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Formation of microplastic fibers and fibrils during abrasion of a representative set of 12 polyester textiles

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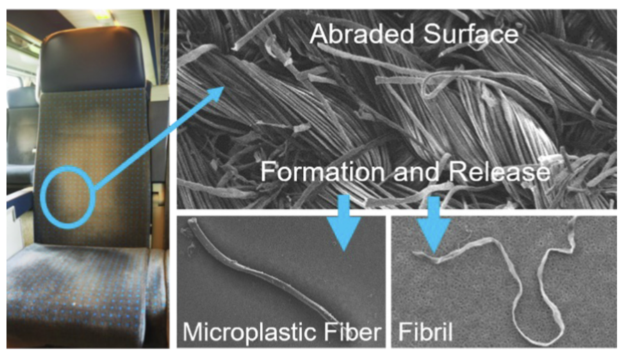
HIGHLIGHTS

- Abrasion of textiles is an underestimated formation pathway of microplastic fibers.
- The release potential of 12 different polyester textiles was investigated.
- Not only fibers but also much smaller fibrils are released.
- One gram of textile can release 4900–640,000 fibers and 0–350,000 fibrils.
- Abrasion (5000 rubs) can release 2–540 times more fibers than washing the textiles.

GRAPHICAL ABSTRACT



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ABSTRACT

Microplastic fibers (MPFs) released from synthetic textiles have been found to be a major source of microplastic in the environment. There is increasing evidence available that MPFs released during washing were likely formed during the manufacturing stage. However, real-life use of textiles is often associated with textile-on-textile abrasion, and the first evidence is available that MPFs and finer microplastic fiber fragments (fibrils) are formed during abrasion. In this study, we characterized the formation of MPFs and fibrils from a representative set of 12 polyester textiles after abrasion tests conducted with a Martindale tester. We also investigated the influence of rub intensity and the extractability of MPFs and fibrils from the abraded fabrics. For all textiles, the MPFs extracted after abrasion showed the same diameter as the fibers in non-abraded textiles (10–20 μm), while the extracted fibrils were much thinner (3–5 μm). The variability in the structure of the different polyester textiles led to a broad range of MPF and fibrils extracted during the first wash after 5000 rubs. One gram of textile released between 4900 and 640,000 MPFs and between 0 and 350,000 fibrils with an average fibril/MPF ratio of 0.8. The total number of MPFs and fibrils formed during abrasion was positively correlated with the increase in the number of rubs up to 10,000 times. Visible pilling on the textile surface was an important indicator for the formation of MPFs and fibrils. Our study revealed that textile abrasion is a critical, realistic, and overlooked mechanism for the formation of MPFs and fibrils, as abraded textiles (after 5000 times rubs) can release more than ten times the number of MPFs and fibrils compared to washing only.

1. Introduction

Fibers are a significant type of microplastics (plastic particles smaller than 5 mm) found in wastewater treatment effluents (Chan et al., 2021), lakes (Anderson et al., 2017; Su et al., 2016), rivers (McCormick et al., 2016), the ocean (Wang et al., 2022), and sediments (Willis et al., 2017). The fibrous microplastics are termed “microplastic fibers” (MPFs) in this article as the other often used term “microfiber” is defined in the textile industry as staple fibers or filaments with a linear density from 0.3 to 1 dtex (Song et al., 2011). Synthetic fibers, especially polyester fibers, have dominated global fiber production since the mid-1990s (Suaria et al., 2020).

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Polyester fibers found in environmental samples resemble the MPFs released from polyester textiles in terms of diameter and length (Cai et al., 2020b; Lindeque et al., 2020; Reineccius et al., 2020), suggesting synthetic clothes as an essential source of MPF pollution as it was also predicted by a modeling approach (Kawecki and Nowack, 2019). The release mechanism of MPF during washing/laundry is well investigated in terms of the influence of material, fabric structure, washing solution, duration, repeated wash cycles, and temperature (Cai et al., 2020b; Carney Almroth et al., 2018; Hernandez et al., 2017; Kärkkäinen and Sillanpää, 2021; McIlwraith et al., 2019). Recent studies suggest that the MPFs were formed during fiber and yarn production and textile finishing processes (predominantly mechanical cutting of the textiles), and are then released from the fabric during washing (Cai et al., 2020a; Cai et al., 2020b; Pinlova et al., 2022). It was estimated that 0.28 million tons of MPFs flow to the aquatic environment per year through washing and including the removal during waste water treatment (Belzagui et al., 2020). The presence of these MPF can pose a potential threat to freshwater and marine organisms (Taylor et al., 2016; Ziajahromi et al., 2017). The concentrations of MPFs in surface waters could be underestimated due to the used sampling and analysis methods (Rebelein et al., 2021).

While washing is a mechanism that releases only MPFs from textiles, abrasion is a mechanism forming both new MPF and also fibrils (Cai et al., 2021; Yang et al., 2021b). Fibrils are defined as fiber fragments of microplastic fibers with a diameter smaller than 5 μm, formed due to the fragmentation of axially split MPFs during abrasion (Cai et al., 2021). Fibrillation is also observed for natural fibers (Hearle et al., 1998). Fibrils are presumably more inhalable than MPFs as their sizes are smaller. The release of MPFs directly into the air from synthetic textiles is an overlooked source. It was suggested that abrasion could be of a similar order of magnitude compared to the release to wastewater by laundering (De Falco et al., 2020). Body movements indoors can be potential pathways for MPFs release into the air (Yang et al., 2021a). Dusting bedsheets, clothes, and other synthetic household textiles results in indoor MPF concentrations of up to 60 microfibers/m^3 and deposition rates between 1586 and 11,130 fibers/day/m^2, which is also the reason for the formation of fiber clusters at corners of the rooms (Dris et al., 2017). By comparing the ingestion of MPFs via food consumption and inhalation, a study suggests that the risk of plastic ingestion via mussel consumption is minimal compared to fiber exposure during a meal via dust fallout in a household (Catarino et al., 2018).

Particles with an aerodynamic diameter of <10 μm are often referred to as "inhalable particles" (Englert, 2004), and only particles with a physical diameter smaller than 3 μm can enter the alveolar region of the lung (Donaldson et al., 1993). According to a simulation study, MPFs constitute a non-negligible fraction of indoor airborne particulates, which can be inhaled and ingested. In particular, 4 % of the inhaled organic particles identified were polyester (Vianello et al., 2019). A monitoring study showed that PP and PET MPFs were the most abundant microplastics that reached the lower lung tissues, and microplastic particles identified within the tissue samples had a mean particle length of 223 ± 436 μm (range 12–2475 μm) and a mean particle width of 22 ± 20 μm (range 4–88 μm) (Jenner et al., 2022). Workers processing polyester and nylon fibers were reported to experience coughing, breathlessness, and reduced lung capacity, suggesting a link between MPFs inhalation and health problems (Gasperi et al., 2018; Prata, 2018).

The real-life abrasion of synthetic textiles and the formation of MPFs and fibrils is therefore likely prevalent but so far inadequately investigated. We know little about how many of MPFs and fibrils can be formed during our activities by abrasion and how many can be released during washing. These processes are complicated, so some standardisations are needed. Therefore, we conducted textile abrasion tests in a Martindale tester to mimic the gentle and rapid textile-on-textile abrasion using a set of 12 representative textiles. Our objectives are to 1) understand the formation potentials of MPFs and fibrils in polyester textiles with various fabric structures during abrasion and 2) investigate the progressive surface changes of the abraded textile samples with increased numbers of rubs and the formation of fibrils and MPFs.

2. Materials and methods

2.1. Textiles

In the present study, we tested 12 different polyester fabrics (purchased directly from textiles manufacturers), which can be grouped into woven, knit, and surface-treated textiles based on their fabric structure and properties. Those 12 fabrics represent various applications, including clothing and fashion, household, and technical textiles. The textiles' physical properties characterized in previous MPF release studies (Cai et al., 2021; Cai et al., 2020b) are reported in Table 1. Fabrics with the suffix "F" designate fabrics made from filament yarns (endless fiber bundles), while those with "S" were made from spun yarns (staple-length fibers). "Plain B", Fleece, and Microfiber are three fabrics with special surface treatment, as mechanical forces were used during production to damage their surfaces to create fuzzy and soft textures intentionally. The textiles were cut by a laser cutter (tt-1300, Times technology) into 140 mm (abradant) and 38 mm (specimen) round pieces following the ISO standard 12,947–2:2016(ISO, 2016). Triplicates of both abradant and specimen samples were weighted (Table S1). Three repeated washes were performed to remove dust and MPFs produced during textile production (Cai et al., 2020a; Cai et al., 2020b). The washing protocol was established in a previous MPF washing study (Cai et al., 2020b) and is described in more detail in the following extraction section. No steel balls were added to avoid mechanical damage to the fabric surface. After prewash, the samples were dried at room temperature and covered with aluminium foil.

2.2. Abrasion experiments with the Martindale tester

A Martindale tester (4-station Martindale tester SN-103/06/1049, James Heal) was used to rub pieces of sample polyester fabrics against each other according to the procedure adapted from ISO 129477-2:2016 (ISO, 2016). The Martindale method is widely used for testing the abrasion resistance of clothes and household textiles, decorative fabrics, and furniture (Textor et al., 2019). It was previously used to investigate MPF and fibril formation during abrasion of polyester Fleece and Interlock S textiles (Cai et al., 2021). The same polyester fabrics were used as specimens and abradant to ensure all MPFs and fibrils recovered in the analysis were from the same source (a difference to the original ISO method). Rubber sheets (thickness of 1.5 mm) were used to replace the standard woven felt textile and the polyether urethane foam material as the base underlays of abradant and specimen to avoid the introduction of unrelated fibers into the test system. The apparatus used was washed, rinsed, and dried before the experiment, and white cotton lab coats and nitrile gloves were worn through sample preparation, installation, removal, and transfer.

The abrasion test was performed with 12 kPa pressure and was stopped after 5000 rubs when pilling phenomena can be observed (Cai et al., 2021). The release of MPF and fibrils into the air and onto the apparatus during the abrasion test was studied in the previous study and was found to be negligible (Cai et al., 2021). All the formed MPF and fibrils remained inside the fabrics. After the abrasion experiment, the specimens were removed and washed to extract the formed MPFs and fibrils. For each fabric type, triplicate samples were rubbed at the same time. There were 12 abrasion experiments and 36 specimens collected to investigate varied resistance by different fabric types.

Fleece (woven) and Interlock S (knit) fabrics were selected to study the effect of the increased number of rubs on the MPF and fibril formation. The number of rubs was set to 1000, 2500, 5000, 7500, and 10,000. Triplicates of specimens for both Fleece and Interlock S fabrics were washed one more time after the prewash steps, serving as the control (rub = 0). These controls are defined as "no abrasion" or non-abraded textiles in the results and discussion sections. Experiments were performed with three replicates.

Table 1
Characterization of textile physical properties. The fiber diameter is taken from (Cai et al., 2020b).

Textile category	Fabric name	Yarn	Structure	Density [g/m^2]	Fiber diameter[m]
Knit	Interlock S	Spun	Interlock	209 ± 1	12.2 ± 0.8
	Jersey S	Spun	Jersey	226 ± 1	12.8 ± 0.8
	Rib S	Spun	Rib	208 ± 2	13.0 ± 1.3
	Rib F	Filament	Rib	294 ± 2	12.7 ± 1.1
	Terry S	Spun	Terry	199 ± 1	15.9 ± 2.2
Woven	Plain S	Spun	Plain	100 ± 0	12.7 ± 0.5/13.4 ± 0.9[a]
	Plain F	Filament	Plain	149 ± 1	7.5 ± 0.6/7.9 ± 0.5[a]
	Twill F	Filament	Twill	154 ± 1	12.4 ± 1.8/19.9 ± 1.7[a]
	Satin F	Filament	Satin	75 ± 0	13.0 ± 0.7/16.4 ± 1.7[a]
Surface treated	Fleece	Filament	(Knit)	185 ± 1	11.7 ± 1.3
	Plain B	Filament	Plain	131 ± 0	9.0 ± 1.2/10.1 ± 1.5[a]
	Microfiber	Filament	(Woven)	191 ± 3	19.9 × 8.9/7.7 × 2.2[b]

[a] The diameters of the weft and the warp yarns of the woven textiles.
[b] The width and length of the weft yarn (19.9 ± 1.1 × 8.9 ± 1.2 μm) and the warp yarn (7.7 ± 0.9 × 2.2 ± 0.5 μm) with a rectangular cross-section for the microfiber samples.

2.3. Extraction of MPFs and fibrils

A Gyrowash machine (James Heal, Gyrowash Model 1615) with eight steel beakers was used to extract the abraded MPF and fibrils. The standard washing conditions were based on ISO 105-C06(ISO, 1994) for colour fastness to domestic and commercial laundering with modifications for the investigation of MPFs release (Cai et al., 2020b). 150 mL linear alkylbenzene sulfonic acid (LAS) solution (0.75 g/L) was used as the optimal extractant (Cai et al., 2021). Each round of washing takes 45 min at a temperature of 40 °C, and the speed of the rotating beakers was 40 rpm. No steel balls were added during the wash.

2.4. Sampling and filtration

After washing, the beakers were removed from the washing machine and were placed at room temperature until the liquid inside cooled down and the foam disappeared. The specimens were squeezed with a flat tweezer. 1 mL out of 150 mL extraction solution was transferred to a vacuum filtration system with a pipette. The MPF and fibrils were deposited onto a cellulose acetate membrane (diameter 13 mm, pore size 0.45 μm; Sartorius GmbH). Before sampling the 1 mL solution, the beaker was mildly stirred 30 times with a cleaned glass stick to homogeneously diffuse the fibers in the extraction solution. The sampling method was validated in previous MPF studies (Cai et al., 2021; Cai et al., 2020b). During filtration, the deposition speed was controlled, and the fibers were separated evenly onto the filter as good as possible. The filters were carefully removed from the filtration unit and dried in Petri dishes overnight at room temperature. Foil paper was put between the dish cap and the filter to reduce the loss of fibers on the filters due to electrostatic effects.

2.5. Characterization

The filters were sputtered with a 7 nm layer of Au/Pd by a high vacuum sputter coater (LEICA EM ACE600) before observation under SEM (7 kV, Quanta FEI 650) magnification 200×, resolution 1536 × 1024 pixels, dwell time 3 μs. MPF/fibril number and length were determined using an SEM "mapping" method developed in a previous MPF study (Cai et al., 2021). A grid of 8*11 images (88 pictures in total) was acquired to cover the whole filter with a horizontal width of 15.111 mm. The 88 images were manually merged and checked after acquisition for the correct position.

The surface of the specimen was captured with SEM and iPhone 13 (for pills on the surface). SEM images were taken at a magnification of 100×, 200×, 500×, 750×, and 1000× to observe the surface change after abrasion and washing.

2.6. Image analysis

The SEM "mapping" images were analyzed in ImageJ with manual labeling of all MPFs and fibrils using a Microsoft Surface tablet and a stylus pen. Two fiber morphologies (aspect ratio > 3) were identified. The first type had a cylindrical shape, referred to as "MPF" in the text. The second type had a "tape-like" form and a much smaller diameter. They are referred to as "fibrils" (Cai et al., 2021). The diameter of the MPF is usually larger than 10 μm, while fibrils are smaller than 5 μm. The length results may include some uncertainties as distortion of fibers during SEM mapping can result in underestimating the real fiber length. Fig. 1 illustrates the fiber counting processes and representative morphologies of MPF and fibrils. Fig. 1a shows the overview of labeled MPFs and fibrils from the filter for Fleece fabrics with 7500 rubs. With careful handling of the filtration process, MPFs and fibrils were relatively evenly deposited on the filter, as shown in Fig. 1b. MPFs (Fig. 1c) and fibrils (Fig. 1d) were labeled when zoomed in at higher magnifications. The results from different textiles are normalized to the number of released MPF/fibrils divided by the weight of the specimen, as detailed in Supplementary Note 1.

2.7. Statistics

The effect of fabric type on the number of released MPF and/or fibrils was tested with one-way ANOVA performed in Rstudio (R version 4.0.5). Fabrics were classified into woven (W), knit (K), and surface-treated (ST) groups; group comparisons were tested using the Benjamini–Hochberg group comparison, also performed in Rstudio. The effect of yarn type (Filament-F or Spun-S) on the number of MPF or fibril was also tested using the same method.

The difference in length distribution of the recovered MPFs and fibrils was tested using Tukey pair-wise (Tukey HSD) comparison by different fabric structures. A p-value of <0.05 was considered statistically significant.

3. Results

3.1. Varied resistance to abrasion of different fabrics

In total, 60 SEM mapping images were examined in ImageJ to investigate MPFs and fibrils released from 12 different fabrics, consisting of 36 images for abrasion samples, 12 images for non-abraded samples after prewash, and 12 images for blank samples. Contamination of the samples during the abrasion process was minimal, especially for the fibrils. On average, five MPFs and less than one fibril were identified in 12 blank samples (Table S2). The severe overlapping of fiber debris on the filters for Plain B made it impossible to label the MPFs and fibrils. This sample released large amounts of broken fibers and agglomerates of fiber debris, and

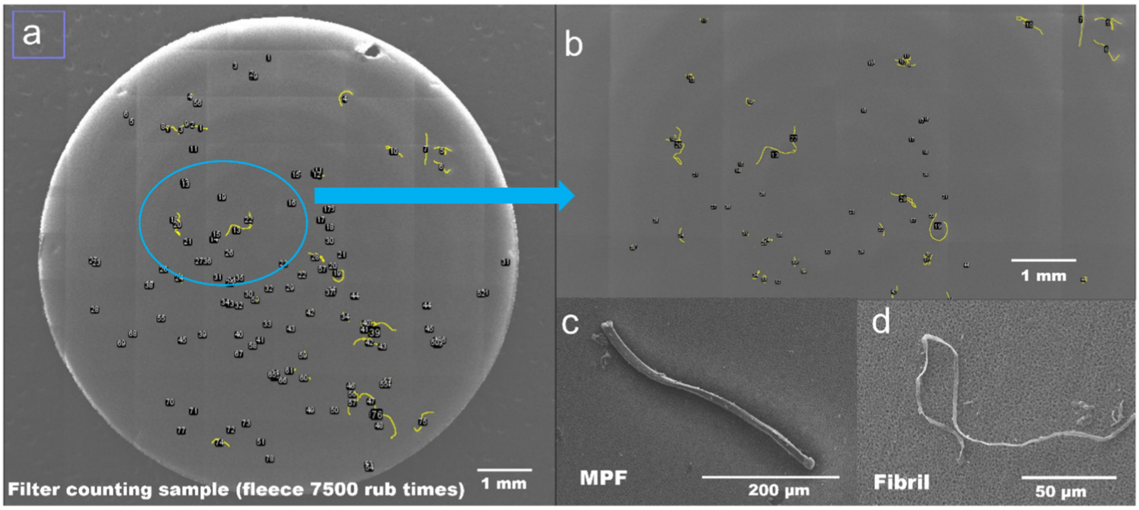

Fig. 1. Mapping and measuring MPF and fibrils on the filter. a) Example of SEM image of a filter for abraded Fleece textiles after 7500 rubs under 12 kPa pressure (taken at 200× magnification). b) MPFs and fibrils labeled in ImageJ using a stylus pen. c) MPFs are visible at 750× magnification, and d) fibrils are labeled at 1000× magnifications.

identification of single MPF and fibrils was not possible. Therefore, no results for Plain B are shown in Fig. 2.

Large variability in the number of released MPFs and fibrils was observed for the different fabrics (Fig. S4). The numbers of MPFs and fibrils were extrapolated to 150 mL and were normalized to the number released per gram textile (Fig. 2a). One g textile released between 4900 and 640,000 MPFs and between 0 and 350,000 fibrils after 5000 rubs. Jersey S released 500,000 ± 130,000 MPFs/g textiles and 300,000 ± 70,000 fibrils/g textiles, the highest release in both MPF and fibrils. No fibrils were recovered in the filters for Plain S, and its MPF release was also the lowest.

The length distribution of MPFs and fibrils are shown as violin and boxplots in Fig. 2b. Most MPFs range from 100 to 800 μm, while fibrils range from 50 to 150 μm. The length of the released MPFs is significantly longer than the released fibrils for all fabrics ($p < 0.05$) (Fig. S2). The influence of fabric structure on the number and the length distribution of released MPFs and fibrils was tested with a one-way ANOVA test, BH group comparison, and paired *t*-tests (Table S3). There was a significant influence of fabric type on the total sum of released MPF and fibrils ($p < 0.05$). However, when grouped into surface treated, knit, and woven fabrics, no significant difference in the number of fibers was observed for the paired comparison within these three groups. Besides, the different yarn types did not affect the released number of MPF and fibrils ($p > 0.05$).

Based on the assumption that MPFs and fibrils are cylinders, we can estimate the released mass by summing up the total length and then multiplying the cross-section area with the measured diameters (in Table S4). We determined the MPF and fibril mass released per gram of abraded samples to be 0.3–18.7 mg MPF/g textile and 0–0.7 mg fibril/g textile (Table S5). Regarding the total mass of MPF and fibrils released during washing, the mass of fibrils only accounted for <3 % of the mass of MPF and fibrils. Jersey S is released with 19.4 mg MPFs and fibrils per g the most, while Satin F has the lowest release at 0.3 mg/g in total (Fig. S3).

After 5000 rubs, the 12 fabrics showed various degrees of pilling on the surface (Fig. S4). For woven fabrics, MPFs and fibrils were formed at the intersections of the warps and wefts. A loosening of the spun yarns is observed for the abraded knit samples and MPFs/fibrils were formed at the

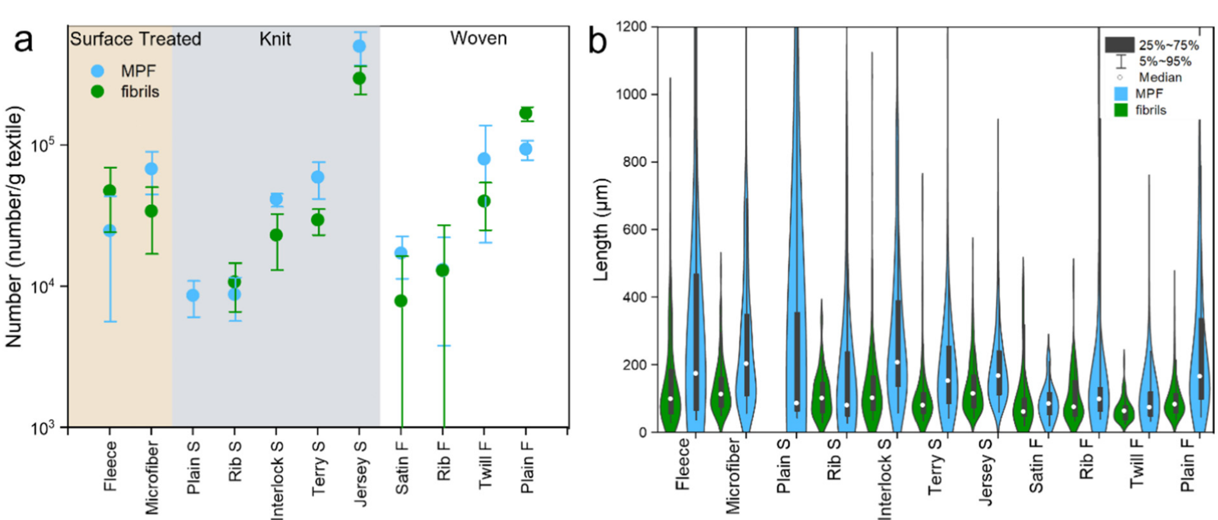

Fig. 2. a) Number of MPFs and fibrils formed during abrasion, normalized to gram textile for 11 different fabric structures, extracted by washing after 5000 rubs. Fleece and Microfiber are fabrics with mechanically treated surfaces. b) the length distribution of MPFs and fibrils extracted from the different fabrics.

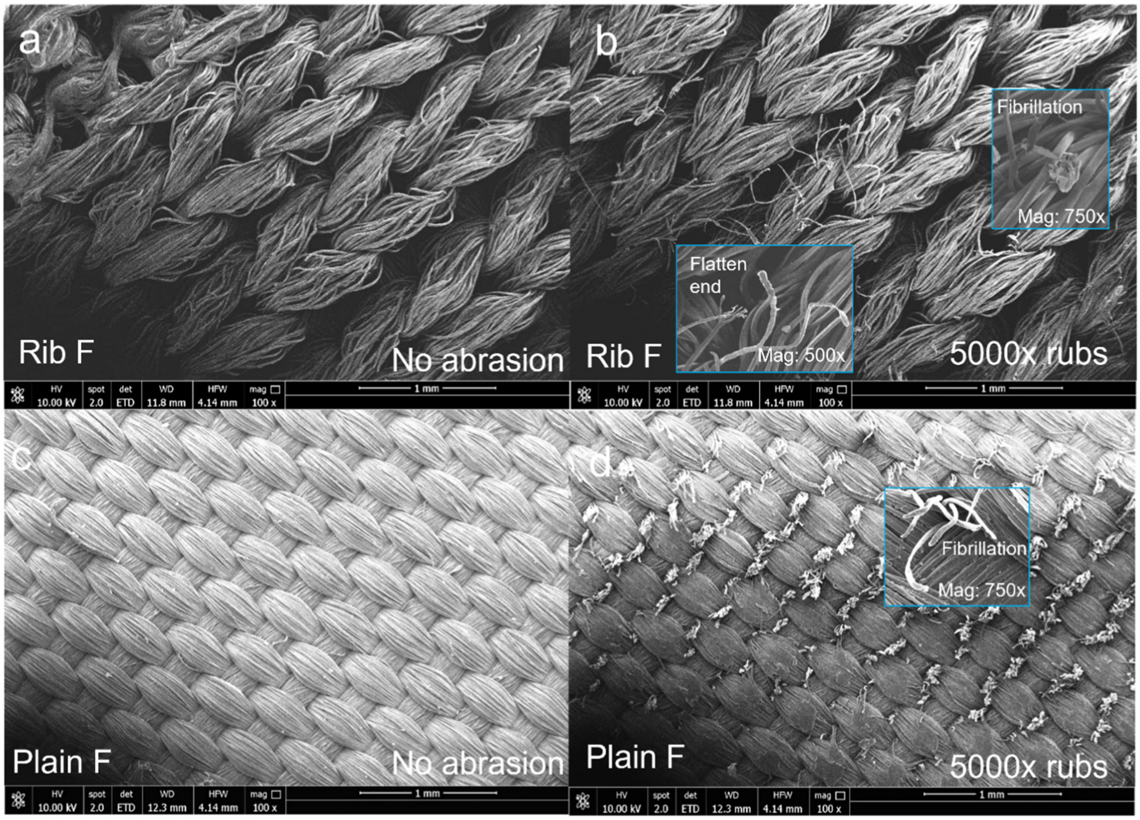

Fig. 3. SEM images (100 × magnification) of the Rib F fabric surfaces a) before abrasion and b) after 5000 rubs. The yarn bundle of filament fibers became loose due to abrasion. Fibrillation was also observed when zoomed in at 750 × magnifications. Woven fabrics such as Plain F showed different surface changes compared with areas c) without abrasion and d) after 5000 rubs under 12 kPa pressure.

opening yarn strings. More pills were formed on the surface of knit fabrics than that on woven fabrics (Fig. S4).

Fig. 3a shows the surface of Rib F before abrasion, one of the knit fabrics with the lowest release. Fig. 3b shows the loosening of the spun yarns after 5000 rubs. We can also observe fibrillation at the end of fibers, as well as the tendency for fiber ends to become flattened. Fig. 3c and d show the surface of Plain F samples before and after abrasion, the fabric with the highest release in the woven category. The mechanism of the formation of the released MPFs and fibrils seems to be different. The warp yarns remain undamaged, while some loose fiber ends appear at the intersection of the warps and the wefts. Fibrillation was also observed at the fiber ends and was likely the source of the fibril release. However, even within the different woven fabrics, the surface changes were quite different for different structures. For instance, in the SEM image of Satin F, there are fewer fibers seen at the intersections of the warp and weft than other woven fabrics (Fig. S4—Satin F). Fig. S4 shows the surface changes of the fabrics for all 12 fabrics tested, including the MPFs and fibrils extracted by washing, and the fabric structures before and after abrasion.

3.2. Varying the number of rubs

We selected Fleece (surface treated) and Interlock S (knit) fabrics to study the effect of increasing the number of rubs on the release of MPFs and fibrils. Triplicates of those two fabrics were abraded up to 10,000 times, and MPFs and fibrils formed during abrasion were characterized at 1000, 2500, 5000, 7500, and 10,000 rubs (Table S6). We observed different patterns of the increase of released MPF and fibrils, as shown in Fig. 4a. In Table S7, we calculated the total number of MPFs and fibrils extracted from Fleece and Interlock S. For both fabrics, there is a linear relationship between the number of rubs and the amount released (Fig. S5, Pearson's $r = 0.96$ and 0.90). For Interlock S, the MPF number increased more than the fibrils, while Fleece had the opposite behavior. For both fabrics, there is a severely damaged surface after 7500 rubs, accompanied by an increasing number of pills and an increase in the number of released fibers (Fig. S6c/e).

The length distribution and the diameter statistics are given in Table S8. As we can see in the violin plots in Fig. 4b, there is no clear trend of the changing length distribution for fibrils recovered from Fleece and Interlock S. However, for MPFs formed in Fleece samples, the median length as well as the 25th to 75th percentage length was decreasing with increasing number of rubs.

With the help of SEM images of the abraded fabric surfaces, we can see a shared progression of the formation of MPFs and fibrils during increased rub times for Fleece and Interlock (Fig. 4c and d). First, at 1000 rubs, the "free" fibers on the surface start to cluster, and in this stage, not many MPFs and fibrils were formed. Then after more rubs, there are more structural changes visible, especially when, after 10,000 rubs, fibrillation was prevalently identified at the fiber ends.

3.3. Extraction efficiency

Repeated washes/extractions were performed for Fleece and Interlock S fabrics (after 5000 rubs) to understand how efficient domestic washing is in extracting MPFs and fibrils formed during abrasion. We calculated the cumulative percentages of the released MPFs and fibrils for 5 consecutive washes (Fig. 5 a and Table S9). During the 1st wash, 46 % of the MPFs and 56 % of the fibrils were extracted from Fleece fabrics. For Interlock S, 78 % of the MPFs and 81 % of the fibrils were extracted in the first wash. It is much easier to extract the MPFs and fibrils from Interlock S compared to Fleece due to the more complicated

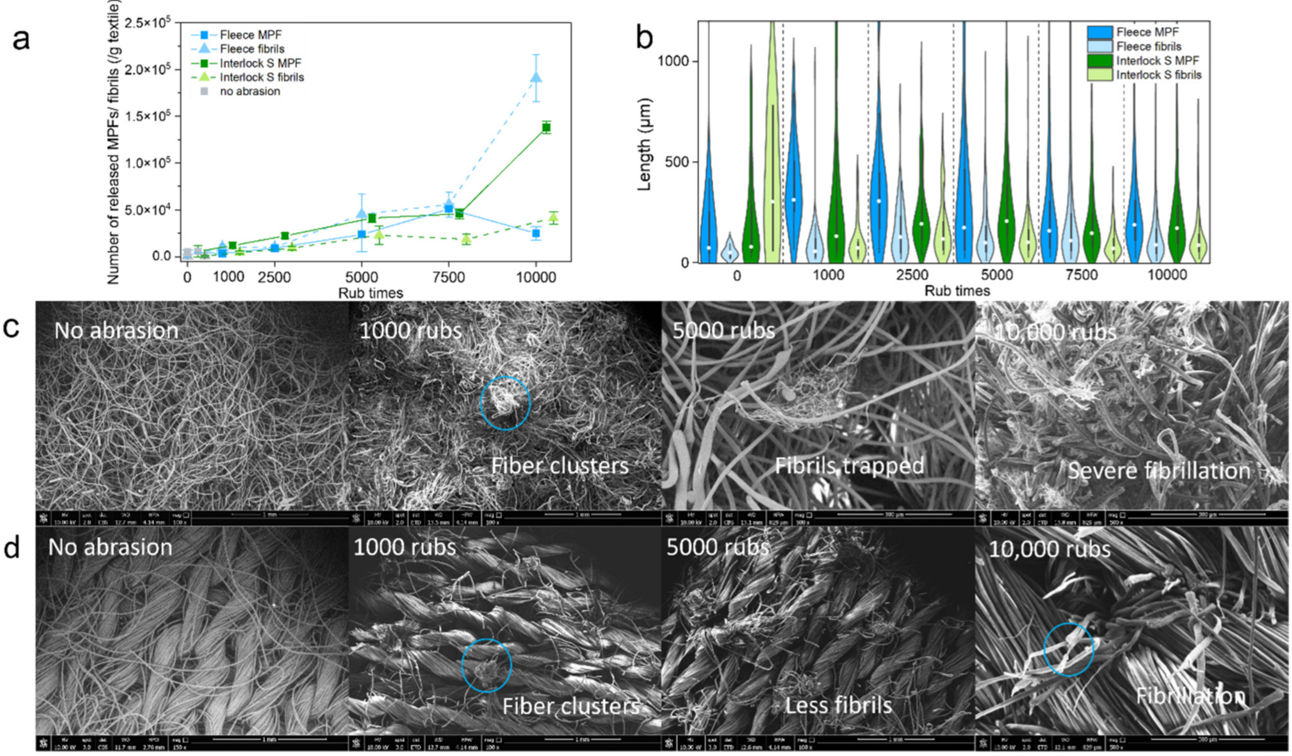

Fig. 4. Fleece (blue) and Interlock S (green) were selected to study the effect of increased rub times on a) the number of released MPFs and fibrils and b) the length distribution of MPFs and fibrils presented in violin plots with the median length in white dots, 25th and 75th percent in the black box. In c) Fleece fabrics demonstrated the formation of fibrils with increased rubs, especially after 10,000 rubs, while in d) Interlock S fabrics, there are far fewer fibrillations observed on the surface. The SEM images were taken at magnifications from 100× to 500×. Scale bars in the plot are 500 μm or 1 mm.

surface structure of Fleece, which can trap the formed fibrils within the surface fibers (Fig. 4c, 5000 rubs).

Shorter MPFs and longer fibrils were released from abraded Fleece samples with repeated washes, especially when the 5th wash was compared with the 1st wash. However, this was not observed in Interlock S samples. Regarding the diameter of MPFs and fibrils released during repeated washes, the diameter of fibrils remained unchanged: 3–4 μm for Fleece and 4–5 μm for Interlock S. For MPFs released from Fleece samples, there is a slight increase in the diameter with repeated washes (Table S10).

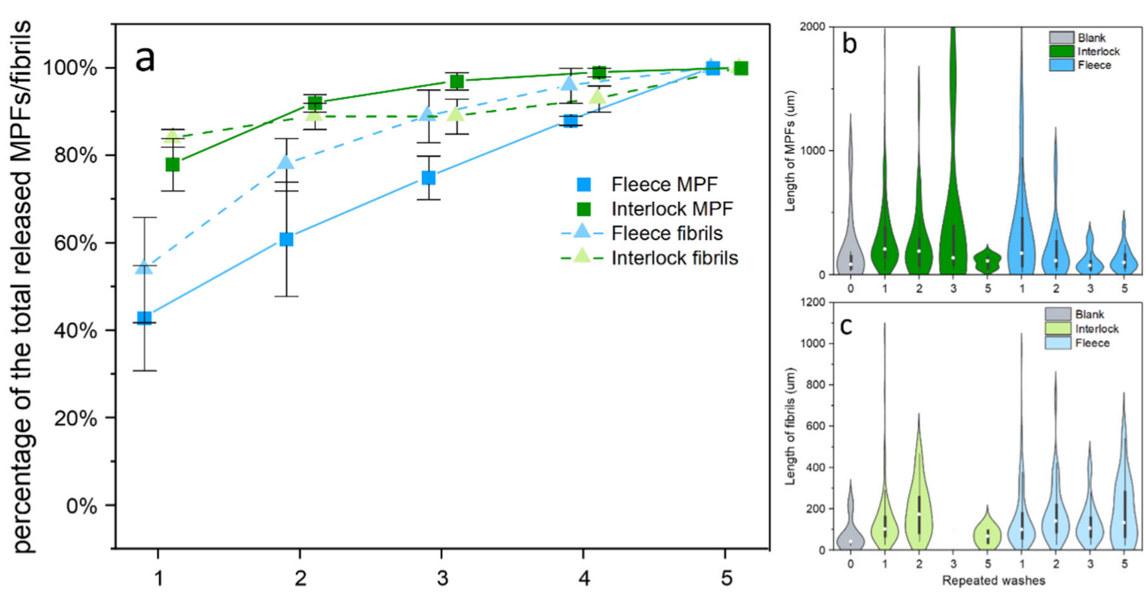

Fig. 5. a) The accumulative percentages of recovered MPF/fibril, extracted from Fleece (blue) and Interlock S (green) fabrics after 5000 rubs, are calculated for 1 to 5 wash cycles (the 4th wash was calculated as the average of 3rd and 5th wash). Violin plots for the length distribution of the b) MPF and c) fibrils recovered from the 1st to 5th wash are also presented. The black boxplot covers 25–75 % of the size/length with the median fiber length (μm) / NP size (nm) value labeled next to the white dot. Only one fibril was identified in the 3rd wash of Interlock S fabric.

4. Discussion

4.1. Martindale tests to investigate the formation of MPFs and fibrils

The Martindale abrasion test was designed to simulate the controlled amount of abrasion between fabric surfaces at comparatively low pressures in continuously changing directions (Wang et al., 2008). The results of the tests are used to decide whether the textiles can be used for certain applications such as clothes (Geršak, 2013), automotive interiors, and other transportation applications (Hardcastle, 2012). The test endpoints are usually breakage of threads or pin holes observed on the surfaces, and this usually means for clothes after 10,000 to 20,000 rubs under 9 kPa (Geršak, 2013). We stopped at 5000 rubs under 12 kPa when pills were observed for different fabrics to compare the MPFs and fibrils formed during the same number of rubs. A previous study compared different abrasion testers, including the Martindale tester, and they stopped the test at only 1000 rubs (Jerkovic et al., 2010). Our settings of up to 10,000 rubs are representative for applications such as seat covers in public transportation, where each year, over 30,000 rubs can be easily exceeded (50 passengers per day*2 unintentional rubs*365 days). Other applications related to frequent textile-on-textile abrasions are sportswear, backpack stripes, socks and underwear in the clothes textiles, and carpets and bedsheets in household textiles.

4.2. MPF and fibril formation mechanism

Interlock S and Fleece share the same deterioration of the surface with an increased number of rubs. Pills started to form at small rub times when mobile fibers at the surface clustered (Roy Choudhury, 2017). With more rubs after the point of fiber fatigue (Hearle et al., 1998), the knit structure became loose, and the pills started to break, resulting in MPF formation. Fibrils are formed when the fiber ends start to fibrillate and then break off fibrils. In particular, the decrease in the number of MPFs released from Fleece at the largest number of rubs could be due to the increased number of pills. The longer MPFs formed by abrasion can presumably be better trapped inside the pills than the short fibrils. This effect was not observed for Interlock which formed much less pills.

The surface-treated fabrics are expected to shed more MPFs and fibrils compared with the other groups because their surfaces are mechanically sheared to gain fuzzy features (Choudhury, 2017). However, the statistics failed to demonstrate a significant difference because the Plain B fabric (which released a lot of material based on the amount collected on the filters) was not included in the quantitative evaluation due to very different types of released debris (Fig. S4 – Plain B). Knit fabrics with spun yarns are more resistant to abrasion compared with woven filament fabrics, which is similar to the lower observed release to both air and water recorded for garments with looser structures (De Falco et al., 2020).

Although the fibril/MPF ratio ranges from 0 to 2 with an average of 0.8, fibrils are only accounting for <3 % of the mass of the emitted fibers. However, particle effects of organisms are often related to particle number and not mass; therefore, fibrils may be relevant despite their low mass fraction (Oberdorster, 1996). The number of fibrils is positively correlated with the number of MPFs as shown in Fig. 6 (slope = 0.62, p-value <0.01, R^2 = 0.58). This indicates that MPF and fibril formation is related and that formation of MPF during abrasion is likely a prerequisite for fibril formation. A possible explanation for not observing any difference in fibril formation influenced by the fabric type could be the difference in the quality of the different fabrics. Therefore, more abrasion tests are needed to compare the same type of fabrics from different manufacturers.

4.3. Abraded textiles are a significant source of MPFs and fibrils

The present study has shown that abrasion of textiles is a significant source of MPFs and fibrils in synthetic textiles, especially for textile uses related to frequent abrasion. We tested 12 different polyester textiles covering a wide range of applications in the abovementioned scenarios. The number of MPFs formed during abrasion of Fleece and Interlock S textiles is 10-fold higher than previously reported (Cai et al., 2021) because we only considered the specimen (rather than the specimen and abradant combined) when normalizing to MPF release per gram textile. Adding the MPF and fibrils contained in the abradant will underestimate the formation because the abradant was exposed to fewer rubs per unit surface than the specimen due to its much higher surface area. An explanation with calculations is available in Supplementary Note 1. Compared with the MPFs released during washing of the same polyester textiles (Cai et al., 2020b), the abraded textiles can release between 2.4 (for Fleece) to 540 times (for Jersey S) more MPFs than unabraded textiles during washing (Fig. 6b). However, with a p-value of 0.4 and $R^2 < 0.1$), no linear correlation was observed between MPF released during abrasion and washing.

So far, only a few washing studies with up to 5 - 10 wash cycles have been published, and in all of them, the number of released MPFs decreased with an increasing number of washings (Cai et al., 2020b; De Falco et al., 2019; Kärkkäinen and Sillanpää, 2021). In those studies, the effect of

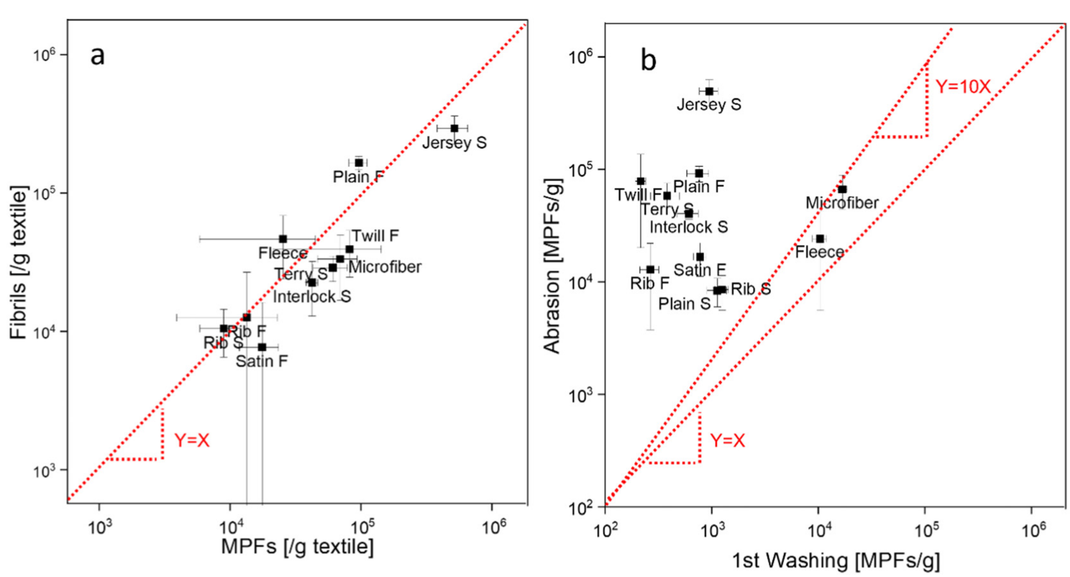

Fig. 6. a) the number of MPFs and fibrils extracted after abrasion (5000 rubs, 12 kPa). b) comparison between the number of MPFs extracted during 1st wash of non-abraded samples(Cai et al., 2020b) and abraded samples. (x- and y-axis are in logarithmic scale).

daily wearing of clothes was not considered as the textiles did not experience any mechanical stress between the washings. Our study found that textiles released more MPFs and fibrils after abrasion with an increasing number of rubs (= increased time). If abrasion is incorporated into the washing studies, a U-shaped release curve could be expected: First, a high number of MPFs is released from the MPFs embedded in textiles during production. These MPFs are washed out rapidly within the first 10 washes, resulting in only small releases afterward. Later, abrasion could become more critical as textiles are worn off over time, and new MPF (and fibrils) that are produced during abrasion can be released from the textiles during washing, so the MPF number could increase again. So far, no such extended washing/abrasion studies are available.

The MPFs and fibrils not only can be released into the water during washing but also directly emitted to air (De Falco et al., 2020; Yang et al., 2021a). The fibrils are smaller than fiber fragments reported in microplastic atmospheric samples (major size between 25 and 200 μm) (Li et al., 2020) or indoor samples (Yao et al., 2022). The fibrils (3–5 μm) found in our study should deserve more attention in monitoring studies because of their smaller sizes. Based on the observed MPF/fibril ratio, we predict that there are 2–120 $/m^3$ microplastic fibrils in indoor environments (Pratiwi et al., 2020; Xumiao et al., 2021) and human intake of fibrils via breathing could be estimated to be 120–1780 fibers/kg body weight/day(Liu et al., 2019). Because of the smaller size of fibrils, the deposition rate of fibrils is lower than that of MPFs (Riley et al., 2002), which will result in even higher concentrations of fibrils in indoor air than predicted.

4.4. Environmental and human health implications

Athough the influence of the shape on microplastic toxicity was found not to bestatistically significant (Adam et al., 2019), the length and diameter of MPFs were proven to affect their toxicity to *Hyalella azteca and Danio rerio* (Gray and Weinstein, 2017; Zhao et al., 2021). The diameters of MPFs used in those studies were about 20 μm, similar to some of the MPFs we found from 12 different textiles. The fibrils formed during abrasion are smaller than MPFs, therefore, might also have higher ecotoxicity than that of MPFs. Besides, the fibrils may significantly impact occupational health and human exposure to indoor air pollutants because their size (from 3 to 5 μm) falls into the inhalable particle size range and even can reach the lower respiratory tract (Donaldson et al., 1993; Englert, 2004). Previous knowledge has shown a correlation between inhaled fibers with occupational respiratory disease (Pimentel et al., 1975) and cardiovascular risks (Mossman et al., 2007). A recent study has demonstrated the possible adverse effect of inhalable microplastic fibers (nylon and polyester fibers with diameters of 10 to 15 μm) on the growth and repair of airway epithelial cells (Song et al., 2022), but the toxicity of fibrils is poorly understood.

5. Conclusions

Although much attention has so far paid to the release of MPF during laundry, only few investigations of the effect of abrasion on the formation of fibers are available. The present study showed, using a large dataset of 12 different polyester textiles, that abrasion of synthetic textiles can be an important source of microplastic pollution, forming not only MPFs but also causing the fibrillation of fibers. Abraded textiles are able to shed much more MPF than new textiles. In particular, the formation of fibrils with much smaller diameter and shorter length raises questions about the potential effects on humans and the environment.

CRediT authorship contribution statement

Tong Yang: Methodology, Investigation, Formal analysis, Writing – original draft, Visualization. **Manqi Gao:** Methodology, Investigation, Formal analysis, Writing – review & editing. **Bernd Nowack:** Conceptualization, Validation, Investigation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability

Data will be made available on request.

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.

Appendix A. Supplementary data

Details about experimental methods; numerical data on the number, size, and length of MPFs and fibrils; additional photos and SEM images. Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.160758

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