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RESEARCH ARTICLE

Release of polyester and cotton fibers from textiles in machine washings

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Abstract Microplastics are widely spread in the environment, which along with still increasing production have aroused concern of their impacts on environmental health. The objective of this study is to quantify the number and mass of two most common textile fibers discharged from sequential machine washings to sewers. The number and mass of microfibers released from polyester and cotton textiles in the first wash varied in the range 2.1×10^5 to 1.3×10^7 and 0.12 to 0.33% *w*/*w*, respectively. Amounts of released microfibers showed a decreasing trend in sequential washes. The annual emission of polyester and cotton microfibers from household washing machines was estimated to be 154,000 (1.0×10^{14}) and 411,000 kg (4.9×10^{14}) in Finland (population 5.5×10^6). Due to the high emission values and sorption capacities, the polyester and cotton microfibers may play an important role in the transport and fate of chemical pollutants in the aquatic environment.

Keywords Microplastic · Polyester · Cotton · Washing machine · Household · Emission

Introduction

The plastics are used in huge and growing range of applications due to their advance properties such as lightweight, durability, corrosion resistance, insolation, and plasticity combined with the low production and processing costs. The global plastic production has continuously grown for more than five decades being 322 million t in 2015 that is a 3.4% increase compared to 2014 (Plastics 2016). Due to the immense production and demand, the plastic litter occurs all over the globe, which has raised an environmental concern (Browne et al. 2011; Dubais and Libezeit 2013; Eriksen et al. 2013; Imhof et al. 2013; Lusher et al. 2015; Mani et al. 2015; Setälä et al. 2016; Sruthy and Ramasamy 2017; van der Hal et al. 2016).

Plastics are synthetic polymers composed of many repeated subunits, i.e., monomers. In addition, plastics typically contain additives such as fillers, plasticizers, UV blockers, and colorants. For the environmental studies, small plastic litters are called microplastics that generally refer to the solid, water-insoluble, and persistent particles smaller than 5 mm (JRC 2013). The shape of microplastic particles varied from fibers and spheres to irregular fragments depending on their origin. Cotton, a natural fiber, has also a polymeric structure comprised mainly of cellulose. Since cotton requires several steps of chemical treatments prior to the manufacturing of cotton textiles, the cotton fibers contain some residues of chemicals.

Murphy et al. (2016) have reported that 98% of the microplastics are removed from influent at the modern wastewater treatment plant. The major portion of plastics is removed in primary and secondary sedimentation, and removal is improved by biological filtrations (Talvitie et al. 2015; Carr et al. 2016). However, a proportion of microplastic load passes in influent to the environment. Most of the studies have focused on the microplastics larger than 20 or even 200 μm, and little is known about the removal efficiency of the smallest microplastics.

The presence and abundance of microplastics have been mainly studied from sea and ocean samples (e.g., Lusher

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et al. 2015), but they have been found also in the beaches, sediment, and waters of lakes and rivers (Eriksen et al. 2013; Imhof et al. 2013; Mani et al. 2015). The sampling and sample pretreatment methods varied largely between the published studies (Hidalgo-Ruz et al. 2012; Rocha-Santos and Duarte 2015); therefore, special attention must be paid to these analytical stages while comparing the concentrations of microplastics (Setälä et al. 2016). The quantitation of microplastics from environmental samples has generally been based on the use of optical microscope (Hidalgo-Ruz et al. 2012; Rocha-Santos and Duarte 2015) or a scanning electron microscopy (Eriksen et al. 2013), whereas the type of microplastics has been identified by a Fourier transformation infrared spectrometer (Song et al. 2013) or Raman spectrometer (Imhof et al. 2013; Collard et al. 2015). In addition, Dümichen et al. (2015) have developed a thermal decomposition method coupled with gas chromatography mass spectrometer (Py-GC-MS) for the quantification of polyethylene microplastics.

Microplastics are of special concern, since their bioaccumulation potential increases with decreasing size. They may be ingested by organisms ranging from zooplanktons to fish and birds, and there are several alternative routes to transfer in food webs (van Franeker et al. 2011; Setälä et al. 2014; Collard et al. 2015; Romeo et al. 2015). Even though the microplastic particles may be chemically inert in their pristine form, they may cause physical impairment such as blockage of feeding appendages and pseudo-saturation (van Franeker et al. 2011; Yamashita et al. 2011), and moreover, they typically contain a large variety of harmful additives (Browne et al. 2013; Syberg et al. 2015). In addition, small microplastics have potential to adsorb hydrophobic substances (Lee et al. 2014) and subsequently to act as a vector (Teuten et al. 2009) though its importance should be critically assessed in relation to local environmental conditions (Koelmans et al. 2016). All mentioned previously go also for the cotton fibers discharged into the environment, though they are not as persistent as polyester (Li et al. 2010).

The emissions of polyester microfibers have been reported in four scientific papers. Browne et al. (2011) investigated the fiber numbers released from different polyester garments. The experiments were done by using three different front-loading washing machines without detergent or conditioner. Their concluding result was that a garment can shed over 1900 fibers per wash. Dubais and Liebezeit (2013) reported the fiber discharge of 0.033 to 0.039% *w*/*w* from polyester garment per washing. These two papers do not give the methods and technical conditions in detail. Recently, Hartline et al. (2016) concluded their study on the new and mechanically aged polyester clothes by stating the released fiber masses exceeding 0.3% *w*/*w* of the unwashed garment mass across all treatments. All the experiments of these three studies were performed as detergent-free washing. Pirc et al. (2016) found out in 10 mild, successive washings of polyester fleece textile that fiber emission initially decreased and stabilized at approximately 0.0012% *w*/*w*. In the selected washing conditions, use of detergent and softener did not significantly influence the amount of fiber emission. The emissions of cotton fibers have not been studied earlier, but their importance has been highlighted in various contexts (e.g., Ladewig et al. 2016; Browne 2015). The cotton fibers have more varying chemical composition, i.e., the presence of functional groups such as hydroxyl and carboxyl (Grancaric et al. 2005), than synthetic fibers. Therefore, as a sorbent and carrier, the natural and synthetic fibers may play an important, but different, role in the environmental fate of hydrophobic compounds.

The sources of microplastics in the environment are still not well characterized (Wagner et al. 2014; Eerkes-Medrano et al. 2015). One of the remarkable routes is wastewater treatment plants that are impacted by the load of washing textiles and personal care products (Fendall and Sewell 2009; Browne et al. 2011). Polyester and cotton are the most common textile fibers with a total annual demand of 46 and 24 million t, respectively (Carmichael 2015). The objective of this study was to carry out a systematic investigation of the polyester and cotton emissions stemmed from the machine washes of selected new and unused textiles. The samples were collected from five sequential washes. The amounts of released polyester and cotton microfibers were quantified by performing gravimetric and microscopic analysis, and the concentrations are expressed in masses and numbers per textile mass and surface area. In addition, the annual emission of domestic sources is estimated in Finland. To our knowledge, this is the first study that presents both number and mass of fibers released from textile washings by taking also the smallest fibers into consideration.

Materials and methods

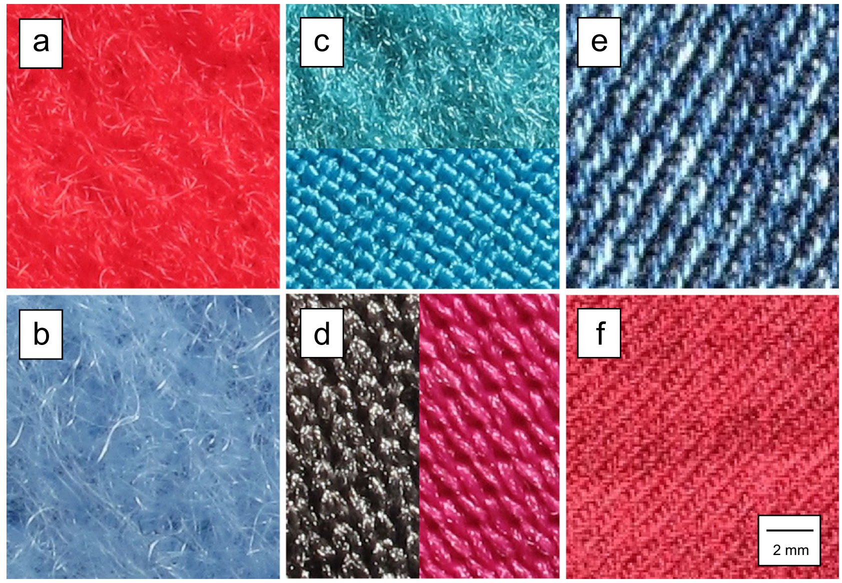
Textiles

Four different types of polyester textiles and two garments of cotton were selected for the study (Fig. 1). All the textiles studied were new and unused. The monochromatic textiles were selected so that they had a bright color differing from each other. The detailed information on the tested textiles is presented in Table 1.

Machine washes

The polyester and cotton textiles were washed with a brand new front-load washing machine (Bosch WAE28477SN) using 50 ml of liquid detergent (pH = 8.0, Bio Luvil Color, Unilever). All the fabrics were separately washed by the washing program “Mix” with the settings as follows: water

Fig. 1 Photos of the studied textiles. **a** Red anti-pill fleece. **b** Light blue fleece. **c** Two sides of turquoise blue Softshell. **d** Black and pink technical sport shirts. **e** Blue cotton jeans. **f** Red cotton shirt. All the textiles were new and unused



temperature 40 °C, spin-dry rate 1200, and total duration 75 min. A total volume of effluent, i.e., both washing and rinsing water, varied in the range of 27 to 39 l prior to each wash; the unloaded machine was cleaned by running a "Super fast" program: water temperature 30 °C, total duration 15 min, and a total volume of effluent 35 l. In order to detect the possible transfer of released fibers to the sequential wash, the textiles of a different color were alternately washed. The five sequential washes were done for each textiles. The textiles were allowed to dry by hanging on clothesline in a room absent of colorful textile fiber sources.

Separation of microplastics

Whole washing effluent was collected into a large polyethylene barrel, and water was stirred until the sampling. To avoid stray fibers between the washes, the barrel was carefully rinsed with tap water after each wash. Sample volume varied from 100 to 600 ml on the basis of fiber concentration. The volumes of three replicate samples were equal. Sampling and filtration were performed immediately after the end of wash. Water samples were filtered (diameter 47 mm, pore size 0.7 μm, type HC, Millipore, Bedford, MA, USA) under vacuum. Sample flasks were rinsed with deionized water (Millipore), and rinsing water was also filtered. The filters were placed into the petri dishes (Millipore) with the caps ajar for drying in the laminar flow bench overnight.

Quantification of microplastics

The filters were weighed with a microbalance (Mettler Toledo XP56) before and after the filtration of water samples. The temperature and relative humidity of the weighing room were recorded. The electrostatic charges of filters were eliminated by using a U-shaped ionizing electrode (PRX U27, HAUG GmbH, Germany). All weightings were done as duplicates, and their means were used in calculations.

The microplastic fibers were counted under the optical stereoscopic microscope (Nikon SMZ-1B, magnification ×35). Altogether, 13 or 14 grids were counted, which represents 10 or 11% of the total effective area (14.2 cm^2) of filters, respectively. Since the fibers were not homogenously distributed

Table 1 Descriptions of the five polyester and two cotton textiles

Sample	Description	Composition	Area (m^2)	Mass (g)	Color
Fleece-AP	One blanket, anti-pill fleece	100% polyester	3.80	762.5	Red
Fleece-nAP	One blanket, no anti-pill fleece	100% polyester	4.45	740.3	Light blue
Softshell	One fabric with finished borders	96% polyester, 4% elastane	3.34	1097.2	Turquoise
Tech sport[a]	Two T-shirts	100% polyester	1.25	254.7	Black
Tech sport[a]	Two T-shirts	100% polyester	1.10	190.6	Pink
Jeans-cotton	One jeans	100% cotton	0.91	748.5	Blue
Shirts-cotton	Two shirts	100% cotton	2.56	475.3	Red

[a] Tech sports were washed at the same time

over the effective area of the filter, but the fibers were more concentrated in the center than in the edge of the filter, the grids were selected on one diagonal line in order to represent all the distance from the centre of filter. The uncertainty caused by the partial counting of the fibers is estimated in "Estimate of fiber emission." The fiber number in washing water (N) was calculated according to the formula:

$$N = \frac{\sum_{i=1}^{n} n(i)}{n_g} \times \frac{A(f)}{A(g)} \times \frac{V(t)}{V(s)}$$

where $n(i)$ is fiber number in a grid i, n_g number of calculated grids, $A(f)$ effective filter area, $A(g)$ area of grid, $V(t)$ volume of total washing water, and $V(s)$ volume of sample.

The results are presented as a mean of three replicate samples (taken from each washing water) by normalizing the masses or numbers of released fibers against the mass of the textiles.

Estimate of fiber emission

The estimate of total fiber emission from Finnish domestics was derived by multiplying the mean of released polyester or cotton fibers with a coefficient of 3.95×10^9 or 5.08×10^{10}, respectively. The mean of released fibers were calculated from the released numbers and masses of all four polyester or two cotton textiles on a basis of the fifth washes. The coefficients were obtained by multiplying the population of Finland (5.5×10^6; Population Register Centre) by the average washing machine load (2.6 kg dry weight), average wash frequency (79 washes per person per year), and portions of fabric types in the washes (polyester 40%, cotton 45% including fabric mixtures). The last three values are based on the consumer survey made by Kristiina Aalto in 2000 (printed report only in Finnish). The portions of fabric types have been re-estimated for representing the current use.

Quality control

For the minimization of sample contamination, all the surfaces being in contact with samples were cleaned carefully with water before the use. The white laboratory dress was worn while handling the sample textiles and samples. The white fibers would increase the mass if contamination takes place after the gravimetric analysis of the clean filters, but they would have no impact on fiber numbers since they can be ignored while counting the fibers on filter. The filters were stored in closed petri dishes to avoid the deposition of airborne particles and fibers. The petri dishes were opened only during the gravimetric and microscopic analysis. After filtration, the wet filters were dried with the petri dish caps ajar in a dust-free laminar flow bench.

Altogether, nine blank samples were taken from the washing water of intermediate washes. Since the blank samples were identically handled with the actual samples, the blank samples quantify the contamination caused by the fibers straying from the wash to another, the deposition of airborne fibers, and the method-based defects such as a possible erosion of filter during the sample treatment.

Since only a part of whole washing water was filtered, the homogeneity of suspension was evaluated by collecting three replicates of each washing water. The average of relative standard deviations (RSD = standard deviation/ mean × 100%) was clearly lower for the fiber masses (RSD = 4.5%) than for the fiber numbers (RSD = 18%) due to the partial counting of the fibers collected on the filters (see "Quantification of microplastics"). When additionally taking the blank samples into consideration, the total uncertainty of fiber masses and numbers presented in this study is 10 and 20%, respectively.

Results

Quantities of released microfibers to the washing machine effluents

The mass of released microplastic fibers varied between 0.12 and 0.33% *w/w* in the first wash. The highest fiber mass discharged was from Tech sport followed by Softshell, Fleece-nAP, and Fleece-AP (Fig. 2a). The corresponding mass was 0.17% *w/w* for Jeans-cotton and 0.26% *w/w* for Shirts-cotton (Fig. 2b). In the second wash, the masses of released polyester fibers were only one third or less compared to first wash. This level remained for Fleece-AP and Fleece-nAP in third to fifth washes, whereas it dropped down to one tenth for Softshell and Tech sport in the fifth wash. The mass of released cotton fibers from first to fifth wash showed a relatively even decrease being approximately 40% in the last wash.

The number of released microplastic fibers ranged from 2.1×10^5 to 1.3×10^7 per fabric kilogram during the first wash. The highest number discharged from Softshell followed by Tech sport, Fleece-AP, and Fleece-nAP (Fig. 3a). The number of released cotton fibers in the first wash was 3.6×10^6 for jeans and 4.6×10^6 for shirts sequential (Fig. 3b). The number of released fibers decreased into one tenth from the first to fifth washes for all polyester and cotton textiles with the exception of Fleece-nAP that had higher numbers in fourth and fifth than in second and third washes.

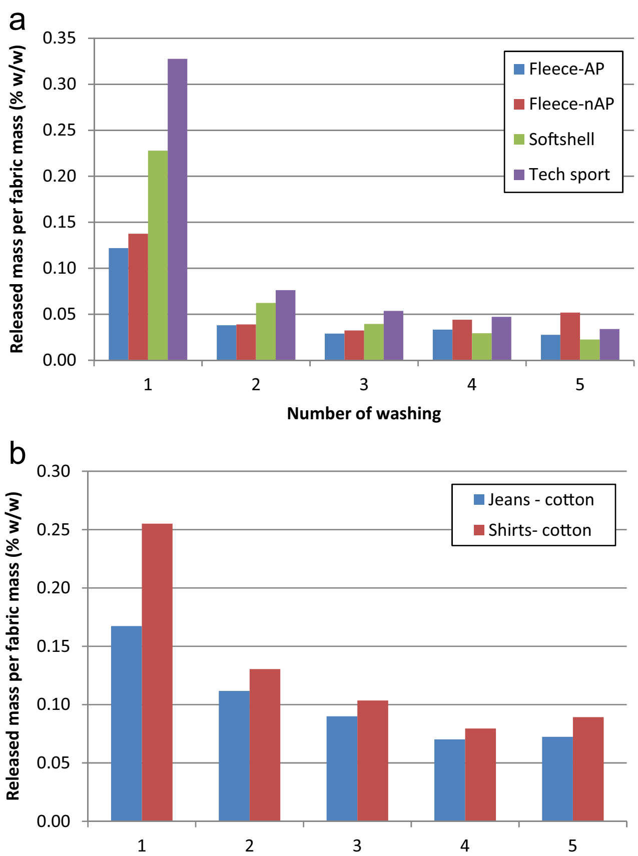


Fig. 2 The masses of released (**a**) polyester and (**b**) cotton fibers per fabric mass (mg/kg) in five sequential washes

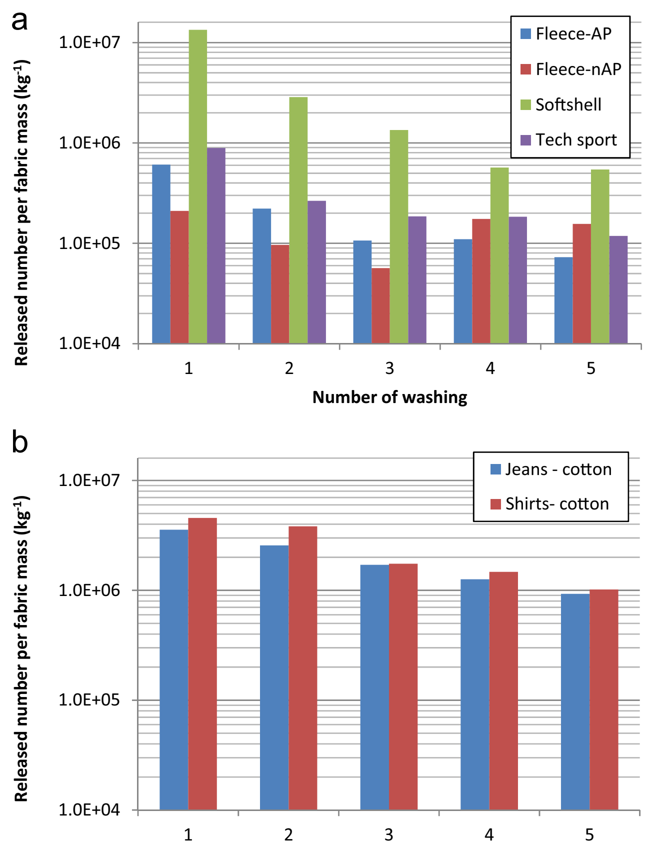


Fig. 3 The numbers of released (**a**) polyester and (**b**) cotton fibers per fabric mass (per kg) in five sequential washes

Mean mass of released single microfibers

The mean mass of single microplastic fibers was estimated by dividing the total mass of released fibers by their total number. Figure 4a shows the mean mass of single fibers of four textiles in five sequential washes. The largest fibers were released from Fleece-nAP followed by Tech sport and Fleece-AP. Their mean masses of single fibers varied between 1.70 and 7.0 μg. The fibers released from Softshell were substantially smaller with a mean mass of 0.2–0.5 μg. The mean masses of single fibers varied to some extent between the sequential washes, but no clear decreasing or increasing trends were observed.

The mean masses of single fibers released from cotton textiles varied in the range 0.3–0.6 μg, but they were slightly heavier in the fifth wash (0.8–0.9 μg) (Fig. 4b). The masses did not remarkably differed between two types of cotton fabric.

Figure 5 shows the photographs of the fibers collected on the filters from the first washing effluents. The photographs suggest that the smallest polyester fibers were released from Softshell which is in line with the results derived from gravimetric and microscopic analyses. The cotton fibers are less homogenous in size than those of polyester.

Estimated annual emission of microfibers in Finland

The annual fiber emissions from domestic textile washes in Finland are estimated on a basis of values given in "Estimate of fiber emission" and the means of fibers released in the fifth washes of the present study. The means of released fibers from polyester textiles were 340 mg and 2.23×10^5 per washing machine effluent. The corresponding means for two cotton textiles were 809 mg and 9.73×10^5. Thus, the annual mass of polyester fibers released in washing machine effluents is 154,000 kg that is roughly one third of the load of cotton fibers (411,000 kg). The total number of polyester fibers is annually approximately 110 trillion that is approximately 20% of the annual fiber number discharged from cotton textiles (4.9×10^{14}). The emission estimate values are given for figuring out the magnitude of the microplastic source, but they should be used only with concern due to the uncertainties discussed in the following chapter.

Discussion

The numbers of microplastic fibers released from washing machines found in this study is high. Browne et al. (2011)

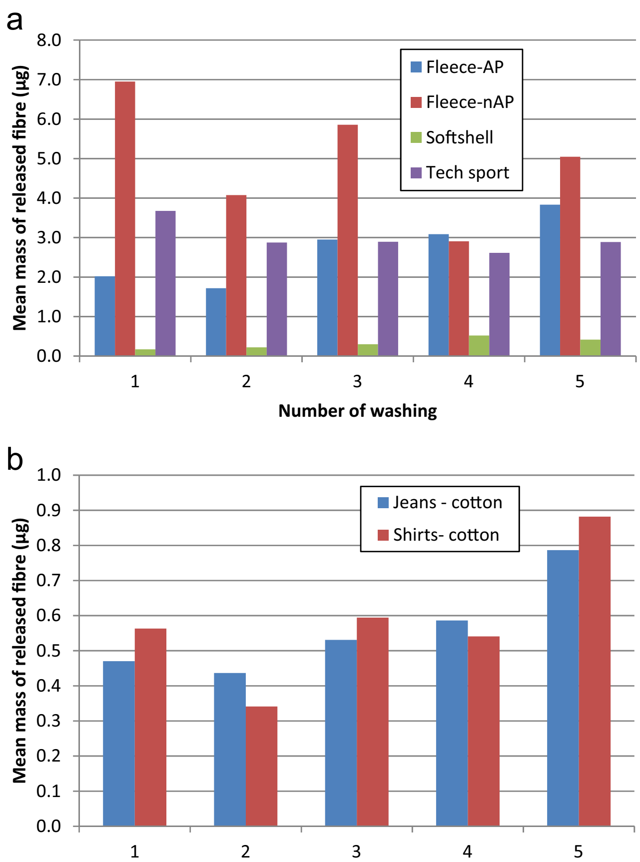


Fig. 4 The mean masses of single fibers in five sequential washes. **a** Polyester. **b** Cotton

Table 2 Comparison of the washing conditions and analytical methods between two studies

	Present study	Browne et al. (2011)	Hartline et al. (2016)	Pirc et al. (2016)
Water temperature (°C)	40	40	30–40	30
Detergent	Yes	No	No	Yes/no
Spin-dry speed (RPM)	1200	600	NDA/1200	600
Duration (min)	75	NDA	30/48	15
Textile studied	Fleece, anti-pilling fleece, Softshell, and technical sport shirts	Blankets, fleeces and shirts	Five different types of outwear jackets (two fleeces)	Six identical fleece blankets
Pore size of sample filter (μm)	Pore size 0.7 μm	NDA	333 20	200 × 200 μm
Quantitation	Microscope and balance	Microscope	Balance	Balance

Dubaish and Liebezeit (2013) data on experimental conditions is not available

NDA no data available

reported that a single garment can produce >1900 fibers per wash that is two to three orders of magnitude less than observed in the present study. The remarkable differences between two studies are likely due to the different sample pretreatment particularly the pore size of the filters (Table 2). In addition, the different spin-dry speed and uses of detergent may play a role in the release of fibers from the textiles. On the other hand, this substantial difference cannot be explained by the design of the washing drum or type or quality of the tested textiles since Browne et al. (2011) made the experiments with three different washing machines and three polyester textiles. However, they did not report the differences between these factors.

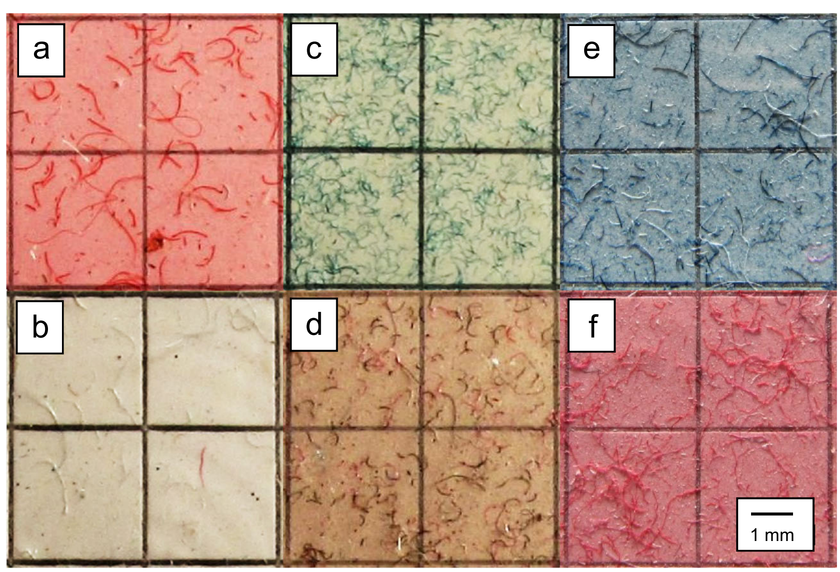


Fig. 5 Images of fibers filtrated from the first washes. **a** Red anti-pill fleece. **b** Light blue fleece. **c** Two sides of turquoise blue Softshell. **d** Black and pink technical sport shirts. **e** Blue cotton jeans. **f** Red cotton shirt. Note that the sample volumes were not equal

Instead of fiber numbers, the studies published recently have investigated the relative masses released from washing machines. The different polyester garments have been shown to discharge 0.033 to 0.3% *w/w* in the first wash (Dubaish and Liebezeit 2013; Hartline et al. 2016), which is consistent to values presented in this study. Pirc et al. (2016) found that the average relative fiber emission initially decreased and then stabilized at approximately 0.0012% *w/w* in ten sequential washes. The similar trend was found in this study, but the relative emission value (0.02 to 0.05% *w/w* in the fifth sequential washes) was clearly higher than that reported by Pirc et al. (2016). The difference is likely due to the filtration of samples, as Pirc et al. (2016) used a stainless steel filter with 200 × 200-μm openings that is much larger than a filter of pore size 0.7 μm used in this study. Most of the fibers were approximately 10 to 20 μm in thickness and 100 to 1000 μm in length (Fig. 5), and therefore, part of them may pass the filters of pore size >20 μm. For instance, the small fibers and particles may play an important role in the environmental fate of hydrophobic chemicals since the surface area per mass increases inversely with particle size to the power of two.

The annual emission of polyester and cotton fibers discharged from using domestic washing machines into wastewater is remarkable and probably one of the main sources that release microfibers with a continual flow. The released fiber masses are only 0.5 and 1.8% of the total annual sales of polyester and cotton textiles, respectively, which scales the values on realistic level. It must bear in mind that the estimation of annual emissions includes at least three sources of uncertainty: (a) the estimate of washing machine load should be weighted with the washing frequencies of different textiles. For instance, the technical sport clothes are typically washed after every use, whereas the fleece jackets are washed only one or a few times in a year. (b) The type, age, and abrasion of the textile as well as manufacturing process including finishing treatment may play a role in the release of fibers during the laundering. (c) The estimation is based on the certain washing conditions, but many factors may influence on the release of textile fibers as mentioned in the previous paragraph. (d) In the present study, the washing conditions were selected so that they represent the most common and average settings. The release of textile microfibers is dependent on several factors such as (1) spin-dry rates of current washing machines vary typically between 600 and 2000 spins per minute. As the centrifugal force is proportional to square of peripheral speed, an increasing spin-dry rate is supposed to enhance the release of textile fibers. The distance of washing textiles from the center point of the drum depends on the load and the shape of drum. (2) The drum load affects the abrasion between the textiles and the abrasion between textiles and washing drum. The latter type of abrasion has striven to minimize by designing to be especially gentle to textiles. (3) Temperature of washing water should not play an important role in the emissions of textile fibers when followed the washing instruction (30 or 40 °C). The future studies are needed to fill the knowledge gaps and to quantify the factors mentioned previously before the precise emission assessment is possible.

The numerous physico-chemical properties of particles and fibers affect their transport and fate in aquatic environment. Due to the gravitational forces, the fibers with micrometric dimensions and density larger than that of water will eventually end up to the sediment, and thus, both polyester and cotton fibers will accumulate in the sediments. As a consequence of the difference in surface properties and functional groups, polyester and cotton fibers possess different capacity to sorb and release chemical pollutants (Grancaric et al. 2005). In addition, the chemical treatment of these two most common textile fibers varies largely, and therefore, they possess different content of additives and possible contaminants from manufacturing processes. Because of the facts mentioned previously, it requires more research to understand the different roles of these most common textile fibers in the transport and fate of chemical pollutants in the aquatic environment (Ladewig et al. 2015).

Summary and conclusions

The study aimed to quantify the number and mass of two most common textile fibers that were discharged from washing machine to sewers and to estimate their annual emissions in Finland. Four various types of polyester and two cotton textiles were investigated in five sequential washes. The number of microfibers released from polyester and cotton textiles in the first wash varied in the range 2.1×10^5 to 1.3×10^7 and 0.12 to 0.33% *w/w*, respectively. The highest numbers were discharged from Softshell followed by cotton textiles. Both number and mass of released microfibers showed a decreasing trend in sequential washes. The mean masses of single microfibers varied in 1.7 to 7.0 μg for Fleece-nAP, Tech sport, and Fleece-AP, while they were less than 1.0 μg for Softshell and cottons. Most of the fibers were approximately 10 to 20 μm in thickness and 100 to 1000 μm in length, and therefore, they are able to pass the meshes that have been used for the sampling of microplastics in numerous studies. The annual emission of polyester and cotton microfibers from household washing machines to waste water treatment plants was estimated to be 154,000 (1.0×10^{14}) and 411,000 kg (4.9×10^{14}) in Finland (population 5.5×10^6). These emission values indicate that the domestic washing of textiles is a remarkable source of microplastics and natural fibers, but the values should be used with concern until the input data of the washing frequency and ratios per wash of different types of textiles are precisely known. Due to the high emission values and sorption capacities, the polyester and cotton microfibers may play an important role in the transport and fate of chemical pollutants in the aquatic environment. Therefore, it requires more research to fill the gap in knowledge on the transport and fate of these most common textile fibers in the aquatic environment. Special attention should be paid to these microfibers due to their high surface-area-to-mass ratio, though it requires to overcome the analytical challenges related to feasible and efficient sample pretreatment, identification, and quantification methods.

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