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Evaluating microfiber emissions and point-of-use filtration efficiency in household washing and drying cycles

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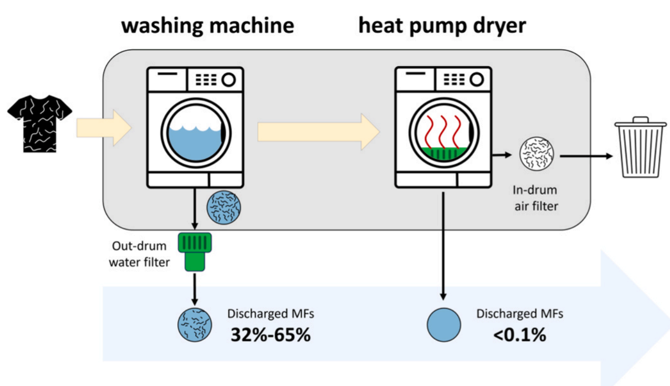
HIGHLIGHTS

- 70 % of textile microfibers are released during the first four wash cycles.
- Filters capture 35–65 % of microfibers while drying cycles increase release by 50 %.
- Heat pump dryers are safer for the environment than vented dryers.
- A trade-off exists between filtration efficiency and hydraulic performance.
- A robust method was developed to evaluate microfiber filtration efficiency.

GRAPHICAL ABSTRACT



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ABSTRACT

This study investigates microfiber (MF) generation and discharge during household washing and drying cycles, focusing on the effectiveness of three commercial filtration systems designed to reduce MF discharge from wash wastewater. Experiments followed a standardized protocol and involved 10 washing cycles at 40 °C with polyester fleece garments, followed by drying cycles in a heat pump-based dryer. Key process parameters, such as drain flow rates and pressure gradients across the filters, were monitored in real-time. MF capture rates ranged from 35 % to 68 %, depending on the filter type. In some cases, a microfiber layer formed on the filter, enhancing capture but increasing hydraulic resistance, highlighting a trade-off between filtration efficiency and flow performance. Drying cycles also contributed to significant MF generation. However, the heat pump-based dryer safely captured most microfibers in the condensation water. While air vent-based dryers were not directly tested, they can reasonably be expected to pose a higher environmental risk due to their limited ability to contain airborne fibers. Drying did not reduce MF shedding during subsequent washes, emphasizing the cumulative nature of MF generation. This research underscores the strengths and limitations of current filter designs, highlighting the need for improved MF capture technology and standardized testing methodologies to reduce microfiber pollution.

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1. Introduction

The release of microplastics into the environment, particularly in aquatic and marine ecosystems, has emerged as a critical global pollution issue with far-reaching ecological and human health implications [1–3]. Microplastics are broadly defined as plastic particles smaller than 5 mm, originating from primary sources (e.g., microbeads in cosmetics) or secondary fragmentation of larger plastics [4]. Microfibers (MF) are a subset of microplastics, specifically, thread-like particles primarily derived from synthetic textiles, which account for a significant portion of microplastic pollution [5].

Microfiber pollution is particularly concerning due to its ubiquity and persistence in the environment. Each year, approximately 360 kilotons of MFs enter natural ecosystems, contaminating marine, freshwater, and terrestrial environments and posing documented risks to biodiversity and food webs [6–8]. In marine environments, MFs have been found in plankton, fish, and other aquatic organisms, leading to bioaccumulation and potential trophic transfer. In freshwater systems, MFs infiltrate rivers, lakes, and drinking water sources, while in terrestrial environments, they contribute to soil contamination and may impact agricultural systems. Additionally, human exposure to MFs through ingestion and inhalation is an emerging health concern, with potential toxicological effects that require further investigation [9].

The textile industry and domestic appliances, particularly washing machines, are major contributors to global MF pollution, as synthetic garments shed fibers during laundering [10–12]. Growing recognition of this issue has led to increased regulatory attention from governments and environmental agencies worldwide, driven by scientific research and advocacy efforts [11,13–16]. Addressing microfiber pollution requires urgent interdisciplinary collaboration to develop effective mitigation strategies, including improved filtration technologies, sustainable textile production, and regulatory measures aimed at reducing emissions at the source.

Researchers have proposed a wide spectrum of approaches to address the emission of MFs from household washing machines, including examining the effects of washing conditions, water chemistry, detergents, chemicals, and fiber materials [11,12]. While much research has centered on quantifying MF emissions, some studies have explored techniques to capture MFs post-discharge [17–19]. Approaches can be broadly classified as ex-situ MFs removal, typically in wastewater treatment plants (WWTPs), and point-of-use MFs capture, which involves intercepting shed MFs before they enter the sewage network [11]. The reported efficiency of conventional WWTPs in removing microplastics and MFs varies from 55 % to 95 %, with the highest removal efficiencies achievable only with advanced tertiary treatment units [20–23]. Tertiary treatment units, commonly employed in WWTPs, typically comprise advanced filtration systems designed to eliminate residual pollutants, MFs included, that are not removed by primary and secondary treatment processes. These steps often incorporate processes such as sand filtration, membrane filtration, or advanced oxidation processes, which improve the removal efficiency of fine particles and dissolved contaminants. The effectiveness of tertiary treatments in capturing MFs is utterly dependent upon their ability to target particles at micro and nano scales, thereby tackling their discharge into aquatic ecosystems [11]. Additionally, the disposal of sludge generated by WWTPs can be a significant pathway for MF pollution, ultimately leading to soil contamination. Many wastewater treatment processes designed for MF removal primarily transfer MFs from water to sludge, effectively creating a new, concentrated MF stream. Without proper management and disposal practices, this sludge can become a significant source of MF pollution. Moreover, sludge is often applied to agricultural fields as a fertilizer or soil amendment within circular economy practices, further contributing to MF contamination in soil [11].

Point-of-use devices are emerging as promising solutions to curb MF pollution at the household level. In-situ devices include in-drum systems designed for the sequestration of MFs during the washing cycle and out-drum filters utilized for extracting MFs from washing machine drains. Examples of commercially available in-drum systems include laundering mesh bags (inside which the garments are placed before washing), such as *Guppyfriend* and *4th Element*, and the *Cora ball*, a ball shaped device with stalks that have small hooks on their ends able of collecting MFs from wash water directly inside the washing machine. Examples of commercial out-drum filters include *Lint LUV-R filter* , *PlanetCare Filter*, *Filtrol160^{TM}*, *XFiltra*, *AEG Microplastic Filter*, and *Gulp Microplastic Filter*.

Although the proper implementation of household MFs capture devices requires increased public awareness and proper usage guidelines, in-situ systems are arguably the most effective strategy in controlling pollution at the point-of-use [24,25]. For this reason, research on the efficiency of these devices, while still limited, is steadily expanding [26, 27]. For example, some studies compared the MF removal efficiency of different devices, including washing bags, ball-shaped in-drum devices and filters [17,18,28]. However, these studies showed heterogeneous results, even when analyzing the same device, due to the lack of standardized characterization approaches. Also, in the investigations testing out-drum filters, the MF filtration was often conducted using a constant-flow pump which does not necessarily represent the behavior of the filters under real conditions.

In addition to capture technologies, researchers have investigated how washing practices influence MF release, identifying key parameters that drive textile degradation and MF shedding, including washing temperature, cycle duration, water chemistry, and the use of additives like detergents and softeners. Recommendations to reduce MF emissions include lowering washing temperatures and detergent quantities and reducing mechanical abrasion. However, adjusting washing conditions alone may not fully address the issue of MF release [11].

An issue hampering progress in this field is the lack of standardized methodologies, both experimental and analytical. For instance, employing a count-based method to enumerate MFs and to evaluate filter performance can introduce variability and inaccuracy [29–31]. Also, the experimental protocols adopted by several, previous research studies were not a reliable representation of real-world conditions and/or overlooked consideration of important parameters of the process, e.g., used systems with constant drain or performed a limited number of washes, often ignoring altogether the hydraulic behavior of the filters [17,18]. Another somewhat underrated issue, at least from analysis of the available literature, is the effect of tumble dryers on MF emissions into the atmosphere. While natural drying by sunlight and wind remains the most common method worldwide, tumble dryers are widely used, particularly in colder regions. These devices may release airborne MFs around households, especially when air vent dryers are employed [11]. In fact, the use of dryers may pose two challenges with respect to MF emission, the first being related to the direct emission of MFs during the drying cycle if there are no filters to capture them, the second being associated with the release of MFs generated but not emitted during the drying process, which may be shed during subsequent use and wash of the garment [32]. Unlike washing machines, dryers operate without water, which could otherwise reduce mechanical abrasion, thus leading to a potentially high amount of MF generation. Moreover, in condensate-based dryers, the distillate stream may include a significant portion of MFs that would ultimately end up in the sewage network [32,33]. Given the limited literature on MF emissions from dryers, this aspect remains an underexplored area in MF pollution research.

This work investigates MF generation and discharge during washing, as well as the behavior of three commercial point-of-use filters for MF capturing from wash wastewater, namely, the devices produced by *LUV-R*, *AEG* microplastic, and *PlanetCare*. Additionally, it investigates MF release in a heat-pump-based tumble dryer and the impact of drying on MF discharge in subsequent washing cycles. Unlike most previous research, MF release was evaluated under real operating conditions, providing a more representative assessment of washing machine emissions. In particular, to ensure a standardized and reproducible

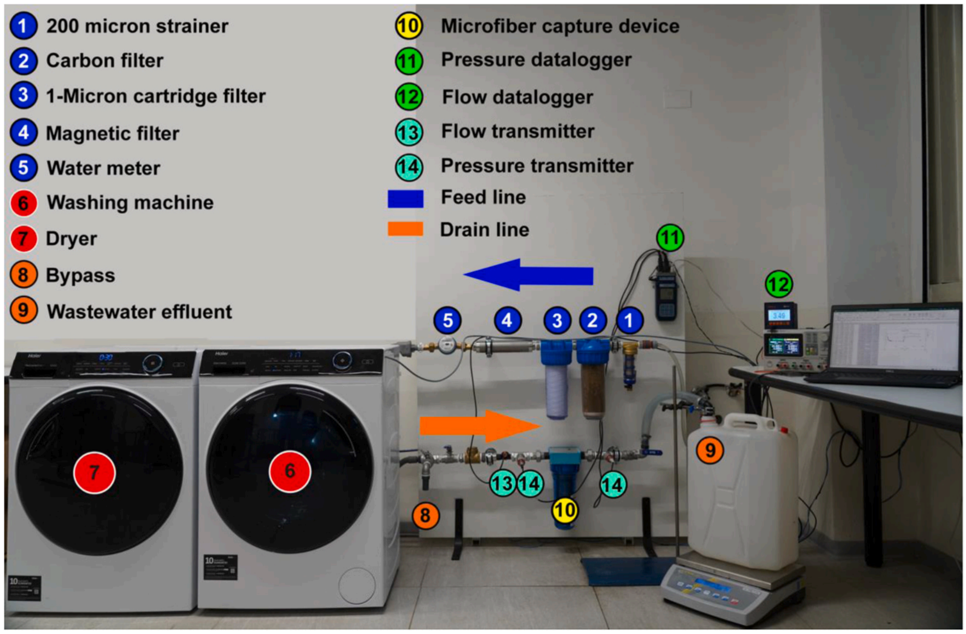

Fig. 1. Experimental setup equipped with the feed pre-treatment system, MFs capturing device, and logging systems connected to the washing machine and tumble dryer.

evaluation, we developed a reliable and reproducible protocol for quantifying MFs generated during washing and retained by point-of-use filtration systems. The proposed protocol integrates a combination of ISO standards specifically tailored to guide the selection of garments, washing machines, and dryers, and continuous monitoring of hydraulic parameters for system optimization. This approach stands out from prior studies that examined MF release from generic garments, with no reference to ISO standards for garment selection and preparation. Furthermore, real-time monitoring of washing cycles and filter performance — including flow rates and pressure gradients — yields valuable insights for improving MF-capturing technologies. This approach enables a detailed examination of the hydraulic impact of washing machine discharge, its interaction with tumble dryer operation, and the influence of drum rotational patterns and phases on MF release. Notably, to the author knowledge, this is the first study where the rotational patterns and phases of a washing cycle are extracted and analyzed, offering a novel perspective on MF release mechanisms.

2. Materials and methods

2.1. Materials and equipment

Polyester fleece blankets with a nominal specific mass of 270 g m^{-2} were used as reference garment for evaluation of MF generation; four equal pieces measuring 0.45 m $\times$ 0.4 m each were inserted into the machine drum for each wash or drying cycle, corresponding to a total mass of 200 g. Fourier-transform infrared (ATR-FTIR) spectroscopy was conducted on the material to ascertain its main composition; see Figure SI1 of the SI. The chemical analysis of the feed water supplied to the washing machine is provided in SI (Table S1). To reduce potential impurities in the feed line, such as particles, microorganisms, and hardness, a series of pre-treatment units were installed, including, in sequence: a 200-µm strainer, a granular activated carbon filter equipped with a 5-µm pore size filter, a 1-µm cartridge filter, and a magnetic filter (see Fig. 1 presenting the main experimental setup and its components).

LUV-R (LUV), *PlanetCare (PLC)*, and *AEG microplastic (AEG)* filters were studied as out-drum point-of-use devices. The filter characteristics are summarized in Table 1.

The selection of filtration devices used in this study was based on a combination of factors, including availability, pore size, layers or stages of filtration, filtration flow patterns, filter and casing material, price range, and potential efficiency. *LUV-R* was chosen due to its large pore size, which suggested a distinct hydraulic behavior, and its single-layer filter made of stainless steel, in contrast to other options predominantly composed of plastic. The *AEG* filter, a newly introduced device with a pore size of 50 µm, features an innovative design and a reusable filter. As the *LUV-R* device, also the *AEG* is a single stage filter. The *PlanetCare* filter offers instead two layers of filtration containing embedded foam

Table 1
Dimensions and physical characterizations of the studied filters.

Filter		Lint LUV-R	AEG Microplastic	PlanetCare
Filtration configuration		Outside-in	Inside-Out	Inside-Out
Casing	**Material**	Plastics	Plastics	Plastics
	Bottom diameter (mm)	84	125	90
	Top diameter (mm)	120	145	94
	Length (mm)	280	215	275
Filter	**Material**	Stainless steel	Plastics	Plastics
	Diameter (mm)	67	100	70
	Length (mm)	250	150	235
	Nominal pore size (µm)	150–180	50	~200
	Filer layers	Single layer	Single layer	Supported mesh with embedded friction foam inside
	Filtration area (cm^2)	526.2	471.2	516.8

strips, known as friction foam, which provide a different approach to microplastic retention. Finally, both *AEG* and *PlanetCare* devices use an inside-out filtration configuration, whereas in the *LUV-R* filter the flow is outside-in through the stainless-steel mesh.

2.2. Experimental setup

The main setup consisted of a Type-B washing machine (HW80) and a heat pump-based tumble dryer (HD90), supplied by Haier, Germany, and connected to a feed line, a drain line, and the filtration system. The term filtration setup refers here to the equipment shown in Fig. 1 and numbered 8–14, with the core of this stage represented by the microfiber capture device (numbered 10). The technical information is provided in Table S2. The drain line was equipped with two pressure transmitters, one upstream and the other downstream of the MFs capturing device, as well as a flow transmitter. All transmitters were connected to the data logger, enabling the recording of real-time hydraulic data every second. MFs capturing devices were installed in the drain line; in control tests, a filter bypass was installed. A check-valve was also incorporated in the drain line to prevent the back-flow of wash wastewater. Furthermore, a digital balance was used to quantify the collected wastewater.

2.3. Washing runs and drying procedure

The selection of the garment, the washing machine, and the washing cycle protocol was based on ISO standards 4484 [34], 6330 [35] and 5077 [36], respectively. Fig. 2 shows the details of washing phases and the general spinning and drain flowrate profiles. This program consisted of a set temperature of 40 °C, and included tumbling and rinsing phases, and spinning rates of 52, 90, and 1400 rpm for the various phases of the cycle. The nominal duration of the program was 77 min. For each set of experiments, the garment was washed in 10 separate and subsequent washing cycles, followed by two additional "blank" washes without the garment [17,18,37]. The two blank washes were performed to capture any MFs that may have remained inside the machine in previous cycles

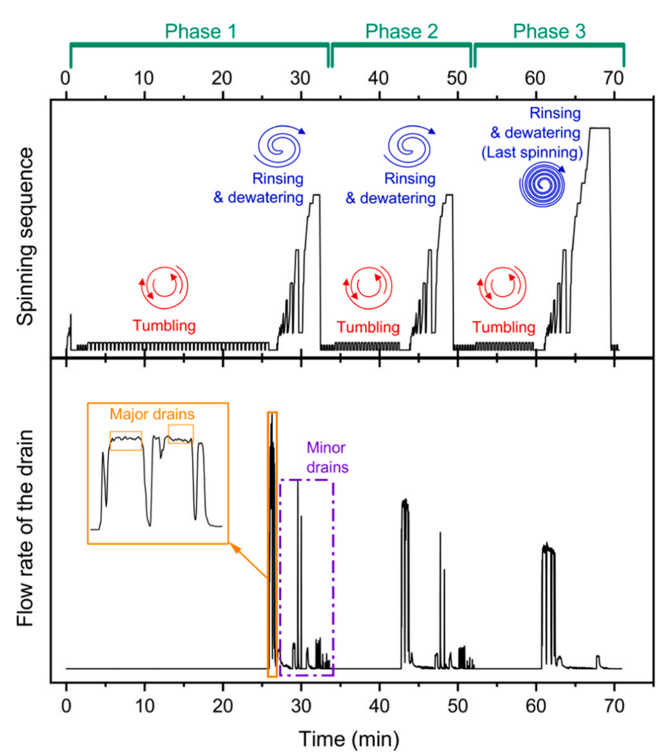

Fig. 2. Profiles of spinning and drain flowrate of the washing machine over time.

and to effectively clean the drum and lines, thus avoiding any interference in the subsequent set of experiments. Thanks to these blank washes, it can be safely assumed that nearly the entire mass of MFs generated during one experimental set was discharged by the washing system before the beginning of a new set and collected for quantification. Each washing cycle included three phases, and in each phase tumbling, rinsing and dewatering occurred, with the first two phases producing about 16 L of wash wastewater each, and the last one producing an additional volume of 16 L. Tumbling refers to the phase in which the washing machine takes in water and the drum rotates at slow speeds. During a typical household wash, the tumbling of the first phase involves the detergent interacting with dirt on the garments, while tumbling of the subsequent phases involves water alone working to remove the loosened dirt from the fabric structure. Rinsing takes place between draining and the high-speed dewatering spins: here, used water is drained, and fresh water is added to thoroughly rinse the garments. At the end of each phase, the drum spins at high speeds to remove water from the garments using centrifugal force, with the highest spinning rate occurring in the final phase. Phase durations are not uniform within a single cycle; the first phase is typically longer due to extended tumbling, while the last high-speed dewatering spin is prolonged to ensure thorough water removal, as shown in Fig. 2. This diagram highlights three subsequent phases, each including a rotational configuration and sub-phases. Sequential sub-phases were: tumbling (minutes 1–26; 33–42; 53–59), rinsing and dewatering (minutes 26–33; 42–53; 59–77). Two distinct drain patterns, termed major and minor drains, can be observed: the major drain precedes rinsing, while the minor drain occurs during rinsing and dewatering. Specifically, the major drain involves a continuous discharge of wash wastewater, whereas the minor drain involves shorter, repeated drains. Four sets of wash experiments were conducted, including one set without microfiber capturing filter, referred to as the control group (*CTR*). All experiments used identical washing protocols, and the resulting MFs were analyzed with the same methodology across both the control and filtered tests. In the *CTR* tests, the only difference was the absence of a filter on the washing machine's drain line.

Unless otherwise stated, after each wash the garment was dried using a heat-pump-based tumble dryer in a 30-minute cycle. Unlike vent dryers, the heat-pump dryer circulates air by drawing it from the drum through triple washable internal filters before air reaches the heat pump, effectively capturing the MFs generated during drying. After each drying cycle, the filters were removed and washed with deionized water, and the resulting water was filtered using the Buchner system to measure the collected MFs, as better explained in Section 2.5. The evaporated water from the garment condenses and ends up in an embedded water chamber. This evaporated water was also collected and filtered after the drying cycle to measure any MFs that reached this chamber, corresponding to the discharged MFs. Heat pump-based dryers were selected in this study to enable a more accurate quantification of the microfibers generated and discharged during the drying process. Due to their closed-loop air circulation, these dryers are expected to allow for more accurate measurement of both the fraction of fibers exiting the drum in a dry state and that accumulating in the distillate tank. However, it is important to note that the impact of heat pump-based dryers on MF generation is considered comparable to that of other dryer types, such as vented dryers, since the primary factors influencing MF release — mechanical abrasion and heat within the drum — remain consistent across different models. The method by which air circulates or how MFs exit the unit is not expected to significantly affect MF generation behavior. On the other hand, vented dryers, which operate with an open-air circulation system that expels air from the drum directly into the surrounding environment, may contribute to the widespread dispersal of in-drum generated fibers into households. This could be a particular concern in regions where vented dryers are commonly used. Despite this difference, the findings of this study could be extended also to vented dryers by conservatively assuming that the amount of discharged MFs is equal to the total amount

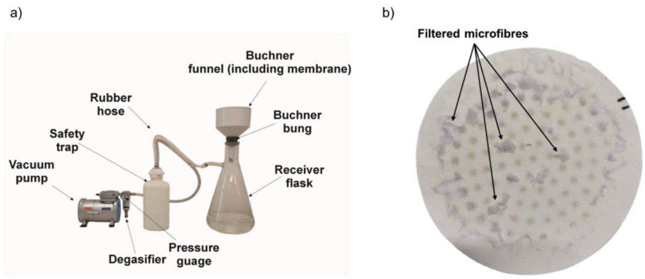

Fig. 3. Methodology for quantifying the mass of microfibers dispersed in water: (a) Laboratory setup for water filtration, and (b) picture of a representative membrane after wash water filtration, with visible microfibers.

of fibers that are generated.

2.4. Filtration procedure and microfiber content calculation

Throughout the text, the terms "generation" and "discharge" are used as follows: "generation" refers to the shedding of fibers from the garment within the washing machine drum or dryer drum; "discharge" refers to the MFs expelled by the appliance and reaching the sewage system (washing machine) or the ambient air (dryer). In the presence of a filtering device, the portion of generated MFs not retained by the device is considered discharged. In the control group related to the washing cycle, the terms "generated" and "discharged" MFs are synonymous, as no filter was installed on the drain line.

To quantify the discharged MFs during each wash cycle, a Buchner filtration system equipped with a vacuum pump, a 125 mm funnel, a 5 L flask, and binder-free 1.6 µm fiberglass membranes (LLGLABEWARE, Germany) were used (Fig. 3). The membrane was pre-dried overnight in an oven at 70 °C and weighed prior to use. Subsequently, the wash wastewater from one wash cycle was filtered through the membrane, which retained virtually all the MFs suspended in the wastewater. The used membrane was then dried overnight in an oven at 70 °C, weighed again, and the mass of collected MFs was calculated. This calculation was performed by subtracting the weight of the pre-dried membrane from the weight of the dried membrane after use. The resulting mass is referred to as MF_w.

The mass of MFs captured by each filter device at the end of the respective set of experiments (MF_f) was quantified by carefully dismantling the filtering device from the drain line and thoroughly washing the mesh and casing with deionized water. The accumulated water was then filtered using the Buchner system and the amount of MFs was measured as described above. The summation of MF_f and MF_w, the latter referring to the MFs escaping the filtration device, represents the total mass of MFs generated in a specific set of experiments (MF_T); see Eq. 1. The filter overall capture efficiency was determined by applying Eq. 2.

$$MF_T = MF_w + MF_f \tag{1}$$

$$Capturing\ Effcicency(\%) = \frac{MF_f}{MF_T} \times 100 \tag{2}$$

2.5. Hydraulic behavior of the filters

An ideal filtration system is expected to be compatible with the current washing machines on the market, which typically use an open impeller centrifugal pump that generates relatively high flow rates but at low pressure heads. This often-overlooked aspect is critical for assessing optimal filter design, which must not cause excessive pressure buildup that would in turn impede the washing machine's discharge. In this study, the hydraulic behavior of the washing machine during drainage in the presence of the fiber filtrations devices was investigated through drain flow rate and pressure drop measurements. Measurements were performed during the second phase of the washing cycle, by recording drain flow rate and pressure drop across the filter with a one data point per second logging frequency. The investigation was conducted under three different conditions to characterize the hydraulic behavior of each filter and assess the additional head losses induced by filter clogging due to MF accumulation: i) with the empty filter casing (no filtering unit installed inside the casing); ii) with a complete filtration system equipped with a pristine filter (before use for microfibers removal); iii) with a complete filtration system equipped with a filter previously used in 10 wash cycles. The details are provided in Table 3. Each evaluation was replicated three times, and the results were averaged.

Table 2
Microfiber capture efficiency of the filter devices, based on the entire set of experiments comprising 10 washes with garments and two additional blank washes without the garments. Control conditions refer to the absence of the filter.

Device	Short name	Generated MFs (mg)	Captured by Device (mg)	Efficiency (%)
Control	CTR	448.2	n.r.	n.r.
Lint LUV-R	LUV	408.2	142.5	34.9
AEG microplastic	AEG	487.2	253.5	52.0
PlanetCare	PLC	471.1	317.9	67.5

n.r.: not relevant

Table 3
Hydraulic characteristics of the filters with and without installing the mesh, before and after use, and compared to the control condition (no device).

Test	Filter	Mesh	Average Flowrate (Q, L/min)	Average (ΔP, mbar)	Q/ΔP
CTR	NA	Control	* 14.3 ± 0.5	**0	n.r.
LUV	Fresh	Not installed	12.0 ± 0.1	44.0 ± 0.4	0.272 ± 0.005
		Installed	11.8 ± 0.4	44.7 ± 0.8	0.263 ± 0.013
	Tested	Installed	7.9 ± 0.3	44.9 ± 0.5	0.165 ± 0.009
AEG	Fresh	Not installed	11.5 ± 0.3	36.0 ± 0.2	0.310 ± 0.011
		Installed	11.2 ± 0.4	44.2 ± 0.3	0.261 ± 0.022
	Tested	Installed	11.8 ± 0.3	44.7 ± 0.6	0.263 ± 0.010
PLC	Fresh	Not installed	13.1 ± 0.6	23.7 ± 0.1	0.553 ± 0.027
		Installed	12.2 ± 0.1	24.9 ± 0.1	0.487 ± 0.005
	Tested	Installed	12.0 ± 0.5	26.8 ± 0.1	0.447 ± 0.020

[*] Maximum drain flowrate.
[**] The pressure gradient was zero when no device was installed. n.r.: not relevant.

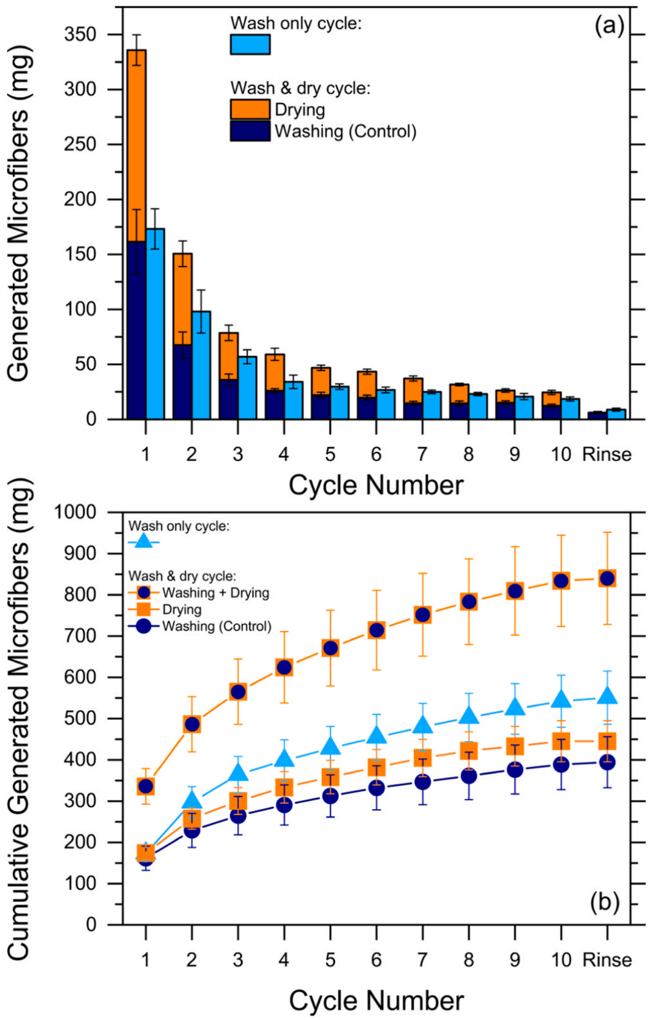

Fig. 4. Mass of MFs generated in washing and drying cycles. a) Data for individual cycles and b) cumulative data. Lines connecting the data points are included only as a guide for the eye.

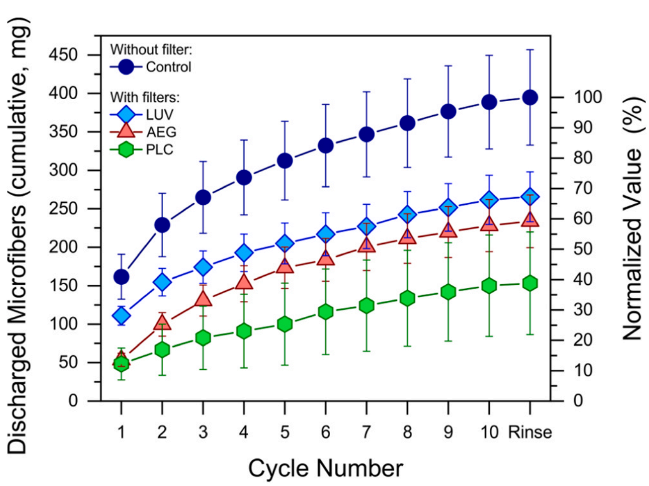

Fig. 5. Cumulative and normalized data of discharged MFs by the washing machine in the absence (control) and in the presence of point-of-use microfiber filtering devices, namely, *LUV*, *AEG*, and *PLC*. Lines connecting the data points are included only as a guide for the eye.

3. Results and discussions

3.1. Generated microfibers during washing and drying

Fig. 4 compares the amount of MFs generated during the various washing and drying cycles. When considering the mass of MFs generated during washing, more than 70 % of the MFs were collected within the first four washes, and roughly 40 % in the first washing cycle, which corresponded to a mass in the range 160–175 mg (Fig. 4a). This result, which was observed regardless of the presence of drying cycles between washes, is consistent with previous studies and may be attributed to the loss of MFs present on and within the structure of unused garments [10, 37–39]. That being said, the shedding process continued throughout the washes, albeit at a slower rate, reaching a value of approximately 15–20 mg per cycle by the 10th wash [38]. When washes were alternated with drying cycles, the same or slightly more MF mass was generated during drying compared to the corresponding washing cycle. These findings indicate that tumble dryers significantly contribute to MF generation due to the additional mechanical abrasion they exert on garments; in fact, mechanical abrasion in hot air is likely more intense than in water, as the higher viscosity of water may reduce abrasion [10, 32,39]. However, it must be noted that, although the mechanical stress during natural drying is expected to be lower than that in tumble drying, MF generation may still occur. Furthermore, prolonged exposure to direct sunlight can weaken fabric fibers through sun bleaching and discoloration, as ultraviolet rays break down the chemical bonds in fabrics, leading to fading and structural weakening over time.

When comparing the MFs generation during washes with and without a drying cycle between each wash, a slightly lower mass of MFs was generated in each wash preceded by a drying cycle compared to the values measured in the absence of drying. The difference was always below 25 mg for individual washes. The smaller mass of MFs generated during washes preceded by drying can be attributed to the additional wear on garments caused by the drying phase, which may reduce the amount of "sheddable" MFs during the subsequent wash. Concerning Fig. 4, the washing cycle characteristics were: duration = 77 min; temperature = 40 ℃; max spinning rate = 1400 rpm. Drying cycle characteristics were instead: duration = 30 min; temperature = 50–55 ℃. The initial mass of garments used for each set of experiments was ~200 g.

Fig. 4b presents the cumulative MFs release data and helps visualize the total mass of MF generated after 10 cycles. Although the drying phase helped reduce MF generation during the subsequent wash, the total mass of microfibers generated throughout the entire cleaning process – considering both washing and drying – was consistently higher than the amount measured with washing alone. While a total MF mass of approximately 400 mg was collected from washes alternated with drying (dark blue circles), compared to around 550 mg from washes only (light blue triangles), the combined MF mass generated from the set including both washes and drying cycles was roughly 850 mg (dark blue circles inside orange squares). In other words, the combination of washing and drying of a garment leads to increased mechanical abrasion, ultimately accelerating the garment's aging process [39]. It is also possible that a portion of MFs generated during washes and self-filtered by the garments are generated during the subsequent drying cycle.

3.2. Filter efficiency

The investigated devices, namely, the *Lint LUV-R, AEG microplastic*, and *PlanetCare* filters, were abbreviated as *LUV, AEG,* and *PLC*, respectively. Table 2 presents the overall efficiency of the tested devices based on the total MFs captured by the given device in the 10-cycle set of experiments. *PLC* exhibited the highest efficiency, while *LUV* showed the poorest performance. Both *PLC* and *LUV* have a mesh pore size of 200 μm, but the embedded foam strips inside the *PLC* filter and its inside-out filtration configuration enhanced MF capture compared to single-layer outside-in *LUV* filters [11,40,41]. Although *AEG* has considerably finer pore sizes (50 μm) compared to *PLC,* it did not achieve better removal results [11]. This outcome may be due to a portion of the generated MFs typically having dimensions smaller than 50 μm, mostly between 5 and 50 μm [37,42,43]. It is worth noting that the low and narrow pressure head range provided by the typical drain pump of household washing machines necessitates that filtration devices have mesh pore sizes equal to or larger than 50 μm. Smaller pore sizes may result in head losses across the filter that exceed the capacity of typical pumps.

Fig. 5, presents the cycle-to-cycle cumulative data relative to the mass of microfibers that escaped the filters, i.e., discharged MFs, when the following washing cycle characteristics were applied: duration = 77 min; temperature = 40 ℃; max spinning rate = 1400 rpm; initial mass of garment used for each set of experiments ~200 g. Data are reported both in absolute values and normalized to control conditions (i.e. in the absence of a filtration device). The trends exhibited a different rate of growth, likely due to the evolving behavior of the devices as MFs deposited on the filters [37,44]. For example, the steeper initial slope observed with the *LUV* and *AEG* filters may indicate a weaker ability of these devices to handle large amounts of released MFs compared to *PLC*, which showed a more linear cumulative profile. The constant slope for the PLC filter suggests that, while it can consistently capture a significant fraction of MFs regardless of filter age, cake filtration did not substantially improve performance within the 10 washes, allowing smaller fibers to continue escaping the filter [42,45]. Overall, more than half of the MF mass escaped *LUV* and *AEG* filters, while the *PLC* device was able to reduce the mass of discharged MFs by 60–70 %.

In typical filtration systems involving the retention of particles, where wastewater is commonly fed at uniform flow rates, a layer of particles/pollutants gradually accumulates on the surface of the filter, forming a secondary filter-like cake layer that enhances particle retention [46,47]. However, during the filtration of MFs released from a washing machine, as in this study, the formation of a uniform cake layer seemed to be disrupted due to fluctuations in drain flow rates and pressure gradients across the filter (discussed in the following section). Consequently, instead of forming a uniform cake layer, a few patchy MF areas were observed, which appeared to be loose and prone to detachment or breakage, especially in single-stage filters like LUV and AEG (Figure S2). Additionally, the variations in flow and pressure gradients may also lead to backflow within the filter casing, which could be sufficiently strong to further disturb the accumulation of MFs. In this sense, the internal foam present in the *PLC* may also act as a pressure dampener, in addition to serving as a secondary filtration step [11,17,18,37,48]. Note that the filter design ensures that water remains inside the casing between washes, which may increase the likelihood of MFs cake layer detachment, further reducing the consistency of the removal performance.

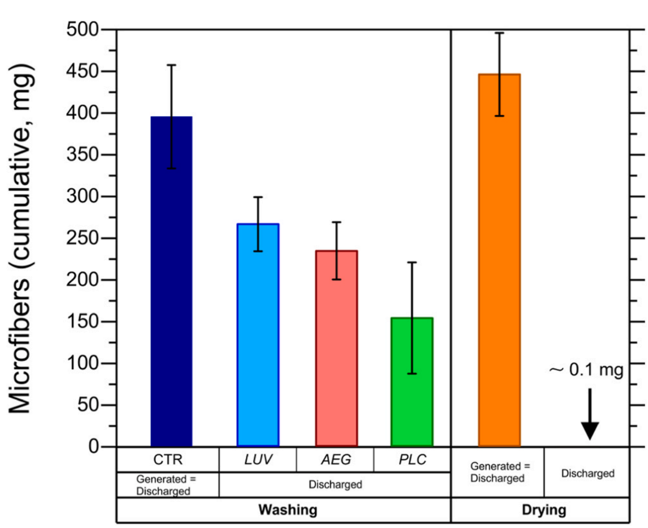

Fig. 6. Comparison of the total mass of MFs released and/or discharged from the washing machine (with and without filters) and from the heat pump-based drying machine employed in this study.

Fig. 6 summarizes the mass of MFs released and discharged from the washing machine drain line compared to that from the dryer. The data indicates a higher efficiency of the dryer in collecting the released MFs compared to the washing machine, with nearly no discharged MFs (~ 0.1 mg) despite a larger mass of generated MFs. Note that discharged MF coincided in this work with the amount present in the distillate volume produced by the machine during the drying process, since the airborne MFs were effectively captured by the internal filters. Therefore, although dryers contribute significantly to MF generation due to mechanical wear on garments, their overall use may result in lower MF emissions compared to natural drying. This is because most MFs generated inside the dryer drum are captured by the built-in filtration system, whereas no control exists over MFs released during natural drying, allowing direct emissions into the environment and potentially impacting indoor and outdoor air quality. However, important considerations arise regarding the design of commercially available dryers and their potential for MF discharge. This study employed a heat pump-based dryer, which is common in Europe, whereas air-vent types are more widespread in North America [32,33]. The former type makes it easier to safely dispose of released MFs, as fibers are largely collected by an air-phase filter integrated with the heat pump. In contrast, air-vent dryers release most fibers into the atmosphere [32,33], suggesting that MF emissions are likely higher with air-vent dryers compared to condensate or heat pump-based models. Nonetheless, proper disposal of fibers collected by condensate or heat pump dryers is essential to prevent secondary MF release, for example avoiding filter rinsing with water that may then be discharged into the sink.

3.3. Hydraulic behavior of the filters

The developers of currently available laundry machine filters appear to have prioritized hydraulic performance over nominal removal efficiency by using relatively large mesh sizes, relying instead on potential secondary filtration mechanisms, such as cake filtration, to enhance retention [11]. In this study, we conducted a series of experiments to analyze the hydraulic characteristics of the filters, including their casings and embedded meshes, in terms of flow rates and pressure gradients. The calculations were conducted over the major drain intervals throughout the second phase of the washing cycle, chosen as a representative phase. Table 3 presents the average flow rates (Q), pressure gradients (ΔP), and their ratio ($Q/\Delta P$). Q and ΔP were also measured without a filter installed in the drain line, whereby $\Delta P = 0$, and the Q value indicates the maximum possible drain flowrate generated by the drain pumps. A higher $Q/\Delta P$ ratio indicates better compatibility of the filters with the washing machine and durability in maintaining hydraulic performance. Based on the data, the sole addition of the filter casing itself into the drain lines, even without the mesh, produced a considerable reduction of flow rate. Including the mesh did decrease the $Q/\Delta P$ for *AEG* and *PLC* filters, and the flow rates measured with the entire device (casing + mesh) were in the range 11.2–12.2 L/min, compared to an average value of 14.3 L/min observed under control conditions. Interestingly, the AEG system, despite the much smaller pore-size, showed $Q/\Delta P$ values comparable to the LUV filter, indicating that mesh size is not the only factor affecting head losses. On the other hand, the PLC filtration system, which was expected to provide the highest head losses due to the presence of the internal foam, showed the best hydraulic behavior (highest $Q/\Delta P$).

After using the filters over 10 washing cycles, $Q/\Delta P$ decreased substantially (~37.3 %) for the LUV device due to MF deposition, whereas *PLC* filter was associated with 8.2 % reduction. In absolute terms, the ratio was higher for *PLC* followed by *AEG* and *LUV* devices. Therefore, it may be stated that the design of the *PLC* device translated into lower overall pressure head losses, while simultaneously being associated with a higher capture performance.

4. Conclusion

Microfibers generated and discharged during household laundry activities constitute a significant portion of global microplastic pollution. This study investigated MF release from household washing machines and dryers during realistic washing and drying cycles. Additionally, the MF capture efficiency and hydraulic behavior of three commercially available filtration systems designed for household washing machines were characterized. A standardized protocol involving a series of 10 washing cycles at 40 °C with polyester fleece garments, followed by additional drying cycles with a heat pump-based dryer, was proposed to ensure comparable results. ISO standards were adapted for rigorously quantifying MFs, while real-time monitoring allowed to capture important process parameters, such as drain flow rates and pressure gradients across the filters. Key findings from this investigation include:

- 70 % of total MF release occurred within the first four washes, with subsequent cycles producing significantly less.
- Washing and drying together released twice the MF mass compared to washing alone, indicating that dryers generate additional fibers and do not help reducing MF generated during washing.
- Secondary filtration by MF cake layers improved capture but was inconsistent due to cake breakage from pulsed washing flows.
- Filter casing design influenced hydraulic performance, with both casing and mesh adding flow resistance. Also, MF deposition impacted hydraulic behavior over time.
- Heat pump-based dryers effectively contain MFs in condensed water. In contrast, air vent-based dryers are expected to pose a higher environmental risk due to limited control over airborne fiber release. Heat pump dryers can even reduce MF emission compared to natural drying on airers, which lacks control over MF release and may negatively impact both indoor and outdoor air quality. However, it is essential that heat pump dryer users are informed about proper disposal of collected fibers to prevent secondary release into the environment, such as by avoiding the use of water for filter cleaning or the direct discharge of MFs into sinks.

In conclusion, this work provides a guide to test and improve the design of point-of-use microfiber filtering devices for household washing machines and underlines the role of drying cycles in MF emissions. This study also presents standardized protocols and parameters for the evaluation of the release and discharge of microfibers from household appliances and for the characterization of the hydraulic behavior of filtering devices, thus supporting further efforts to address this environmental issue.

Environmental Implications

This study addresses the growing issue of microfiber pollution, a major source of microplastics in aquatic ecosystems. Approximately 360,000 tons of microfibers are released into the environment each year, with household laundry being a key contributor. By assessing point-of-use filtration systems, the research highlights ways to reduce microfiber discharge during washing and drying cycles. Improving these filtration technologies can significantly mitigate environmental pollution, offering a practical solution for reducing the impact of microfibers on aquatic ecosystems and promoting more sustainable household practices.

CRediT authorship contribution statement

Sheikhi Mohammad: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Bianco Carlo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Conceptualization. **Tiraferri Alberto:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization. **Sethi Rajandrea:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2025.137646.

Data Availability

Data will be made available on request.

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