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Plastic Microfibers from Household Textile Laundering: A Critical Review of their Release and Impact Reduction

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Abstract

This review addresses the role of household washing machines in the release of plastic microfibers, and means to minimize emissions. Specifically, various strategies with potential to mitigate microfibers discharge are critically evaluated, such as modifying laundering conditions and implementing point-of-use capturing systems. The currently available point-of use devices for microfiber removal are associated with technical limitations, and obtaining a complete removal of the plastic contaminants remains an open challenge. To allow safe wash water discharge and target impending regulations, point-of-use devices should be user-friendly, compatible with washing machines, easily maintainable, and provide near complete removal of microfibers. Advantages, limitations, and challenges of capturing devices are thus critically discussed, and possible improvement strategies are proposed. Microfibers detection techniques are also briefly presented in this review, and the need for standardization and simplification is highlighted. Overall, efforts are required to promote a wide approach toward environment-friendly laundering of textiles, including source control, encouraging biodegradable materials use and recycling, and implementing effective filtration and treatment processes for microfibers, both at the point-of-use and in centralized treatment plants.

Keywords: Microfibers; Point-of-use filters; Wastewater treatment; Textiles; Washing machines.

Graphical Abstract

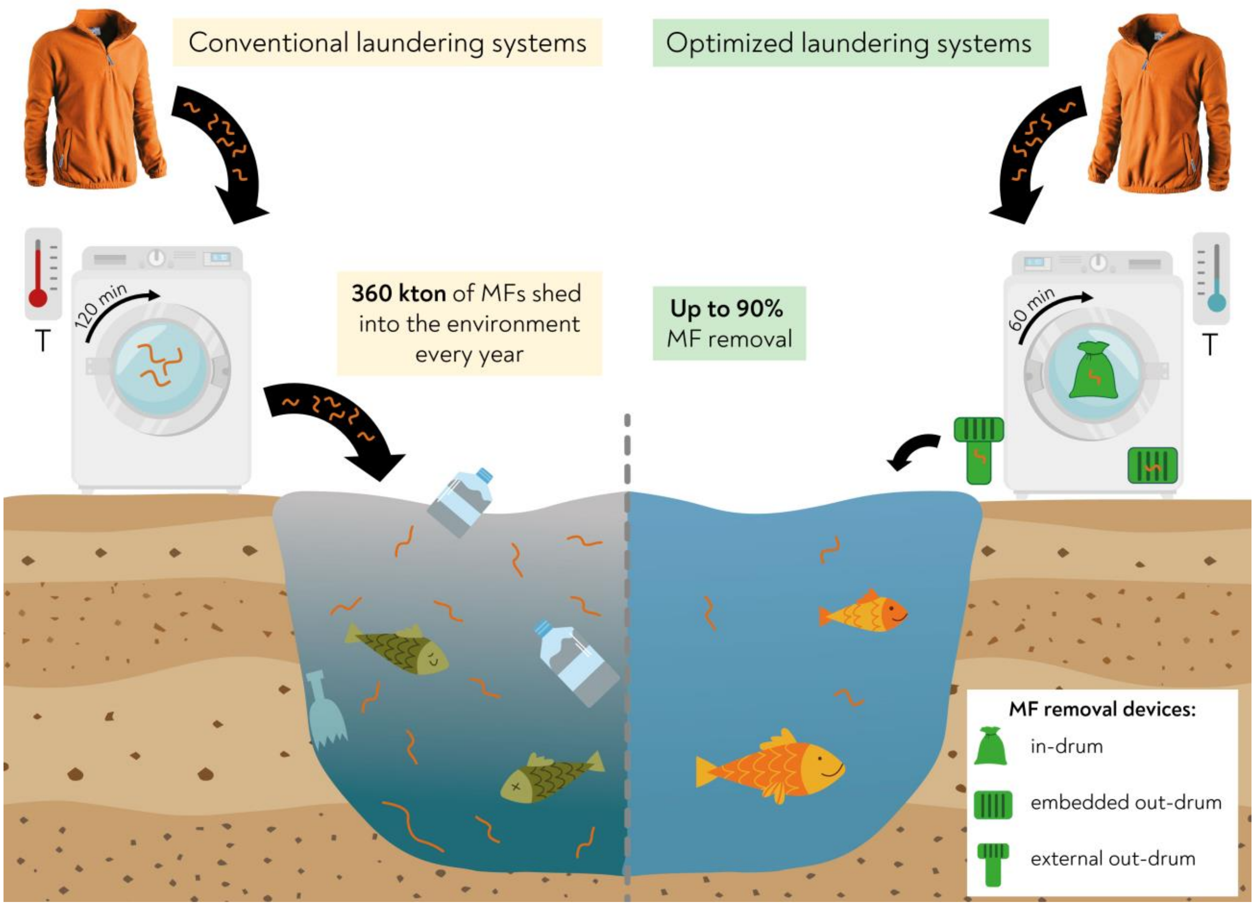

Table of Contents

1. Introduction

Ecosystems have experienced a new form of pollution in recent decades related to “microplastics”, which are defined as plastic fragments measuring no larger than 5 mm (Wright et al., 2013). Microplastic pollution has become a global issue, affecting both freshwater and marine environments, due to the rapid increase in plastics production and the growth of the fashion and textile industries (Boucher & Friot, 2017). In the past few decades, the fashion industry's emphasis on higher volume productions, driven by prevailing trends, has led manufacturers to prioritize quantity over product quality (Rathinamoorthy, 2020).

Overall, microplastics that end up in the environment can be found in numerous shapes, such as fibers, foam, pellets, films, and fragments, with fibers being reported as the most dominant form (Akyildiz et al., 2022; Gaylarde et al., 2021; Miller et al., 2017). Specifically, microfibers (MFs) are characterized by their thread-like structure, with diameters typically smaller than 10 μm and lengths up to 5 mm (typically 10s to 100s of μm) (Akyildiz et al., 2022; Dreillard et al., 2022; Weinstein et al., 2016). When it comes to composition, MFs may be made of various polymeric materials, such as polyesters (Napper & Thompson, 2016; Zambrano et al., 2019), polyethylene (Weinstein et al., 2016), polyamide (Gavigan et al., 2020), acrylic (Belzagui & Gutiérrez-Bouzán, 2022), polypropylene (De Falco et al., 2018b), elastane (Rathinamoorthy et al., 2023; Sillanpää & Sainio, 2017), rayon (Zambrano et al., 2019). Synthetic MFs have not only polluted marine and aquatic environments, but they have also been detected in soils and in the atmosphere (Blettler et al., 2017; Kapp & Miller, 2020; Sundt et al., 2014). These MFs typically enter the marine and aquatic environment through direct sources or via wastewater treatment plant (WWTP) effluents. WWTPs equipped with primary and secondary treatment processes are able to typically achieve MF and microplastic mass removal up to 90-95% at best, resulting in the estimated number-wise release of around 85 million fibers per day into the aquatic environment, along with another 3.68 billion accumulated in the separated sludge (Blair et al., 2019; Madhav et al., 2018; Petroody et al., 2020).

An important fraction of plastic MFs being discharged into the sewage or dispersed in the environment through other pathways comes from laundering activities. Accordingly, numerous research studies have been conducted to understand the MF release from washing machines under different conditions and using different types of garments (Choi et al., 2018; Madhav et al., 2018; Napper & Thompson, 2016). Other studies have investigated approaches to reduce the amount of MFs reaching the environment by, for example, integrating specific processes into WWTPs as tertiary treatments, or deploying ad hoc removal steps (Meng et al., 2023; Murphy et al., 2016; Ramasamy & Subramanian, 2021). Following this direction, several products emerged on the market aiming at the in-situ removal of MFs before the household wastewater from washing machines enters the sewage network, *i.e.*, in-drum equipment and ex-drum filters (Ramasamy & Subramanian, 2021). Although none of the current commercial products addresses the issue of MFs release from washing machines without limitations, they can serve as inspiration for researchers and manufacturers to develop more reliable filtration systems. However, without proper and mandatory national or international laws and regulations in place, there is a lack of significant incentives for individuals and manufacturers to invest in this issue.

This paper presents a review of current strategies to reduce emission of plastic MFs during household textile laundering, as well as potential solutions for the future. First, the origin and fate of microfibers, as well as analytical methodologies for their characterization, are briefly discussed. Then, techniques to reduce and to remove these pollutants directly acting on the laundering cycles and/or on laundering wastewater are presented, i.e., deploying point-of-use strategies. Updated knowledge on microfibers release as a function of laundering conditions is provided to help scientist and engineers design washing cycles that would minimize release while guaranteeing suitable washing of the garments. Then, information around the functioning and performance of the latest point-of-use microfiber capturing systems is discussed, and these devices are evaluated against an ideal capturing system. A series of advantages, limitations, and opportunities are described for the various systems, with the goal to guide the design and development of new, better, and cheaper devices.

2. Brief Overview of Production, Origin, and Fate of Textile Microplastics and Plastic Microfibers

Desirable properties of plastics-based garments, such as strength, stain resistance, softness, perspiration and evaporation properties, have led to a significant increase in the production of synthetic fabrics. However, synthetic fibers have lower melting points and higher combustion rates compared to natural fibers, hence raising environmental concerns (Carr, 2017; Mishra et al., 2019). This section provides a concise overview of production data, sources, and fate of synthetic textile microplastics and plastic MFs, with a focus on those emitted in laundering activities. See Figure S1 and Text S1 of the Supporting Information for a more detailed overview and for a review of recent regulations pertaining to this issue.

Synthetic fibers and cotton together hold a dominating position in the global textile fiber production landscape, where synthetic fibers make up 60% of the total output, while cotton accounts for roughly 30%. Particularly, the demand for polyester fibers has seen a global growth rate of approximately 7% in the last decade (Boucher & Friot, 2017). MF shedding to the environment has surged from approximately 122 tons per year in 1950s to figures close to 360 kilotons in 2016, meaning a compound annual growth rate of 12.9% (Gavigan et al., 2020).

In terms of environmental fate, synthetic MFs are believed to be the most widespread anthropogenic pollutant in the environment (Athey & Erdle, 2022). In fact, the majority of the MFs released into the environment ultimately find their way, whether directly or indirectly, into aquatic ecosystems, specifically in marine and surface water bodies. This is especially prevalent in regions where WWTPs are either absent or inadequately equipped to ensure adequate MF removal. Conversely, in areas with well-established WWTPs, a significant portion of the released MFs may enter terrestrial environments through typical sludge disposal processes, if the sludge is used as agricultural fertilizer (Saliu & Oladoja, 2021; Santos et al., 2021). The presence of MFs in the environment is therefore ubiquitous. Table S1 summarizes the proportions of synthetic MFs found in various matrices (Jia et al., 2019; Miller et al., 2017; Sun et al., 2019; Vidal et al., 2018; Yang et al., 2019; Yuan et al., 2019).

Polyesters is the most common synthetic fiber globally; hence it is the most polluting, making up over 56% of the accumulated microplastics in the ocean (Browne et al., 2011; Carney Almroth et al., 2018). During the user phase, the primary cause of microfiber release into water sources is arguably represented by domestic laundering of textiles, as noted by Sillanpää & Sainio (2017). While research studies claim that synthetic textiles release more MFs through natural weathering processes (De Falco et al., 2018b; Hernandez et al., 2017; Napper & Thompson, 2016), microfibers from domestic sewers and WWTP have been identified as two of the most significant sources of MF contamination for marine and freshwater systems (Murphy et al., 2016; Ramasamy & Subramanian, 2021).

3. Brief Overview of Sampling, Detection, and Analytical Techniques

This section provides a concise overview of the current best practices in terms of sampling, detection, and techniques for the analyses of plastic MFs, based on previous studies and on the authors' experience. Readers may refer to Text S2 of the Supporting Information for a more detailed review of this topic.

Wastewater Sampling Procedures and Considerations

Microplastics and plastic MFs can either settle or float, making it imperative to minimize the presence of clumped fibers before characterizing them, as emphasized by Belzagui et al. (2019). Depending on the type of analysis to be performed, pre-filtration of the collected samples may be necessary and the volume of the water sample should typically be 50 mL or more, depending on the source and on the filtration system configuration (Mishra et al., 2019; Singh et al., 2020; Sun et al., 2019). A study conducted by Hong et al. suggested that the use of filters with pore sizes <5 μm may be sufficient to capture all MFs in wastewater samples (Hong et al., 2021). The fibers collected on the filter paper should be air- or vacuum-dried. Subsequently, oxidation is a useful means to eliminate organic matter and other contaminants (Aghdasinia et al., 2017; Hong et al., 2021; Masura et al., 2015).

Detection and Analytical Approaches

Table 1 summarizes the most employed analytical approaches for MF characterization and highlights the main advantages and limitations associated with each method. Scanning electron microscopy (SEM) is the most employed microscopy technique utilized to identify MFs and microplastics. However, other microscopy analyses, such as fluorescent microscopy, stereo microscopy, optical microscopy, bright-field microscopy, phase contrast microscopy, and X-ray analysis are also utilized for this purpose (Hamzah et al., 2021; Mishra et al., 2022; Padervand et al., 2020; Tripathy et al., 2022; Yin et al., 2019). SEM is widely used because it allows gaining information on the morphological structure of the fabrics, length and diameter, ageing and, indirectly, their origin (Mishra et al., 2022). Moreover, SEM systems equipped with energy dispersive X-ray spectroscopy (EDS) can inform on the elemental composition of the polymeric and composite materials (Ding et al., 2019). Another commonly used method for the detection of microplastics and MFs is fluorescence microscopy, which allows for the characterization of all fluorescence-emitting materials, including non-plastic materials (Anjana et al., 2020; Payton et al., 2020). Nevertheless, microscopic approaches may not provide adequate information on chemical composition.

Chemical characterization of MFs can be performed utilizing spectroscopic analyses. FT-IR has become one of the most employed techniques for polymers identification, especially aimed at the identification of synthetic MFs released during garment laundering (Hale et al., 2020). One drawback of this technique is that it is normally unable to characterize materials with dimensions below 10 μm, due to diffraction phenomena (Dümichen et al., 2017). Raman spectroscopy has been increasingly used to overcome such limitations since it can be used for the characterization of particles smaller than 1 μm, the results not being affected by diffraction effects (Hale et al., 2020). In these analyses, reference spectra libraries are needed for the proper identification and for differentiation of different materials, which may prove challenging as individual spectra overlap in mixed samples (Dey et al., 2021).

Thermo-analytical analyses are destructive methods, yet valid option for chemical characterization of microplastics and synthetic MFs. In particular, mass spectrometry associated with gas chromatography (GC-MS) allows the chemical characterization and the subsequent identification of the polymers exploiting thermal properties of different compounds. Similar to spectroscopy, MS-GC requires reference pyrogram libraries as reference in the course of the analysis (Dey et al., 2021). An alternative method is thermal extraction desorption-gas chromatography/mass spectrometry (TED-MS/GC), which offers the advantage of trapping degradation products of the original polymers on the solid phase. Consequently, subsequent analysis can be performed directly on the solid phase, by thermal desorption GC-MS, thus eliminating the need for pyrolysis (Dümichen et al., 2017). In general, methods based on GC require extensive pretreatment, and the samples should be isolated and concentrated before conducting the analysis.

A quick method for the quantification of microplastics and MFs in an aqueous sample is total organic carbon (TOC) analysis (Hong et al., 2021). Drawbacks of TOC analysis is that it is a destructive method and that it provides information on overall organic mass without distinguishing fibers of different size, shape, or chemical composition, or microfibers from other organic contaminants. Yet another approach for the classification and quantification of microfibers is selective solvent extraction. Hexafluoroisopropanol was used as a suitable solvent for synthetic MFs made of PET, nylon-6 (N-6), and polyacrylonitrile (Lim et al., 2022).

Summary and Unresolved Issues in Detection and Characterization

The vast majority of the techniques utilized for microfibers detection are offline, thus requiring the collection of samples, for example during or after washing cycles, and subsequent analysis. Weighing microfibers retained by proper filters is currently the most adopted offline strategy to obtain a quick quantification of the fiber concentration in water. However, this technique is prone to experimental errors and cannot obviously provide information on the nature of the fibers. Moreover, as indicated by Rathinamoorthy & Raja Balasaraswathi (2023b), while weight-based methods are simple and quick ways to quantify microfibers, the inclusion of surfactants and other contaminants from the fabric or from the water can add additional weight and skew the measurements. Many of the other, current techniques, *e.g.*, SEM, FTIR, GC-MS, rely on cumbersome sample preparation procedures and require the availability of expensive equipment, also involving skilled personnel. More streamlined, yet robust, offline techniques would contribute to simplifying, widening, and standardizing investigations. Furthermore, the availability of a technique allowing online or in-situ quantification of the microfibers suspended in the wash water during the washing cycle would represent a critical simplification of both investigations and emission control strategies. While in principle some characteristics of the wash water could be exploited to quantify microfibers, such as turbidity or light absorbance, these methods are typically affected by other constituents of the effluent and are impacted by several confounding factors. In conclusion, major efforts are needed to provide robust, yet simple, analytical techniques for quantification and characterization of microfibers, with the ideal goal of developing a methodology that works effectively online and/or that can be standardized and adopted widely by all stakeholders.

4. Textile Laundering as a Source of Microplastics and Plastic Microfibers

The following sections provide as summary of the numerous studies and research papers investigating the effects of garment material, washing temperature, washing machine type, washing cycle, water chemistry, and chemicals (with focus on the addition of detergents and softeners), on release of plastic MFs during laundering activities. These aspects and their overall effects are also visually represented in Figure 1 for better clarity.

Effects of Garment Material and Characteristics

The nature of garment materials has been studied considering 6 kg as a typical washing machine load (Napper & Thompson, 2016; Pirc et al., 2016). The data available in the literature on MFs release based on the material were classified in this review, and typical values are listed in Table S3 (Supporting Information). Variability in washing cycle methodologies and fiber analysis methods presents a significant challenge in comparing and systematizing available data.

However, general trends suggest that a more substantial fibers release occurred when exclusively synthetic materials were used. Moreover, according to O'Loughlin (2018), the maximum MFs release usually occurs during the first wash, which may be related to the loose fibers left on and within the garment structure during production. The data also suggest that MFs release from polyester garments is lower compared to that from other synthetic materials, such as acrylic or polypropylene.

Effects of Washing Temperature

Multiple studies have shown that the higher the washing temperature, the more pronounced the MF release (Galvão et al., 2020; Le et al., 2022; O'Loughlin, 2018; Rathinamoorthy & Raja Balasaraswathi, 2021). Higher temperatures promote the expansion of yarns, reduce the strength between the bonds of the filaments, both mechanisms possibly resulting in an increase of MF release (Le et al., 2022). For instance, Yang et al, indicated that the release of MFs from a garment made of polyester was considerably higher at 60 °C compared to a washing cycle performed at 30 °C (at full load washing condition) (Yang et al., 2019). Other than yarn expansion, De Falco et al. (2018b) pointed at the increase in surface hydrolysis of the synthetic textile as an explanation for release at higher temperatures.

Effects of Washing Machines Type

Hartline et al. (2016) investigated MF emission in two types of top-loaded (drum rotation around the vertical axis) and front-loaded (drum rotation around the horizontal axis) machines. They observed that MFs release in top-loaded machines was much more substantial (1906 mg) compared to that observed with the front-loaded ones (220 mg). Reportedly, this result was due to a higher abrasion as a result of stronger agitation and friction in the top-loaded machines, which was also confirmed by other studies (Hazlehurst et al., 2023).

Effects of Washing Cycle

MFs shedding is reportedly influenced by the mechanical stress and the duration of agitation applied during washing (Rathinamoorthy & Raja Balasaraswathi, 2021). As a general trend, the intensity of the MF shedding was observed to decline significantly after the first couple of washes, particularly after the first wash (Napper & Thompson, 2016). For example, a study by Cai et al. (2020) indicated that MF release was stabilized after the fifth wash, with levels potentially being 6 to 120 times higher in the first wash compared to the tenth wash. There are studies implying that the duration of the washing cycle does not have a significant impact on MF release (Kelly et al., 2019). These studies indicated that the amount of MFs found in samples collected after 15 min and 60 min washing cycles was nearly the same, leading to the reasonable conclusion that the main release of MFs occurred within the first 15 min of washing cycle. However, the outcome varies based on diverse textiles and washing cycle patterns. Based on the authors' observation, the longer the tumbling portion of the cycle, the more mechanical abrasion occurs, leading to a higher likelihood of MF shedding, while the effect of spinning rate remains uncertain.

Effects of Water Chemistry and Chemical Additives

To the best of our knowledge, there are no detailed research studies conducted to fully understand the influence of initial water chemistry. De Falco et al. (2018b) assessed the effect of water hardness, detergents, laundering duration, and temperature, revealing that the use of hard water increased MF shedding compared to distilled water. On the other hand, chemical additives (*i.e.*, detergents and softeners) are outlined as critical parameters intensifying the MF shedding during the washing of the garments. It is believed that the application of both solids and liquids detergents usually results in a more substantial MF release compared with cases whereby no detergents are present (Le et al., 2022; Zambrano et al., 2019). Typically, commercial detergents and softeners elevating water pH may induce chemical damage and textile degradation as a result of hydrolysis (Bishop, 1995; Rathinamoorthy & Raja Balasaraswathi, 2021). In another research study, a significant increase in MF shedding was observed when non-bio detergent was employed compared to cases involving bio or no detergent (Napper & Thompson, 2016). However, there are also research reports implying the positive role of surfactants against MF release (Bishop, 1995; Hernandez et al., 2017). Solid detergents seem to contribute to MF release compared to liquid counterparts due to increased friction and cloth abrasion, but this phenomenon is currently subject of conflicting study outcomes (Issac & Kandasubramanian, 2021). While some studies suggest that washing products do not have a significant influence, one research study reported that their use may reduce MF release (Acharya et al., 2021; Li et al., 2023; Madhav et al., 2018). In summary, no strong consensus has been reached on the impact or effect of detergents or softeners on MF release, although the majority of studies indicate a likely increase in emission in the presence of chemicals.

Effects of Drying Conditions

Tumble dryers play a direct role in MF emission to the ambient atmosphere. More specifically, considering the fact that such equipment operates at medium to high spinning rates and temperatures, when a piece of garment is rotating in the drum of a forced-air dryer, MFs can be shed from the textiles (O'Brien et al., 2020). Moreover, the emission of MFs originating from large-scale dryers are unspecified, yet might be not negligible (Kapp & Miller, 2020; Tao et al., 2022). The use of tumble dryers may translate into a release of MFs from garments due to mechanical abrasion (Amber M. Cummins et al., 2023). Unfortunately, most of the studies on the impact of garment laundering activities focused on MF release during washing, while drying has not been investigated adequately. In a recent research study, Tao et al. (2022) estimated that an average

Canadian household releases from 9×10^7 to 12×10^7 MFs from a single dryer per year. They also developed a filtration system to reduce the emission of MFs into the atmosphere. In another study, Kapp & Miller (2020) confirmed the emission of the MFs by household tumble dryers into the air through ventilation. They indicated that small fibers could travel over 9 meters away from the effluent of the ventilation.

Other Influential Parameters

There are other influential parameters on plastic MFs release, such as the garment loading into the washing machine, the quantity of washing water, yarn type, the specific mass of the garment (mass per unit area), the garment design, sewing, thickness, and compactness. A higher loading leads to reduced friction and, consequently, lower MFs release per unit of load (Hazlehurst et al., 2023). Moreover, according to a research study, the amount of washing water seems to have a direct impact on MF release, specifically, higher water/load ratios tend to increase MF release because of higher hydrodynamic pressure on the fabric structure (Lant et al., 2020). Additionally, washing garments with different yarn types leaves different footprints on MF release: spun yarns was observed to cause larger MF release compared to filaments, since the former are shorter in length and are characterized by higher mobility (Choi et al., 2021). Also, by comparing twisted and non-twisted filament yarns, the latter seem to release higher quantity of MFs with respect to the former. Focusing on the characteristics of the garment structure, larger mass per unit of area and larger thickness of the structure result in a higher release of MFs, due to an increase in the number of fibers per unit area (Raja Balasaraswathi & Rathinamoorthy, 2022). Moreover, a more compact structure is more resistant to mechanical friction, potentially reducing MF release (De Falco et al., 2019b; Raja Balasaraswathi & Rathinamoorthy, 2022; Yang et al., 2019).

Summary and Unresolved Issues

The release of MFs varies extensively depending on the garment material, design, and laundering conditions. Attempting to provide a concise summary, it may be stated that, according to the current understanding, polyester is characterized by lower shedding with respect to other synthetic MFs. Moreover, higher washing temperatures and top-loaded washing machines are regarded to contribute to higher emissions of MFs. Most of the MFs from an individual garment seem to be released in the first or in the first few (1-4) washes. The use of hard water and detergents may also increase microfiber shedding. Additional parameters may also affect microfiber release, but further research is needed to better understand such phenomena.

Despite significant efforts to study the release of MFs from household washing machines, there is a lack of standardized test methods (Gaylarde et al., 2021). Most existing protocols are adapted from garment dye resistance testing and do not precisely replicate MF emission from washing machines (Mishra et al., 2022). Furthermore, the wide variety of garments, detergents and chemicals, variations in source water chemistry, and differences in washing programs, creates variability in experimental parameters and data analysis across different studies. To the best of our knowledge, the entire body of investigation has been conducted so far using fresh apparel. The amount MFs released from the clothes that have been already extensively worn, as well as the possible effects of dirt and microorganisms on MFs shedding during laundering, are largely unknown. Another issue that has not been studied is that a broad range of textile structural compactness can be obtained using different machineries employed to produce apparels in different companies, which may significantly affect MFs release during laundering. Regarding this issue, Zambrano et al. (2019) suggested that fabrics with higher abrasion resistance, lower hairiness, and higher yarn strength released lower amounts of microfibers. In addition to that, while research reporting absolute values of MFs released during laundering activities are important, statistically robust analyses of the trends may arguably provide a more consequential knowledge and ideally providing means to predict microfibers release. For example, correlations should be proposed that describe the amount of MFs released as a function of different variables (*e.g.*, temperature, softener amount, washing time), and normalized parameters may be identified that provide a way to more easily compare the number of microfibers released per unit variable.

Another important characteristic that is seldom reported but which may play a critical role in our ability to intercept shed microfibers and reduce their impacts, is related not merely to their amount but to their shape and size. Different variables related to the garments or to the laundering activity produce microfibers of different morphological characteristics, because these properties govern the mechanism of filtration by centralized or point-of-use treatment devices. In other words, a washing cycle producing a high amount of easily filterable MFs may be regarded as more advantageous from a practical point of view, and it should be preferred to a different cycle producing less shedding of recalcitrant materials.

5. Point-of use Removal from Laundering Wastewater

Approaches for removing microplastic and MFs released into aqueous streams and wastewaters by textile laundering (Figure 2) may be classified in two distinct strategies based on the point of application: a) point-of-use treatment methods to remove contaminants directly at the origin, such as in-drum systems designed for the sequestration of microfibers during the washing cycle and out-drum filters utilized for extracting microfibers from washing machine drains; b) ex-situ treatment methods, which encompass approaches for MF removal in centralized or decentralized large scale systems (*e.g.*, wastewater treatment plants). The subsequent sections exclusively delve into the point-of-use strategies, presenting an overview of the primary solutions available in the market while emphasizing the strengths and limitations of each approach.

Characteristics of an Ideal Point-of-use Device

Essentially, an ideal in-situ filtration system is defined as a device able to capture all or near all the microplastics and MFs, whereby pore clogging or cake formation phenomena are minimized or controlled, such that they do not occur or do not significantly interrupt or disrupt the removal target in long-term operation. Moreover, an ideal device is inexpensive, easy to install, use, clean and maintain, occupies minimal space inside or outside the washing machine and ideally allows retrofitting of existing washing machines (Figure S4 of the Supporting Information).

In-drum Devices

To the best of our knowledge, there are only two types of in-drum devices available on the market: *Cora Ball* and laundry bags.

i. Cora ball:

Cora ball is a ball shaped device with stalks that have small hooks on their ends with the aim of collecting MFs from wash water by direct application inside the washing machine (Cora Ball, n.d.). Such balls are placed in the machine drum along with the garments, where MFs are captured by the hooked stalks. According to the founder of *Cora ball*, these devices can capture up to 35% of the shed MFs during a washing cycle (Anis & Classon, 2017). McIlwraith et al. (2019) assessed the release of MFs from fleece blankets made purely from polyester, both in the presence and in the absence of *Cora ball*. In another study, Napper et al. (2020) evaluated five different commercially available MF capturing devices, *Cora ball*s included. These authors used three textiles made respectively of 100% polyester, 100% acrylic, and a 60% polyester / 40% cotton blend. Results showed that the *Cora ball* was able to reduce the amount of MFs released in the drained wastewater by 31 ± 8%, based on mass measurements. However, the performance of the device was affected by the types of clothes washed. In particular, the *Cora ball* was more efficient at capturing longer microfibers compared to shorter ones.

In general, *Cora ball* devices are considered simple and user-friendly. However, their cleaning may be tedious, due to the fibers getting entangled in the stretchy plastic material (Ramasamy & Subramanian, 2021). Additionally, their overall performance in terms of MF abatement is not necessarily satisfactory, and they are not recommended for use when washing knits, delicate fabrics, fabrics with tassels, or those with fraying threads, as the devices may pull the threads and cause damage to the garments, as stated by the *Cora ball* manufacturer. Technically, any additional device inside the drum that increases the tension and abrasion of the garments may be a potential factor to increase MFs shedding.

ii. Washing bags

Guppyfriend and *Fourth Element* are two types of laundering mesh bags inside which the garments are placed before washing. Both bags have a mesh pore size of 50 µm, which enables them to capture some MFs released from garments and prevent their release into the washing effluent. Napper et al. (2020) conducted a study to evaluate the efficiency of *Guppyfriend* and *Fourth Element* washing bags under different washing conditions and with various garments. They found that the *Fourth Element* washing bag showed the least effective results, with only 21 ± 9% MF removal compared to other devices tested. On the other hand, *Guppyfriend* was the second-best performer and retained 54 ± 1% of the released MFs during washing. O'Loughlin (2018) investigated the release of MFs from fleece jackets and swimwear made of different synthetic fibers and evaluated the performance of washing bags in capturing MFs. They observed that

Guppyfriend bags were able to retain 87% of the MFs released from swimwear, while the retention rate was 91% for fleece jackets. Notably, the utilization of laundry bags also led to a substantial reduction in MF release from garments, with rates ranging from 0.4% to 5%. This reduction is likely a result of washing bags mitigating abrasion and the negative impacts of mechanical agitation during the washing process.

Overall, washing bags have a straightforward design and do not require complicated instructions. Additionally, washing bags are not limited in application in terms of materials or garments type, and they can be used for almost all types of clothes. However, further investigations are needed to assess their efficiency, as demonstrated by the lesser performance of the *Fourth Element* bags, despite their similar structure and pore sizes to *Guppyfriend* bags. Additionally, a drawback of laundry bags pertains to their material composition, being primarily constructed from nylon, a substance known for its propensity to shed. Furthermore, the microfibers captured within the bag, in constant contact with the clothing, can eventually re-deposit onto the garments.

Out-drum Devices

Compared to in-drum devices, a larger number of devices have been developed for installation outside of washing machine drums, as inline equipment that filter microplastics and MFs from the drain of washing machines.

i. LUV-R lint filter

LUV-R lint filters are among the earliest developed filters designed for MF capture. According to the manufacturer, Environmental Enhancements (n.d.), these filters can effectively reduce MFs by 65% when freshly placed inside the casing and by nearly 100% when their surface has already accumulated filtered material. They consist of two types of metal meshes with pore sizes of 285 μm and 175 μm, housed in a transparent casing, which facilitates easy and rapid inspection. However, it is important to note that this design may potentially encourage the growth of microalgae and other photosynthetic microorganisms within the filter (Burrows et al., 2021). McIlwraith et al. (2019) conducted a study to evaluate the efficiency of these filters in removing MFs emitted from polyester garments. According to their findings, the *LUV-R* lint filter was able to retain 87% of the released MFs based on count and 80% based on weight measurements. However, the filter demonstrated greater capability in capturing longer fibers compared to shorter ones. Napper et al. (2020) also investigated the *LUV-R* lint filter for the removal of MFs emitted during the washing of various garments. However, their results differed significantly from the other study, with only 29 ± 2% MF removal observed. This discrepancy may be attributed to differences in experimental conditions and washing machines employed. McIlwraith et al. deployed a top-loaded laundry machine, which resulted in higher MF emissions compared to the study by Napper et al., whereby front-loaded machines were used. In other words, the higher the MF emissions during washing, the faster the filter saturation occurs, potentially leading to better removal rate, consistent with the manufacturer claims. The *LUV-R* lint filters are easy to install outside of washing machines and they are mechanically resistant and washable, being made of metal meshes. However, it is crucial to highlight that washable filters may potentially represent a secondary source of contamination. Although the accumulated cake inside the filter or casing is easy to clean, improper cleaning methods, such as rinsing in a sink, could lead to the inadvertent reintroduction of microfibers into the sewage network, thus defeating the filtration purpose. *LUV-R* lint filters are large in size and can retain a significant volume of drain water even after the washing cycle has concluded. This lingering water can create a fertile environment for microorganisms' growth if the filters are used infrequently or if they are not adequately emptied and cleaned. Additionally, their relatively coarse mesh design may sometimes prove less effective in adequately capturing MFs characterized by shorter lengths.

ii. PlanetCare Filter

Unlike *LUV-R* filters, *PlanetCare* out-drum filters do not contain any metal parts, and their outer filter meshes have a pore size of 200 μm (Napper et al., 2020). They contain foam-like strings embedded inside the filters. This design allows the filter to capture larger/longer MFs and enhance the removal of smaller/shorter MFs as well. According to the manufacturer, PlanetCare (n.d.), these filters have a 90% efficiency in removing MFs from washing machine wastewaters. Martinko (October 13, 2020) reported that *PlanetCare* filters achieved approximately 60-80% MF removal from washing machine wastewaters, although these results have not yet been published in a scientific journal at this time. However, according to the results obtained by Napper et al. (2020), the efficiency of *PlanetCare* filters in capturing MFs released from polyester and acrylic garments was only 29 ± 2%. As a drawback, similar to *LUV-R* lint filters, the accumulation of a considerable amount of wastewater inside the casing increases the risk of biological growth that may lead to biofouling of the filters. On the other hand, unlike the *LUV-R* lint filter, the *PlanetCare* filter has no transparent casing, thwarting the growth of microalgae but in turn preventing the possibility to observe the containing wastewater and the status of the filter. In line with their environmental protection objectives, *PlanetCare* currently collects used filters from customers and provides them with new filters, which is a cautious move that may reduce the unconscious and inappropriate disposal of filters by the users. The company has also announced that the recovered MFs from the filters will be utilized in manufacturing insulation panels for washing machines or in-car upholstery (Brodin et al., 2018). Unfortunately, there is no sufficient data in the literature regarding the performance of *PlanetCare* filters measured under different conditions and for different apparels.

iii. Filtrol160^{TM}

Filtrol 160^{TM} lint filter is another type of inline filtration system that does not contain any metal parts. It consists of a transparent casing and a reusable bag/lint flexible filter, which is similar to wine filtering bags with rubber sealings. According to the manufacturer, Filtrol (n.d.), the lint filter, with pore sizes of about 100 µm, can be washed and reused after 10-15 cycles of washing. In a simple experiment reported in an internet blog (Olivia, 2020), it was found that *Filtrol 160*^{TM} achieved approximately 89% MF removal based on weight measurements . On the other hand, The Swedish Environmental Protection Agency reported in 2018 that *Filtrol 160*^{TM} was capable of reducing the release of MFs in the washing effluent by about 30-60% (Brodin et al., 2018). *Filtrol 160*^{TM} has a simple structure that makes it easy to install, maintain, and clean. Similar to washing bags, *Filtrol 160*^{TM} includes a flexible bag-like filter that simplifies the removal of the captured MFs aggregate, especially when they contain moisture. However, proper handling of the collected microfibers is imperative, as these should not be washed in a sink or any other way that would represent a new source of contamination. In addition, similar to other mentioned filtrations systems, the performance of *Filtrol 160*^{TM} has not been systematically evaluated.

iv. XFiltra

Xeros Technology Group (n.d.) developed a filtration system named *XFiltra*, designed to capture microplastics and MFs from washing machine wastewater, which, unlike the other alternatives, is installed inside the machine's cabinet. *XFiltra* is an inline filtration system comprising a pump, a dewatering device, and an outer filter with a mesh pore size of 60 µm. The company claims that the device can remove more than 90% of the microplastics released during washing. Additionally, the fibers trapped inside the filter are spun dry, facilitating the cleaning process, although the system has a more complex structure compared to other alternatives (Brodin et al., 2018). Napper et al. (2020) tested and evaluated the efficiency of *Filtra* for different garments using a front-loaded washing machine. They concluded that *XFiltra* showed the best performance among all the alternatives tested (*Cora ball*, *Guppyfriend* washing bag, *Fourth Element* washing bag, *PlanetCare*), achieving a removal efficiency of 78 ± 5%. This performance was attributed to the finer meshes, as also mentioned by Ramasamy & Subramanian (2021). However, due to their pore size and the presence of only one filter in the system, the device is susceptible to pore clogging, thus reducing its performance after repeated washing cycles. Additionally, the inclusion of a spun dryer in the system requires extra maintenance compared to alternative filters. Regarding the cleaning process, the manufacturer states that it is a simple procedure that requires minimal manual handling and the collected MFs can be removed in dry state, even allowing for disposal as recycled plastic waste when in line with the local policies. Currently, Xeros does not provide the filters separately and *XFiltra* is being sold pre-installed on washing machines produced by the manufacturer. Xeros has also introduced *XFiltra 2*, a larger and more sophisticated filtration system for industrial laundry facilities. Unfortunately, no data are available about its structure or performance.

v. AEG Microplastic Filter

The *AEG* microplastic filter includes a plastic straining mesh and a casing, similar to other out-drum filtration devices. According to the manufacturer, AEG (n.d.), it is capable of capturing over 90% of MFs larger than 45 μm that are released during the washing process. The collected MFs need to be manually removed whenever an indicator signals that cleaning is required. *AEG* also claims that more than half of the accessories used in the *AEG* microplastic filter are made from recycled plastics. AEG microplastic filter has an appealing design, is easy to dismount and generally user-friendly. The casing is not transparent and is larger than that of other filters mentioned above, being able to hold about ~2.4 L of wastewater. As of now, there is no published research or case study available in the literature that examines the performance of *AEG* filters.

vi. Gulp Microplastic Filter

Gulp microplastic filters include a transparent casing, a holder, and a metal filter. Currently in the fundraising stage, this product has not yet been released to the market. According to the developers (Gulp, n.d), *Gulp* filters offer ease of use and maintenance, eliminating the need for wall or panel mounting. Additionally, they claim that the filter efficiently captures virtually all microplastics and MFs released during washing, accumulating them in a near-dry pile of collected fibers. According to the *Gulp* developers, manual cleaning of the filter is needed approximately every 10-15 washes, as indicated by a LED light on the device. Interestingly, the developers accept the collected MFs from customers and recycle them for future use. However, it is worth noting that no published reports indicating the filter performance are available in the literature.

Advantages, Disadvantages, and Challenges

Table 2 provides a summary of the properties of current commercial point-of-use MF removal systems, based on the available literature and manufacturers' specifications. Compared to out-drum devices, *Cora ball* and laundry bags are easier to use, as they do not require installation and take up no space inside or outside the washing machine. In terms of microfiber capture, neither in-drum nor out-drum systems alone seem to be incapable of capturing more than roughly 91% of released microfibers. In-drum devices seem to provide poorer results compared to out-drum devices. While certain washing bags have proven effective in limiting MF shedding by minimizing mechanical abrasion on garments, they may also diminish the washing efficiency and encourage the re-deposition of released microfibers onto the clothing.

Except for the *Cora ball* device, all the other available filtration systems contain mesh-based filtration materials with different pore sizes. This highlights the potential for efficiency enhancement through the creation of innovative, optimized filters. However, the use of finer meshes cannot be considered the only viable solution to improve filter efficiency, due to mechanical and technical limitations. Specifically, the use of smaller pore sizes increases the risk of filter fouling and clogging, which can lead to a higher-pressure gradient across the filters and low water flow. Over the long term, heightened pressure losses may pose a risk of failure for the washing machine's drain pump and electrical components. Nearly all the filters currently available on the market use meshes with sizes larger than 50 µm, likely due to the use of relatively weak drain pumps in the washing machine Replacement with stronger, more expensive pumps in the case of denser filters may be needed. However, studies found that the majority of released MFs have sizes smaller than 50 µm, mostly ranging from 10 to 15 µm. This implies that the efficacy of the filters relies substantially on secondary filtration mechanism, e.g., cake filtration, provided by previously deposited fibers. Ultimately, a trade-off exists between the water flux reduction and the filtration efficiency enhancement due to cake formation. In this direction, the introduction of self-cleaning systems, such as the *XFiltra*, is anticipated to be the next area of focus for filtration system developers.

Several challenges should still be tackled to effectively mitigate the release of microfibers into the environment. A chief example is the cleaning and disposal of clogged filters and the management of collected MFs. There is risk of improper disposal of used filters and collected microfibers, as users may be tempted to wash the filters and discharge waste into sewage, thus completely defeating the removal device's purpose. Furthermore, inadequate cleaning procedures may lead to potential airborne microfiber release, an often-overlooked issue. In conclusion, manufacturers and consumers would prefer a filtration system that does not add extra space requirements when installed outside washing machines and requires less frequent or more manageable cleanings.

6. Future Perspectives and Final Remarks

The textile industry plays a crucial role in addressing plastic microfibers source control. Indeed, some authors indicate that manufacturers and retailers must take most of the responsibility for fiber shedding and reduction thereof. Encouraging industry to limit the production of synthetic plastic-based fabrics and promote the use of biodegradable materials and environmentally friendly manufacturing processes is a first and important step in this direction (Anjana et al., 2020; Choi et al., 2021). Possibly the first and foremost action to limit MF release during laundering consists of mitigation strategies at the production stage, as indicated and proposed by several authors (De Falco et al., 2019a; De Falco et al., 2018a; Kang et al., 2021; Qian et al., 2023; Ramasamy & Subramanian, 2023; Rathinamoorthy & Raja Balasaraswathi, 2023a; Rathinamoorthy & Raja Balasaraswathi, 2023c). Note that these topics are not in the scope of this review. Furthermore, manufacturers should be encouraged to utilize recycled/recyclable materials and facilitate garment recovery strategies. Despite ongoing efforts, the textile industry remains predominantly linear, with significant room for enhancement in moving towards a circular model.

Thus, important emphasis should also be put on mitigating the release of microfibers during laundering activities, since household washing machines are a major source of MF release into sewage networks and subsequently into the environment. Several researchers have provided recommendations for modifying laundering conditions, such as lowering washing temperature, detergent consumption, and mechanical abrasion. However, simply changing washing conditions may not completely address the issue of MF release. Acknowledging this constraint, manufacturers of filtration systems have opted for a practical approach by developing point-of-use devices, chiefly filters, to directly capture a sizable portion of MFs released during washing. Nevertheless, the performance of these systems remains insufficient to achieve reliably high MF removal from wash water effluents. This limitation may also be attributed to fouling and pore clogging occurrences, which demand either the selection of filters with larger pore sizes or the application of more frequent cleaning and replacement of the filter systems. In fact, while enhancing MF removal efficiency, the use of filters with excessively small mesh/pore sizes would exacerbate fouling and pore blockage, thus compelling the utilization of drain pumps capable of generating higher water heads to ensure uninterrupted drainage and to prevent damage to the washing machines.

In this framework, new filtration systems are being designed and proposed, not only by the industry but also by academic researchers (Belzagui et al., 2023). To maximize efficiency and sustainability, filter design is expected to shift towards self-cleaning devices or systems that incorporate dewatering or drying processes. Manufacturers have employed strategies to minimize filter fouling and find a balance between removal efficiency and water fluxes. The primary objective of this approach is therefore to extend the filter's operational duration between cleanings, increasing it from the current 10-15 cycles to, ideally, 50 cycles or more. However, no matter how excellent the filters performance, fouling is inevitable and cleaning procedure will be necessary. Therefore, an ideal scenario would involve a cleaning procedure that is performed by the filtration system itself, relieving the consumer of this task. Moreover, since self-cleaning systems would need less frequent maintaining services, they may be embedded inside the washing machine volume, avoiding occupation of external space. Alternatively, it is essential that the cleaning process or filter replacement is straightforward, accompanied by clear instructions for customers to guarantee the safe removal of microfibers once they have been captured during washing. Without appropriate guidance on the proper disposal of filters or collected microfibers, there is a risk of them ending up in sewage networks or the environment. Additionally, other separation or transformation processes, such as electrochemistry, dielectrophoresis, biodegradation or chemical oxidation, may be combined with standard filtration systems to enhance separation efficiency without compromising filtrate fluxes and minimizing pressure drops. This approach would lead to the development of more sophisticated systems with higher removal efficiencies; it is important to note that these advancements may increase the final product costs as well as maintenance-related burdens and expenses.

Recently, authors have rightly pointed out that the textile industry and that MFs reduction methods should be tailored based on different stakeholders (Stanton et al., 2023). MF release from laundry machines is highly relevant for the Global North and current textile design is vastly based on the assumption that an infrastructure for MF interception is available, which is however not found everywhere in the world. Such an approach is only relevant for about 50% of the global population. In the Global South community, people often launder without a machine, which presents a significant challenge to quantifying, controlling, and intercepting shed MFs. In this respect, the responsibility of the textile industry seems even higher, as garment construction and design may be the primary way to reduce MF release for a large portion of the global population (Stanton et al., 2023). In conclusion, addressing the release of microplastics and MFs requires a comprehensive approach that encompasses source control, laundering design, and the treatment of wastewater containing these pollutants. However, mitigating MF emissions is a global-scale problem that can be only partly solved through the technical means reviewed in this work. Like global warming and CO_2 emissions, addressing this issue requires the initiation of a worldwide campaign, the establishment of appropriate regulations, and their enforcement by local governments and agencies. While users should not carry the main burden of microfiber release reduction, raising global awareness remains a key step, for example encouraging individuals to choose environmentally friendly clothing and laundering options, thus potentially placing some pressure on manufacturers and retailers of textiles, garments, and washing machines. Achieving the required level of awareness and responsibility requires collaborative efforts from the textile industry, environmental groups, institutions, and all other stakeholders.

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Figures and Tables

(in the order they are mentioned in the text)

Table 1. Analytical approaches for MF characterization.

Method	***Qualitative information***	***Quantitative information***	***Destructive approach***	***Main advantages***	***Limitations***
[1]*SEM*	morphology, structure of the fabrics, length, diameter, ageing	semi-quantitative number of fibers	might be	• high-resolution images • reveal fine surface and morphological characteristics • provides a larger depth of field compared to optical microscopy	• requires samples to be conductive or coated with a conductive layer • can be time-consuming • provides 2D images of the sample surface • cannot provide information about the fibers internal structure • the electron beam can damage samples, particularly sensitive biological materials
[2]*EDS*	elemental composition	-	yes	• provides information about the elemental composition of MFs • can quantitatively determine the concentration of elements • suitable for characterizing a wide range of elements • provide high spatial resolution when coupled with SEM or [3]TEM • allows to pinpoint the location of specific elements	• it is primarily a surface technique and may not provide information about the composition of elements within the MFs core • sensitivity to sample thickness • limitations in detecting elements with very low atomic numbers (*e.g.*, hydrogen and helium) • is primarily used for qualitative and semi-quantitative analysis rather than quantitative analyses
Fluorescence microscopy	material identification	-	no	• highly sensitive: can detect small traces of fluorescently labeled molecules or structures • can be used for live cell imaging, making it suitable for studying dynamic processes and interactions in microfibers and biological samples • Multiple fluorophores with distinct emission spectra can be used simultaneously	• photobleaching after continuous exposure to light • has a limited resolution by the diffraction limit, which is around 200 nanometers • samples need to be appropriately labeled with fluorophores before testing • has limitation in depth penetration • limited elemental information
[4]*FT-IR*	polymer identification	-	no	• highly effective for identifying the chemical composition of MFs • can be used for both qualitative and quantitative analysis • sensitive to small quantities of material • rapid data acquisition • can be applied to a wide range of MFs materials	• sensitive to water and solvents, which can affect the measurements • primarily analyzes the surface of the MFs • for solid samples, they must be ground into a fine powder and typically pressed into a pellet or mixed with a matrix • does not offer data on elemental composition, making it less suitable for identifying trace elements • limited to infrared region
Raman spectroscopy	polymer identification	-	no	• highly effective for identifying the chemical composition of MFs • sensitive to small quantities of material, allowing for the detection of trace components • provide excellent spatial resolution, enabling microspectroscopy • can be applied to a wide range of MFs materials	• fluorescence from the sample can interfere with Raman signals • sample heating or damage can occur under high-energy laser used in Raman spectroscopy • limited depth profiling • water can strongly absorb and scatter the Raman signals, making it challenging to analyze samples in aqueous environments • lack of elemental information

[1] Scanning electron microscopy
[2] Energy dispersive X-ray spectroscopy
[3] Transmission electron microscopy
[4] Fourier Transform Infrared spectroscopy

[5]*MS/GC*	chemical composition, polymer identification	semi-quantitative mass concentration	yes	• highly sensitive: can detect and quantify trace levels of compounds • allows for the identification of specific compounds when MS is combined with GC • enables quantitative analysis • an effective separation technique for compounds in complex mixtures • offering information about the mass-to-charge ratio of ions • providing high specificity in compound identification • Multicomponent Analysis	• sample preparation for GC-MS can be labor-intensive and may require solvents or derivatization for certain compounds • GC is most effective for volatile compounds than non- volatile • incompatibility with certain materials • interpreting GC-MS results can be complex, as it involves identifying peaks in chromatograms • lack of elemental information
[6]*TED-MS/GC*	chemical composition, polymer identification	semi-quantitative mass concentration	yes	• highly sensitive: can detect and quantify trace levels of compounds • allows for the identification of specific compounds • selective analysis for the compounds of interest • multicomponent analysis	• sample preparation for TED-GC/MS can be labor-intensive and may require specific procedures to extract and prepare the compounds of interest • It is most effective for volatile compounds than non- volatile • sensitivity to thermal decomposition • interpreting GC-MS results can be complex, as it involves identifying peaks in chromatograms • lack of elemental information
[7]TOC analysis	-	total mass concentration	yes	• provides a quantitative measurement of the total organic carbon content • rapid analysis • can be applied to a wide range of MFs materials • modern TOC analyzers can achieve low detection limits • can be easily calibrated and standardized	• it does not provide specific information about the nature of the organic compounds • inorganic carbon, such as carbonate and bicarbonate, can interfere with TOC measurements • sample preparation may be required, especially for solid samples • it may overestimate the organic carbon content when inorganic carbon is present • lack of structural information • limited sensitivity to low molecular weight compounds • high-quality TOC analyzers can be expensive • incompatibility with some materials
Statistical Analyses	-	number of fibers	no	• provides quantitative insights into various aspects of microfibers, such as size, shape, composition, and distribution • allow drawing inferences about populations based on samples, which is particularly useful when characterizing MFs that are challenging to examine entirely • can reveal patterns and relationships within large datasets of MFs characteristics	• the quality of the statistical analysis is highly dependent on the quality of the data. • inaccurate or incomplete data can lead to erroneous conclusions • the reliability of the data relates to the considered assumptions such as normal distribution or homoscedasticity, and violating these assumptions can lead to inaccurate results • establishing relationships often requires additional experimental design • small sample sizes may limit the statistical power, making it challenging to detect significant differences or relationships between microfiber properties

[5] Gas chromatography
[6] Thermal extraction desorption-gas chromatography/mass spectrometry
[7] Total organic carbon

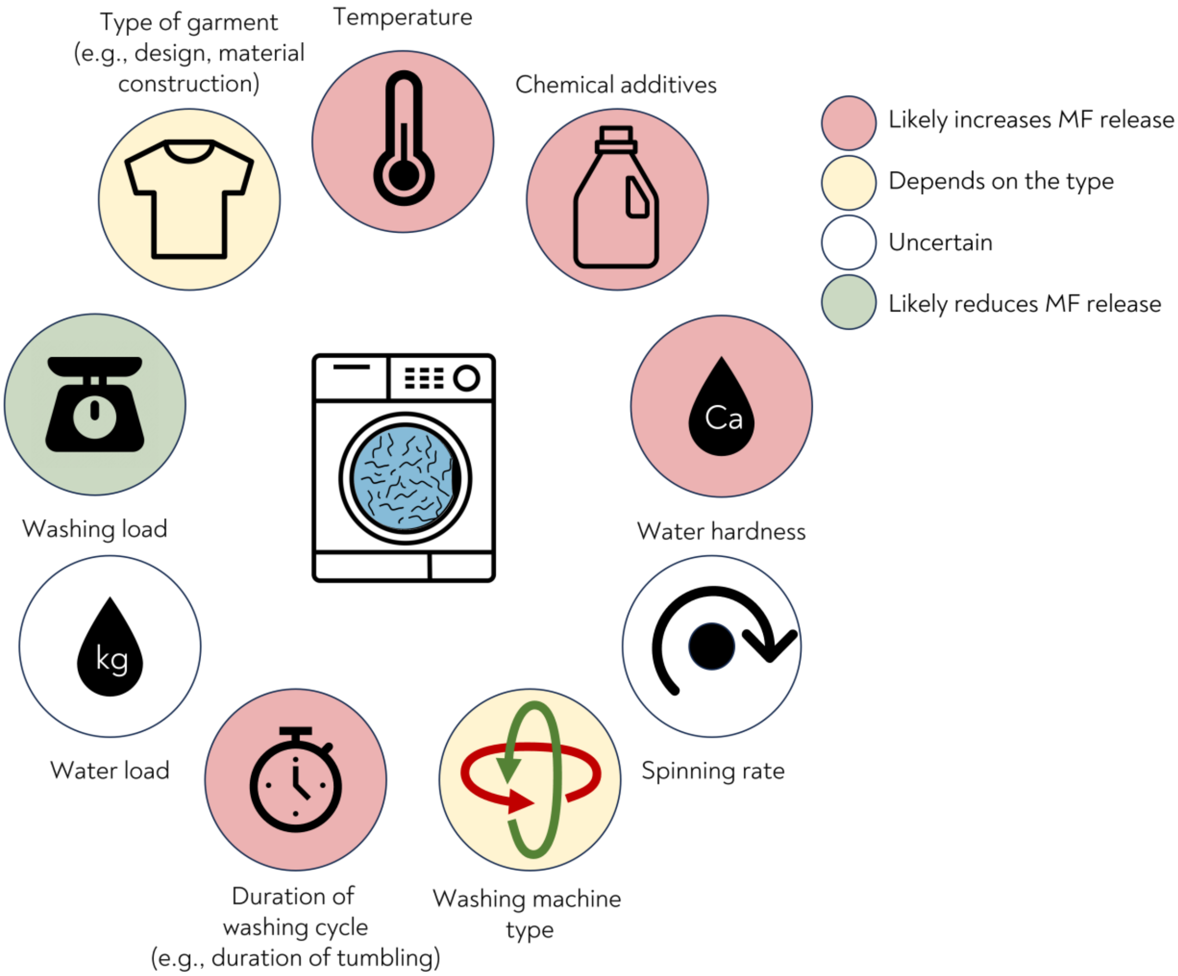

Figure 1. Main parameters affecting the release of microfibers during household laundering of textiles based on current literature, and their effect on the emitted quantity. The washing parameters are qualitatively classified in four categories of relevance.

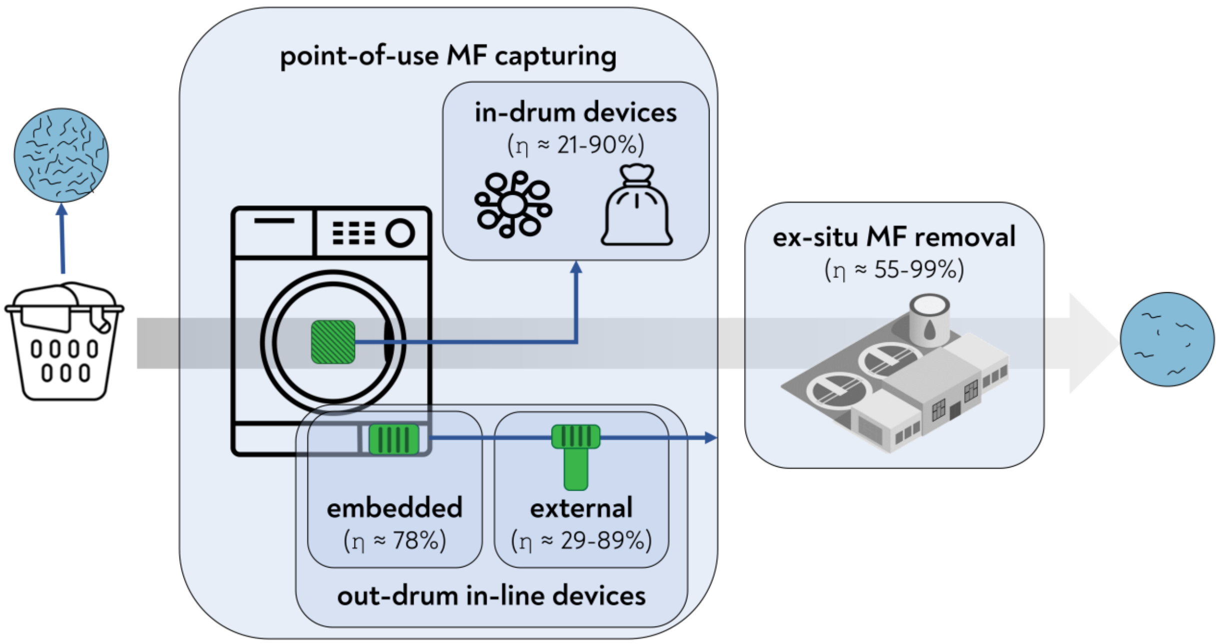

Figure 2. Different approaches for capturing of microfibers released during the laundering of textiles with household washing machine. Each approach is associated with a value or a range of values of microfiber retention efficiency (η) based on current literature.

Table 2. Comparison of available point-of-use devices aimed at capturing plastic microfibers.

MFs capturing device	Type of device	MFs mass removal efficiency (%)	Garments used	Price (Euro)	Technical characterizations	Advantages	Drawbacks	Reference (other than the manufacturer)
Cora ball	in-drum	~25-31	polyester fleece blanket polyester acrylic 60% polyester / 40% cotton blend	62 (USD)	• Flow configuration: - • Material: Plastics • Filtration surface area (cm^2): N/A	• Simple structure • Easy to use • Reusable for numerous times	• Low efficiency • Hard to clean • Increasing mechanical abrasion • Non-biodegradable plastic structure	(McIlwraith et al., 2019; Napper et al., 2020)
Washing bag	in-drum	~21 (Forth element) ~54 – 91 (Guppyfriend)	Polyester Acrylic 60% polyester / 40% cotton blend	30	• Material: Polyamide (100%) • Layers: Single-layer • Pose size (μm): 50 Filtration surface area (cm^2): 7400	• Simple concept • Easy to use • Inexpensive • Reducing mechanical abrasion	• Low efficiency • Possibility of MFs release from the bags • Non-biodegradable plastic structure	(Napper et al., 2020; O'Loughlin, 2018)
LUV-R lint	out-drum	~29 – 87	Polyester Acrylic 60% polyester / 40% cotton blend	190 (USD)	• Flow configuration: Outside-in • Filter material: Stainless steel • Filter layers: Double-layer • Casing volume (mL): ~1300 • Filter pore size (μm): 150-180 • Filtration surface area (cm^2): 526.2	• Easy to use and install • Non-plastic meshes • Washable and reusable filters	• Low efficiency • High price • Requires repetitive maintenance • Not applicable in capturing small-length MFs • Outside-machine installation	(McIlwraith et al., 2019; Napper et al., 2020)
PlanetCare	out-drum	~29 – 80	Polyester Acrylic 60% polyester / 40% cotton blend	54	• Flow configuration: Inside-out • Filter material: Plastic (supported mesh and foam) • Filter layers: Single-layer mesh (with foams strips embedded inside) • Casing volume (mL): ~1200 • Filter pore size (μm): ~200 • Filtration surface area (cm^2): 516.8	• Easy to use and install • 2-step filtration • Returnable filters to company	• Moderate efficiency • Outside-machine installation • Non-biodegradable plastic structure	(Martinko, October 13, 2020; Napper et al., 2020)
Filtrol 160	out-drum	~89	*N/A	160	• Flow configuration: Inside-out • Filter material: Plastics (Flexible bags) • Filter layers: Single-layer (fine mesh) • Casing volume (mL): N/A • Filter pore size (μm): 100 • Filtration surface area (cm^2): N/A	• Easy to use and install • Simple structure • Flexible and reusable filters • Higher operational cycles • Easy maintenance and cleaning	• High price • Outside-machine installation • Non-biodegradable plastic structure • Outside-machine installation	(Olivia, 2020)
XFiltra	out-drum (embedded)	~78	Polyester Acrylic	N/A	• Flow configuration: multi-stage processes (cyclone, filtration and drying)	• Inside-machine installation • High Performance	• Not available separately in the market	(Napper et al., 2020)

			60% polyester / 40% cotton blend		• Filter material: N/A • Filter layers: Single-layer (fine mesh) • Casing volume (mL): N/A • Filter pore size (μm): 60 Filtration surface area (cm^2): N/A	• Higher operational cycles • MFs drying • Easy cleaning	• Non-biodegradable plastic structure • Complicated structure • Difficult maintenance
AEG Filter	out-drum	N/A	N/A	82	• Flow configuration: Inside-out • Filter material: Plastic • Filter layers: Single-layer (Fine mesh) • Casing volume (mL): ~2600 • Filter pore size (μm): 50 Filtration surface area (cm^2): 471.2	• Easy to use and install • Easy cleaning • Reusable and washable filters • Cleaning indicator	• High price • Outside-machine installation • Non-biodegradable plastic structure • Large wastewater accumulation
Gulp Filter	out-drum	N/A	N/A	N/A	• Flow configuration: Inside-out • Filter material: Metal • Filter layers: Single-layer (Fine mesh) • Casing volume (mL): N/A • Filter pore size (μm): N/A Filtration surface area (cm^2): N/A	• Easy to use and install • Easy cleaning • MFs drying • Reusable filter • LED cleaning indicator	• Outside-machine installation • Non-biodegradable plastic structure • Large size

*N/A: Not available

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