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5 **Release of Synthetic Microplastic Plastic Fibres From Domestic Washing**

6 **Machines: Effects of Fabric Type and Washing Conditions**

7 *Imogen E. Napper, Richard C. Thompson*

8 *Marine Biology and Ecology Research Centre (MBERC), School of Marine Science*
9 *and Engineering, Plymouth University, Drake Circus, Plymouth, Devon, PL4 8AA*

10 Corresponding author: Imogen.Napper@Plymouth.ac.uk

11
12 **Abstract**

13
14 Washing clothes made from synthetic materials has been identified as a potentially
15 important source of microscopic fibres to the environment. This study examined the
16 release of fibres from polyester, polyester-cotton blend and acrylic fabrics. These
17 fabrics were laundered under various conditions of temperature, detergent, and
18 conditioner. Fibres from waste effluent were examined and the mass, abundance
19 and fibre size compared between treatments. Average fibre size ranged between
20 11.9–17.7µm in diameter, and 5.0–7.8 mm in length. Polyester-cotton fabric
21 consistently shed significantly fewer fibres than either polyester or acrylic. However,
22 fibre release varied according to wash treatment with various complex interactions.
23 We estimate over 728,000 fibres could be released from an average 6kg wash load
24 of acrylic fabric. As fibres have been reported in effluent from sewage treatment
25 plants, our data indicates fibres released by washing of clothing could be an
26 important source of microplastics to aquatic habitats.

27 Keywords:

28 • Microplastic; Fabric; Waste Water Treatment; Ocean pollution; Litter; Debris

29

30

31 **1. Introduction**

32 Microplastics have accumulated in marine and freshwater environments, and in
33 some locations outnumber larger items of debris (Browne et al., 2011; Thompson et
34 al., 2004; Wagner et al., 2014). The sources of microplastic include the
35 fragmentation of larger plastic items once they have entered the environment
36 (secondary sources), and also the direct input of microplastic sized particles, such as
37 microbeads used in cosmetics and pre-production pellets (Napper et al., 2015), or
38 particles and fibres resulting from the wear of products while in use (primary
39 sources). Microplastics can be ingested by a wide range of species both in marine
40 (Anastasopoulou et al., 2013; Gall and Thompson, 2015; Lusher et al., 2013) and
41 freshwater environments (Sanchez et al., 2014; Eerkes-Medrano et al., 2015).
42 Laboratory studies indicate the potential for physical harm to biota from the result of
43 ingestion (Wright et al., 2013). Ingestion could also facilitate the transfer of chemicals
44 to organisms, however the relative importance of plastic debris as a vector in the
45 transport for chemicals is not certain (Besseling et al., 2013; Rochman et al., 2013;
46 Koelmans et al., 2013; Koelmans et al., 2014). Encounter rate, as well as polymer
47 type and any associated chemicals (sorbed or additives) will influence the potential
48 for effects in the environment (Teuten et al., 2007; Bakir et al., 2012; Koelmans et al.,
49 2014; Bakir et al., 2014), therefore it is important to understand the relative
50 abundance, as well as the sources of various types of microplastic.

51

52 Microplastic has been reported in a wide range of aquatic habitats, including
53 beaches, surface waters, the water column and subtidal sediments (Lattin et al.,
54 2004; Thompson et al., 2004), and there is evidence that the abundance is
55 increasing (Thompson et al., 2004). They are also reported in some of the most
56 remote environments, including the deep sea and the arctic, indicating their ubiquity
57 and the need for further understanding about the potential environmental
58 consequences (Obbard et al., 2014; Woodall et al., 2014).

59

60 Release of microplastic sized fibres as a result of washing of textiles has been widely
61 reported as a potential source of microplastic (Browne et al., 2011; Dris et al., 2015;
62 Essel et al., 2015; GESAMP, 2015; Wentworth and Stafford, 2016), however there
63 has been little quantitative research on the relative importance of this source or on
64 the factors that might influence such discharges. This is the focus of the research
65 described here. In this context we consider microplastics as particles of plastic
66 <5mm in their smallest dimension. While some fibres may be longer than 5mm they
67 will usually have a diameter considerably less than 5mm. There is a lack of clarity on
68 the formal definition for the lower size limit of microplastic and in environmental
69 studies this has tended to relate more to the method of capture, e.g. mesh size of
70 plankton nets used to sample water, or the method of identification such as
71 spectroscopy. At present the smallest particles identified from the environment are
72 around 20µm in their smallest dimension.

73

74 Textiles have the potential to release fibres into the environment, and one pathway is
75 via laundering in washing machines. A range of fibres are used in the production of

76 textiles; these include natural fibres (such as cotton and wool), synthetic fibres (such
77 as nylon) and some are blends of natural and synthetic (such as polyester-cotton).
78 Synthetic fibres have been used to supplement cotton, wool, and linen in textiles for
79 more than 50 years, and fabrics such as polyester and acrylic are now widely used in
80 clothing, carpets, upholstery and other such materials. Washing of clothing has been
81 suggested as a potentially important source of microplastic fibres (Browne et al.,
82 2011).

83

84 Synthetic microplastic fibres are frequently reported in samples from sediments, the
85 water column and biota (Browne et al., 2011). Waste effluent from washing
86 machines, containing released fibres, will then travel via wastewater to sewage
87 treatment plants (Leslie et al., 2013; Dris et al., 2015). Due to the small size of the
88 fibres a considerable proportion could then pass through preliminary sewage
89 treatment screens (typically coarse, >6 mm, and fine screens, 1.5–6 mm) (Water
90 Environment Federation, 2003), and be released into aquatic environments. As
91 synthetic fibres are not readily decomposed by aerobic or anaerobic bacteria, any
92 that are intercepted in the sewage treatment plant will accumulate in sewage sludge,
93 and may subsequently be released back to the environment; for example if the
94 sludge is returned to the land or dumped at sea (Habib et al., 1998). Hence, there is
95 a considerable potential for fibres from synthetic textiles to accumulate in the
96 environment; for example, Gallagher et al (2016) found predominately fibres when
97 surveying the Solent estuarine complex (U.K.) for microplastic, similarly Dris et al
98 (2015), found considerable quantities of fibres in the River Seine. There is evidence
99 that some of this material can be transported as airborne particulates (Dris et al.,
100 2015); however it would appear that considerable quantities enter directly from

101 sewage treatment (Browne et al., 2011). To date, there has been limited research to
102 establish the importance of clothing as a source of microplastic contamination to the
103 environment.

104

105 A study by Browne et al (2011), sampled wastewater from domestic washing
106 machines and suggested that a single garment could produce >1900 fibres per
107 wash (Browne et al., 2011). To examine the role of the sewage system as a pathway
108 to the environment, Browne extracted microplastic from effluent discharged by
109 treatment plants, and also examined the accumulation of microplastic in sediments
110 from sewage sludge disposal sites. On average, the effluents contained one particle
111 of microplastic per litre, including polyester (67%) and acrylic (17%) and polyamide
112 (16%); these proportions were similar to the relative proportions found on shorelines
113 and disposal-sites (Browne et al., 2011). Similarly, a high number of plastic fibres
114 were observed in the sediments near to a sewage outfall in Amsterdam (Leslie et al.,
115 2013), and have been reported even 15 years after application in terrestrial soils that
116 have received sewage sludge (Zubris and Richards, 2005). Unless the release of
117 microplastics to waste water or sewage treatment practices change, the release of
118 microplastic to the environment via sewage is likely to increase, as the human
119 population grows. It is anticipated, for example, that reductions in emissions of
120 microbeads via sewage will be reduced as a consequence of legislation to prohibit
121 their use in cosmetics (Napper et al., 2015).

122

123 However, there are currently no peer reviewed publications that compare the
124 quantity of fibres released from common fabrics due to laundering. In addition, the

125 potentially important influence of washing practices including temperature, the use of
126 detergent and fabric conditioners have not been examined. Here we tested three
127 different fabrics that are commonly used to make clothes; polyester, polyester-cotton
128 blend, and acrylic. These fabrics were then laundered at two temperatures (30°C
129 and 40°C), using various combinations of detergent and fabric conditioner. The fibres
130 extracted from the waste effluent were examined to determine the typical size, and to
131 establish any differences in the mass / abundance of fibres among treatments.

132

133 **2. Method**

134

135 Three synthetic fabric types were selected based on their prevalence in high-street
136 retail stores close to Plymouth, UK. The chosen fabric types were all from jumpers
137 (Fig. 2), with each being a different colour so they could be readily distinguished after
138 fragmentation; 100% polyester (black), 100% acrylic (green) and 65% polyester / 35%
139 cotton blend (blue). Four replicates of each garment were purchased, with each
140 replicate sourced from a different retail outlet to provide a representative sample.

141 The identity of each fabric type was confirmed by Fourier transform infra-red
142 spectroscopy (FTIR), using a Hyperion 1000 microscope (Bruker) coupled to an IFS
143 66 spectrometer (Bruker). The spectra obtained were compared to a spectral
144 database of synthetic polymers (Bruker I26933 Synthetic fibres ATRlibrary). As each
145 garment varied in overall size, 20cm X 20cm squares were cut from the back panel
146 of the garments and the edges hemmed by 0.5 cm using black and white cotton
147 thread to deter the excess loss of fibres.

148

149 A Whirlpool WWDC6400 washing machine was used to launder the garment
150 samples. While it would be valuable to compare a range of washing machines this
151 was beyond the budget of the current research. This machine was selected as it is a
152 popular brand used for domestic laundry. The number of fibres released from the
153 wastewater outlet, as a result of laundering, was recorded. To achieve this, a nylon
154 CellMicroSieve™ (Fisher Scientific), with 25 µm pores, was attached to the end of
155 the drain hose. Once a cycle was complete, the CellMicroSieve™ was removed and
156 the fibres collected. Due to the potential build-up of detergent or conditioner on the
157 collected fibres, they were washed using 2L of water and filtered again over
158 Whatman N°4 filter papers, and then dried at 30°C to constant weight. Once dry, the
159 fibres were weighed by a Cubis® precision balance (Sartorius). The weight of fibres
160 were compared across four factors: Factor one, (fabric type, fixed factor, 3 levels:
161 100% polyester, 100% acrylic, and 65% polyester / 35% cotton blend); Factor two
162 wash temperature (fixed factor, 2 levels; 30°C and 40°C); Factor three, detergent (3
163 levels; detergent absent, 20ml bio-detergent present (contains enzymes), 20ml non-
164 bio detergent present); Factor four, conditioner (2 levels; 20ml conditioner absent or
165 present). Factors gave a total of 36 treatments (Fig.1).

166

167 In this study the main factors of interest were: fabric type, temperature, presence of
168 detergent and / or conditioner. The time of each wash and the rotations per minute
169 are clearly also factors of potential relevance but in order not to confound the
170 experimental design these were kept constant (Duration, 1 hour 15 minutes and
171 1400 rotations per minute (R.P.M)). Each treatment had four replicates.

172

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

181

182 i) $Vt = \frac{Mt}{D}$ ii) $V(\text{avg.fibre}) = \pi r^2 l$ iii) $N = \frac{Vt}{V(\text{avg.fibre})}$

183 where Vt is the total volume of fibres collected, Mt is the total mass of fibres collected,
184 D is the density, $V(\text{avg.fibre})$ is the mean volume of one fibre, N is number of fibres, l
185 is the height and r is the radius.

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

191

192 Fibres were visualised by scanning electron microscopy (JEOL, 7001F); images
193 taken were used to measure the width of the fibres, and also to analyse their

194 topography. Images of the fibres were also taken by using LEICA M205C light
195 microscope and analysed by Image J to measure their length (Rasband, 2015). For
196 each fabric type, a mean size was calculated for length and width based on data
197 from 10 individual fibres.

198

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

202

203 **3.0 Results**

204

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

216 change in fibre release between the 4th and 5th wash data, data from the 5th wash
217 was recorded for formal analysis.

218

219 While there was a consistent trend between fabric types, ANOVA revealed
220 significant complex interactions between the 4 Factors (Table 1). Focussing on the
221 type of fabric, polyester-cotton blend was consistently found to shed fewer fibres
222 than both the other fabric types, regardless of the differing treatments. This trend
223 was consistent for all 12 relevant interactive effects, and was significantly so for 9 out
224 of these 12 interactions (Table 2a). However, the significance of this effect varied
225 according to the treatment used, creating different interactions. There were some
226 effects of temperature; For example, polyester was often found to release more
227 fibres than acrylic at 40°C, when compared against 30°C (Table 2c).

228

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

239

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

245

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

252

253 **4.0 Discussion**

254 The environmental consequences of microplastic contamination are not fully
255 understood. The quantity of microplastic in the environment is expected to increase
256 over the next few decades since even if new emissions of plastic debris halted the
257 fragmentation of legacy items that are already in the environment would be expected
258 to lead to an increase in abundance (Law and Thompson, 2014). There are concerns
259 about the potential for microplastics to have harmful effects if ingested and some
260 evidence of particle and chemical toxicity have come from relatively high dose
261 laboratory studies. Because of the persistent nature of plastic contamination, there is

262 growing awareness of the need to reduce inputs at source; this includes the direct
263 release of microplastic sized particles including microbeads from cosmetics, and
264 fibres from textiles.

265 Fibres from fabrics are known to be lost due to pilling. Pilling is defined as the
266 entangling of the fabric surface during wearing or washing, resulting in formation
267 of fibre balls (or pills) that stand proud on the surface of the fabric (Hussain et al.,
268 2008). This occurs as a consequence of two processes: (i) fuzzing; the protrusion of
269 fibres from the fabric surface, and (ii) pill formation; the persistence of formed neps
270 (entangled masses of fibres) at the fabric surface (Naik and Lopez-Amo, 1982). The
271 pill may be worn or pulled away from the fabric, as a consequence of mechanical
272 action during either laundering or wear (Yates, 2002).

273

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

282

283 The rate or extent to which the pilling stages occur is determined by the physical
284 properties of the fibres which comprise the fabric (Gintis and Mead, 1959). From the

285 fabrics tested here, polyester-cotton blend consistently shed significantly fewer fibres
286 than either of the other fabric types which were entirely synthetic. Polyester is often
287 added to cotton fabric to reduce cost, whilst also increasing tenacity and resilience.
288 This is because cotton fibres have a lower tenacity, and as the pills are formed, the
289 anchor fibres are easily broken; if the tenacity of the fabric is increased with added
290 polyester, the pill break-off rate is lower, resulting in less fibres being released
291 (McCloskey and Jump, 2005).

292

293 Polyester fibres have many desirable properties, including good resistance to strain
294 and deformation (Pastore and Kiekens, 2000). 100% polyester fabrics are renowned
295 for pilling, but because of their high tenacity, the anchor fibres rarely break releasing
296 the pills (Nunn, 1979). Previous research has even reported that as the polyester
297 fibre content in a polyester-cotton blend fabric increases, the pilling gets worse
298 (Gintis and Mead, 1959; Ruppenicker and Kullman, 1981). On the contrary our
299 research found that polyester fabrics yielded significantly more fibres than polyester-
300 cotton blend. It has previously been suggested that pilling of polyester can be
301 controlled by the modification of the polyester properties, where a greater fibre
302 release can improve polyester fabrics surface appearance (Doustaneh et al., 2013).
303 Weakening the fibres (reduced ultimate bending stiffness), leads to more rapid
304 break-off of pills due to fibre fatigue, leading to greater fibre release while at the
305 same time improving the fabrics topography and surface appearance (Doustaneh et
306 al., 2013). Hence from an aesthetic perspective, there may be benefits to the release
307 of pills from garments during washing. However, this can also create a trade-off
308 between garment appearance, and fibre release. More research would be needed to

309 establish how release rates vary over the lifetime of a garment in service in order to
310 fully establish the temporal dynamics of fibre emissions.

311

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

320

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

329

330 Detergent use presented the least clear pattern for fibre release when compared
331 against the other factors. However, it was found that having no detergent or bio-

332 detergent in a wash cycle occasionally resulted in the fewer fibres being released.
333 Previous research has also shown that when polyester-cotton blend fabric has been
334 laundered with a bio-detergent, it exhibited less piling than when laundered using a
335 non-bio (Chiweshe and Crews, 2000). Our research produced some similar results,
336 where polyester-cotton blend was also found to shed fewer fibres when detergent
337 was absent, and the most when non-bio detergent was used.

338

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

349

350 Wastewater Treatment Plants (WWTPs) play a critical role in the fate and transport
351 of microfibres into the environment. In countries with sewage infrastructure, the
352 effluent from washing machines is discharged into the local sewer system. This is
353 then treated by a WWTP and discharged as treated effluent, which is released into
354 the aquatic environments. Effluent discharge often contains suspended solids, such
355 as microfibres, which are not removed during the treatment processes. In

356 Amsterdam, Leslie et al. (2013) found concentrations from WWTP effluent ranged
357 from 9 particles/L (min.) to 91 particles/L (max.) with a mean and median of 52
358 particles/L. However, a study by Murphy et al., (2016) compared the influent and
359 effluent from a WWTP. The influent contained on average 15.70 (± 5.23)
360 microplastic/L, and was found to be reduced to 0.25 (± 0.04) microplastic/L in the final
361 effluent, a decrease of 98.41%. However, Mintenig et al. (2014) calculate emissions
362 of between 93 and 8.2 billion microplastics and synthetic fibres being discharged
363 from wastewater treatment plants in Germany (Essel et al., 2015). However, even a
364 small amount of microplastic being released per litre can result in substantial
365 amounts of microplastics entering the environment due to the large volumes being
366 treated. It has been predicted that a WWTP plant in the United Kingdom could
367 release up to 65 million microplastics into the receiving water every day (Murphy et
368 al., 2016).

369

370 Even if WWTPs are completely effective in the removal of microfibrils, the extracted
371 plastic particles may still enter the environment if the resultant sewage sludge, a by-
372 product of the wastewater treatment process is returned to the land, for example as
373 a fertilizer (Habib et al., 1998; Zubris and Richards, 2005). Microfibrils in sewage
374 sludge may subsequently persist in the terrestrial environment, or be transported to
375 aquatic environments via runoff. The potential for sewage sludge to transfer
376 microplastic into the marine environment was shown in a preliminary study by Habib
377 et al. (1998), where sediments were collected from a bay downstream of a sewage
378 treatment plant. It was found that the sediment contained numerous synthetic fibres
379 and as distance from the sewage treatment plant increased the size and number of
380 fibres decreased. This effect was also observed by McCormick et al (2014), where a

381 higher concentration of microplastic (17.93 m³) was recorded downstream of a
382 WWTP, compared to upstream (1.91 m³) (McCormick et al., 2014).

383

384 Clothing design, including the type of fabric used, clearly has considerable potential
385 to influence fibre release; for example our research, found that a fabric made from a
386 synthetic-natural combination released around 80% fewer fibres than acrylic.

387 Further work to better understand how fabric design and textile choice influence fibre
388 release should therefore be undertaken. Important direction for future research
389 include comparing release between different types of washing machine and using a
390 variety of wash duration and spin speed together with an assessment of the
391 temporal dynamics of fibre release throughout a products life time.

392

393 From the perspective of sustainability and environmental contamination, criteria for
394 synthetic garment manufacture should consider: 1) performance in service, giving a
395 long lasting product that remains attractive during usage; 2) minimal release of non-
396 degradable synthetic fibres and 3) a product that is compatible with end of life
397 recycling. Such factors need to be taken into account throughout the design and
398 manufacturing stages; for example including consideration of fibre properties
399 (composition, length), spinning method and the weaving/knitting process. Inadequate
400 consideration of potential environmental impacts at the product design stage has led
401 to considerable negative publicity and restrictive legislation relating to emissions of
402 plastic microbeads from cosmetics (Napper et al., 2015); clearly illustrating the
403 benefit of a precautionary approach. As well as considering direct environmental
404 impacts of manufacture, product use and disposal there is a growing realisation of

405 the need for a more circular approach to material usage in order to maximise long
406 term resource sustainability and waste minimisation via a circular economy
407 (European Commission, 2012; World Economic Forum, 2016). The Plastic Soup
408 Foundation and MERMAIDS Life+ project are currently promoting development of
409 innovative solutions to minimise the release of plastic fibres from garments. Filters
410 for washing machines are also being developed, (Mermaids Organisation, 2015).
411 These are made of a stainless steel mesh with hole diameters of 0.0625 inches, to
412 collect fibres (Environmental Enhancements, 2016). For this measure to be
413 successful it will be essential to ensure the filters are not subsequently disposed of
414 via household liquid waste. However, from a material usage and efficacy perspective
415 minimising fibre release at the design stage should be regarded as the most effective
416 priority in a management hierarchy.

417

418 In conclusion, this work examined the release of textile fibres from three fabrics that
419 are commonly used to make clothing (polyester, polyester-cotton blend and acrylic).
420 The results show that laundering 6kg of synthetic materials could release between
421 137,951 – 728,789 fibres per wash. Our results indicate significant effects of wash
422 conditions, but no clear picture based on the two detergents and one conditioner
423 used. Hence, further work to examine in more detail differing washing machines and
424 wash treatments involving wash duration and spin speed as well as temperature,
425 detergent and conditioner may be worthwhile. This could help establish whether
426 specific wash conditions could be used to help minimise fibre release. Temporal
427 dynamics of release over the life time of a product should also be examined and as
428 this could help extend garment life while at the same time reducing fibre emissions.

429

Figures

430

431

432

433

435



436 **Figure 1.** *Experimental design showing Factors used for each fabric type (acrylic,*
437 *polyester, polyester-cotton blend).*

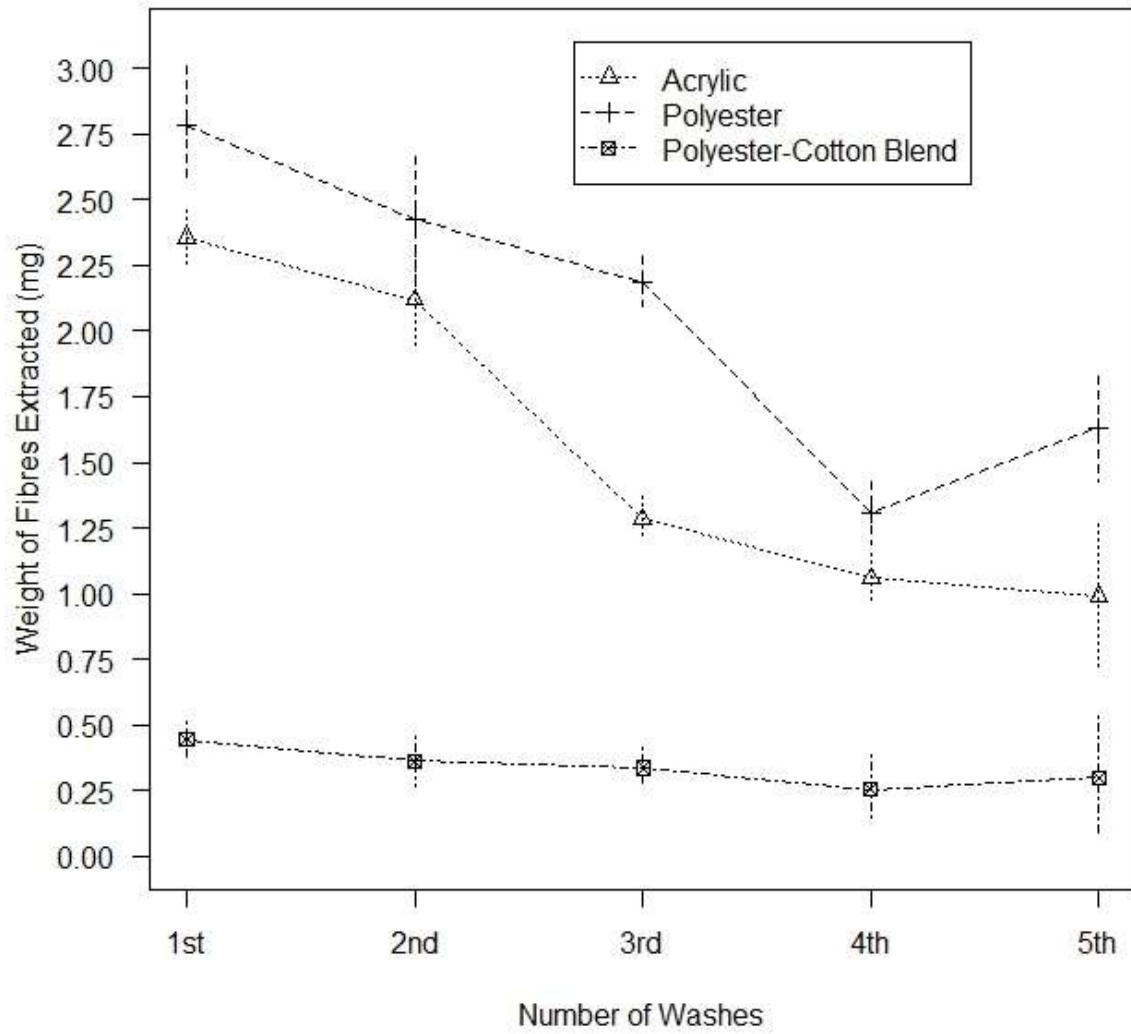
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439



440

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



447

448 **Figure 3.** Fibre loss from three fabrics (acrylic, polyester & polyester-cotton blend),
 449 over the first 5 washes. Data from the 5th wash was used in the analysis (n =
 450 4, \pm SD).

451

452

453

454

455

456

Tables

457

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
FabricXTemp	2	0.02	0.33	0.72
FabricXCond	2	0.12	1.88	0.16
FabricXDeter	4	0.20	3.13	0.02
TempXCond	1	0.15	2.28	0.13
TempXDeter	2	0.13	2.09	0.13
CondXDeter	2	0.58	9.00	0.00
FabricXTempXCond	2	0.06	0.86	0.43
FabricXTempXDeter	4	0.06	1.00	0.41
FabricXCondXDeter	4	0.33	5.05	0.00
TempXCondXDeter	2	0.64	9.91	0.00
FabricXTempXCondXDeter	4	0.38	5.95	0.00
Residual	108	0.06		
Total	143			

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459 **Table 1.** *Analysis of variance (ANOVA) for factors affecting release of fibres as a*
460 *consequence of various laundering treatments (n=4; **bold** = p = <0.05). Key:*
461 *Temp (temperature), Deter (Detergent), Cond (Conditioner).*

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a) FABRIC				b) DETERGENT			
Factors		Order		Factors		Order	
30	C-	No Powder	Blend<*Acr<*PE	Acr	30	C-	bio-NB-A
30	C-	Bio	Blend<*Acr-PE	Acr	30	C+	A-NB-bio
30	C-	Non Bio	Blend-PE-Acr	Acr	40	C-	A-NB-bio
30	C+	No Powder	Blend<*PE-Acr	Acr	40	C+	bio-NB<*A
30	C+	Bio	Blend<*PE-Acr	Blend	30	C-	bio-A-NB
30	C+	Non Bio	Blend<*Acr-PE	Blend	30	C+	A-bio-NB
40	C-	No Powder	Blend<*Acr<*PE	Blend	40	C-	A-bio<*NB
40	C-	Bio	Blend<*PE<*Acr	Blend	40	C+	A-NB-bio
40	C-	Non Bio	Blend-Acr<*PE	PE	30	C-	bio-NB<*A
40	C+	No Powder	Blend<*PE<*Acr	PE	30	C+	A-bio-NB
40	C+	Bio	Blend-Acr<*PE	PE	40	C-	bio<*A<*NB
40	C+	Non Bio	Blend<*Acr-PE	PE	40	C+	A-NB-bio
c) TEMPERATURE				d) CONDITIONER			
Factors		Order		Factors		Order	
Acr	C-	No Powder	40-30	Acr	30	No Powder	C-A
Acr	C-	Bio	30<*40	Acr	30	Bio	A<*C
Acr	C-	Non Bio	30-40	Acr	30	Non Bio	A-C
Acr	C+	No Powder	30-40	Acr	40	No Powder	A<*C
Acr	C+	Bio	40<*30	Acr	40	Bio	C-A
Acr	C+	Non Bio	40-30	Acr	40	Non Bio	C-A
Blend	C-	No Powder	40-30	Blend	30	No Powder	A-C
Blend	C-	Bio	40-30	Blend	30	Bio	A-C
Blend	C-	Non Bio	30<*40	Blend	30	Non Bio	A-C
Blend	C+	No Powder	30-40	Blend	40	No Powder	A-C
Blend	C+	Bio	30-40	Blend	40	Bio	A<*C
Blend	C+	Non Bio	30-40	Blend	40	Non Bio	C<*A
PE	C-	No Powder	40-30	PE	30	No Powder	C<*A
PE	C-	Bio	40-30	PE	30	Bio	A-C
PE	C-	Non Bio	30<*40	PE	30	Non Bio	A<C
PE	C+	No Powder	40-30	PE	40	No Powder	C-A
PE	C+	Bio	40-30	PE	40	Bio	A<*C
PE	C+	Non Bio	40-30	PE	40	Non Bio	C<*A

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468 **Table 2.** *Outcomes of SNK tests for specific combinations of the factors: a) fabric, b)*

469 *de detergent, c) temperature, d) conditioner. For each combination the relative*

470 *number of fibres released is indicated by the sequence shown with*

471 *permutation leading to the greatest release of fibres being shown to the right.*

472 *Specific variables tested against three different fabric types (acrylic,*

473 *polyester & polyester-cotton blend), and the subsequent fibre extract from*
474 *laundering (n=4; * = p (<0.05)). Key: PE (polyester), Blend (polyester-cotton*
475 *blend), Acr (acrylic), A (conditioner/detergent absent), C (conditioner*
476 *present), NB (non-bio detergent), bio (bio detergent).*

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