of this study.

First of all, it is clear that the number of studies available is limited, thus it is difficult to assess their representativeness. In addition to uncertainty in the results, more studies are needed to cover the variability in behaviour, activities and other external factors that influence microplastic sources. These factors differ in time and per location. For instance, the types of sampling locations vary from office buildings to living rooms, and with that, microplastic abundance and deposition also vary. Sources of microplastic also vary depending on the location in the world for example regarding types of plastics used, and thus the resulting emissions vary due to different usage/customs, different climate, etc. Furthermore, robust analytical techniques are still under development and currently, no standardized method is available. This is needed in order to reduce uncertainty solely related to the measurement methods. The following conclusions should be seen in light of these limitations, and have been used to identify knowledge gaps and formulate recommendations. Following these recommendations and improving our understanding of microplastics in indoor air will contribute to taking more effective measures for improving air quality.

Conclusions

- The average concentrations of microplastics in indoor air reported in three studies ranged between 1.6 - 9.3 microplastics/m^3.
- The lower particle size limit of measured microplastics is very high compared to the size scales relevant for indoor air quality. Most are related to the resolution level of visual microscopy, ~50 µm. Some studies used µFTIR-Imaging analysis, and were able to measure particle sizes down to 11 µm.
- Although concentrations (in microplastics/m3) could be higher when considering smaller microplastics, the measurements available (particles mainly larger than 10 µm) show relatively low concentrations compared to some of the existing safety limits available for a worst-case baseline, such as asbestos.
- Microplastic fibres from textiles are highlighted in many studies and reports as a major contribution to microplastics in indoor air and in air in general, together with tyre wear particles. However, recent measurements of abundance of microplastics highlight the potential large contribution of microplastic fragments (up to 90%) instead of fibres. Although these fragments can still be related to degraded microfibres or be directly released from textiles, other potential sources of microplastics need to be investigated.

Recommendations

- Additional research is required on measuring indoor air concentrations and their sources as these are relevant for risk assessments. Studies are needed on the links between sources and indoor activities to better understand microplastic release, in particular for identifying sources of microplastic fragments. Research on deposition is also relevant for estimating exposure through ingestion and further microplastic fate in the environment.
- Investigate the use of proxy measurements based on existing PM2.5 and PM10 sampling and detection methods.
- Future research should focus on the smaller microplastics and improve detection limits in order to retrieve microplastics down to the PM2.5 and ultrafine (nanometre) size scales. This is necessary in order to understand whether microplastics significantly contribute to PM2.5 and PM10 exposure.
- Develop widely accepted guidance on approaches for sampling, analytical methodology, and data reporting to support further exposure assessment, i.e. using modelling and with the aim of informing risk assessment. This should be done by contributing to test guideline development, e.g. by OECD or ISO.
- Though little relevant literature was available for this study, the topic of microplastics (in air) is increasingly attracting more public and research attention. It is therefore recommended to re-evaluate the rapidly growing body of literature on microplastics in air in about two years and introduce quality criteria, such as minimal data requirements, to enable best use of the data.
- Our understanding of the health effects of microplastics should be increased. Specific attention should be paid to health effects in order to better understand any hazards and support risk assessment. This then should include the results from several current projects, such as MOMENTUM and several other ZonMw projects (e.g. EXPLAIN and PLASTICS).

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