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Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions

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ABSTRACT

Washing clothes made from synthetic materials has been identified as a potentially important source of microscopic fibres to the environment. This study examined the release of fibres from polyester, polyester-cotton blend and acrylic fabrics. These fabrics were laundered under various conditions of temperature, detergent and conditioner. Fibres from waste effluent were examined and the mass, abundance and fibre size compared between treatments. Average fibre size ranged between 11.9 and 17.7 μm in diameter, and 5.0 and 7.8 mm in length. Polyester-cotton fabric consistently shed significantly fewer fibres than either polyester or acrylic. However, fibre release varied according to wash treatment with various complex interactions. We estimate over 700,000 fibres could be released from an average 6 kg wash load of acrylic fabric. As fibres have been reported in effluent from sewage treatment plants, our data indicates fibres released by washing of clothing could be an important source of microplastics to aquatic habitats.

1. Introduction

Microplastics have accumulated in marine and freshwater environments, and in some locations outnumber larger items of debris (Browne et al., 2011; Thompson et al., 2004; Wagner et al., 2014). The sources of microplastic include the fragmentation of larger plastic items once they have entered the environment (secondary sources), and also the direct input of microplastic sized particles, such as microbeads used in cosmetics and pre-production pellets (Napper et al., 2015), or particles and fibres resulting from the wear of products while in use (primary sources). Microplastics can be ingested by a wide range of species both in marine (Anastasopoulou et al., 2013; Gall and Thompson, 2015; Lusher et al., 2013) and freshwater environments (Sanchez et al., 2014; Eerkes-Medrano et al., 2015). Laboratory studies indicate the potential for physical harm to biota from the result of ingestion (Wright et al., 2013). Ingestion could also facilitate the transfer of chemicals to organisms, however the relative importance of plastic debris as a vector in the transport for chemicals is not certain (Besseling et al., 2013; Rochman et al., 2013; Koelmans et al., 2013; Koelmans et al., 2014). Encounter rate, as well as polymer type and any associated chemicals (sorbed or additives), will influence the potential for effects in the environment (Teuten et al., 2007; Bakir et al., 2012; Koelmans et al., 2014; Bakir et al., 2014), therefore it is important to understand the relative abundance, as well as the sources of various types of microplastic.

Microplastic has been reported in a wide range of aquatic habitats, including beaches, surface waters, the water column and subtidal sediments (Lattin et al., 2004; Thompson et al., 2004), and there is evidence that the abundance is increasing (Thompson et al., 2004). They are also reported in some of the most remote environments, including the deep sea and the arctic, indicating their ubiquity and the need for further understanding about the potential environmental consequences (Obbard et al., 2014; Woodall et al., 2014).

Release of microplastic sized fibres as a result of washing of textiles has been widely reported as a potential source of microplastic (Browne et al., 2011; Dris et al., 2015; Essel et al., 2015; GESAMP, 2015; Wentworth and Stafford, 2016), however there has been little quantitative research on the relative importance of this source or on the factors that might influence such discharges. This is the focus of the research described here. In this context we consider microplastics as particles of plastic <5 mm in their smallest dimension. While some fibres may be longer than 5 mm they will usually have a diameter considerably less than 5 mm. There is a lack of clarity on the formal definition for the lower size limit of microplastic and in environmental studies this has tended to relate more to the method of capture; e.g. mesh size of plankton nets used to sample water, or the method of identification such as spectroscopy. At present the smallest particles identified form the environment are around 20 μm in their smallest dimension.

Textiles have the potential to release fibres into the environment, and one pathway is via laundering in washing machines. A range of fibres are used in the production of textiles; these include natural fibres (such as cotton and wool), synthetic fibres (such as nylon) and some are blends of natural and synthetic (such as polyester-cotton). Synthetic

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fibres have been used to supplement cotton, wool and linen in textiles for >50 years, and fabrics such as polyester and acrylic are now widely used in clothing, carpets, upholstery and other such materials. Washing of clothing has been suggested as a potentially important source of microplastic fibres (Browne et al., 2011).

Synthetic microplastic fibres are frequently reported in samples from sediments, the water column and biota (Browne et al., 2011). Waste effluent from washing machines, containing released fibres, will then travel via wastewater to sewage treatment plants (Leslie et al., 2013; Dris et al., 2015). Due to the small size of the fibres, a considerable proportion could then pass through preliminary sewage treatment screens (typically coarse, >6 mm, and fine screens, 1.5–6 mm) (Water Environment Federation, 2003), and be released into aquatic environments. As synthetic fibres are not readily decomposed by aerobic or anaerobic bacteria, any that are intercepted in the sewage treatment plant will accumulate in sewage sludge, and may subsequently be released back to the environment; for example if the sludge is returned to the land or dumped at sea (Habib et al., 1998). Hence, there is a considerable potential for fibres from synthetic textiles to accumulate in the environment; Gallagher et al. (2016) found predominately fibres when surveying the Solent estuarine complex (U.K.) for microplastic. Similarly Dris et al. (2015), found considerable quantities of fibres in the River Seine. There is evidence that some of this material can be transported as airborne particulates (Dris et al., 2015); however it would appear that considerable quantities enter directly from sewage treatment (Browne et al., 2011). To date, there has been limited research to establish the importance of clothing as a source of microplastic contamination to the environment.

A study by Browne et al. (2011), sampled wastewater from domestic washing machines and suggested that a single garment could produce >1900 fibres per wash (Browne et al., 2011). To examine the role of the sewage system as a pathway to the environment, Browne extracted microplastic from effluent discharged by treatment plants, and also examined the accumulation of microplastic in sediments from sewage sludge disposal sites. On average, the effluents contained one particle of microplastic per litre, including polyester (67%) and acrylic (17%) and polyamide (16%); these proportions were similar to the relative proportions found on shorelines and disposal-sites (Browne et al., 2011). Similarly, a high number of plastic fibres were observed in the sediments near to a sewage outfall in Amsterdam (Leslie et al., 2013), and have been reported even 15 years after application in terrestrial soils that have received sewage sludge (Zubris and Richards, 2005). Unless the release of microplastics to waste water or sewage treatment practices change, the release of microplastic to the environment via sewage is likely to increase, as the human population grows. It is anticipated, for example, that reductions in emissions of microbeads via sewage will be reduced as a consequence of legislation to prohibit their use in cosmetics (Napper et al., 2015).

However, there are currently no peer reviewed publications that compare the quantity of fibres released from common fabrics due to laundering. In addition, the potentially important influence of washing practices including temperature, the use of detergent and fabric conditioners have not been examined. Here we tested three different fabrics that are commonly used to make clothes; polyester, polyester-cotton blend, and acrylic. These fabrics were then laundered at two temperatures (30 °C and 40 °C), using various combinations of detergent and fabric conditioner. The fibres extracted from the waste effluent were examined to determine the typical size, and to establish any differences in the mass/abundance of fibres among treatments.

2. Method

Three synthetic fabric types were selected based on their prevalence in high-street retail stores close to Plymouth, UK. The chosen fabric types were all from jumpers (Fig. 2), with each being a different colour so they could be readily distinguished after fragmentation; 100% polyester (black), 100% acrylic (green) and 65% polyester/35% cotton blend (blue). Four replicates of each garment were purchased, with each replicate sourced from a different retail outlet to provide a representative sample. The identity of each fabric type was confirmed by Fourier transform infra-red spectroscopy (FTIR), using a Hyperion 1000 microscope (Bruker) coupled to an IFS 66 spectrometer (Bruker). The spectra obtained were compared to a spectral database of synthetic polymers (Bruker I26933 Synthetic fibres ATRlibrary). As each garment varied in overall size, 20 cm × 20 cm squares were cut from the back panel of the garments and the edges hemmed by 0.5 cm using black and white cotton thread to deter the excess loss of fibres.

A Whirlpool WWDC6400 washing machine was used to launder the garment samples. While it would be valuable to compare a range of washing machines, this was beyond the budget of the current research. This machine was selected as it is a popular brand used for domestic laundry. The number of fibres released from the wastewater outlet, as a result of laundering, was recorded. To achieve this, a nylon CellMicroSieve™ (Fisher Scientific), with 25 μm pores, was attached to the end of the drain hose. Once a cycle was complete, the CellMicroSieve™ was removed and the fibres collected. Due to the potential build-up of detergent or conditioner on the collected fibres, they were washed using 2 L of water and filtered again over Whatman No. 4 filter papers, and then dried at 30 °C to constant weight. Once dry, the fibres were weighed by a Cubis® precision balance (Sartorius). The weight of fibres were compared across four factors: Factor one, (fabric type, fixed factor, 3 levels: 100% polyester, 100% acrylic, and 65% polyester/35% cotton blend); Factor two wash temperature (fixed factor, 2 levels; 30 °C and 40 °C); Factor three, detergent (3 levels; detergent absent, 20 mL bio-detergent present (contains enzymes), 20 mL non-bio detergent present); Factor four, conditioner (2 levels; 20 mL conditioner absent or present). Factors gave a total of 36 treatments (Fig. 1).

In this study the main factors of interest were: fabric type, temperature, presence of detergent and/or conditioner. The duration of each wash and the rotations per minute are also factors of potential relevance, but were beyond the scope of this study. Therefore, in order not to confound the experimental design they were kept constant (Duration, 1 h 15 min and 1400 rotations per minute (R.P.M)). Each treatment had four replicates.

Cross-contamination was minimized to <8 fibres per wash between washes, by running the washing-machine at 30 °C, 1400 R.P.M for 45 min between washes with no fabric present. Any initial spike in fibre loss from new clothes was reduced by washing each fabric four times before recording any data. Care was taken to ensure any potential sources of airborne contamination were minimized during the analysis (Woodall et al., 2015). The number of fibres released in the effluent from each wash, N, was then estimated from the weight of captured fibres using the following equations and assuming the fibres were of cylindrical shape:

$i)\, Vt = \frac{Mt}{D}\; ii)\, V(avg.fibre) = \pi r^2 l\; iii)\, N = \frac{Vt}{V(avg.fibre)}$ where *Vt* is the total volume of fibres collected, *Mt* is the total mass of fibres collected, *D* is the density, *V(avg.fibre)* is the mean volume of one fibre, *N* is number of fibres, *l* is the length and *r* is the radius.

For each product: equation i) allowed calculation of the total volume of fibres collected; equation ii) allowed calculation of the average volume of a fibre from each garment; by dividing the total volume of fibres by the average volume of a single fibre, equation iii) allowed estimation of the approximate number of fibres released in the effluent from each wash.

Fibres were visualised by scanning electron microscopy (JEOL, 7001F); images taken were used to measure the width of the fibres, and also to analyse their topography. Images of the fibres were also taken by using LEICA M205C light microscope and analysed by Image J to measure their length (Rasband, 2015). For each fabric type, a mean

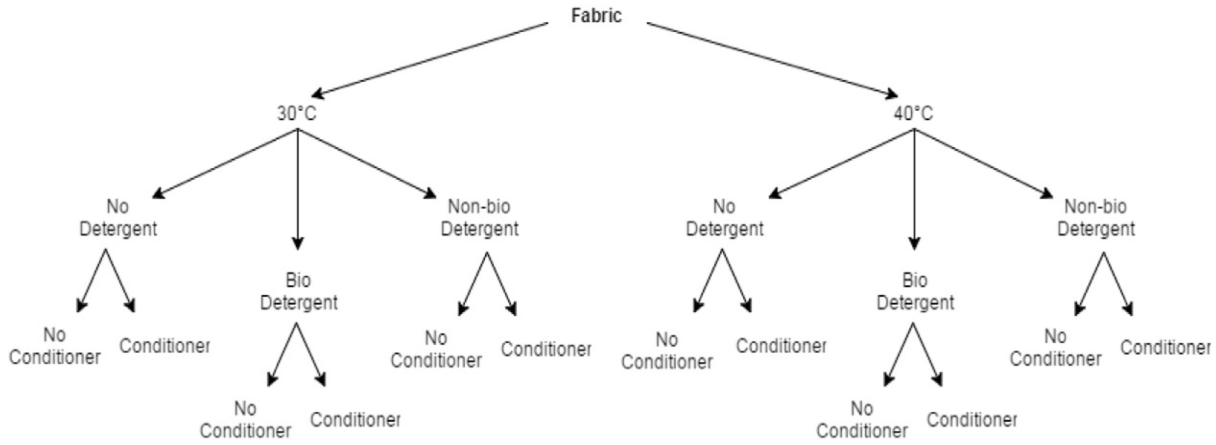

Fig. 1. Experimental design showing factors used for each fabric type (acrylic, polyester, polyester-cotton blend).

size was calculated for length and width based on data from 10 individual fibres.

Using GMav for windows, 4-Way Analysis of Variance (ANOVA) was used to establish any significant effects ($p < 0.05$) between treatments. Post-hoc SNK tests were then used to identify the location of any significant effects.

3. Results

Substantial numbers of microplastic fibres (smallest dimension, <5 mm) were collected from jumpers made out of all three of the common man-made fabrics (polyester, acrylic and polyester-cotton blend) examined (Fig. 2). These were discharged into wastewater from a generic cycle of a domestic washing machine. The fibres were confirmed to be the material type stated on the garment by Fourier transform infra-red spectroscopy. Loss of fibres during the first 4 washes were recorded (Fig. 3), but not included in the data analysis. Polyester showed a steady decrease in fibre loss overall: 1st wash (2.79 mg) to 5th (1.63 mg). Acrylic followed a similar pattern, but the fibre loss decreased more rapidly: 1st wash (2.63 mg) to 4th (0.99 mg). Polyester-cotton blend had the least variation, and showed little decrease between subsequent washes: 1st wash (0.45 mg) to 4th (0.30 mg). Since there was little change in fibre release between the 4th and 5th wash data, data from the 5th wash was used for formal analysis.

While there was a consistent trend between fabric types, ANOVA revealed significant complex interactions between the 4 Factors (Table 1). Focussing on the type of fabric, polyester-cotton blend was consistently found to shed fewer fibres than both the other fabric types, regardless of

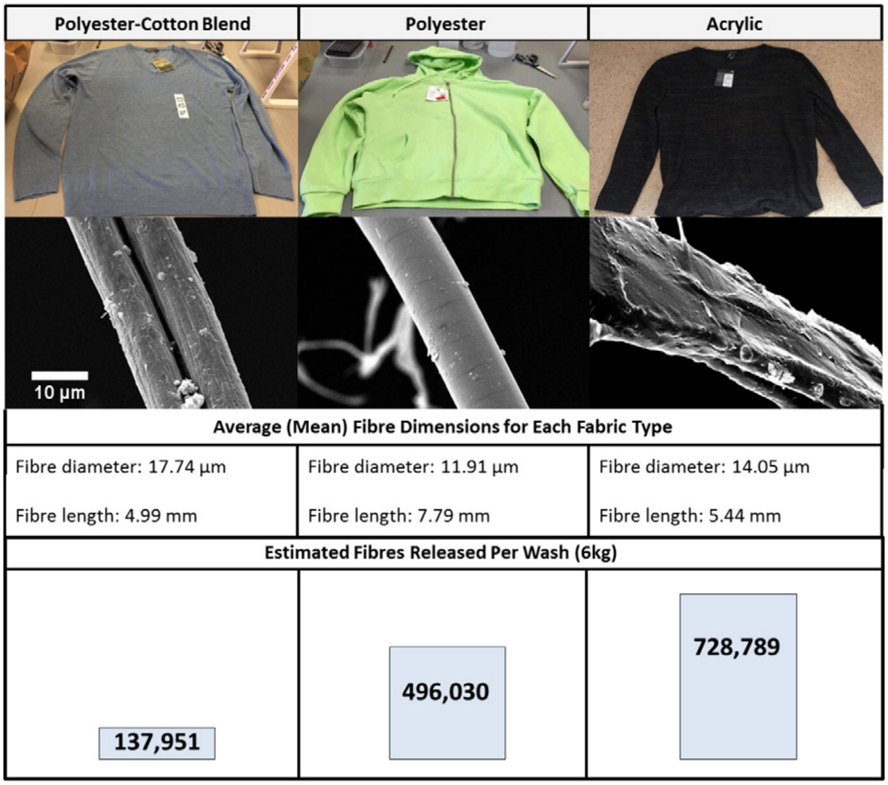

Fig. 2. Images to show the original garments (each representing a different fabric), and a scanning electron microscopy image (SEM) of a typical fibre from each fabric (the scale bar is consistent for all images - 2500× magnification). Key details are included below about the mean dimensions of fibres released during laundering, and estimated quantity released from the fabric during each wash (assuming a typical washing load of 6 kg).

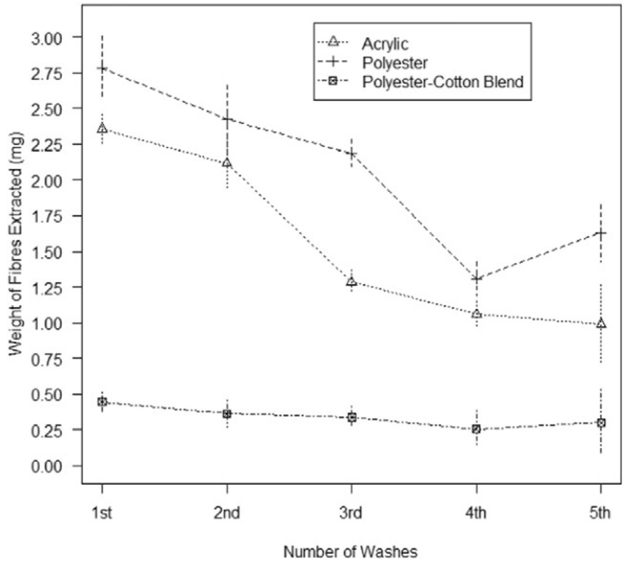

Fig. 3. Fibre loss from three fabrics (acrylic, polyester & polyester-cotton blend), over the first 5 washes. Data from the 5th wash was used in the analysis (n = 4, ±SD).

the differing treatments. This trend was consistent for all 12 relevant interactive effects, and was significantly so for 9 out of these 12 interactions (Table 2a). However, the significance of this effect varied according to the treatment used, creating different interactions. There were some effects of temperature; for example, polyester was often found to release more fibres than acrylic at 40 °C, when compared against 30 °C (Table 2c).

There were also some significant effects of conditioner usage, where polyester-cotton blend consistently shed more fibres when conditioner was used. It was also shown that more fibres tended to be released with the addition of bio-detergent and conditioner. Detergent showed the least clear pattern; however, in some treatment combinations, having no detergent or using bio-detergent resulted in lower quantities of fibres being released. Polyester-cotton blend was also found to shed the least fibres when detergent was absent, and the most when non-bio detergent was used. Hence while there was a clear and fairly consistent trend between fabric types, the effects of temperature, detergent and conditioner were less consistent with some significant effects depending on the specific combinations of factors used.

The extracted fibres were visualised by scanning electron microscopy to examine the differing shapes and surface topography. Polyester-cotton blend fibres had a rough texture, and were regularly observed as a fusion of 2 smaller fibres. Similarly, acrylic fibres had an extremely coarse surface. Polyester fibres were smooth, without any fracturing (Fig. 2).

Table 1
Analysis of variance (ANOVA) for factors affecting release of fibres as a consequence of various laundering treatments (n = 4; **bold** = p ≤0.05). Key: Temp (temperature), Deter (detergent), Cond (conditioner).

Source	Df	MS	*F*	P
Fabric	2	5.36	83.18	**0.00**
Temp	1	0.10	1.54	0.22
Cond	1	0.37	5.67	**0.02**
Deter	2	0.52	8.07	**0.00**
Fabric × Temp	2	0.02	0.33	0.72
Fabric × Cond	2	0.12	1.88	0.16
Fabric × Deter	4	0.20	3.13	**0.02**
Temp × Cond	1	0.15	2.28	0.13
Temp × Deter	2	0.13	2.09	0.13
Cond × Deter	2	0.58	9.00	**0.00**
Fabric × Temp × Cond	2	0.06	0.86	0.43
Fabric × Temp × Deter	4	0.06	1.00	0.41
Fabric × Cond × Deter	4	0.33	5.05	**0.00**
Temp × Cond × Deter	2	0.64	9.91	**0.00**
Fabric × Temp × Cond × Deter	4	0.38	5.95	**0.00**
Residual	108	0.06		
Total	143			

Acrylic fibres were on average 14.05 μm in diameter and 5.44 mm in length, giving an average of 763,130 fibres/mg of dry fibres collected from the effluent. Polyester fibres were on average 11.91 μm in diameter, but were longer at 7.79 mm, resulting in around 475,998 fibres/mg of dry fibres collected from the effluent. Polyester-cotton blend fibres were the widest fibres being on average at 17.74 μm, but had the shortest length at 4.99 mm, with an average 334,800 fibres/mg of dry fibres collected from the effluent.

4. Discussion

The environmental consequences of microplastic contamination are not fully understood. The quantity of microplastic in the environment is expected to increase over the next few decades; even if new emissions of plastic debris halted the fragmentation of legacy items that are already in the environment, it would be expected to lead to an increase in abundance (Law and Thompson, 2014). There are concerns about the potential for microplastics to have harmful effects if ingested and some evidence of particle and chemical toxicity have come from relatively high dose laboratory studies. Due to the persistent nature of plastic contamination, there is growing awareness of the need to reduce inputs at source; this includes the direct release of microplastic sized particles including microbeads from cosmetics, and fibres form textiles.

Fibres from fabrics are known to be lost due to pilling. Pilling is defined as the entangling of the fabric surface during wearing or washing, resulting in formation of fibre balls (or pills) that stand proud on the surface of the fabric (Hussain et al., 2008). This occurs as a consequence of two processes: (i) fuzzing; the protrusion of fibres from the fabric surface, and (ii) pill formation; the persistence of formed neps (entangled masses of fibres) at the fabric surface (Naik and Lopez-Amo, 1982). The pill may be worn or pulled away from the fabric, as a consequence of mechanical action during either laundering or wear (Yates, 2002).

Most fabrics pill to some extent and this has always been a concern in the industry as it spoils surface appearance and comfort, reduces the fabric's strength and diminishes its serviceability (Hussain et al., 2008; Chiweshe and Crews, 2000). This problem has become more prominent with the widespread use of synthetic fibres, such as polyester and acrylic, due to their higher tensile strength (Cooke, 1985). These synthetic fibres are widely used because of their low cost and versatile use. Laundry methods have been recognised as being important to minimise the pilling tendency (Cooke, 1985).

The rate or extent to which the pilling stages occur is determined by the physical properties of the fibres which comprise the fabric (Gintis and Mead, 1959). From the fabrics tested here, polyester-cotton blend consistently shed significantly fewer fibres than either of the other fabric types which were entirely synthetic. Polyester is often added to cotton fabric to reduce cost, whilst also increasing tenacity and resilience. This is because cotton fibres have a lower tenacity, and as the pills are formed, the anchor fibres are easily broken; if the tenacity of the fabric is increased with added polyester, the pill break-off rate is lower, resulting in less fibres being released (Mccloskey and Jump, 2005).

Polyester fibres have many desirable properties, including good resistance to strain and deformation (Pastore and Kiekens, 2000). 100% polyester fabrics are renowned for pilling, but because of their high tenacity, the anchor fibres rarely break releasing the pills (Nunn, 1979). Previous research has even reported that as the polyester fibre content in a polyester-cotton blend fabric increases, the pilling gets worse (Gintis and Mead, 1959; Ruppenicker and Kullman, 1981). On the contrary, our research found that polyester fabrics yielded significantly more fibres than polyester-cotton blend. It has previously been suggested that pilling of polyester can be controlled by the modification

Table 2

Outcomes of SNK tests for specific combinations of the factors: a) fabric, b) detergent, c) temperature, d) conditioner. For each combination the relative number of fibres released is indicated by the sequence shown with permutation leading to the greatest release of fibres being shown to the right. Specific variables tested against three different fabric types (acrylic, polyester & polyester-cotton blend), and the subsequent fibre extract from laundering ($n = 4$; $* = p\ (<0.05)$). Key: PE (polyester), Blend (polyester-cotton blend), Acr (acrylic), A (conditioner/detergent absent), C (conditioner present), NB (non-bio detergent), bio (bio detergent).

a) Fabric

Factors			Order
30	C−	No powder	Blend < *Acr < *PE
30	C−	Bio	Blend < *Acr-PE
30	C−	Non-bio	Blend-PE-Acr
30	C+	No powder	Blend < *PE-Acr
30	C+	Bio	Blend < *PE-Acr
30	C+	Non-bio	Blend < *Acr-PE
40	C−	No powder	Blend < *Acr < *PE
40	C−	Bio	Blend < *PE < *Acr
40	C−	Non-bio	Blend-Acr < *PE
40	C+	No powder	Blend < *PE < *Acr
40	C+	Bio	Blend-Acr < *PE
40	C+	Non-bio	Blend < *Acr-PE

b) Detergent

Factors			Order
Acr	30	C−	Bio-NB-A
Acr	30	C+	A-NB-bio
Acr	40	C−	A-NB-bio
Acr	40	C+	Bio-NB < *A
Blend	30	C−	Bio-A-NB
Blend	30	C+	A-bio-NB
Blend	40	C−	A-bio < *NB
Blend	40	C+	A-NB-bio
PE	30	C−	Bio-NB < *A
PE	30	C+	A-bio-NB
PE	40	C−	Bio < *A < *NB
PE	40	C+	A-NB-bio

c) Temperature

Factors			Order
Acr	C−	No powder	40–30
Acr	C−	Bio	30 < *40
Acr	C−	Non-bio	30–40
Acr	C+	No powder	30–40
Acr	C+	Bio	40 < *30
Acr	C+	Non-bio	40–30
Blend	C−	No powder	40–30
Blend	C−	Bio	40–30
Blend	C−	Non-bio	30 < *40
Blend	C+	No powder	30–40
Blend	C+	Bio	30–40
Blend	C+	Non-bio	30–40
PE	C−	No powder	40–30
PE	C−	Bio	40–30
PE	C−	Non-bio	30 < *40
PE	C+	No powder	40–30
PE	C+	Bio	40–30
PE	C+	Non-bio	40–30

d) Conditioner

Factors			Order
Acr	30	No powder	C-A
Acr	30	Bio	A < *C
Acr	30	Non-bio	A-C
Acr	40	No powder	A < *C
Acr	40	Bio	C-A
Acr	40	Non-bio	C-A
Blend	30	No powder	A-C
Blend	30	Bio	A-C
Blend	30	Non-bio	A-C
Blend	40	No powder	A-C
Blend	40	Bio	A < *C
Blend	40	Non-bio	C < *A
PE	30	No powder	C < *A
PE	30	Bio	A-C
PE	30	Non-bio	A < C
PE	40	No powder	C-A
PE	40	Bio	A < *C
PE	40	Non-bio	C < *A

of the polyester properties, where a greater fibre release can improve polyester fabrics surface appearance (Doustaneh et al., 2013). Weakening the fibres (reduced ultimate bending stiffness), leads to more rapid break-off of pills due to fibre fatigue, leading to greater fibre release while at the same time improving the fabrics topography and surface appearance (Doustaneh et al., 2013). Hence from an aesthetic perspective, there may be benefits to the release of pills from garments during washing. However, this can also create a trade-off between garment appearance, and fibre release. More research would be needed to establish how release rates vary over the lifetime of a garment in service in order to fully establish the temporal dynamics of fibre emissions.

During the laundering of clothes, detergent and fabric conditioner are often used in combination. Synthetic detergents remove the oils and waxes that serve as lubricants in natural fibres, making a garment clean but harsh, scratchy, and uncomfortable to wear (Egan, 1978). Fabric softeners are used to counteract these effects. In addition, the use of fabric conditioners can reduce the build-up of static electricity, which can make the fabric objectionable to the wearer. Fabric softeners act as antistatic agents by enabling synthetic fibres to retain sufficient moisture to dissipate static charges (Ward, 1957).

Fabric conditioners may also increase pilling, and this is especially the case for synthetic fibres (Smith and Block, 1982). Work by Chiweshe and Crews (2000), showed that use of fabric conditioner on all cotton-containing fabrics resulted in increased pilling and/or an increase in the size of pills, as well as increased breaking strength losses in polyester woven fabric. Hence, it might be expected that the presence of conditioner could increase the release of fibres. This was observed in some of the treatment combinations here, but there was no clear trend relating to the presence of conditioner.

Detergent use presented the least clear pattern for fibre release when compared against the other factors. However, it was found that having no detergent or bio-detergent in a wash cycle occasionally resulted in the fewer fibres being released. Previous research has also shown that when polyester-cotton blend fabric has been laundered with a bio-detergent, it exhibited less piling than when laundered using a non-bio (Chiweshe and Crews, 2000). Our research produced some similar results, where polyester-cotton blend was also found to shed fewer fibres when detergent was absent, and the most when non-bio detergent was used.

Using the results from this experiment, the number of fibres potentially released into washing machine waste water per wash was estimated. This was achieved by examining the average fibre size, the various Factors tested and assuming a typical washing load of 6 kg. Based on this, a washing load (6 kg) of polyester-cotton blend was estimated to release 137,951 fibres, polyester to potentially release 496,030 and Acrylic 728,789. The large number of fibres released when clothing is laundered is therefore likely to represent a substantial contributor to microplastic contamination in the environment. Our estimates are similar to research by Browne et al. (2011), where it was suggested that a single garment could produce >1900 fibres per wash (Browne et al., 2011).

Wastewater Treatment Plants (WWTPs) play a critical role in the fate and transport of microfibres into the environment. In countries with sewage infrastructure, the effluent from washing machines is discharged into the local sewer system. This is then treated by a WWTP and discharged as treated effluent, which is released into the aquatic environments. Effluent discharge often contains suspended solids, such as microfibres, which are not removed during the treatment processes. In Amsterdam, Leslie et al. (2013) found concentrations from WWTP effluent ranged from 9 particles/L (min.) to 91 particles/L (max.) with a mean and median of 52 particles/L. A study by Murphy et al. (2016), compared the influent and effluent from a WWTP. The influent contained on average 15.70 (±5.23) microplastic/L, and was found to be reduced to 0.25 (±0.04) microplastic/L in the final effluent, a decrease of 98.41%. However, emissions of microplastics may still be substantial. For example, Mintenig et al. (2014) calculate between 8.2 and 93 billion microplastics and synthetic fibres being discharged from wastewater treatment plants in Germany (Essel et al., 2015). Even a small amount of microplastic being released per litre can result in substantial amounts of microplastics entering the environment due to the large volumes being treated. It has been predicted that a WWTP plant in the United Kingdom could release up to 65 million microplastics into the receiving water every day (Murphy et al., 2016).

Even if WWTPs are completely effective in the removal of microfibres, the extracted plastic particles may still enter the environment if the resultant sewage sludge, a by-product of the wastewater treatment process, is returned to the land; for example as a fertilizer (Habib et al., 1998; Zubris and Richards, 2005). Microfibres in sewage sludge may subsequently persist in the terrestrial environment, or be transported to aquatic environments via runoff. The potential for sewage sludge to transfer microplastic into the marine environment was shown in a preliminary study by Habib et al. (1998), where sediments were collected from a bay downstream of a sewage treatment plant. It was found that the sediment contained numerous synthetic fibres, and as distance from the sewage treatment plant increased, the size and number of fibres decreased. This effect was also observed by McCormick et al. (2014), where a higher concentration of microplastic (17.93 m^3) was recorded downstream of a WWTP, compared to upstream (1.91 m^3) (McCormick et al., 2014).

Clothing design, including the type of fabric used, clearly has considerable potential to influence fibre release; for example, our research found that a fabric made from a synthetic-natural combination released around 80% fewer fibres than acrylic. Further work to better understand how fabric design and textile choice influence fibre release should therefore be undertaken. Important directions for future research include comparing release between different types of washing machine, and using a variety of wash durations and spin speeds together with an assessment of the temporal dynamics of fibre release throughout a products life time. The Plastic Soup Foundation and MERMAIDS Life + project are currently promoting development of innovative solutions to minimise the release of plastic fibres from garments. Filters for washing machines are also being developed (Mermaids Organisation, 2015). These are made of a stainless steel mesh, with hole diameters of 0.0625 in. to collect fibres (Environmental Enhancements, 2016). For this measure to be successful, it will be essential to ensure the filters are not subsequently disposed of via household liquid waste. However, from a material usage and efficacy perspective, minimising fibre release at the design stage should be regarded as the most effective priority in a management hierarchy.

From the perspective of sustainability and environmental contamination, criteria that synthetic garment manufactures should consider might therefore include: 1) performance in service, giving a long lasting product that remains attractive during usage; 2) minimal release of non-degradable synthetic fibres and 3) a product that is compatible with end of life recycling. Such factors need to be taken into account throughout the design and manufacturing stages; for example, including consideration of fibre properties (composition, length), spinning method and the weaving/knitting process. Inadequate consideration of potential environmental impacts at the product design stage has recently led to considerable negative publicity and restrictive legislation relating to emissions of plastic microbeads from cosmetics (Napper et al., 2015); clearly illustrating the benefit of a precautionary approach. With microbeads in cosmetics, one of the considerations guiding policy intervention was the lack of clear societal benefit from incorporating microplastic particles into the cosmetics, coupled with concerns about environmental impacts. The societal benefits of textiles are without question, and so any voluntary or policy intervention should be directed toward reducing emissions either via changes in textile design or filtration of effluent, or both. As well as considering direct environmental impacts of manufacture, product use and disposal, there is a growing realisation of the need for a more circular approach to material usage in order to maximise long term resource sustainability and waste minimisation via a circular economy (European Commission, 2012; World Economic Forum, 2016).

In conclusion, this work examined the release of textile fibres from three fabrics that are commonly used to make clothing (polyester, polyester-cotton blend and acrylic). The results show that laundering 6 kg of synthetic materials could release between 137,951–728,789 fibres per wash. Our results indicate significant effects of wash conditions, but no clear picture based on the two detergents and one conditioner used. Hence, further work to examine in more detail differing washing machines and wash treatments, involving wash duration and spin speed as well as temperature, detergent and conditioner may be worthwhile. This could help establish whether specific wash conditions could be used to help minimise fibre release. Temporal dynamics of release over the life time of a product should also be examined, as this could help extend garment life while at the same time reducing fibre emissions.

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