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Article

Release of Microplastic Fibers from Polyester Knit Fleece during Abrasion, Washing, and Drying

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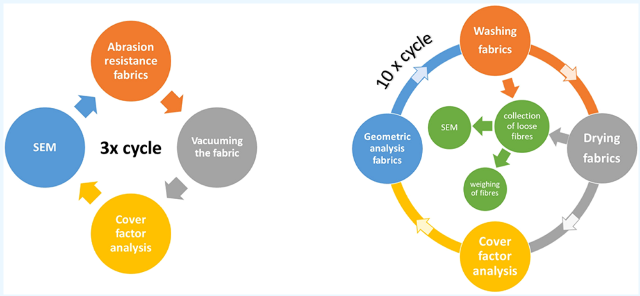
ABSTRACT: Today, microplastics are found in soil, air, and all water sources, including rivers, groundwater, and treated drinking water, with the majority originating from wastewater produced during the washing process. The aim of this study is to determine how standard washing, drying, and wearing simulated by mechanical abrasion of 100% polyester multifilament fleece knitted fabrics contribute to the release and formation of microplastics and fibrous fragments by determining changes in their total weight, thickness, dimensions, and relative surface area. In addition, a new textile surface evaluation methodology was developed to assess the cover area (cover ratio) of released microplastic fibers trapped on the treated fabric surface. The standard and new methods confirmed that the amount of microplastic fibers released from the fleece fabric increased continuously until the third to fifth washing cycle, after which the released amount was nearly constant. Furthermore, a large proportion of the released microplastic fibers was shown to have originated as residue from the manufacturing process. We recommend that (i) washing machines should include a 25 × 30 μm mesh fabric filter to reduce the number of microplastic fibers released down the drain, (ii) flat textiles should be prewashed in the factory, thereby effectively capturing the more significant part of fibers released during the first washing cycle, (iii) the construction and properties of fleece fabrics should be improved to meet environmental requirements, and (iv) the newly developed method for analyzing the cover area of loose fibers on fabric surfaces can be more widely used for quality control.



1. INTRODUCTION

One of the most serious environmental issues today is the presence of macro-, micro-, and nanoplastics in soil, air, and water worldwide. The ubiquitous presence of microplastics has meant they have entered the food chain to be consumed by animals and also humans.[1,2] Owing to their small size and chemical composition, microplastics can even penetrate between cells and tissues, allowing them to accumulate in the body, potentially causing chronic effects on human health.[3−5] Such microplastics have also been shown to affect aquatic organisms such as plankton and fish, as well as larger animals.[6,7] Ingesting such particles can lead to physical blockage of the digestive system,[8] reducing feeding efficiency and causing internal injuries, potentially leading to death.[6,9] Synthetic textiles are a significant source of nanoscopic, microscopic, and macroscopic fibrous waste, with realistic estimates of microplastic leakage into the environment after standard textile maintenance (washing and drying) being around 3.5−80 kg per 100,000 inhabitants per year and is still increasing.[10,11] These primary fibrous waste products, which degrade into micro- and nanoplastic particles and fibrous forms over time,[12] are generally sourced from higher-density polymers, which means they do not easily spread through the environment in their primary form.[13] Nevertheless, owing to their complex chemical composition, they are expected to release more toxic decomposition products, making their elimination from the environment more challenging.[14,15] Furthermore, the physical and mechanical properties of knitted fabrics vary depending on the production technologies (e.g., knitting machine type, pattern, process parameters) and fiber and yarn structural properties.[16−18] During the spinning of yarn, fibers are subjected to harsh mechanical influences that can further damage them. Fibers that are not sufficiently tightly bound in the yarn by surface friction forces tend to be released during further processing and maintenance.[19]

Fibers and microplastic fibers sourced from polyester are known for their high flexibility, dimensional stability, and high resistance to rubbing and creasing, making them the most used fibers in the clothing and textile industry.[20] Conventional

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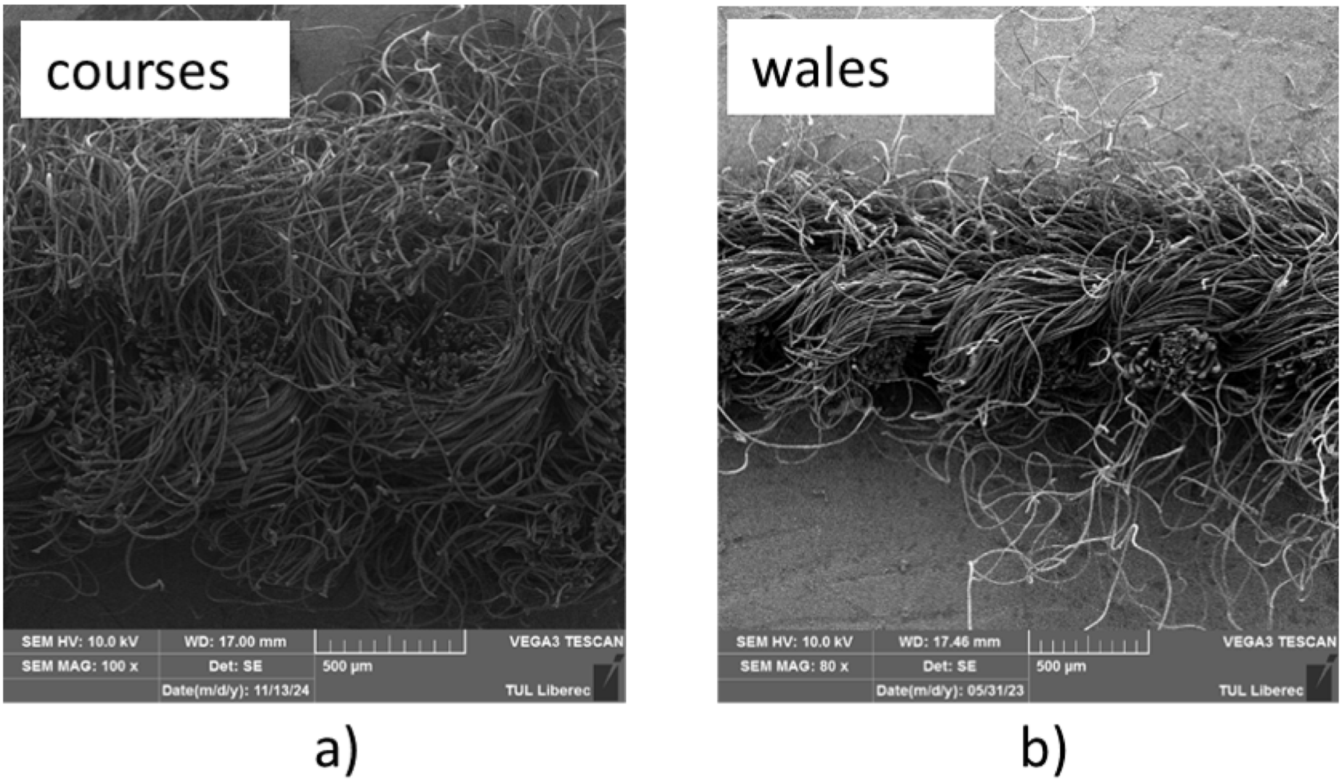

Figure 1. SEM image showing: (a) cross-section single jersey fleece fabrics—row (courses), (b) cross-section single jersey fleece fabrics—column (wales).

polyester fibers, usually produced using terephthalic acid and ethylene glycol, can be manufactured as continuous filaments or as staple fibers, with circular, multilobal, hollow, or custom-shaped cross sections.[21] Some textiles made from polyester fibers, such as "fleece", from bulky, soft knitted fabric are characterized by a dense and soft pile structure. These fabrics are utilized globally for clothing used in cold conditions. When washing such textiles with water and detergent, microplastic fibers may be redeposited on their surface.[22] These redeposited microplastic fibers (MPF) and fibrous fragments, primarily released by washing clothes or by abrasion,[23] are one of the main sources of microplastics in residential interiors and the environment.[17] It should be noted here that some previous studies on MPF release during textile maintenance (especially washing and drying) have incorrectly applied the term "microfibers" to fibers of 10−30 μm length;[22,24] however, in the textile industry, microfibers are defined by their diameter not length[21] as microfibers are often fragments of fibers with a length to diameter ratio of around 1000:1 due to their internal fibrillar structure and thin geometric needlelike shape.

Several recent studies have addressed the release of MPF from textiles during washing, most findings show that MPF release decreases with each washing cycle, usually reaching a constant level around the fifth wash.[25−32] The addition of liquid or powder detergents to pure water either increases[31] or has no impact[27] on MPF release. In the present study, we explore the effect of maintenance (washing and tumble drying) and simulated wear (through mechanical abrasion using a standard Martindale tester) on the release of MPF from a flat multifilament polyester knit-fabric fleece. Standard methods currently do not usually include the assessment of fibers released during washing. As part of this study, therefore, we also verify a newly developed method for determining the coverage area of released fibers and microplastic fibers trapped on the fabric surface. The fibrous filters for retaining fibers released in washing and drying machines are proposed.

2. MATERIALS AND METHODS

2.1. Fabric. For the purposes of this study, we used commercial single jersey fleece fabrics prepared by pull knitting technology. These single-ply fabrics were especially knitted with complementary yarns made of polyester fibers. Figure 1 shows a section of the knitted fabric in the direction of the rows and columns. The fabric structure comprised three types of filament yarn: basic yarn (face yarn and binding yarn) and loop yarn (filling layer); see Figures S1 and S2, Table 1.

Table 1. Fabric Characteristics and Manufacturing Standards

Parameters	Characteristics	Standard
Composition	100% polyester multifilament	-
Fabric pattern	Single jersey fleece fabric	ČSN EN ISO 8388 (800014)
Area density [g/m^2]	222.40 ± 0.15	ČSN EN 12127 (800849)

2.2. Sample Preparation. To prepare our initial samples, we used a hand fabric cutter, i.e., a similar method to that used in the textile industry, where fabrics are cut to shape using mechanical cutting devices, with the edges of the cutting tool being positioned vertically to cut multiple layers of fabric.[33] In a previous study,[30] Pirc et al. compared several fabric cleaning methods in relation to the release of MPF from microfiber fleece and found that most cutting/sewing methods had no

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significant impact on the release of MPF from fabric samples. However, in a study,[34] it was found that laser-cut samples release significantly less MPF than all other mechanical cutting methods. During the preparation of the samples, care was taken to avoid tensile stresses during material handling to prevent deformation of the samples. The fabric samples were prepared, marked, and measured according to standard EN ISO 3759 (80 0825). All fabric samples (for washing and drying experiments) were cut to 50 × 150 cm using a hand fabric cutter, with the edges left unsewn, and pairs of 500 mm × 500 mm reference points marked with nonwashable paint on each sample. For the abrasion resistance test, circular fabric samples of 14 cm diameter (as abradant) and 3.8 cm diameter (as abraded material = specimen) were cut using a hand fabric cutter, with the edges left unsewn. The specimens were then left in a conditional chamber (i.e., brought to atmospheric equilibrium) for a minimum of 24 h until a constant weight was reached, after which the distances between each pair of reference points were measured according to EN ISO 139 (80 0056). Throughout the experiments, researchers wore white cotton laboratory coats and nitrile gloves, and experimental equipment was thoroughly rinsed, cleaned, and vacuumed after each experiment cycle to avoid accidental contamination with fibers and to microplastic fibers from the external environment.

2.3. Fiber Characteristics. Fiber structure and microstructure were evaluated using a VEGA 3 TESCAN scanning electron microscope (SEM; TESCAN GROUP a.s., Czech Republic), while fiber diameter was assessed from 100 randomly chosen fibers using a Lext OLS 3000 IR confocal microscope with associated image analysis software (Olympus America Inc., USA).

2.4. Washing and Drying. All washing experiments were carried out according to the ISO 105-C06 1994 standardized washing procedure, with washing solution treatment. Briefly, four samples were washed over 10 cycles in a Romo EURONOVA 1000 front-loading washing machine (Romo, Czech Republic), with no prior prewashing or soaking, using the P3 washing cycle (max. capacity 1.5 kg, water consumption 38 L, speed 1000 rpm, temp. 40 °C, washing time 80 min), with 1 g of commercial detergent (Persil Color, containing 92% biodegradable ingredients and 5% anionic surfactants, with <5% nonionic surfactants, zeolites, phosphonates, polycarboxylates, enzymes, and perfumes) used for the first cycle. There are currently no standardized procedures worldwide for the assessment of microfibre pollution released during the washing and drying of textile materials. In this study, information on washing procedures was drawn from European standards EN ISO 105-C06 (800123) and EN ISO 4484−1: in EN ISO 105-C06 (800123), the recommended dosage of detergent is 4 g/1 L of washing bath, and this procedure is also used by Cai et al.[28] No detergent is recommended in EN ISO 4484-1 (textiles and textile products − microplastics from textile sources). Different information is given in the literature regarding the use of detergents during experiments. Refs [30], [31], [35], [36] state that the use of laundry detergent has no effect on the amount of fibers released. Therefore, and also based on the pilot experiments published in ref 37, a low dosage of detergent was used in this experiment. The washing machine was cleaned between tests using washout cycles as described by Lant et al.[25] After each wash (until 10 min), the washing machine was run on rinse cycle P4 (max. capacity 1.5 kg, water consumption 27 L, speed 1000 rpm, temp. 30 °C, time 50 min). The wash water was subsequently passed through a fine 25 × 30 μm mesh woven monofilament filter placed directly on the washing machine hose and collected in a clean 50 L polyethylene (PE) drum. The filter, along with any associated fibers and particles, was first dried inside Petri dishes (caps ajar) in a laminar flow hood overnight, after which the dried mixture of fibers and particles was collected in a Petri dish for further gravimetric analysis. The textile samples were then transferred to a BEKO DPS 7405 G B5 heat pump condenser dryer (BEKO, UK) and dried for 30 min. The dryer contained a built-in standard filtration system; this filter had two parts that could be removed and cleaned, as shown in Figure S4. Loose fibers were collected from both filters. There was no release of fibers into the free space during drying. This release of fibers occurs mainly in vented tumble drying, as reported Cummins et al.[38] During this experiment, a very small amount of loose fibers settled in the condenser space, but this additional release of fibers was not included in this study. Fibers released in the condenser dryer were collected on a coarse 174 × 168 μm mesh filter and a secondary finer 52 × 55 μm mesh filter. At the end of the cycle, the filters were rinsed off, dried, and stored in Petri dishes for gravimetric analysis. Prior to the next wash cycle, the test samples were conditioned according to standard EN ISO 139:2005 (standard atmospheres for conditioning and testing). In each case, the weight of released fibers, fibrous residue, and microplastics was evaluated on a Secura 125-1CEU semimicro laboratory balance (Sartorius AG, Germany) with a resolution of 0.01 mg.

2.5. Abrasion Resistance. For wear simulation, the abrasion resistance (i.e., propensity to surface fuzzing, pilling, and MPF production) of the fabrics was tested using a standard eight-station M235 Martindale tester (SDL Atlas, USA), which rubs textile samples against a standard surface at standard pressures, according to ISO 12947-2:2016. The same polyester fabrics were used as specimens and absorbents to ensure that all MPFs and fibrils recovered during the analysis were from the same source (a major difference from the original ISO method). The abrasion test was performed with a 12 kPa pressure. In the Cai et al.[28,34] and Yang et al.[29] study, this procedure was used to examine MPF and fibril release due to the abrasion of polyester fleece fabrics. In Yang et al.'s[29] study, the layer consisting of the standard test material was backed with rubber (instead of the usual felt). This rubber formed the base backing layer for the abradant and prevented the introduction of foreign, unrelated fibers into the test system. The number of rubs was set to 500, 1000, and 2000. Before each abrasion test, the equipment was cleansed with 75% isopropyl alcohol and a vacuum cleaner to remove all possible contaminants. For each series of tests, 6 samples were prepared each time, for a total of 18 pieces of samples tested. After the abrasion experiment, the samples were thoroughly vacuumed to avoid the presence of MPFs and fibrils remaining inside the fabrics. Due to the very low number of cycles (compared to the standard), no wrinkling or visible changes on the surface of the tested knitted fabric occurred.

2.6. Assessment of Dimensional Changes and Weight Loss. Changes in fabric thickness after each washing and drying cycle were measured according to EN ISO 5084, while dimensional changes against a standard were measured with a calibrated ruler. Relative row (courses per cm) and column (wales per cm) dimensional changes after washing and drying were characterized as area changes calculated relative to the starting sample area [ΔSw_i], using the equation:

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$$\Delta Sw_i = \frac{Sw_i - S_0}{S_0} \quad (1)$$

where Sw_i is the measurement after washing and drying, S_0 is the relevant measurement before washing and drying, and index i corresponds to the number of cycles. Likewise, relative changes in thickness after washing and drying [ΔTw_i] were characterized using the equation:

$$\Delta Tw_i = \frac{Tw_i - T_0}{T_0} \quad (2)$$

where Tw_i is the measurement after washing and drying, T_0 is the relevant measurement before washing and drying, and index i corresponds to the number of cycles.

2.7. Novel Method for Assessing Loose Fiber and Fragment Cover Area. The loose fiber cover area (fiber CF; also known as fiber cover ratio) was assessed for each textile sample after each maintenance cycle and each abrasion cycle (55 ratios in total) under standard climatic conditions outlined in EN ISO 139:2005. Translucent adhesive tape was first applied to a defined part of each fabric sample and loaded with a weight of 430 g for 30 s. Subsequently, the adhesive tape was removed and stuck, along with any MPF adhering to the surface, onto a clean white sheet of paper. The tape/paper sample was then run through an Epson Perfection V370 (Epson America Inc., USA) photo scanner at 4800 dpi in 24-bit RGB, and original images of size 5669 × 5669 px (real size is 29.9985 × 2.9985 mm, i.e., 1 px = 25.4/4800 = 0.0053 mm) were obtained. To aid fiber detection, image processing operations were carried out in MATLAB R2023a (version 9.14.0, The MathWorks, Inc., USA) software with the Image Processing Toolbox (version 11.7). Briefly, for contrast enhancement, contrast-limited adaptive histogram equalization of the L (lightness) channel (parameters: Num Tiles = [8 8], Clip Limit = 0.005) was used, and an unsharp mask algorithm (parameters: radius = 2, amount = 1.5) was applied for image sharpening. As the polyester fibers were red on a white background, segmentation was based on color thresholding of the HSV color model, where Hue = 0.835−0.177, Saturation = 0.081−1.000, and Value = 0.000−0.906 (for an example of images produced at each algorithm step, see Figure 2). After segmentation, fiber CF (%) was quantified as the total area of fibers as a proportion of the total image area.

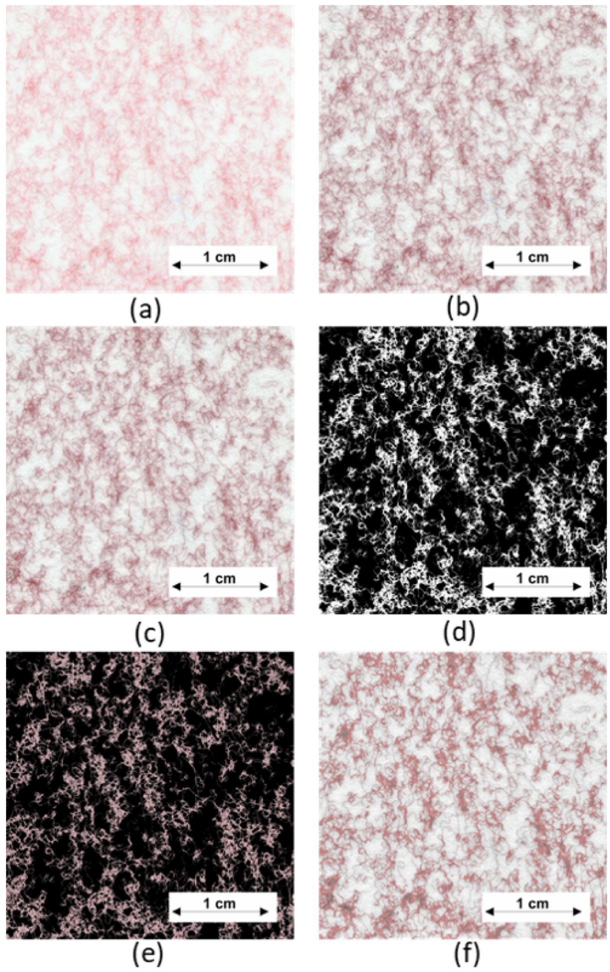

Figure 2. Images taken at each contrast enhancement stage during assessment of loose fiber cover factor: (a) original RGB image of a sample after one maintenance cycle; (b) auto contrast; (c) sharpening; (d) binary image after color segmentation in HSV color space; (e) binary masked image; and (f) final masked RGB image.

3. RESULTS AND DISCUSSION

3.1. Effect of Abrasion on MPF Release. To study the effect of increasing the friction number on the release of MPF and fiber fragments, both types of samples from the Martindale test heads were tested and evaluated (see Section 2.5 for a description of the methodology). The same polyester fabrics were used as samples and absorbents to ensure that all MPF and fibrils obtained in the analysis came from the same source. The fabric samples were abraded up to 2000 times, and MPFs and fibrils produced during abrasion were characterized at 500, 1000, and 2000 abrasions (Figure 3). For each fabric sample, the free fiber coverage area (CF) was evaluated after each cycle under standard climatic conditions. Five samples of loose fiber abrasion were taken from each fabric/abradant sample using adhesive tape (180 ratios in total). As with washing and drying, the fleece samples showed a high initial mean CF (i.e., MPF and fiber release) followed by a gradual decrease with an increasing number of abrasion cycles. For a proper understanding of Figure 3, it is important to note that the data presented in the first column of the graph are obtained from the surface of the untreated fabric (unwashed, undried, unvacuumed), while the data for the columns with the indicated number of abrasion cycles were obtained from samples from which loose fibers were removed by vacuum extraction before and after the abrasion cycles.

Using SEM images of the fibers obtained from the wiped fabric surfaces, we can observe the evolution of the MPF and fiber formation over an extended period of fabric rubbing (Figure 4). Initially, at 500 rubs, the "loose" fibers start to aggregate on the surface, and already at this stage, the fibers fibrillate along their length. Then, after further rubs, more structural changes are evident, especially when, after 1000 rubs, the first fibrillation at the ends of the fibers was identified. After 2000 rotations, knotting of the loose fibrils was observed, the number of loose fibrils increased significantly, and there was significant fibrillation in the structure of the fiber ends (Figure 4c).

3.2. Effect of Repeated Washing and Drying on MPF Release. In this study, 38 L of water was used per wash cycle, and the total area of textile samples washed in one wash cycle was 3 m^2. Kelly et al.[36] have already shown that the amount of

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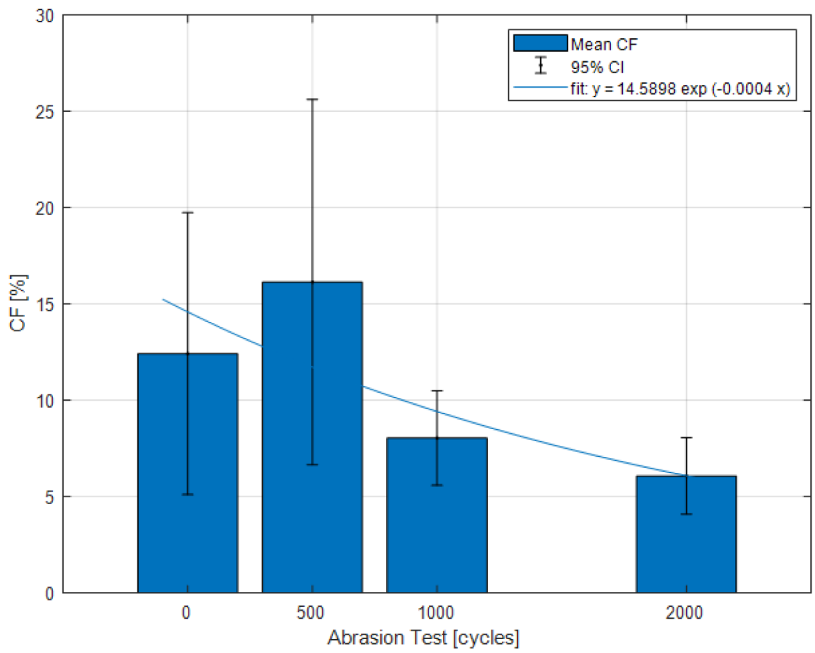

Figure 3. Mean cover factor (CF) determined before and after the Martindale abrasion test.

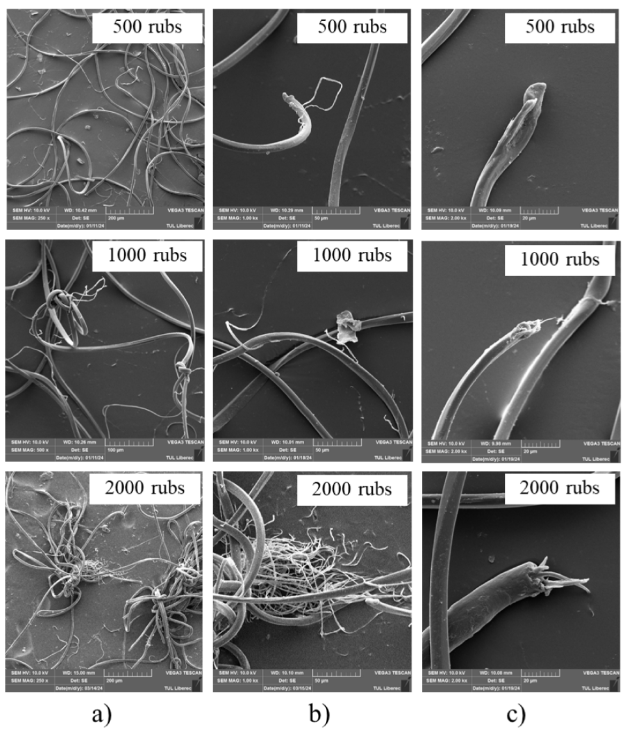

Figure 4. SEM images of microplastic fibers and fibrils after the Martindale abrasion test: (a) longitudinal view of loose fibers and fibrils, (b) detailed view of loose fibers and fibril formation, and (c) gradual change of fibrillation of the fiber end.

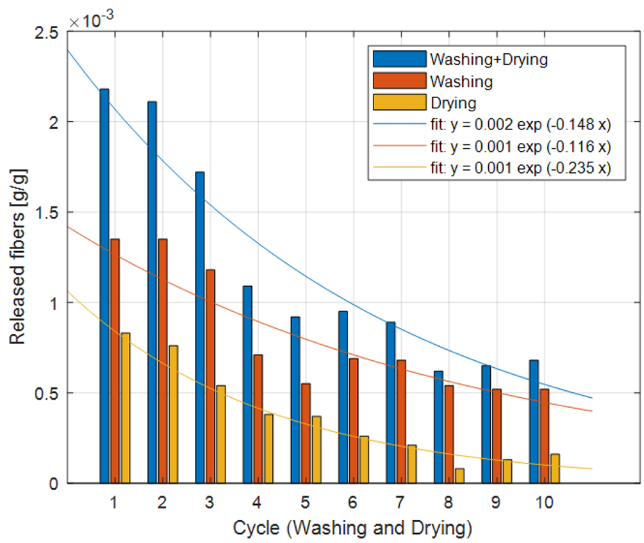

Figure 5. Weight of fiber fragments and MPF (g/g) released after each washing cycle, drying cycle, and over the whole maintenance cycle (washing and drying).

water used affects the amount of microplastics released. The ratio between the amount of wash water and the sample area in this study is 0.078. Cai et al.[28] in his study stateed that 150 mL of wash water was used, the area of the tested samples was 0.01 m^2, and the ratio between the amount of wash water and the sample area was 0.067, which can be considered comparable to this study. In contrast to some previous studies,[28,32,39,40] we captured all MPF released during the washing process. This was possible as we used a filter with a relatively large pore size (25 × 30 μm mesh), which allowed wastewater to flow continuously during the washing cycle. We registered an average of 1.4 mg MPF/g fabric following the first wash, 1.3 mg during the second to fifth washes, and 0.59 mg during the sixth to tenth wash cycles. This is a similar trend to that reported by Hernandez et al.,[31] who also reported that emissions of polyester fleece fabrics decreased with successive washings, with emission values dropping to ca. 0.1 mg/g by the fifth wash (Figure 5 and Table S1).

The relatively constant release of MPF over the third to fifth washing cycles suggests that the fabric itself displays slow-release fiber dynamics (i.e., a continuous release of sheared fibers released during the maintenance process). In contrast, the earlier washing cycles were characterized by the additional

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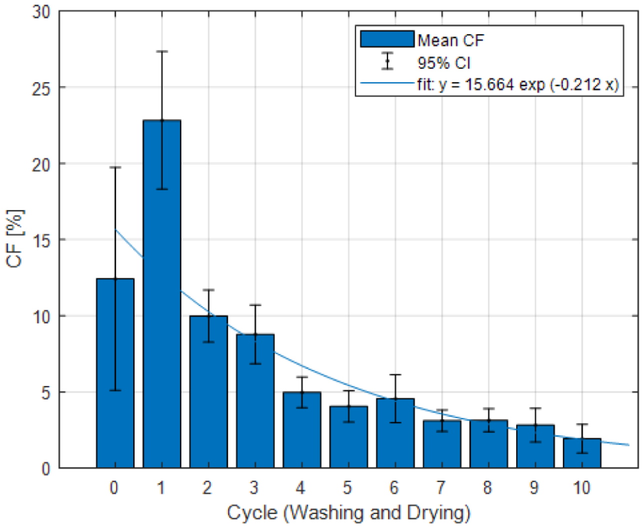

Figure 6. Mean cover factor (CF) and 95% confidence intervals (CI) determined after each washing and drying cycle.

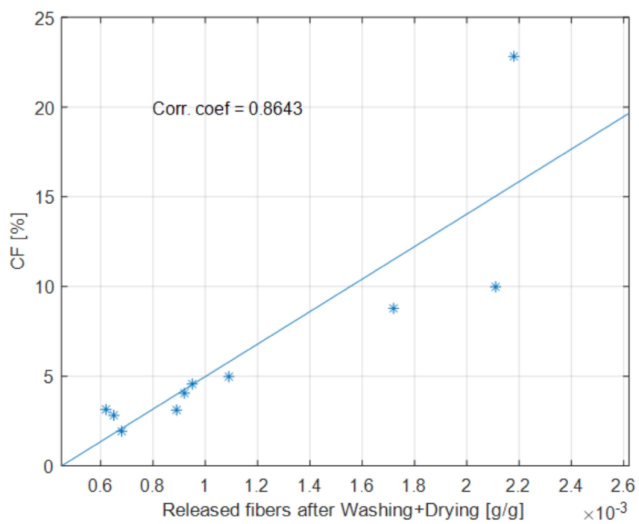

Figure 7. Correlation between two methods for assessing fiber quantity released during washing/drying, (i) the weight of fiber fragments released (x axis) and (ii) fiber cover factor (CF; a.k.a. cover ratio), determined through image analysis (y axis).

Table 2. Relative Changes (±) in Fabric Thickness and Dimensional Changes after One, Five, and Ten Cycles of Washing

Change in thickness			Change in wales per cm			Change in courses per cm		
T_{w+D1}	T_{w+D5}	T_{w+D10}	S_{w+D1}	S_{w+D5}	S_{w+D10}	S_{w+D1}	S_{w+D5}	S_{w+D10}
0.05	0.11	0.16	0.00	−0.01	−0.01	0.00	0.01	0.01

release of fibers insufficiently bonded on the surface of the yarn structure and those deposited on the surface of the fabric as a result of the production process. As with sequential washing, MPF emissions was decreased during sequential tumble drying, with the first drying cycle releasing an average of 0.83 mg MPF/g fabric, while the sixth to tenth drying cycles released an average of 0.168 mg in each drying cycle (Figure 5, Table S1). Kärkkäinen and Sillanpää[32] reported ca. 1.7 mg MPF/g fabric released initially from polyester fleece in a drum dryer, with a

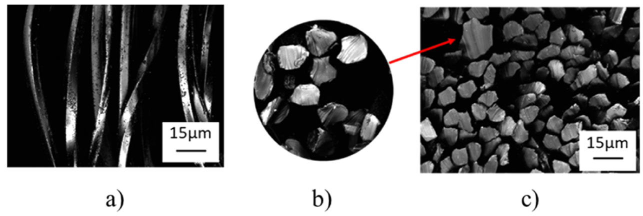

Figure 8. Confocal scanning laser microscope images of (a) longitudinal view of the fibers, (b) fiber cross sections (from basic yarn), and (c) fiber cross sections (from loop yarn).

downward trend in MPF release thereafter. Pirc et al.[30] reported that polyester fleece released 0.2 mg MPF/g after its first tumble drying and showed a downward trend with subsequent cycles, reaching an average of 0.084 mg MPF/g released by the tenth cycle. Nevertheless, further research on tumble drying will be necessary to better characterize the effect of drying on different textile material properties on MPF release. A comparison of fiber release during the washing and drying cycles shows that, during the first to fifth cycle, the mass of fibers and MPF released during the drying process is about two-thirds of that released during washing (Figure 5, Table S1). Over the sixth to tenth cycle, however, this ratio changes, with the mass of fibers and MPF released during drying being around one-third of that released during washing. The higher release levels during washing may be due to the fabric being subjected to greater mechanical stress and water-supported loosening of the structure than when drying in a tumble dryer. It is likely that soaking in water opens the structure of the material, while drying causes the material to contract (shrink), making the fibers to be hold tightly.

Mean CF was highest after the first washing/drying maintenance cycle, with CF values decreasing rapidly over the second and third cycles and the number of MPF released stabilizing thereafter (Figures 5 and 6; Tables S1 and S2). This was confirmed using two different methods, i.e., the "standard" method, where the amount of fibers and MPF released is weighed directly, and the newly developed, nearly equivalent method assessing the CF of released fibers and MPF trapped on the fabric surface. These two methods have a relatively strong positive linear correlation, despite the variation increasing considerably with the released amount of fibers and MPF (Figure 7; correlation coefficient 0.86), suggesting that, at least for lower amounts, the novel method presented here is suitable for accurately assessing cover area (CF). Our results strongly support the idea that a significant proportion of the MPF released during textile washing was already present in and on the textile as a residue from the manufacturing process, i.e., it was not created during the washing/drying cycles and, therefore, is released into the environment during the first few washes of the garment mainly.

3.3. Effect of Repeated Washing and Drying on Fabric Dimensions. The tested material's input thickness was measured at 1.921 ± 0.006 mm, and the number of wales/courses was calculated at 11.5/14.0 per cm, according to standard EN 14971 (800868).

Although there was clear evidence of fiber and MPF release during washing and drying (Figure 5), this did not cause significant dimensional changes in the material tested. On the contrary, relative changes in fabric thickness after one, five, and ten washing and drying cycles (S_{W+D1}, T_{W+D1}; S_{W+D5}, T_{W+D5}; S_{W+D10}, T_{W+D10}; Table 2) indicated an increase in fabric

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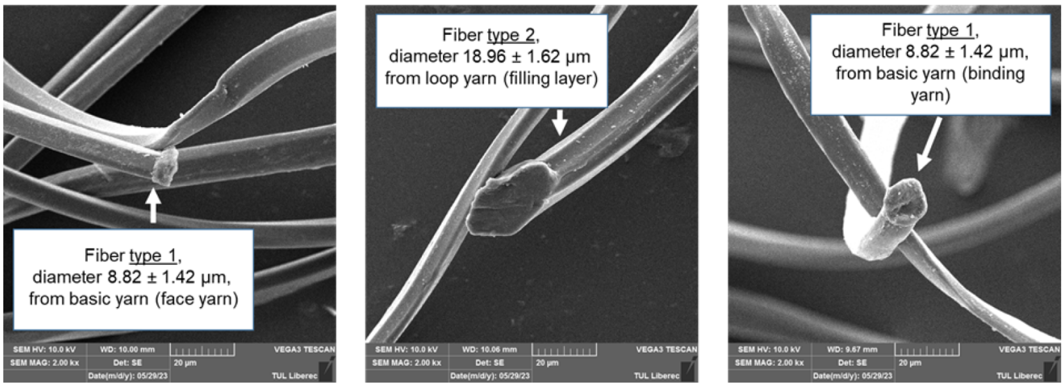
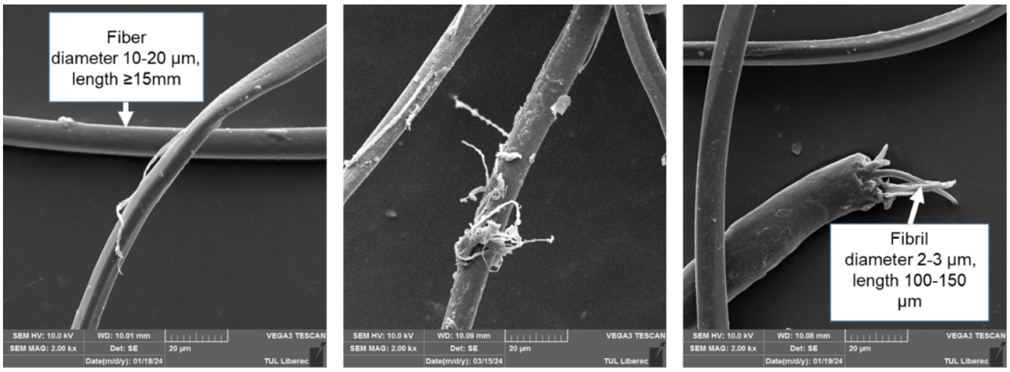


Figure 9. SEM images of the two types of fibers released during washing and drying.



a) b) c)

Figure 10. SEM image showing examples of fibrillation on polyester fibers due to mechanical abrasion, (a) gradual peeling on a fibril, (b) fibril "frosting", (c) fibrillation of the fiber end.

thickness over repeated maintenance cycles, probably caused by "fluffing" (incorporation of air) after drying in the tumble dryer. On the other hand, relative changes in fabric dimensions along the wales axis indicated an overall shrinkage of the material with each maintenance cycle (Table 2). As no comparative studies are available on this issue, our data can be taken as baseline data for future studies.

3.4. Fiber Characteristics. Our fabrics comprised fibers of two diameters, with those forming the basic yarn (face yarn and binding yarn; Fiber Type 1) having a diameter of 8.82 ± 1.42 μm and those of the filling layer (loop yarn, Fiber Type 2) having a diameter of 18.96 ± 1.62 μm (see Figure 8).

Following the washing and drying experiments, SEM images of the fibers indicated no signs of fibrillation or splitting at the fiber end (Figure 9). Indeed, most fibers released during the washing and drying cycles showed a blunt end, somewhat like the cut ends on the factory-prepared samples (Figure 9). This would suggest that washing and drying are not the primary sources of whole fibers and MPF produced by cleavage or breakage. Similar results were also reported in a previous study on 12 different polyester materials by Cai et al.[34] Following the mechanical abrasion experiments, however, SEM images showed clear evidence of fiber fibrillation, with examples of microfibril formation on both the fiber surface (Figure 10 a,b) and at the fiber ends (Figure 10c). This would suggest that direct abrasion, in addition to producing whole fibers (see above), is the main source of MPF (i.e., polyester fiber fragments). Again, similar results were reported by Cai et al.,[28,34] with the authors reporting evidence of fibrillation in polyester materials after 5000 cycles on the Martindale device. However, in our study, we first observed fibrillation of the fibers after 500 friction cycles and fibrillation at the ends of the fibers after 1000 friction cycles (Figure 4).

4. CONCLUSION

This study examined the impact of stresses from abrasion and maintenance (washing and drying) on fiber release and dimensions in samples of polyester fleece fabric using a Martindale apparatus to simulate textile wear through mechanical abrasion and repeated machine washing and tumble drying to simulate textile maintenance. We recorded significant release of fibers and MPF into the environment during textile maintenance, confirmed using standard evaluation methods and a novel method for assessing released fibers retained on the fabric surface. In general, the number of fibers released was high during the first three to five wash/dry cycles, with levels declining and leveling off thereafter. Overall, our results suggest that a large proportion of the fibers released originate as residues from the manufacturing process, with a relatively constant number of fibers released thereafter through abrasion. Our use of a relatively large pore size (25 × 30 μm) mesh filter was effective for collecting fibers and MPF from the washing machine/dryer for testing. Consequently, we recommend (i) the inclusion of a fabric filter in washing machine outlets to reduce fiber and MPF released into the environment during textile washing, (ii) prewashing textiles before they leave the factory to capture the greater part of fibers and MPF released during the first washing cycle, (iii) improving the properties of fleece fabrics to help meet environmental

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standards, and (iv) including our newly developed method for analyzing the CF of loose fibers on fabric surfaces into standard laboratory testing. Furthermore, this study confirmed that microplastic fibers and fibrils can be released from abraded textiles. In particular, the formation of fibrils, as fibers with a much smaller diameter, raises questions about their potential effects on humans and the environment. We have shown that a wide range of factors affect the quality and characteristics of clothes made from polyester fleece fabrics. Generally, it is not feasible to protect against all factors related to fiber and MPF release because fibers and MPF release will always occur during normal maintenance and use. Considering the vast scale of textile production globally, it is becoming increasingly important that legal limits are established, backed up by new technologies, to ensure environmentally sustainable production of polyester fabrics by textile manufacturers.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.5c00258.

> Figure S1: analysis and reconstruction of the Single jersey fleece fabrics structure; Figure S2: single jersey fleece fabrics structure; Figure S3: differential scanning calorimeter analysis; Figure S4: the lint standard filter system heat pump condenser dryer; Table S1: weight of fiber fragments and MPF [g/g] released after each washing cycle, drying cycle, and over the whole maintenance cycle; Table S2: mean, standard deviation and 95% confidence intervals (CI) for fiber cover factors (CF, %) after each of ten washing and drying cycles (PDF)

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Notes

The authors declare no competing financial interest.

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