

Plastic microfibers from household textile laundering: a critical review of their release and impact reduction

*Original*

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(Article begins on next page)

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

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17        **Abstract**

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

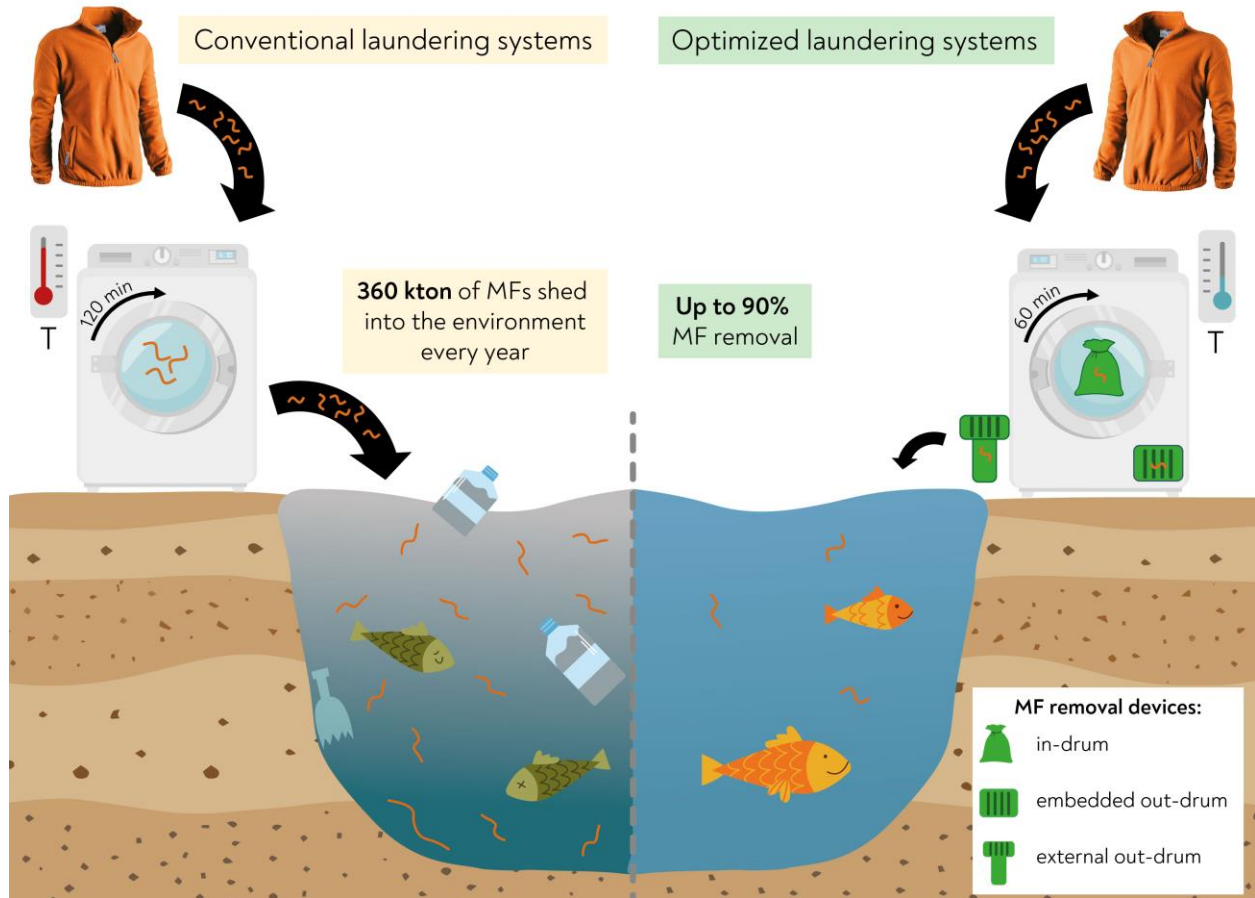
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35        **Keywords:** Microfibers; Point-of-use filters; Wastewater treatment; Textiles; Washing machines.

36

37 **Graphical Abstract**



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68 **1. Introduction**

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

76 Overall, microplastics that end up in the environment can be found in numerous shapes, such  
77 as fibers, foam, pellets, films, and fragments, with fibers being reported as the most dominant form  
78 (Akyildiz et al., 2022; Gaylarde et al., 2021; Miller et al., 2017). Specifically, microfibers (MFs)  
79 are characterized by their thread-like structure, with diameters typically smaller than 10  $\mu\text{m}$  and  
80 lengths up to 5 mm (typically 10s to 100s of  $\mu\text{m}$ ) (Akyildiz et al., 2022; Dreillard et al., 2022;  
81 Weinstein et al., 2016). When it comes to composition, MFs may be made of various polymeric  
82 materials, such as polyesters (Napper & Thompson, 2016; Zambrano et al., 2019), polyethylene  
83 (Weinstein et al., 2016), polyamide (Gavigan et al., 2020), acrylic (Belzagui & Gutiérrez-Bouzán,  
84 2022), polypropylene (De Falco et al., 2018b), elastane (Rathinamoorthy et al., 2023; Sillanpää &  
85 Sainio, 2017), rayon (Zambrano et al., 2019). Synthetic MFs have not only polluted marine and  
86 aquatic environments, but they have also been detected in soils and in the atmosphere (Blettler et  
87 al., 2017; Kapp & Miller, 2020; Sundt et al., 2014). These MFs typically enter the marine and  
88 aquatic environment through direct sources or via wastewater treatment plant (WWTP) effluents.  
89 WWTPs equipped with primary and secondary treatment processes are able to typically achieve  
90 MF and microplastic mass removal up to 90-95% at best, resulting in the estimated number-wise

91 release of around 85 million fibers per day into the aquatic environment, along with another 3.68  
92 billion accumulated in the separated sludge (Blair et al., 2019; Madhav et al., 2018; Petroody et  
93 al., 2020).

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

109 This paper presents a review of current strategies to reduce emission of plastic MFs during  
110 household textile laundering, as well as potential solutions for the future. First, the origin and fate  
111 of microfibers, as well as analytical methodologies for their characterization, are briefly discussed.  
112 Then, techniques to reduce and to remove these pollutants directly acting on the laundering cycles  
113 and/or on laundering wastewater are presented, *i.e.*, deploying point-of-use strategies. Updated

114 knowledge on microfibers release as a function of laundering conditions is provided to help  
115 scientist and engineers design washing cycles that would minimize release while guaranteeing  
116 suitable washing of the garments. Then, information around the functioning and performance of  
117 the latest point-of-use microfiber capturing systems is discussed, and these devices are evaluated  
118 against an ideal capturing system. A series of advantages, limitations, and opportunities are  
119 described for the various systems, with the goal to guide the design and development of new, better,  
120 and cheaper devices.

## 121 **2. Brief Overview of Production, Origin, and Fate of Textile Microplastics and** 122 **Plastic Microfibers**

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

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

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

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

### 157 **3. Brief Overview of Sampling, Detection, and Analytical Techniques**

158 This section provides a concise overview of the current best practices in terms of sampling,  
159 detection, and techniques for the analyses of plastic MFs, based on previous studies and on the

160 authors' experience. Readers may refer to Text S2 of the Supporting Information for a more  
161 detailed review of this topic.

## 162 **Wastewater Sampling Procedures and Considerations**

163 Microplastics and plastic MFs can either settle or float, making it imperative to minimize the  
164 presence of clumped fibers before characterizing them, as emphasized by Belzagui et al. (2019).  
165 Depending on the type of analysis to be performed, pre-filtration of the collected samples may be  
166 necessary and the volume of the water sample should typically be 50 mL or more, depending on  
167 the source and on the filtration system configuration (Mishra et al., 2019; Singh et al., 2020; Sun  
168 et al., 2019). A study conducted by Hong et al. suggested that the use of filters with pore sizes <5  
169  $\mu\text{m}$  may be sufficient to capture all MFs in wastewater samples (Hong et al., 2021). The fibers  
170 collected on the filter paper should be air- or vacuum-dried. Subsequently, oxidation is a useful  
171 means to eliminate organic matter and other contaminants (Aghdasinia et al., 2017; Hong et al.,  
172 2021; Masura et al., 2015).

## 173 **Detection and Analytical Approaches**

174 Table 1 summarizes the most employed analytical approaches for MF characterization and  
175 highlights the main advantages and limitations associated with each method. Scanning electron  
176 microscopy (SEM) is the most employed microscopy technique utilized to identify MFs and  
177 microplastics. However, other microscopy analyses, such as fluorescent microscopy, stereo  
178 microscopy, optical microscopy, bright-field microscopy, phase contrast microscopy, and X-ray  
179 analysis are also utilized for this purpose (Hamzah et al., 2021; Mishra et al., 2022; Padervand et  
180 al., 2020; Tripathy et al., 2022; Yin et al., 2019). SEM is widely used because it allows gaining  
181 information on the morphological structure of the fabrics, length and diameter, ageing and,  
182 indirectly, their origin (Mishra et al., 2022). Moreover, SEM systems equipped with energy

183 dispersive X-ray spectroscopy (EDS) can inform on the elemental composition of the polymeric  
184 and composite materials (Ding et al., 2019). Another commonly used method for the detection of  
185 microplastics and MFs is fluorescence microscopy, which allows for the characterization of all  
186 fluorescence-emitting materials, including non-plastic materials (Anjana et al., 2020; Payton et al.,  
187 2020). Nevertheless, microscopic approaches may not provide adequate information on chemical  
188 composition.

189 Chemical characterization of MFs can be performed utilizing spectroscopic analyses. FT-IR  
190 has become one of the most employed techniques for polymers identification, especially aimed at  
191 the identification of synthetic MFs released during garment laundering (Hale et al., 2020). One  
192 drawback of this technique is that it is normally unable to characterize materials with dimensions  
193 below 10  $\mu\text{m}$ , due to diffraction phenomena (Dümichen et al., 2017). Raman spectroscopy has  
194 been increasingly used to overcome such limitations since it can be used for the characterization  
195 of particles smaller than 1  $\mu\text{m}$ , the results not being affected by diffraction effects (Hale et al.,  
196 2020). In these analyses, reference spectra libraries are needed for the proper identification and for  
197 differentiation of different materials, which may prove challenging as individual spectra overlap  
198 in mixed samples (Dey et al., 2021).

199 Thermo-analytical analyses are destructive methods, yet valid option for chemical  
200 characterization of microplastics and synthetic MFs. In particular, mass spectrometry associated  
201 with gas chromatography (GC-MS) allows the chemical characterization and the subsequent  
202 identification of the polymers exploiting thermal properties of different compounds. Similar to  
203 spectroscopy, MS-GC requires reference pyrogram libraries as reference in the course of the  
204 analysis (Dey et al., 2021). An alternative method is thermal extraction desorption-gas  
205 chromatography/mass spectrometry (TED-MS/GC), which offers the advantage of trapping

206 degradation products of the original polymers on the solid phase. Consequently, subsequent  
207 analysis can be performed directly on the solid phase, by thermal desorption GC-MS, thus  
208 eliminating the need for pyrolysis (Dümichen et al., 2017). In general, methods based on GC  
209 require extensive pretreatment, and the samples should be isolated and concentrated before  
210 conducting the analysis.

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

## 218 **Summary and Unresolved Issues in Detection and Characterization**

219 The vast majority of the techniques utilized for microfibers detection are offline, thus requiring  
220 the collection of samples, for example during or after washing cycles, and subsequent analysis.  
221 Weighing microfibers retained by proper filters is currently the most adopted offline strategy to  
222 obtain a quick quantification of the fiber concentration in water. However, this technique is prone  
223 to experimental errors and cannot obviously provide information on the nature of the fibers.  
224 Moreover, as indicated by Rathinamoorthy & Raja Balasaraswathi (2023b), while weight-based  
225 methods are simple and quick ways to quantify microfibers, the inclusion of surfactants and other  
226 contaminants from the fabric or from the water can add additional weight and skew the  
227 measurements. Many of the other, current techniques, *e.g.*, SEM, FTIR, GC-MS, rely on  
228 cumbersome sample preparation procedures and require the availability of expensive equipment,

229 also involving skilled personnel. More streamlined, yet robust, offline techniques would contribute  
230 to simplifying, widening, and standardizing investigations. Furthermore, the availability of a  
231 technique allowing online or in-situ quantification of the microfibers suspended in the wash water  
232 during the washing cycle would represent a critical simplification of both investigations and  
233 emission control strategies. While in principle some characteristics of the wash water could be  
234 exploited to quantify microfibers, such as turbidity or light absorbance, these methods are typically  
235 affected by other constituents of the effluent and are impacted by several confounding factors. In  
236 conclusion, major efforts are needed to provide robust, yet simple, analytical techniques for  
237 quantification and characterization of microfibers, with the ideal goal of developing a methodology  
238 that works effectively online and/or that can be standardized and adopted widely by all  
239 stakeholders.

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

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

##### 246 **Effects of Garment Material and Characteristics**

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

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

### 258 **Effects of Washing Temperature**

259 Multiple studies have shown that the higher the washing temperature, the more pronounced  
260 the MF release (Galvão et al., 2020; Le et al., 2022; O’Loughlin, 2018; Rathinamoorthy & Raja  
261 Balasaraswathi, 2021). Higher temperatures promote the expansion of yarns, reduce the strength  
262 between the bonds of the filaments, both mechanisms possibly resulting in an increase of MF  
263 release (Le et al., 2022). For instance, Yang et al, indicated that the release of MFs from a garment  
264 made of polyester was considerably higher at 60 °C compared to a washing cycle performed at 30  
265 °C (at full load washing condition) (Yang et al., 2019). Other than yarn expansion, De Falco et al.  
266 (2018b) pointed at the increase in surface hydrolysis of the synthetic textile as an explanation for  
267 release at higher temperatures.

### 268 **Effects of Washing Machines Type**

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

## 275 **Effects of Washing Cycle**

276 MFs shedding is reportedly influenced by the mechanical stress and the duration of agitation  
277 applied during washing (Rathinamoorthy & Raja Balasaraswathi, 2021). As a general trend, the  
278 intensity of the MF shedding was observed to decline significantly after the first couple of washes,  
279 particularly after the first wash (Napper & Thompson, 2016). For example, a study by Cai et al.  
280 (2020) indicated that MF release was stabilized after the fifth wash, with levels potentially being  
281 6 to 120 times higher in the first wash compared to the tenth wash. There are studies implying that  
282 the duration of the washing cycle does not have a significant impact on MF release (Kelly et al.,  
283 2019). These studies indicated that the amount of MFs found in samples collected after 15 min and  
284 60 min washing cycles was nearly the same, leading to the reasonable conclusion that the main  
285 release of MFs occurred within the first 15 min of washing cycle. However, the outcome varies  
286 based on diverse textiles and washing cycle patterns. Based on the authors' observation, the longer  
287 the tumbling portion of the cycle, the more mechanical abrasion occurs, leading to a higher  
288 likelihood of MF shedding, while the effect of spinning rate remains uncertain.

## 289 **Effects of Water Chemistry and Chemical Additives**

290 To the best of our knowledge, there are no detailed research studies conducted to fully  
291 understand the influence of initial water chemistry. De Falco et al. (2018b) assessed the effect of  
292 water hardness, detergents, laundering duration, and temperature, revealing that the use of hard  
293 water increased MF shedding compared to distilled water. On the other hand, chemical additives  
294 (*i.e.*, detergents and softeners) are outlined as critical parameters intensifying the MF shedding  
295 during the washing of the garments. It is believed that the application of both solids and liquids  
296 detergents usually results in a more substantial MF release compared with cases whereby no  
297 detergents are present (Le et al., 2022; Zambrano et al., 2019). Typically, commercial detergents

298 and softeners elevating water pH may induce chemical damage and textile degradation as a result  
299 of hydrolysis (Bishop, 1995; Rathinamoorthy & Raja Balasaraswathi, 2021). In another research  
300 study, a significant increase in MF shedding was observed when non-bio detergent was employed  
301 compared to cases involving bio or no detergent (Napper & Thompson, 2016). However, there are  
302 also research reports implying the positive role of surfactants against MF release (Bishop, 1995;  
303 Hernandez et al., 2017). Solid detergents seem to contribute to MF release compared to liquid  
304 counterparts due to increased friction and cloth abrasion, but this phenomenon is currently subject  
305 of conflicting study outcomes (Issac & Kandasubramanian, 2021). While some studies suggest  
306 that washing products do not have a significant influence, one research study reported that their  
307 use may reduce MF release (Acharya et al., 2021; Li et al., 2023; Madhav et al., 2018). In summary,  
308 no strong consensus has been reached on the impact or effect of detergents or softeners on MF  
309 release, although the majority of studies indicate a likely increase in emission in the presence of  
310 chemicals.

### 311 **Effects of Drying Conditions**

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

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

### 326 **Other Influential Parameters**

327 There are other influential parameters on plastic MFs release, such as the garment loading into  
328 the washing machine, the quantity of washing water, yarn type, the specific mass of the garment  
329 (mass per unit area), the garment design, sewing, thickness, and compactness. A higher loading  
330 leads to reduced friction and, consequently, lower MFs release per unit of load (Hazlehurst et al.,  
331 2023). Moreover, according to a research study, the amount of washing water seems to have a  
332 direct impact on MF release, specifically, higher water/load ratios tend to increase MF release  
333 because of higher hydrodynamic pressure on the fabric structure (Lant et al., 2020). Additionally,  
334 washing garments with different yarn types leaves different footprints on MF release: spun yarns  
335 was observed to cause larger MF release compared to filaments, since the former are shorter in  
336 length and are characterized by higher mobility (Choi et al., 2021). Also, by comparing twisted  
337 and non-twisted filament yarns, the latter seem to release higher quantity of MFs with respect to  
338 the former. Focusing on the characteristics of the garment structure, larger mass per unit of area  
339 and larger thickness of the structure result in a higher release of MFs, due to an increase in the  
340 number of fibers per unit area (Raja Balasaraswathi & Rathinamoorthy, 2022). Moreover, a more  
341 compact structure is more resistant to mechanical friction, potentially reducing MF release (De  
342 Falco et al., 2019b; Raja Balasaraswathi & Rathinamoorthy, 2022; Yang et al., 2019).

343 **Summary and Unresolved Issues**

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

352 Despite significant efforts to study the release of MFs from household washing machines, there  
353 is a lack of standardized test methods (Gaylarde et al., 2021). Most existing protocols are adapted  
354 from garment dye resistance testing and do not precisely replicate MF emission from washing  
355 machines (Mishra et al., 2022). Furthermore, the wide variety of garments, detergents and  
356 chemicals, variations in source water chemistry, and differences in washing programs, creates  
357 variability in experimental parameters and data analysis across different studies. To the best of our  
358 knowledge, the entire body of investigation has been conducted so far using fresh apparel. The  
359 amount MFs released from the clothes that have been already extensively worn, as well as the  
360 possible effects of dirt and microorganisms on MFs shedding during laundering, are largely  
361 unknown. Another issue that has not been studied is that a broad range of textile structural  
362 compactness can be obtained using different machineries employed to produce apparels in  
363 different companies, which may significantly affect MFs release during laundering. Regarding this  
364 issue, Zambrano et al. (2019) suggested that fabrics with higher abrasion resistance, lower  
365 hairiness, and higher yarn strength released lower amounts of microfibers. In addition to that, while

366 research reporting absolute values of MFs released during laundering activities are important,  
367 statistically robust analyses of the trends may arguably provide a more consequential knowledge  
368 and ideally providing means to predict microfibers release. For example, correlations should be  
369 proposed that describe the amount of MFs released as a function of different variables (*e.g.*,  
370 temperature, softener amount, washing time), and normalized parameters may be identified that  
371 provide a way to more easily compare the number of microfibers released per unit variable.

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

## 380 **5. Point-of use Removal from Laundering Wastewater**

381 Approaches for removing microplastic and MFs released into aqueous streams and  
382 wastewaters by textile laundering (Figure 2) may be classified in two distinct strategies based on  
383 the point of application: a) point-of-use treatment methods to remove contaminants directly at the  
384 origin, such as in-drum systems designed for the sequestration of microfibers during the washing  
385 cycle and out-drum filters utilized for extracting microfibers from washing machine drains; b) ex-  
386 situ treatment methods, which encompass approaches for MF removal in centralized or  
387 decentralized large scale systems (*e.g.*, wastewater treatment plants). The subsequent sections

388 exclusively delve into the point-of-use strategies, presenting an overview of the primary solutions  
389 available in the market while emphasizing the strengths and limitations of each approach.

### 390 **Characteristics of an Ideal Point-of-use Device**

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

### 397 **In-drum Devices**

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

#### 400 *i. Cora ball:*

401 *Cora ball* is a ball shaped device with stalks that have small hooks on their ends with the aim  
402 of collecting MFs from wash water by direct application inside the washing machine (*Cora Ball*,  
403 n.d.). Such balls are placed in the machine drum along with the garments, where MFs are captured  
404 by the hooked stalks. According to the founder of *Cora ball*, these devices can capture up to 35%  
405 of the shed MFs during a washing cycle (Anis & Classon, 2017). McIlwraith et al. (2019) assessed  
406 the release of MFs from fleece blankets made purely from polyester, both in the presence and in  
407 the absence of *Cora ball*. In another study, Napper et al. (2020) evaluated five different  
408 commercially available MF capturing devices, *Cora balls* included. These authors used three  
409 textiles made respectively of 100% polyester, 100% acrylic, and a 60% polyester / 40% cotton

410 blend. Results showed that the *Cora ball* was able to reduce the amount of MFs released in the  
411 drained wastewater by  $31 \pm 8\%$ , based on mass measurements. However, the performance of the  
412 device was affected by the types of clothes washed. In particular, the *Cora ball* was more efficient  
413 at capturing longer microfibers compared to shorter ones.

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

#### 422 *ii. Washing bags*

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

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

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

#### 446 **Out-drum Devices**

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

##### 450 *i. LUV-R lint filter*

451 *LUV-R* lint filters are among the earliest developed filters designed for MF capture. According  
452 to the manufacturer, Environmental Enhancements (n.d.), these filters can effectively reduce MFs  
453 by 65% when freshly placed inside the casing and by nearly 100% when their surface has already  
454 accumulated filtered material. They consist of two types of metal meshes with pore sizes of 285

455  $\mu\text{m}$  and  $175 \mu\text{m}$ , housed in a transparent casing, which facilitates easy and rapid inspection.  
456 However, it is important to note that this design may potentially encourage the growth of  
457 microalgae and other photosynthetic microorganisms within the filter (Burrows et al., 2021).  
458 McIlwraith et al. (2019) conducted a study to evaluate the efficiency of these filters in removing  
459 MFs emitted from polyester garments. According to their findings, the *LUV-R* lint filter was able  
460 to retain 87% of the released MFs based on count and 80% based on weight measurements.  
461 However, the filter demonstrated greater capability in capturing longer fibers compared to shorter  
462 ones. Napper et al. (2020) also investigated the *LUV-R* lint filter for the removal of MFs emitted  
463 during the washing of various garments. However, their results differed significantly from the other  
464 study, with only  $29 \pm 2\%$  MF removal observed. This discrepancy may be attributed to differences  
465 in experimental conditions and washing machines employed. McIlwraith et al. deployed a top-  
466 loaded laundry machine, which resulted in higher MF emissions compared to the study by Napper  
467 et al., whereby front-loaded machines were used. In other words, the higher the MF emissions  
468 during washing, the faster the filter saturation occurs, potentially leading to better removal rate,  
469 consistent with the manufacturer claims. The *LUV-R* lint filters are easy to install outside of  
470 washing machines and they are mechanically resistant and washable, being made of metal meshes.  
471 However, it is crucial to highlight that washable filters may potentially represent a secondary  
472 source of contamination. Although the accumulated cake inside the filter or casing is easy to clean,  
473 improper cleaning methods, such as rinsing in a sink, could lead to the inadvertent reintroduction  
474 of microfibers into the sewage network, thus defeating the filtration purpose. *LUV-R* lint filters are  
475 large in size and can retain a significant volume of drain water even after the washing cycle has  
476 concluded. This lingering water can create a fertile environment for microorganisms' growth if the  
477 filters are used infrequently or if they are not adequately emptied and cleaned. Additionally, their

478 relatively coarse mesh design may sometimes prove less effective in adequately capturing MFs  
479 characterized by shorter lengths.

480 *ii. PlanetCare Filter*

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

500 the performance of *PlanetCare* filters measured under different conditions and for different  
501 apparels.

502 *iii. Filtrol160<sup>TM</sup>*

503 *Filtrol 160<sup>TM</sup>* lint filter is another type of inline filtration system that does not contain any metal  
504 parts. It consists of a transparent casing and a reusable bag/lint flexible filter, which is similar to  
505 wine filtering bags with rubber sealings. According to the manufacturer, Filtról (n.d.), the lint filter,  
506 with pore sizes of about 100 µm, can be washed and reused after 10-15 cycles of washing. In a  
507 simple experiment reported in an internet blog (Olivia, 2020), it was found that *Filtrol 160<sup>TM</sup>*  
508 achieved approximately 89% MF removal based on weight measurements . On the other hand, The  
509 Swedish Environmental Protection Agency reported in 2018 that *Filtrol 160<sup>TM</sup>* was capable of  
510 reducing the release of MFs in the washing effluent by about 30-60% (Brodin et al., 2018). *Filtrol*  
511 *160<sup>TM</sup>* has a simple structure that makes it easy to install, maintain, and clean. Similar to washing  
512 bags, *Filtrol 160<sup>TM</sup>* includes a flexible bag-like filter that simplifies the removal of the captured  
513 MFs aggregate, especially when they contain moisture. However, proper handling of the collected  
514 microfibers is imperative, as these should not be washed in a sink or any other way that would  
515 represent a new source of contamination. In addition, similar to other mentioned filtrations  
516 systems, the performance of *Filtrol 160<sup>TM</sup>* has not been systematically evaluated.

517 *iv. XFiltra*

518 Xeros Technology Group (n.d.) developed a filtration system named *XFiltra*, designed to  
519 capture microplastics and MFs from washing machine wastewater, which, unlike the other  
520 alternatives, is installed inside the machine's cabinet. *XFiltra* is an inline filtration system  
521 comprising a pump, a dewatering device, and an outer filter with a mesh pore size of 60 µm. The  
522 company claims that the device can remove more than 90% of the microplastics released during

523 washing. Additionally, the fibers trapped inside the filter are spun dry, facilitating the cleaning  
524 process, although the system has a more complex structure compared to other alternatives (Brodin  
525 et al., 2018). Napper et al. (2020) tested and evaluated the efficiency of *Filtra* for different  
526 garments using a front-loaded washing machine. They concluded that *XFiltra* showed the best  
527 performance among all the alternatives tested (*Cora ball*, *Guppyfriend* washing bag, *Fourth*  
528 *Element* washing bag, *PlanetCare*), achieving a removal efficiency of  $78 \pm 5\%$ . This performance  
529 was attributed to the finer meshes, as also mentioned by Ramasamy & Subramanian (2021).  
530 However, due to their pore size and the presence of only one filter in the system, the device is  
531 susceptible to pore clogging, thus reducing its performance after repeated washing cycles.  
532 Additionally, the inclusion of a spun dryer in the system requires extra maintenance compared to  
533 alternative filters. Regarding the cleaning process, the manufacturer states that it is a simple  
534 procedure that requires minimal manual handling and the collected MFs can be removed in dry  
535 state, even allowing for disposal as recycled plastic waste when in line with the local policies.  
536 Currently, Xeros does not provide the filters separately and *XFiltra* is being sold pre-installed on  
537 washing machines produced by the manufacturer. Xeros has also introduced *XFiltra 2*, a larger and  
538 more sophisticated filtration system for industrial laundry facilities. Unfortunately, no data are  
539 available about its structure or performance.

#### 540 v. *AEG Microplastic Filter*

541 The *AEG* microplastic filter includes a plastic straining mesh and a casing, similar to other out-  
542 drum filtration devices. According to the manufacturer, AEG (n.d.), it is capable of capturing over  
543 90% of MFs larger than  $45 \mu\text{m}$  that are released during the washing process. The collected MFs  
544 need to be manually removed whenever an indicator signals that cleaning is required. *AEG* also  
545 claims that more than half of the accessories used in the *AEG* microplastic filter are made from

546 recycled plastics. AEG microplastic filter has an appealing design, is easy to dismount and  
547 generally user-friendly. The casing is not transparent and is larger than that of other filters  
548 mentioned above, being able to hold about ~2.4 L of wastewater. As of now, there is no published  
549 research or case study available in the literature that examines the performance of *AEG* filters.

550 *vi. Gulp Microplastic Filter*

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

560 **Advantages, Disadvantages, and Challenges**

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

568 mechanical abrasion on garments, they may also diminish the washing efficiency and encourage  
569 the re-deposition of released microfibers onto the clothing.

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

587 Several challenges should still be tackled to effectively mitigate the release of microfibers into  
588 the environment. A chief example is the cleaning and disposal of clogged filters and the  
589 management of collected MFs. There is risk of improper disposal of used filters and collected  
590 microfibers, as users may be tempted to wash the filters and discharge waste into sewage, thus

591 completely defeating the removal device's purpose. Furthermore, inadequate cleaning procedures  
592 may lead to potential airborne microfiber release, an often-overlooked issue. In conclusion,  
593 manufacturers and consumers would prefer a filtration system that does not add extra space  
594 requirements when installed outside washing machines and requires less frequent or more  
595 manageable cleanings.

596 **6. Future Perspectives and Final Remarks**

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

610 Thus, important emphasis should also be put on mitigating the release of microfibers during  
611 laundering activities, since household washing machines are a major source of MF release into  
612 sewage networks and subsequently into the environment. Several researchers have provided  
613 recommendations for modifying laundering conditions, such as lowering washing temperature,  
614 detergent consumption, and mechanical abrasion. However, simply changing washing conditions  
615 may not completely address the issue of MF release. Acknowledging this constraint, manufacturers  
616 of filtration systems have opted for a practical approach by developing point-of-use devices,  
617 chiefly filters, to directly capture a sizable portion of MFs released during washing. Nevertheless,  
618 the performance of these systems remains insufficient to achieve reliably high MF removal from

619 wash water effluents. This limitation may also be attributed to fouling and pore clogging  
620 occurrences, which demand either the selection of filters with larger pore sizes or the application  
621 of more frequent cleaning and replacement of the filter systems. In fact, while enhancing MF  
622 removal efficiency, the use of filters with excessively small mesh/pore sizes would exacerbate  
623 fouling and pore blockage, thus compelling the utilization of drain pumps capable of generating  
624 higher water heads to ensure uninterrupted drainage and to prevent damage to the washing  
625 machines.

626 In this framework, new filtration systems are being designed and proposed, not only by the  
627 industry but also by academic researchers (Belzagui et al., 2023). To maximize efficiency and  
628 sustainability, filter design is expected to shift towards self-cleaning devices or systems that  
629 incorporate dewatering or drying processes. Manufacturers have employed strategies to minimize  
630 filter fouling and find a balance between removal efficiency and water fluxes. The primary  
631 objective of this approach is therefore to extend the filter's operational duration between cleanings,  
632 increasing it from the current 10-15 cycles to, ideally, 50 cycles or more. However, no matter how  
633 excellent the filters performance, fouling is inevitable and cleaning procedure will be necessary.  
634 Therefore, an ideal scenario would involve a cleaning procedure that is performed by the filtration  
635 system itself, relieving the consumer of this task. Moreover, since self-cleaning systems would  
636 need less frequent maintaining services, they may be embedded inside the washing machine  
637 volume, avoiding occupation of external space. Alternatively, it is essential that the cleaning  
638 process or filter replacement is straightforward, accompanied by clear instructions for customers  
639 to guarantee the safe removal of microfibers once they have been captured during washing.  
640 Without appropriate guidance on the proper disposal of filters or collected microfibers, there is a  
641 risk of them ending up in sewage networks or the environment. Additionally, other separation or

642 transformation processes, such as electrochemistry, dielectrophoresis, biodegradation or chemical  
643 oxidation, may be combined with standard filtration systems to enhance separation efficiency  
644 without compromising filtrate fluxes and minimizing pressure drops. This approach would lead to  
645 the development of more sophisticated systems with higher removal efficiencies; it is important to  
646 note that these advancements may increase the final product costs as well as maintenance-related  
647 burdens and expenses.

648 Recently, authors have rightly pointed out that the textile industry and that MFs reduction  
649 methods should be tailored based on different stakeholders (Stanton et al., 2023). MF release from  
650 laundry machines is highly relevant for the Global North and current textile design is vastly based  
651 on the assumption that an infrastructure for MF interception is available, which is however not  
652 found everywhere in the world. Such an approach is only relevant for about 50% of the global  
653 population. In the Global South community, people often launder without a machine, which  
654 presents a significant challenge to quantifying, controlling, and intercepting shed MFs. In this  
655 respect, the responsibility of the textile industry seems even higher, as garment construction and  
656 design may be the primary way to reduce MF release for a large portion of the global population  
657 (Stanton et al., 2023). In conclusion, addressing the release of microplastics and MFs requires a  
658 comprehensive approach that encompasses source control, laundering design, and the treatment of  
659 wastewater containing these pollutants. However, mitigating MF emissions is a global-scale  
660 problem that can be only partly solved through the technical means reviewed in this work. Like  
661 global warming and CO<sub>2</sub> emissions, addressing this issue requires the initiation of a worldwide  
662 campaign, the establishment of appropriate regulations, and their enforcement by local  
663 governments and agencies. While users should not carry the main burden of microfiber release  
664 reduction, raising global awareness remains a key step, for example encouraging individuals to

665 choose environmentally friendly clothing and laundering options, thus potentially placing some  
666 pressure on manufacturers and retailers of textiles, garments, and washing machines. Achieving  
667 the required level of awareness and responsibility requires collaborative efforts from the textile  
668 industry, environmental groups, institutions, and all other stakeholders.

669

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673

**Figures and Tables**

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(in the order they are mentioned in the text)

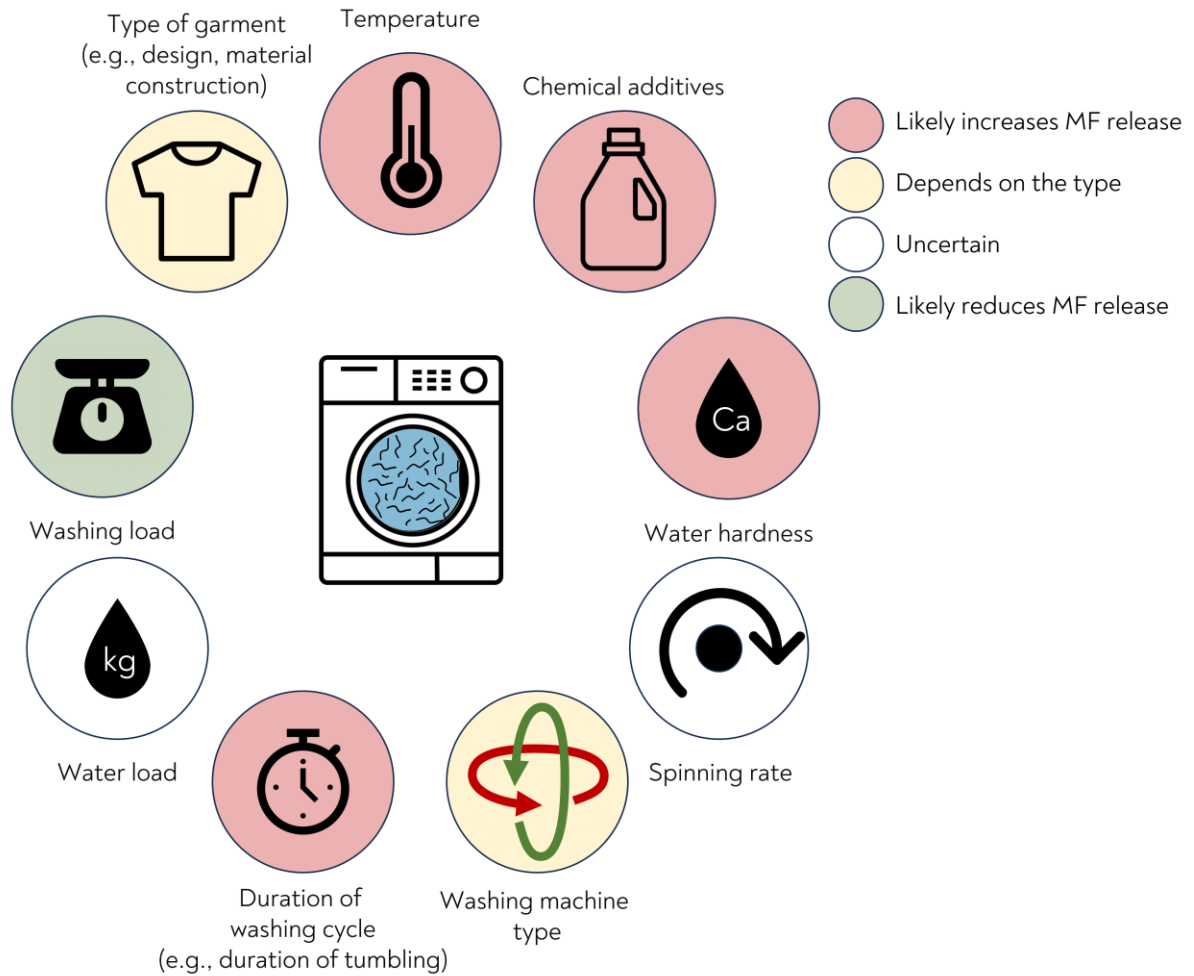
Table 1. Analytical approaches for MF characterization.

<i>Method</i>	<i>Qualitative information</i>	<i>Quantitative information</i>	<i>Destructive approach</i>	<i>Main advantages</i>	<i>Limitations</i>
<sup>1</sup> SEM	morphology, structure of the fabrics, length, diameter, ageing	semi-quantitative number of fibers	might be	<ul style="list-style-type: none"> <li>high-resolution images</li> <li>reveal fine surface and morphological characteristics</li> <li>provides a larger depth of field compared to optical microscopy</li> </ul>	<ul style="list-style-type: none"> <li>requires samples to be conductive or coated with a conductive layer</li> <li>can be time-consuming</li> <li>provides 2D images of the sample surface</li> <li>cannot provide information about the fibers internal structure</li> <li>the electron beam can damage samples, particularly sensitive biological materials</li> </ul>
<sup>2</sup> EDS	elemental composition	-	yes	<ul style="list-style-type: none"> <li>provides information about the elemental composition of MFs</li> <li>can quantitatively determine the concentration of elements</li> <li>suitable for characterizing a wide range of elements</li> <li>provide high spatial resolution when coupled with SEM or <sup>3</sup>TEM</li> <li>allows to pinpoint the location of specific elements</li> </ul>	<ul style="list-style-type: none"> <li>it is primarily a surface technique and may not provide information about the composition of elements within the MFs core</li> <li>sensitivity to sample thickness</li> <li>limitations in detecting elements with very low atomic numbers (e.g., hydrogen and helium)</li> <li>is primarily used for qualitative and semi-quantitative analysis rather than quantitative analyses</li> </ul>
<i>Fluorescence microscopy</i>	material identification	-	no	<ul style="list-style-type: none"> <li>highly sensitive: can detect small traces of fluorescently labeled molecules or structures</li> <li>can be used for live cell imaging, making it suitable for studying dynamic processes and interactions in microfibers and biological samples</li> <li>Multiple fluorophores with distinct emission spectra can be used simultaneously</li> </ul>	<ul style="list-style-type: none"> <li>photobleaching after continuous exposure to light</li> <li>has a limited resolution by the diffraction limit, which is around 200 nanometers</li> <li>samples need to be appropriately labeled with fluorophores before testing</li> <li>has limitation in depth penetration</li> <li>limited elemental information</li> </ul>
<sup>4</sup> FT-IR	polymer identification	-	no	<ul style="list-style-type: none"> <li>highly effective for identifying the chemical composition of MFs</li> <li>can be used for both qualitative and quantitative analysis</li> <li>sensitive to small quantities of material</li> <li>rapid data acquisition</li> <li>can be applied to a wide range of MFs materials</li> </ul>	<ul style="list-style-type: none"> <li>sensitive to water and solvents, which can affect the measurements</li> <li>primarily analyzes the surface of the MFs</li> <li>for solid samples, they must be ground into a fine powder and typically pressed into a pellet or mixed with a matrix</li> <li>does not offer data on elemental composition, making it less suitable for identifying trace elements</li> <li>limited to infrared region</li> </ul>
<i>Raman spectroscopy</i>	polymer identification	-	no	<ul style="list-style-type: none"> <li>highly effective for identifying the chemical composition of MFs</li> <li>sensitive to small quantities of material, allowing for the detection of trace components</li> <li>provide excellent spatial resolution, enabling microspectroscopy</li> <li>can be applied to a wide range of MFs materials</li> </ul>	<ul style="list-style-type: none"> <li>fluorescence from the sample can interfere with Raman signals</li> <li>sample heating or damage can occur under high-energy laser used in Raman spectroscopy</li> <li>limited depth profiling</li> <li>water can strongly absorb and scatter the Raman signals, making it challenging to analyze samples in aqueous environments</li> <li>lack of elemental information</li> </ul>

<sup>1</sup> Scanning electron microscopy<sup>2</sup> Energy dispersive X-ray spectroscopy<sup>3</sup> Transmission electron microscopy<sup>4</sup> Fourier Transform Infrared spectroscopy

<sup>5</sup> MS/GC	chemical composition, polymer identification	semi-quantitative mass concentration	yes	<ul style="list-style-type: none"> <li>highly sensitive: can detect and quantify trace levels of compounds</li> <li>allows for the identification of specific compounds when MS is combined with GC</li> <li>enables quantitative analysis</li> <li>an effective separation technique for compounds in complex mixtures</li> <li>offering information about the mass-to-charge ratio of ions</li> <li>providing high specificity in compound identification</li> <li>Multicomponent Analysis</li> </ul>	<ul style="list-style-type: none"> <li>sample preparation for GC-MS can be labor-intensive and may require solvents or derivatization for certain compounds</li> <li>GC is most effective for volatile compounds than non-volatile</li> <li>incompatibility with certain materials</li> <li>interpreting GC-MS results can be complex, as it involves identifying peaks in chromatograms</li> <li>lack of elemental information</li> </ul>
<sup>6</sup> TED-MS/GC	chemical composition, polymer identification	semi-quantitative mass concentration	yes	<ul style="list-style-type: none"> <li>highly sensitive: can detect and quantify trace levels of compounds</li> <li>allows for the identification of specific compounds</li> <li>selective analysis for the compounds of interest</li> <li>multicomponent analysis</li> </ul>	<ul style="list-style-type: none"> <li>sample preparation for TED-GC/MS can be labor-intensive and may require specific procedures to extract and prepare the compounds of interest</li> <li>It is most effective for volatile compounds than non-volatile</li> <li>sensitivity to thermal decomposition</li> <li>interpreting GC-MS results can be complex, as it involves identifying peaks in chromatograms</li> <li>lack of elemental information</li> </ul>
<sup>7</sup> TOC analysis	-	total mass concentration	yes	<ul style="list-style-type: none"> <li>provides a quantitative measurement of the total organic carbon content</li> <li>rapid analysis</li> <li>can be applied to a wide range of MFs materials</li> <li>modern TOC analyzers can achieve low detection limits</li> <li>can be easily calibrated and standardized</li> </ul>	<ul style="list-style-type: none"> <li>it does not provide specific information about the nature of the organic compounds</li> <li>inorganic carbon, such as carbonate and bicarbonate, can interfere with TOC measurements</li> <li>sample preparation may be required, especially for solid samples</li> <li>it may overestimate the organic carbon content when inorganic carbon is present</li> <li>lack of structural information</li> <li>limited sensitivity to low molecular weight compounds</li> <li>high-quality TOC analyzers can be expensive</li> <li>incompatibility with some materials</li> </ul>
Statistical Analyses	-	number of fibers	no	<ul style="list-style-type: none"> <li>provides quantitative insights into various aspects of microfibers, such as size, shape, composition, and distribution</li> <li>allow drawing inferences about populations based on samples, which is particularly useful when characterizing MFs that are challenging to examine entirely</li> <li>can reveal patterns and relationships within large datasets of MFs characteristics</li> </ul>	<ul style="list-style-type: none"> <li>the quality of the statistical analysis is highly dependent on the quality of the data.</li> <li>inaccurate or incomplete data can lead to erroneous conclusions</li> <li>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</li> <li>establishing relationships often requires additional experimental design</li> <li>small sample sizes may limit the statistical power, making it challenging to detect significant differences or relationships between microfiber properties</li> </ul>

<sup>5</sup> Gas chromatography<sup>6</sup> Thermal extraction desorption-gas chromatography/mass spectrometry<sup>7</sup> Total organic carbon



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Figure 1. Main parameters affecting the release of microfibers during household laundering of textiles

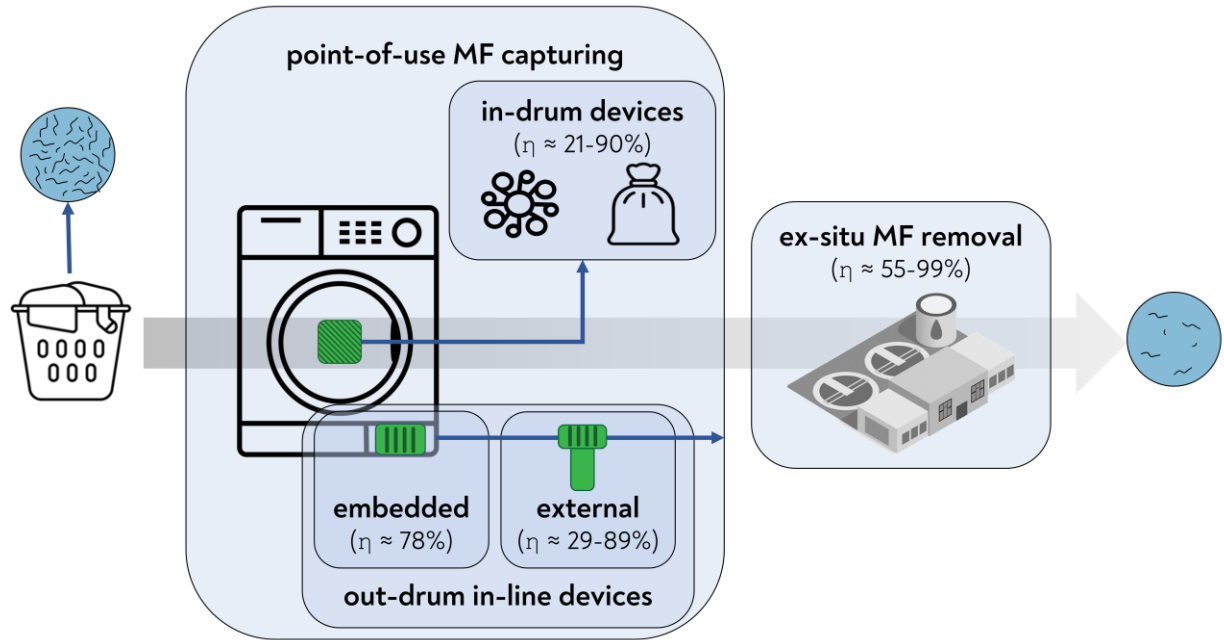
679

based on current literature, and their effect on the emitted quantity. The washing parameters are

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qualitatively classified in four categories of relevance.

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683 Figure 2. Different approaches for capturing of microfibers released during the laundering of textiles

684 with household washing machine. Each approach is associated with a value or a range of values of

685 microfiber retention efficiency ( $\eta$ ) 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)
<b>Cora ball</b>	in-drum	~25-31	polyester fleece blanket polyester acrylic 60% polyester / 40% cotton blend	62 (USD)	<ul style="list-style-type: none"> <li>Flow configuration: -</li> <li>Material: Plastics</li> <li>Filtration surface area (cm<sup>2</sup>): N/A</li> </ul>	<ul style="list-style-type: none"> <li>Simple structure</li> <li>Easy to use</li> <li>Reusable for numerous times</li> </ul>	<ul style="list-style-type: none"> <li>Low efficiency</li> <li>Hard to clean</li> <li>Increasing mechanical abrasion</li> <li>Non-biodegradable plastic structure</li> </ul>	(McIlwraith et al., 2019; Napper et al., 2020)
<b>Washing bag</b>	in-drum	~21 (Forth element) ~54 – 91 (Guppyfriend)	Polyester Acrylic 60% polyester / 40% cotton blend	30	<ul style="list-style-type: none"> <li>Material: Polyamide (100%)</li> <li>Layers: Single-layer</li> <li>Pore size (µm): 50</li> <li>Filtration surface area (cm<sup>2</sup>): 7400</li> </ul>	<ul style="list-style-type: none"> <li>Simple concept</li> <li>Easy to use</li> <li>Inexpensive</li> <li>Reducing mechanical abrasion</li> </ul>	<ul style="list-style-type: none"> <li>Low efficiency</li> <li>Possibility of MFs release from the bags</li> <li>Non-biodegradable plastic structure</li> </ul>	(Napper et al., 2020; O'Loughlin, 2018)
<b>LUV-R lint</b>	out-drum	~29 – 87	Polyester Acrylic 60% polyester / 40% cotton blend	190 (USD)	<ul style="list-style-type: none"> <li>Flow configuration: Outside-in</li> <li>Filter material: Stainless steel</li> <li>Filter layers: Double-layer</li> <li>Casing volume (mL): ~1300</li> <li>Filter pore size (µm): 150-180</li> <li>Filtration surface area (cm<sup>2</sup>): 526.2</li> </ul>	<ul style="list-style-type: none"> <li>Easy to use and install</li> <li>Non-plastic meshes</li> <li>Washable and reusable filters</li> </ul>	<ul style="list-style-type: none"> <li>Low efficiency</li> <li>High price</li> <li>Requires repetitive maintenance</li> <li>Not applicable in capturing small-length MFs</li> <li>Outside-machine installation</li> </ul>	(McIlwraith et al., 2019; Napper et al., 2020)
<b>PlanetCare</b>	out-drum	~29 – 80	Polyester Acrylic 60% polyester / 40% cotton blend	54	<ul style="list-style-type: none"> <li>Flow configuration: Inside-out</li> <li>Filter material: Plastic (supported mesh and foam)</li> <li>Filter layers: Single-layer mesh (with foams strips embedded inside)</li> <li>Casing volume (mL): ~1200</li> <li>Filter pore size (µm): ~200</li> <li>Filtration surface area (cm<sup>2</sup>): 516.8</li> </ul>	<ul style="list-style-type: none"> <li>Easy to use and install</li> <li>2-step filtration</li> <li>Returnable filters to company</li> </ul>	<ul style="list-style-type: none"> <li>Moderate efficiency</li> <li>Outside-machine installation</li> <li>Non-biodegradable plastic structure</li> </ul>	(Martinko, October 13, 2020; Napper et al., 2020)
<b>Filtrol 160</b>	out-drum	~89	*N/A	160	<ul style="list-style-type: none"> <li>Flow configuration: Inside-out</li> <li>Filter material: Plastics (Flexible bags)</li> <li>Filter layers: Single-layer (fine mesh)</li> <li>Casing volume (mL): N/A</li> <li>Filter pore size (µm): 100</li> <li>Filtration surface area (cm<sup>2</sup>): N/A</li> </ul>	<ul style="list-style-type: none"> <li>Easy to use and install</li> <li>Simple structure</li> <li>Flexible and reusable filters</li> <li>Higher operational cycles</li> <li>Easy maintenance and cleaning</li> </ul>	<ul style="list-style-type: none"> <li>High price</li> <li>Outside-machine installation</li> <li>Non-biodegradable plastic structure</li> <li>Outside-machine installation</li> </ul>	(Olivia, 2020)
<b>XFiltira</b>	out-drum (embedded)	~78	Polyester Acrylic	N/A	<ul style="list-style-type: none"> <li>Flow configuration: multi-stage processes (cyclone, filtration and drying)</li> </ul>	<ul style="list-style-type: none"> <li>Inside-machine installation</li> <li>High Performance</li> </ul>	<ul style="list-style-type: none"> <li>Not available separately in the market</li> </ul>	(Napper et al., 2020)

			60% polyester / 40% cotton blend			<ul style="list-style-type: none"> <li>• Filter material: N/A</li> <li>• Filter layers: Single-layer (fine mesh)</li> <li>• Casing volume (mL): N/A</li> <li>• Filter pore size (µm): 60</li> <li>Filtration surface area (cm<sup>2</sup>): N/A</li> </ul>	<ul style="list-style-type: none"> <li>• Higher operational cycles</li> <li>• MFs drying</li> <li>• Easy cleaning</li> </ul>	<ul style="list-style-type: none"> <li>• Non-biodegradable plastic structure</li> <li>• Complicated structure</li> <li>• Difficult maintenance</li> </ul>
<b>AEG Filter</b>	out-drum	N/A	N/A	82	<ul style="list-style-type: none"> <li>• Flow configuration: Inside-out</li> <li>• Filter material: Plastic</li> <li>• Filter layers: Single-layer (Fine mesh)</li> <li>• Casing volume (mL): ~2600</li> <li>• Filter pore size (µm): 50</li> <li>Filtration surface area (cm<sup>2</sup>): 471.2</li> </ul>	<ul style="list-style-type: none"> <li>• Easy to use and install</li> <li>• Easy cleaning</li> <li>• Reusable and washable filters</li> <li>• Cleaning indicator</li> </ul>	<ul style="list-style-type: none"> <li>• High price</li> <li>• Outside-machine installation</li> <li>• Non-biodegradable plastic structure</li> <li>• Large wastewater accumulation</li> </ul>	
<b>Gulp Filter</b>	out-drum	N/A	N/A	N/A	<ul style="list-style-type: none"> <li>• Flow configuration: Inside-out</li> <li>• Filter material: Metal</li> <li>• Filter layers: Single-layer (Fine mesh)</li> <li>• Casing volume (mL): N/A</li> <li>• Filter pore size (µm): N/A</li> <li>Filtration surface area (cm<sup>2</sup>): N/A</li> </ul>	<ul style="list-style-type: none"> <li>• Easy to use and install</li> <li>• Easy cleaning</li> <li>• MFs drying</li> <li>• Reusable filter</li> <li>• LED cleaning indicator</li> </ul>	<ul style="list-style-type: none"> <li>• Outside-machine installation</li> <li>• Non-biodegradable plastic structure</li> <li>• Large size</li> </ul>	

687 \*N/A: Not available

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