[redacted]

From: claire@ocean-remedy [redacted]
Sent: Sunday, 14 April 2019 9:05 AM
To: Plastic Action
Subject: Plastic microfibre pollution
Attachments: Fashion_and_Microplastics_Ocean_Remedy_2018.pdf

Follow Up Flag: Follow up
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Hi there,

I research plastic microfibre pollution from laundry. I am keen to do more, there is so much work to be done in this sphere. Given you are looking at plastic pollution presently, I'm attaching an industry report I created that I share through fashion/textile circles.

I am also awaiting publication of an article this month, that has been peer reviewed, estimating the microplastic burden from laundry in Australia. If we are allowing just 2% of the modelled microplastic fibres coming from our laundry to enter the ocean, each week we could be contributing the equivalent of 7,500 plastic bags to our ocean as microplastic fibres:

Abstract

Microplastic pollution in oceans is widely documented, with strong links to synthetic textiles and laundry waste water. This study focussed on the growing active/swim-wear sector, which utilises textiles yet to be studied for microplastic fibre emissions, including recycled fabrics. Four active/swim-wear knit fabrics (two virgin nylon/elastane blends, recycled nylon/elastane blend, and 100 % polyester) were washed a total of fifteen times in a front-load washing machine (three replicates). Microplastic fibre emissions were captured in the laundry waste water for washes 1–5 and washes 11–15 for each fabric type. There was no significant difference in microfibre emissions among the fabrics. On average, the fabrics released 0.0035 % w/w microplastic fibres per wash, comparable with previous studies of polyester and fleece textiles. The laundry microfibre burden from Australia was modelled and conservatively calculated to be equivalent to 7500 plastic grocery bags entering marine environments weekly. It was found that life-cycle applications and care of apparel may result in a significant microplastic fibre burden from these fabric types. It is imperative the textile and apparel industry includes solutions and full investigation of their product life-cycle environmental burden in their sustainability and research agendas.

Hoping this information may bring to light an aspect of plastic pollution that was omitted from the plastic issues survey and paper.

Best regards,

Claire O'Loughlin

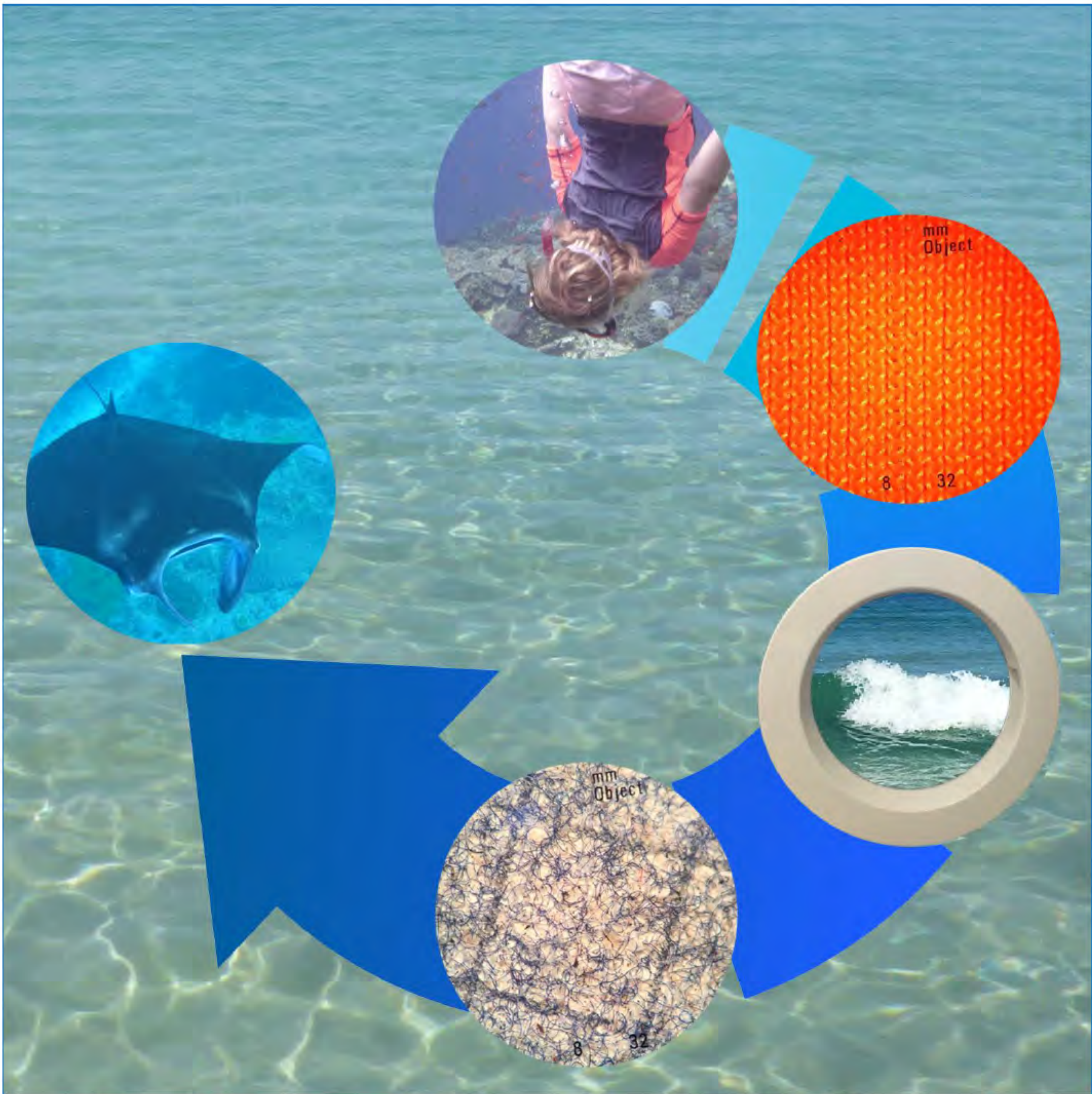
ocean remedy

[redacted]

[redacted]

"Our descendants will inhabit a world vastly different than ours. The only question is whether it will be better or worse" - Joel Solomon

We choose better!



Fashion and Microplastic Pollution

Investigating microplastics from laundry

Microplastic pollution is extensively documented in our oceans with strong links to laundry waste water. With 70% of all textile manufacturing being synthetic, mitigation of microfibres from laundry is needed urgently. There is an opportunity for the fashion and apparel industry to reduce the microfibre burden on oceans, whilst boosting its environmental credentials, by educating consumers, providing laundry filtration options, and researching technical improvements in textile manufacturing.

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Images/figures by author
Sources as cited

Fashion and Microplastic Pollution

Investigating microplastics from laundry

EXECUTIVE SUMMARY

Globalisation and mechanisation has facilitated the rise of *fast fashion* and exponential increases in apparel production in the last 25 years. Whilst sustainable supply chain practices are developing in the fashion and apparel industry, less consideration has been given to garment life-cycles in consumer hands, including laundry regimes. Meanwhile, studies have linked laundry to marine microplastic pollution.

Microplastic pollution is an emerging environmental issue, with microplastics accumulating in marine ecosystems worldwide. A 2011 study found the dominant microplastics on shorelines to be polyester, acrylic and nylon microfibres, in proportions resembling those used in apparel and released from waste water treatment plants. Associated laundry trials have since focused primarily on synthetic fleece fabric and major findings of preceding research include:

- Microplastics are found from the Arctic to the Antarctic and all continents in between, in freshwater ecosystems, from shores to ocean depths.
- Microplastics are being consumed by all levels of the food chain, and are known to adversely affect health.
- Plastics bind pollutants to themselves at levels 25 times the surrounding water, increasing their toxicity when consumed.
- The dominant microplastics found in shoreline and deep-sea sediments are fibres, with proportions resembling those used in the apparel industry.
- Since the 1990s synthetic fibre production has steadily grown worldwide, reaching 70% of all textiles produced in 2016 more than 1.5 times that of natural fibre production.
- Synthetic garments release microfibres in washing machine waste-water at rates from 1,900 – 11,000 fibres per garment.

It is evident that the fashion industry has a role in the global microfibre burden, and synthetic textile markets are experiencing strong growth. As such, trials were run to test plastic microfibre release from previously untested swim/active-wear fabrics (a growing

Motivation for this research

As a beach-wear brand Ocean Remedy relies heavily on synthetic fabrics. In line with Ocean Remedy's commitment to ethical production and sustainability, research was conducted to ensure a comprehensive understanding of the potential impact of the product on marine environments, prior to product release. Hence extensive research was undertaken to consolidate existing knowledge of the problem and its importance, in addition to insightful laundry trials.

market), whilst seeking solutions to reduce microfibres from laundry. Important results include:

- Initial trials compared fabric type and the effect of detergent, finding in general fabrics washed in detergent released significantly more microfibres.
- There was no significant difference in the amount of microfibres released from a recycled nylon compared to two other brands of conventional nylon and polyester.
- Microfibre release was greater for older garments (after 10 washes), than new garments.
- Modelling the microfibres released from laundering swim/active-wear, versus a polyester fleece, showed swim/active wear may produce more microfibres.
- Australia alone, with less than 1% of the washing machines on Earth, could be releasing 62 kg microfibres from laundry into the environment each week. This is the equivalent of 7,750 plastic shopping bags.
- It is recommended further trials are run for a total of 50 plus washes to mimic weekly laundering over a year, to elucidate the life cycle burden from these garments, in addition to differences between fabric types, whether recycled, or low-cost versus higher-cost.
- Microfibres in laundry waste water can be reduced 87-90% through use of a filtering laundry bag to hold synthetic garments during laundering.
- Additionally, the bag appeared to reduce garment damage overall, indicating it may extend the life of the garment.

Plastic microfibres are a pollutant and have been extensively documented in oceans, with strong links to apparel. With growing synthetic garment production, mitigation of microfibres from laundry is needed urgently. Currently, there is no perfect fix to the problem, and technological advances in fabric and washing machines will take time. In the interim, use of filtering laundry bags could be implemented through consumer education programs. Provision of appropriate laundry bags provides a branding opportunity to boost environmental credibility whilst educating consumers, and could restrict a large portion of microfibres from entering oceans.

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Abbreviations

PA	polyamide (nylon)
PBT	polybutylene terephthalate
PCB	polychlorinated biphenyl
PET	polyethylene terephthalate
POP	persistent organic pollutants
PP	polypropylene
RPM	rotations per minute
w/w	weight per weight

Definitions

acrylic	Synthetic wool-like fibre made from a polymer (polyacrylonitrile).
adsorb	Adhered substances to a surface.
bio-magnification	Increase in concentration of a substance as it is consumed in greater quantities by higher levels of the food chain.
in vitro	In a laboratory setting.
in vivo	In the natural environment.
microfibre	Fibres < 5 mm.
microplastic	Plastic particles < 5 mm and including microfibres.
nylon	Synthetically produced polyamide, also known as nylon 6 (PA6).
polyamide	Occurs naturally (wool and silk) and synthetically (nylon), excellent mechanical properties, hard and tough or soft and flexible. Absorbs moisture, excellent slide and wear characteristics, commonly used in the textile and automotive industry; recyclable.
PBT	First fibre-forming polyester with high strength and rigidity, very stable, high heat, water and chemical resistance, exceptional weather resistance. Recyclable, major component of polyester fabrics.
PET	A type of polyester resin usually injection moulded for bottles and films; can be recycled into fibres.
polyester	Polyethylene glycol terephthalate: a category of thermoplastic polyesters all containing an ester functional group in the main chain. Characteristically strong, durable, high chemical and water resistance, easily washed and dried. Used widely in fabrics, ropes and bottles (PET, PBT).
polyethylene	Largest volume polymer produced globally, cheap and easily moulded, flexible and rigid, strong, stable, high chemical resistance, strong UV resistance. Used in containers, tubing, bottles, gas & water pipes, cable insulation, tank linings, plastic bags; recyclable.
polypropylene	A thermoplastic polymer, widely used for its rigidity, toughness, lightweight, stability at high temperature conditions and chemical resistance. Applications include packaging, labelling, ropes, thermal underwear and carpet, also stationery, plastic parts, reusable containers, laboratory equipment, loudspeakers, automotive components and banknotes; recyclable.
tenacity	The tensile force a fibre will withstand before breaking, expressed as force relative to fibre linear density.
toxicant	Any synthetic substance that produces an adverse biological effect.

1. INTRODUCTION

Plastic pollution is a known problem with an estimated eight million tonnes of plastic entering oceans annually[1]. This is plastic that is visible and measurable. An emerging problem is that of microplastic pollution. In 2004, analyses of archived plankton samples from the North Sea revealed microplastic fibres have been present in samples taken since the 1960s, and significantly increased in abundance each decade, with a relationship to global synthetic fibre and plastic production[2,3] (Figure 1). A 2009 study of plastics in the environment found that whilst the amount of plastic entering the environment has stabilised, once in the environment it continues to break down into ever smaller pieces[3]. Further, although plastics remain buoyant in the ocean whilst in motion, as they become fouled by growths and adsorbed particles, and/or momentum is lost, they begin to sink, suggesting further research should investigate sediments and the deep sea[3].

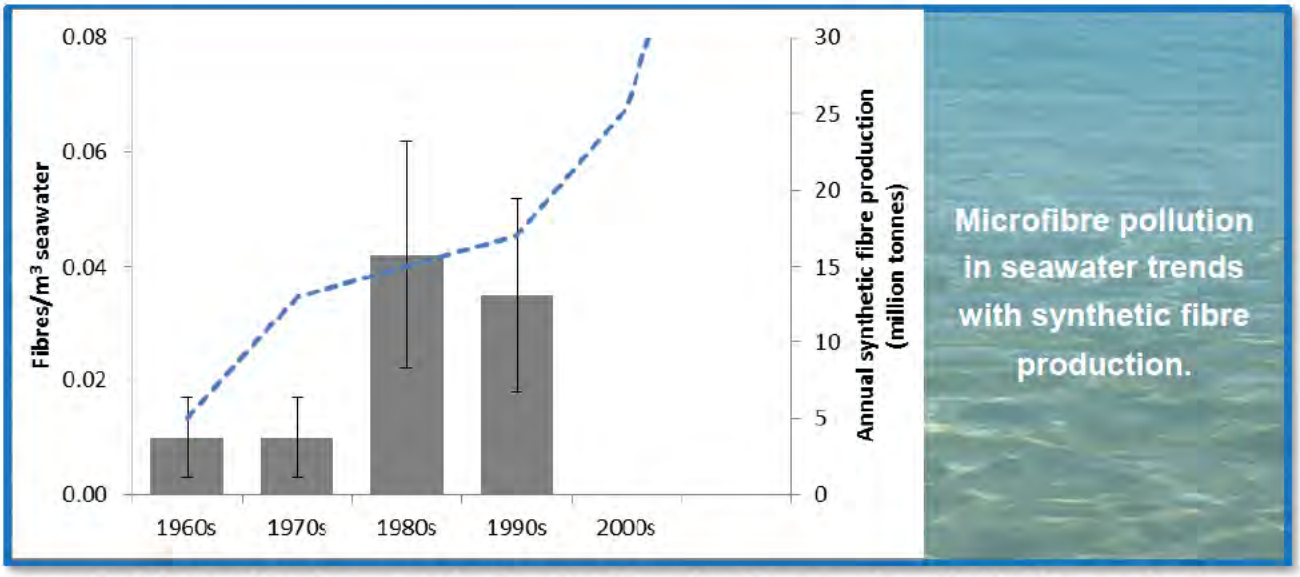


Figure 1. Relationships between plastic microfibre abundance and synthetic fibre production. Microplastic fibres were counted in archived seawater samples from the North Sea. A significant increase in abundance of microplastics occurred from the 1960s and 1970s when compared with the 1980s to 2000s. Global production of synthetic fibre (million tonnes) is overlaid for comparison (dashed line). Grey boxes indicate the number of plastic fibres per metre^3 (Source: Thompson *et al.*, 2004; Barnes *et al.*, 2009; Bruce *et al.*, 2017).

Further investigations into the fate of plastics in oceans probed shoreline sediments worldwide[4], the deep sea[5], Arctic ice-cores[6] and ingestion by fish[7]. In all sediment samples collected, the microplastics discovered were fibres[4,5]. Although not all plastics found in ice-cores and fish were fibres, those found included comparable proportions of polyester, nylon and acrylic fibres to the sediment samples[6,7]. In the case of ingestion by fish, 68% of microplastics discovered were fibres, including nylon, polyester and acrylic[7]. In both sediment and ice-core sampling, the concentration of microplastics found was significantly greater than those reported in oceanic gyres[5,6]. The overwhelming dominance of microplastic fibres in sediments and their presence in waste water treatment plant effluent suggested a link to laundry and prompted an investigation into microfibre emissions from apparel[4,8].

An investigation into accumulation of microplastics on shorelines worldwide, revealed a link between microplastic fibres found in marine environments and domestic laundry effluent[4]. Marine sediments receiving sewerage discharge were found to have proportions of polyester and acrylic fibres resembling those in clothing production[4], which also resembled the proportions present in deep-sea sediments[5], and found ingested by fish[7]. Laundry trials have found synthetic fleece garments release plastic microfibres during domestic laundry[4,9,10]. With increasing synthetic fibre production for apparel[11,12,13] and growing population, it is reasonable to predict the potential for plastic microfibres from laundry will continue to grow.

Microplastic fibres are found in the deep sea, Arctic ice cores, and ingested by fish.

Ideally, textiles will be developed to significantly reduce their yield of microplastic fibres, and greater removal of microplastics would occur in waste water treatment plants[8]. However, textile improvements will take time, and due to very small size and irregular shapes filtration is challenging and costly. Encouragingly, various organisations are working to develop after-market washing machine filters to prevent waste water contamination by microfibres. One apparel company has recognised that the problem of microplastic fibres is significant, particularly from polyester fleece jackets, and has supported development of a 50 micron (µm) laundry bag claiming to restrict 70 to 90% of fibre yield from product (Figure 2)[14]. Another organisation focused on restricting oceanic microplastic pollution has developed a fibre scavenging laundry ball, which catches up to 35% of microfibres per mixed laundry load (Figure 3)[15]. These are simple solutions readily available to consumers to limit microfibre pollution in their laundry water. However, the burden remains on consumers to purchase and use the products. Microfibres captured using these methods remain destined for land-fill, although with growing synthetic apparel markets this remains preferable to direct deposit in aquatic environments[16].

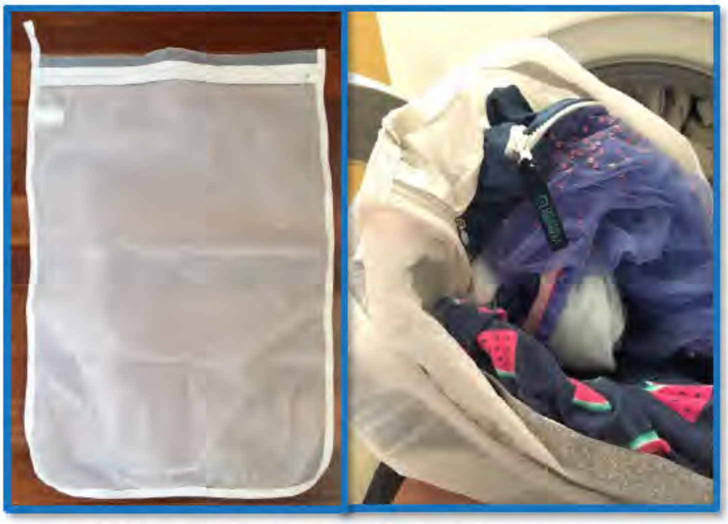


Figure 2: After-market laundry filtration bag, to restrict microfibres in laundry waste water, 50 x 74 cm.

Figure 3: In washing machine microfibre scavenging laundry ball.

Significance of the study

So far studies on microfibre pollution from laundry have considered a range of variables, including mechanical and chemical factors of domestic laundry[9,10,14,17-19]. Initial research trials focused on polyester fleece, due to the early discovery of sediment microfibres comprising 56% polyester[4]. Five published studies have demonstrated that polyester and acrylic garments release a significant amount of microplastic fibres[4,9,10,18,19], with multiple studies demonstrating the dominance of microfibres in sediments and their links to apparel[4,5,8]. The reported loss of fibres ranged from 0.0012–0.2% weight per weight (w/w) of the pre-wash mass, with fibres ranging from 20 µm to 5 mm in length[10,18]. Whilst polyester fleece garments are an important source of microplastic fibres, the nature of their use makes them likely to be laundered less often than other items, depending upon the environment in which they are worn[9,18].

The focus of this study was nylon stretch-performance fabrics, blended with elastane, as commonly found in swim/active-wear. Compared with trials of fleece fabrics, reduced microfibres were anticipated due to the fabric's smoother characteristic. However, due to the nature of this apparel's use, a single wear will potentially result in laundering. Additionally, swim-wear and active-wear are rapidly growing sectors of the fashion industry[20]. The trial compared four fabrics, three nylon/elastane blends (one recycled nylon) and a 100% polyester fabric. This is the first study of its kind (known to the author) to compare these fabrics, conventional and recycled nylon/elastane blends, and polyester with no elastane content.

This trial focusses on the previously untested, growing market of swim/active-wear fabrics.

The trial also aimed to evaluate the ability of two types of laundry filter bag to restrict microfibres from laundry waste-water, whilst retaining microfibres for responsible disposal.

Scope of work

Microfibre emissions from four fabrics were tested under domestic laundry conditions, using a front-loading washer. An additional variable was the presence and absence of a liquid laundry detergent, for comparison with previous studies and to ensure rigorous data collection. No variability in mechanical laundry conditions was trialed. Additionally, two microfibre capture systems were tested: a drawstring filter bag attached to the washing machine waste water hose; and a sealed laundry bag which held garments during laundering.

Research objectives

The trial focused on both research and containment of microplastic fibres from laundry waste water. There were two research aims:

- Research: to measure the microplastic release from stretch-performance fabrics, comparing recycled and conventional nylons, polyester, and the effect of detergent.
- Containment: to evaluate the effectiveness of two laundry bags – external and internal to the washing machine.

Structure of the report

This report provides an understanding of plastic pollution in marine environments and the prevalence of microplastics. The global extent of the problem, including ecological, geographic and plastic distribution in the food chain, and consequently the human milieu was considered. Given the implication of laundry waste water as a source of microplastic pollution, apparel has been discussed as a source within the context of current fashion trends. Previous trials of laundry as a source of microplastic pollution were reviewed and a methodology for the laundry trials established which emphasised the myriad of variables at play in laundry. The results highlighted the need for additional research on laundering of all synthetic fabric types and confirm synthetic fabrics as a source of microplastics. The discussion focused on the value of this information in terms of source reduction, comparisons with earlier trials, and the ability of laundry bags to restrict microfibres from entering the environment via laundry waste water. Corporate and environmental responsibility has been considered in the context of the problem and solutions, and future research recommendations made.

2. PLASTICS

A short history of plastics

The advent of plastic in 1907 heralded a new era of goods production and convenience[21]. When mass production commenced in the 1950s, 1.7 million tonnes of plastic was produced annually[17]. By 2007, 257 million tonnes were produced worldwide, which has increased by 25% to 335 million tonnes in 2016[22] (Appendix 2), not including the more than 64 million tonnes of synthetic textiles produced annually[11,22,23] (Appendix 2 & 3). To be clear, synthetic textiles possess the same characteristics as their related plastic polymers.

Amidst a quest to develop 'super-polymers' the first synthetic textile developed was nylon in 1935, with mass production commencing in 1939 to manufacture stockings. However, with the onset of World War II, the flexibility of nylon was realised and all production was diverted for defence use, including parachutes, protective clothing, hammocks and survival equipment[24]. In 1941 polyester, which today comprises 60% of world textile production, was developed and began mass production in the 1950s[25]. The popularity of polyester is attributed to its availability, cost, flexibility and low moisture retention[26].

Paradoxically, the same properties that drive mass production of plastic render it an environmental menace. Durability, lightweight, buoyancy, and low-cost characteristics facilitate mass production and mass distribution of plastic[3]. The lifespan of plastic is estimated between hundreds and thousands of years, with salt-water and reduced UV environments aiding its persistence[3]. As an example, plastic found consumed by an albatross was documented as originating from a plane crash 60 years earlier, some 10,000 kilometres away[27]. Additionally, plastic is a vector able to transport persistent organic pollutants (POPs)[16], algae, bacteria and invasive species[3] long distances. Whilst plastic readily deteriorates, it is not biodegradable, and reductions in size increase its ability to infiltrate ecosystems and to adsorb pollutants[16,28,29].

> The same properties that make plastic a 'super' product make it an environmental menace.

Plastic as a pollutant and toxicant

Plastic is a chronic pollutant known for its global environmental reach and long term persistence. Although it comprises approximately 10% of anthropogenic waste, plastic accounts for 60–80% of all marine debris[3,7]. Aside from its intrinsic toxic nature, plastic also has an affinity for environmental toxicants, such as pesticides and heavy metals, increasing its detrimental effect on the environment[2,3,16,30,31]. A toxicant is a synthetic substance, not normally encountered by an organism, which adversely affects its health and functioning. Chronic toxicants are those present in the environment at low levels for extended periods of time. In the case of plastic elements, the primary effect is on endocrine disruption which manifests in a range of ill health and fitness effects. Endocrine disruptors interfere with the hormone systems of organisms, often impacting reproduction[32]. Of the suite of toxicants incorporated into plastic the primary offenders include bisphenol A (BPA), phthalate, and polychlorinated biphenyls (PCB)[16,30,31,33]. The non-polar, hydrophobic (water-repelling) nature of plastic allows adsorption of pollutants from surrounding water, concentrating their toxicity up to 25 times the ambient water, magnifying pollutant distribution and restricting their biodegradation, which increases their persistence in the environment[3,16,34]. Examples of adverse health effects from plastic in the environment are provided in Table 1.

> **Plastic can bind toxicants to itself, such as pesticides and heavy metals at amounts 25 times the surrounding water.**

Within the environment toxicants from plastic pollutants are transferred directly to organisms primarily via ingestion, but also via skin contact and inhalation[3,17,31]. Many animals have been established as ingesting plastic, with their health and fitness compromised through either blocking and damaging the digestive tract, or toxicity affecting tissues and organs[7,36,38,40]. Indirect exposure occurs within the food chain, as animals further up the chain consume lower levels that have eaten plastic. For humans the same routes of exposure apply, and inherently bio-magnification is an important consideration for those who are eating from all levels of marine food chains[17,38,39].

Table 1. A summary of the primary toxicants found in plastic, and the chemicals they accumulate in marine environments, which have adverse health effects on humans and animals[16,30-32,35-39].

Element	Characteristics	Mechanism	Examples
Bisphenol A (BPA)	• Provides strength & impact resistance to plastics. • Lines food cans. • Dental sealants, fillings. • Water soluble. • Readily leaches from landfill, more found here than waste water. • Does not bio-magnify. • Acutely toxic to arthropods.	• Major pathway ingestion. • Human endocrine disruptor. • Impacts directly on animal consuming the plastic. • Mimics oestrogen. • Causes heart disease. • Soluble in blood and body fluids. • Degrades from polymer to monomer, and then readily leaches.	• Malformed female organs in aquatic snails. • Exposure in pregnancy limits development, reduced survival and birth weight, and delayed puberty in rats. • Human bio-monitoring annually in USA – present in 93% samples. • Blood levels associated with recurrent miscarriage in humans. • Polycystic ovary syndrome in humans. • Linked to diabetes and heart disease.
Polychlorinated biphenyl (PCB)	• Hydrophobic (water repelling). • Lipophilic (fat loving).	• Concentrated in environment through adsorption onto plastic particles. • Accumulate in the liver and fat tissues.	• Severe reduction of energy stores. • Fatty liver. • Cell death. • Tumour growth in fish. • Transfer to tissues in birds & fish.
Phthalate	• Plastic softener, provide flexibility. • High molecular weight (MW), provide flexibility to plastics. • Low MW used as solvents in perfumes & cosmetics, lacquers, paints etc. • Water soluble.	• High level human exposure. • Human endocrine disruptor. • Inhibits testosterone. • Rapidly metabolized and excreted. • PBT is a major component of polyester fabrics.	• Impairs male reproductive ability: greater sperm DNA damage, decreased sperm motility & concentration. • Premature breast development with absence of puberty. • Asthma (when inhaled).
Polyurethane	• Component of elastane (85%).	• Monomers are carcinogenic and mutagenic.	• Leachates toxic to aquatic invertebrates EC50 24 g/L^{-1}
Polyvinyl chloride (PVC)	• Human dermal irritant • Found on clothing in screen printed designs. • Phthalate rich, up to 50%.	• Reduced energy reserves • Carcinogenic • Human dermal irritant • Enhanced immune response	• Sediment feeding worms (keystone sp.) had reduced feeding activity and 50% less available energy reserves, plus increased phagocytic activity, slowed digestion.
Organotin (OT)	• Stabilising additive. • Water soluble: occurs more in landfill leachate than waste water.	• Promote testosterone. • May be adsorbed from surrounding water.	• Male characteristics in female snails. • Inhibit growth in mussels. • Immune dysfunction in fish.
Nonylphenols (NP)	• Prevent oxidative damage in plastics. • Hydrophobic • Persist in anaerobic environment.	• Impact human immune function. • Mimic oestrogen. • Accumulate in tissues and fats. • Major source is WWTP discharge.	• Female characteristics in male aquatic organisms. • Increased juvenile mortality. • Greater concentration in marine animals than in the surrounding sediments.
Polycyclic aromatic hydrocarbons	• Hydrophobic. • Lipophilic.	• Concentrated in environment through adsorption on plastic particles.	• Human carcinogen, affects heart, stomach, kidneys: bio-monitoring annually in Germany.
Metals	• Chromium. • Copper, silver, zinc. • Antimony.	• Found in fabric dyes for. • Nanoparticles for antifungal, antimicrobial, antiviral properties. • Used to catalyse PET polymerization. • May also be adsorbed from surrounding water.	• Liver damage, pulmonary congestion, carcinogenic.
Triclosan	• Antimicrobial, antifungal	• Readily sorbed to plastic and released in digestive tract.	• Hormone disruptor. • Immune system disturbance.

3. MICROPLASTICS

Microplastics can be defined as plastic particles less than 5 mm and including microfibres. Although it should be noted there is some conjecture as to the definition of microplastics, with various studies providing sizes ranging from less than 1 mm to more than 10 mm[41]. Microplastics are further classified by their source. Primary microplastics are manufactured microscopic and found in personal care products, abrasive materials and pellets for plastic production[10,29]. Secondary microplastics result from degradation of larger products upstream or within the environment[2,8,18,21], such is the case of microfibres in laundry effluent.[8] They are an environmental pollutant known to be accumulating in aquatic and marine ecosystems worldwide[2,3,4,16-18,21]. The result is flow through food-chains, bio-accumulation and potential bio-magnification, with eventual consumption by humans[4,6-8,42,43]. A converging body of research implicates laundry as a pervasive source of microplastic pollution, delivering it at volumes and size to be ubiquitous in ecosystems.

Global distribution of microplastics

Questioning *"Where is all the plastic"* Thompson *et al.*, (2004) discovered microplastic fibres in North Sea plankton samples from the commencement of mass production in the 1960s, with a significant increase in abundance in the 1980s through 2000s (Figure 1). The same study tested sediments from beaches, estuaries and subtidal zones in the UK, with polymers present in 23 of 30 samples, the majority being fibres including nylon and polyester[2]. Microplastic pollution has been found on all continents from the Arctic to the Antarctic, in marine and aquatic environments[4,6,44,45] from high altitude lakes to rivers and estuaries,[46,47] from reefs to deep sea sediments[5,48]. On the ocean surface the vast majority of plastics are microplastic fragments (92.4%).[49] Within the water column and sediment the majority of microplastics are fibres (63-68%), in densities 10,000 times that of surface plastics[5]. Microfibre distribution is related to population density[4], landforms and water movement[3,5,49]. It follows that areas of microplastic accumulation are affected by seasonal influences of rainfall, winds, tides and currents.[3,49] Due to its buoyancy, large rivers carry plastic pollution from inland areas to the coast,[3,5] with strong plumes sweeping debris off the continental shelves to the deeper ocean where prevailing winds and currents influence accumulation[3,5].

In the water column and sediment, **68%** of plastics are microfibres, at densities up to **10,000** times greater than surface plastics.

More recent research sampled coastal sediments worldwide, comparing them with sediment samples from waste water disposal sites and effluent (Appendix 3)[4]. Abundance of microplastic fibres in sediments ranged from 2 – 31 fibres per 250 mL, including polyester (56%), acrylic (23%), and nylon (3%)[4]. Additionally, waste water disposal sites were found to have 250% more fibres than reference sites, even after 10 years without effluent inputs, a testament to the persistence of microplastics in the environment.[4]

Microplastic fibres found in sediments mirror those used in clothing… polyester, acrylic and nylon.

The striking resemblance between proportions of microplastic fibres in the sediments, waste water disposal sites, and those used in apparel, prompted the first trial of microfibre release within domestic laundry waste water, finding a single fleece jacket can release 1900 fibres per wash[4].

The global pervasion of microfibres and their links to domestic waste water has been supported by two further studies. The first demonstrated microplastic fibres were present worldwide and constituted the largest proportion of microplastics in deep-sea sediments, ranging from 1.4 to 40 pieces per 50 ml, with conservative models estimating 4 billion fibres per km^2 of Indian Ocean seamount sediment to 15 billion in the Atlantic and Mediterranean[5]. Additionally, fibre proportions again mirrored textile production, with polyester (53.4%) most prevalent, and other fibres including nylon (34.1%) and acrylic (12.4%). The second study considered a waste water treatment plant, serving a population of 650,000, as a source of microplastic pollution. Although this system removed up to 98.4% of microplastics, the released particles would amount to 65 million microplastics into the environment per day, or 23 billion annually[8]. Additional related studies detailing distribution of microplastics and affected ecosystems are summarised in Table 2.

4-15 billion microfibres per square km found on the ocean floor worldwide.

A population of 650,000 can discharge 65 million microfibres into the environment daily.

Table 2. A summary of studies into the global distribution of microplastic pollution, 2011-2017.

Authors	Ecosystem	Location	Methods and main findings
Browne *et al.*, 2011	Near Coastal	Australia, USA, Africa United Arab Emirates Chile Philippines Portugal, Azores United Kingdom	• 18 shores on 6 continents contaminated with microplastic. • Abundance ranged from 2 (Australia) – 31 (Portugal, UK) fibres per 250 mL sediment. • Greater population, greater microplastic abundance. • Dominant fibres in sediment: polyester 56%, acrylic 23%, polypropylene (PP) 7%, polyethylene (PE) 6%, nylon 3%. • Tested WWTP effluent: polyester 67%, acrylic 17%, nylon 16%.
Eriksen *et al.*, 2013	Lake	Great Lakes USA	• Manta trawl surface water, 333 µm mesh. • Average 43,000 microplastics/km^2. • Maximum 466,000 microplastics/km^2. • Plastics all fragments, not fibres: pellets, polystyrene foam, line or film.
Eriksen *et al.*, 2014	Ocean	Worldwide surface waters.	• Estimate 5.25 trillion plastic particles, weighing 268,940 tons floating at sea. • Indian Ocean may have greater particle count and weight than South Atlantic and South Pacific oceans combined. • 92.3% of tows worldwide captured plastic, predominantly secondary fragments. • Microplastics account for 92.4% of global particle count. • Plastic is moved via wind and surface currents. • Plastic pollution may move between hemispheres and oceanic gyres. • During fragmentation plastic may sink.

Continued on next page

Authors	Ecosystem	Location	Methods and main findings
Free *et al.*, 2014	Lake	Mongolia, Lake Hovsgol	• 333 µm mesh, surface water. • Average 20,264 microplastics/km^2. • Maximum 44,435 microplastics/km^2. • Without proper waste management small populations can heavily pollute freshwater systems with plastics.
Obbard *et al.*, 2014	Sea Ice	Arctic	• Sea ice scavenges particulates, including plastics. • Rayon 54%, polyester 21%, nylon 16%, PP 3%. • Ice cores: 38 to 234 particles/m^3 ice. • Sea ice is a major sink for microplastics.
Woodall *et al.*, 2014	Deep Sea	Worldwide	• Microplastic fibres up to four orders magnitude more abundant (per unit volume) in sediments than in surface waters. • 1.4 (Indian Ocean) – 40 (NE Atlantic) microplastics per 50 ml sediment.
Mani *et al.*, 2015	River	River Rhine, Germany	• Surveyed 820 km of surface water 18cm. • Used 300 µm mesh. • Average 892,777 particles/km^2. • Maximum 3.9 million particles/km^2. • Microplastic abundance proportionate to population and related to proximity of waste water treatment plant. • 60% plastics were spherical. • Fibres 2.5%, and were not likely from textiles.
Sutton *et al.*, 2016	Bay	San Francisco, USA	• 333 µm mesh, 30 mins, surface waters, 16 cm. • Waste water effluent filtered at source through 0.355 mm and 0.125 mm mesh, 2 hours. • Waste water had 0.086 microplastics per litre = 7 million per day. • Fibres dominant (80%) in waste water effluent. • Surface waters all samples contained fragments, fibres, some pellets.
Murphy *et al.*, 2016	WWTP outfall River	Scotland	• Sampled four stages of the waste water treatment process. • Urban population of 650,000 will release 65 million MP daily (23 billion annually). • Apparel fibres most abundant: polyester 28%; nylon 20%; acrylic 12%.
Courtene-Jones *et al.*, 2017	Ocean floor	North Atlantic (West of Scotland) Rockall Trough	• Snapshot: Remote deep ocean floor 2200 m deep in ocean. • Sediment: 0.5mm net trawled on sea floor 60 minutes, then filtered to 4 mm, 0.5 mm, 0.42 mm. 70.8 particles/m^3. • Macroinvertebrates: 359 particles, 45 synthetic, 165 cellulose, 149 unclear. • Deep-sea water: 240 L filtered through 80 µm mesh, 78 particles: 17 synthetic, 28 cellulose, 33 unclear. Between 0.02 – 100 particles/m^3. • Significant difference in microplastic ingestion by species.
Vaughan, Turner & Rose, 2017	Lake, Urban	Birmingham, United Kingdom	• Sediment samples, 0.5m to 1.5 m depth. • 25-30 particles/100 g dry sediment. • Fibres and films most common. • Distribution suggests input by inflow of stream. • No waste water treatment plant in catchment.

Ecological distribution of microplastics

The importance of healthy sediment for ecosystem vitality is well documented. It provides storage for nutrients, an interface for respiration and oxygen exchange, and habitat for keystone species. Healthy marine life need healthy sediment, and healthy sediment needs healthy marine life. Plastics are demonstrated to reduce health across the food chain, placing direct and indirect limitations on ecosystem functioning[4,36,38,56]. Negative health consequences include clogging digestive tracts and starvation[40,56], reduced fertility through hormone disruption[16,31,32], reduced energy reserves[38], compromised immune function[50], and liver damage[36] (Table 1). The capacity of microplastics to limit fitness in organisms from zooplankton, sedimentary worms and detritivores, to grazers and predators naturally restricts biodiversity, consequently degrading ecosystems[4,43,51]. Plastic is being consumed by organisms both as micro and macro particles,[38,40,51,52] it persists in tissues, digestive tracts and body fluids,[42,53] and transfers pollutants when consumed[16,36,42,54].

Microplastics in the food chain

Microplastics have been found in all levels of marine food chains, including bottom-dwelling invertebrates more than 2200 m deep in the ocean[48], zooplankton, amphipods and barnacles[2,51], sedimentary polychaete worms[38], planktivorous fish[40], shrimp[57], sea birds[56], and commercial seafood species[7,54] (Table 3). The ability for corals to ingest microplastics has also been demonstrated in laboratories, but yet to be demonstrated in the environment[58]. Ingestion of microplastics increases exposure to environmental toxicants including metals, persistent organic pollutants, viruses, and chemical additives of plastic[16].

An example of a keystone species that is vital to ecosystem health and readily compromised by plastic pollution in the polychaete lugworm (*Arenicola marina*)[48,50]. These worms are not only an important source of food, but fulfil an important eco-physiological role, aerating sediments whilst feeding non-selectively on detritus and micro-organisms[38,50]. Under laboratory conditions, these worms have been demonstrated to have 50% less energy reserves when exposed to plastic pollution at environmental levels[38,50]. Analogous to the confronting images of birds, whales and turtles with stomachs full of plastic, these keystone species become compromised in their ability to perform their necessary ecosystem services when their stomachs are loaded with plastic and their systems impaired by toxicants[38] (Table 1).

Microplastics have been found in all levels of marine food chains.

Humans eat seafood from all levels of marine food chains.

In a demonstration of uptake and release of toxicants from plastics, fish fed polyethylene pellets from a marine environment suffered greater liver toxicity and stress than fish fed *clean* polyethylene pellets[36]. In a separate trial, plastic pellets steadily increased in pollutant concentration over six days in seawater[34]. Following uptake, toxic additives of plastic are demonstrated to bio-accumulate within organisms[38,50], although transfer within the food-chain and bio-magnification remains subject to debate[42,43,53]. Factors affecting bio-accumulation rates include the plastic type, environment (water/sediment, saline/fresh, temperature), and physical structure (size, fibre/fragment/sphere)[53,39]. In the case of microfibres, the small size and irregular shape maximises their ability to bind toxicants and be consumed by all levels of the food-chain[16].

Bio-magnification can only occur if a consistent source of contaminated prey is consumed. However, in the laboratory it has been demonstrated that transference from prey (mussels) to predator (crabs and fish) will occur at environmental concentrations of plastic pollution[42]. Although it was also demonstrated toxicants and plastics will be purged by crabs and fish given enough time in pollution free conditions[53]. It must be stated based on recent measures of plastic pollution in oceans, areas of plastic free conditions may be challenging to find[4,5]. Additionally, sessile species such as shellfish and sedimentary worms have little means to escape pollution[38,42]. Whilst bioaccumulation has been established[50], transfer through the food chain demonstrated[42], and biomagnification is anticipated, it is challenging to quantify the scale of biomagnification due to the myriad of factors at play[43,53].

Table 3. Distribution of microplastics in the food chain: summary example studies.

Authors	Focus	Trial	Main findings
Teuten *et al.*, 2009	Transport & release of chemicals from plastics to the environment and wildlife.	*In vitro* Shearwater Chicks	• Plastics adhere 25X toxicants of surrounding water. • PCBs transfer from plastics to chicks. • Plasticizers such as phthalates and other monomers leach from landfill to ground and surface waters. • BPA water soluble and readily leaches, concentrations related to population and economic development. • Should not underestimate environmental impact of discarded plastics.
Boerger *et al.*, 2010	Pelagic Plankton eaters	*In vivo* North Pacific Central Gyre	• Trawled for pelagic plankton eating fish. • Found 35% had plastic in gut, average 2.1 pieces, average mass 1.57mg. • Primarily ingested fragments 94%.
Cole *et al.*, 2013	Zooplankton	*In vitro*	• Demonstrated zooplankton will ingest microplastics. • Apparent egestion of MP at natural food rate, although some became trapped in appendages. • Irregular shaped debris more likely to be retained longer. • Microplastic debris negatively impact zooplankton.
Lusher *et al.*, 2013	Pelagic and benthic fish	*In vivo* English Channel	• 36.5% fish had synthetic items in stomach: 58% rayon; 36% polyamide and polyester. • No difference in abundance of plastic ingested between benthic and pelagic fish. • Plastics primarily fibres 68.3%, fragments 16.1%, beads, 11.5%.
Farrell & Nelson, 2013	Trophic transfer mussels to crabs	*In vitro*	• Mussels exposed to polystyrene 1 hr, then immediately fed to crabs. • Highest amount of microspheres in haemolymph of crabs at 24 hours, 0.04% of the amount mussels exposed to. • Microspheres also found in pancreas, ovary and gills.

Continued next page

Authors	Focus	Trial	Main findings
Rochman *et al.*, 2013	Hepatic stress in fish ingesting plastic.	*In vitro*	• Fish exposed to polyethylene and sorbed chemical pollutants from marine environment bio-accumulate in fish, inflicting liver toxicity. • Fish fed virgin polyethylene pellets (not from marine environment) suffered less severe effects.
Wright *et al.*, 2013b	Polychaete worms	*In vitro* Modelled on Wadden Sea.	• Deposit feeding marine worms bio-accumulated PVC. • Reduced energy reserves result from reduced feeding activity, gut retention of plastic, and inflammation. • PVC took 1.5 times natural rate to egestion. • In polluted environments, sediment processing by lug worms could be compromised by 25%.
Devriese *et al.*, 2015	Coastal Shrimp, shallow water habitats.	Southern North Sea and English Channel	• Brown shrimp are epi-benthic, meaning frequent exposure to sediments. • Synthetic fibres ranging from 200 -1000 µm found in 63% shrimp. • 96.5% of plastic found was fibrous.
Tanaka & Takada, 2016	Coastal Planktivores	*In vivo* Japan	• Plastic detected in 77% of fish, mostly irregular shaped. • Clogging of digestive tract observed. • Recommend research into toxicant exposure from plastic retention.
Santana *et al.*, 2017	Crabs and Pufferfish feeding on mussels	*In vitro*	• Low exposure scenario: mussels fed to crabs and fish once plastic present only in haemolymph, absent in gut cavity. • Plastics transferred from prey. After 10 days in clean water, plastics eliminated from predators.

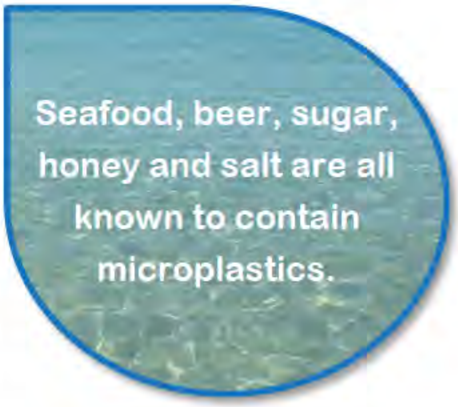
Ingestion of microplastics by fish, both open-water (pelagic) and bottom-dwelling (benthic), corresponds to plastic distribution in the ocean[4,5]. In separate studies in geographically and climatically distinct areas, plastic ingestion rates were similar (35%[59] and 36.5%[7] respectively), although the shapes of the plastic varied. In the open-ocean mid and surface water feeding fish predominantly ingested fragments (94%)[59]. Whilst in near coastal waters, pelagic and benthic fish predominantly ingested fibres (68%)[7]. This is further supported by the high proportion (63%) of bottom-dwelling shrimp found with plastic fibres (96%) in their gut[57]. These are animals all consumed as seafood by humans, emphasising the need for research to understand bio-accumulation and bio-magnification of plastics by seafood species for human health considerations[7,39,40,53,54,57,59].

Generally, microplastic fragments are found in open water, and microplastic fibres are found in sediments.

Human exposure to microplastics

The impact on human health of plastic contaminated seafood will depend upon the concentration, duration and type of plastic exposure in addition to the type of animal being eaten[16,28,39]. It is estimated Europeans ingest up to 11,000 microplastics per year via shellfish consumption[39]. Table salt has also been found to contain between 1-10 microplastics per kilogram, 26% being fibres[60]. Additionally, there are multiple land-based products that result in human exposure to plastics. Food products with known microplastic contamination, not sourced from the sea, include beer with up to 109 fragments per litre[61], sugar and honey[39]. Chemical components of plastic are known to be present within humans and are regularly tested in urinary concentrations world-wide[30].

Primary plastic chemicals of concern for human health are phthalates and BPA, due to their ubiquity in environments, an artefact of their water solubility[16,30,62]. These chemicals also have proven toxicity to animals, and negatively affect the hormonal system (Table 1)[16,30,31,36]. Although they are readily metabolised, almost wholly excreted in urine, due to constant exposure a fraction can be stored in fat tissues, then released slowly into the bloodstream[30,31]. Perhaps of greater concern is plastic exposure during pregnancy, as phthalates and BPA are known to cross placental barriers and impact development[31]. With extensive plastics used for convenience, in addition to plastic contamination in food, humans risk health from chronic low level exposure scenarios[30]. Factoring in direct consumption of plastics in foods like seafood will inevitably increase the risk of ill-health from plastic. Whilst a fiscal cost to human health is yet to be calculated, the United Nations Environment Program estimates the natural capital cost of plastic pollution on oceans at US$13 billion per year[63].



The ubiquitous presence of plastic pollution in oceans is established, with ever smaller particles entering environments on which humans rely for ecosystem services and food. The mechanisms of microplastic deposition, microfibre sources and quantities, and mitigation of microfibres constitute research gaps. With waste water treatment plants and laundry waste water being implicated, further research is needed into the apparel and fashion industry as a source of microplastic pollution.

4. FASHION AND MICROPLASTICS

The link between laundry effluent, waste water treatment and microplastic fibres in sediments has given rise to a small body of research into fibre release from apparel during its consumer life cycle stage[4,9,10,14,18,19,55,64]. However, meaningful opportunities for mitigation and possible regulation of microplastic fibre release from synthetic garments lie within the manufacturing life cycle. Technological advances, de-regulatory economic policies to encourage globalisation, and prolific synthetic textile availability have fuelled the rise of *fast fashion* in recent decades[11,13,65]. With an understanding of current trends in textile use by the fashion industry, comes insight into a source of plastic microfibres in the environment[11,13,65,66].

Textile trends of the fashion industry

Although global textile production has consistently increased for the past 25 years, natural fibre use has remained steady since the 1990s (Figure 1, Appendix 4)[13,67]. However, synthetic fibres, including nylon, polyester, and elastane, have experienced ever increasing production, with synthetic reaching 70% of all textiles produced in 2016[13,67]. By 2010 annual synthetic fibre production was double that of 1992, and 1.5 times that of natural fibre demand[11] with 62 million tonnes of synthetic textiles manufactured in 2015, growing to 71 million tonnes in 2016[12]. The rapidly growing swim/active-wear market accounts for at least one-sixth the overall market and grew 50% in sales during 2012-2014[20]. These garments utilise polyester and nylon based fabrics, often blended with elastane[20]. Elastane is also known by other registered trading names including *Spandex* and *Lycra*. This apparel differs greatly in its wear from fleece fabrics, being worn year-round and washed more frequently, potentially with each wear[68]. Whilst its smoothness is anticipated to result in reduced microfibre yield than fleece, increased laundering provides greater opportunity for emissions.

> No literature was found researching the microfibre emissions from swim/active-wear fabric. As a growing apparel market with high laundering potential, it is an important missing aspect in the microplastic story.

Characteristics of swim/active-wear fabrics

Synthetic fibres have established a stronghold in contemporary apparel and dominate the swim/active-wear market due to their strength, durability and elasticity[65,69]. An array of engineering methods are used to provide the features of stretch and compression desired in these textiles including weave, fabric blends, coatings, polymer choices (Figure 4)[70]. Any of these methods could influence microfibre release. Perhaps controversially, programmed breakage of fibres is an engineering method employed to reduce pilling, for aesthetic and ostensibly life extension of garments[71]. Whilst elastane became known as a 'wonder' fabric in the 1980s for its superior elasticity and wrinkle recovery, its deficiencies of low heat tolerance and chemical resistance have resulted in its frequent combination with both natural and synthetic fibres and may also contribute to its microfibre release[69]. Elastane is common in swim/active-wear textiles blended with nylon or polyester to promote shape retention, and frequently found blended with denim for increased stretch[69]. For chlorine resistance frequently 100% polyester textiles are employed, perhaps due to its hydrophobic characteristic, utilising weave instead of elastane to provide stretch. Synthetic fabrics, including nylon, polyester and elastane, possess distinct properties (Appendix 5), which are likely to affect microfibre yield. Therefore these polymers should be targeted for further research to seek opportunities to reduce their microfibre yield into the environment. Additionally, nylon and polyester are highly recyclable fibres, so understanding their microplastic fibre yield is critical to understanding their environmental life-cycle value[72].

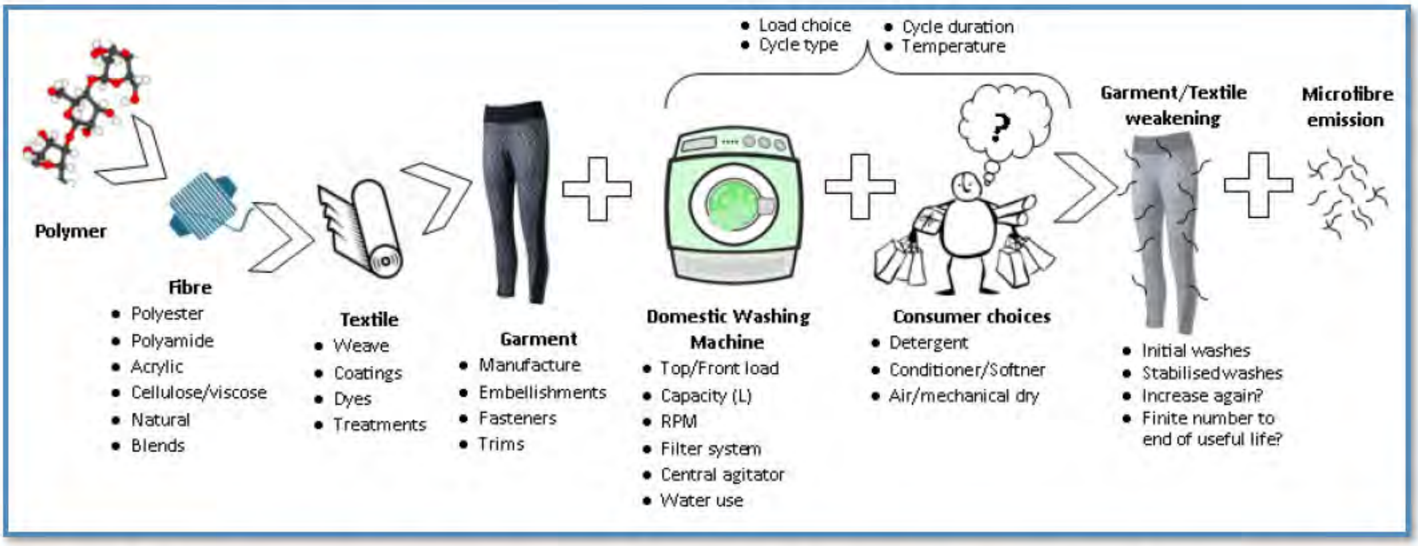


Figure 4. Manufacturing and life-cycle variables of synthetic apparel, which may influence microfibre emissions (Adapted from Salvador Cesa *et al.*, 2017).

Recycling synthetic fibres

Recycled synthetic fibres use 35-55% less energy to produce, require zero crude oil feedstock, reducing emissions of volatile organic compounds, micro-particles, acid gases, and ozone depleting gases, saving 34-58% global warming potential[23,72-74]. Producing recycled polyester saves more than 2.4 billion bottles annually from landfill in the USA alone and produces 85% less air pollution than conventional production[73]. Recycled polyester comprised approximately 8% of all polyester produced in 2007[72] with recycled nylon also recently introduced to the market[69]. Similarly, production of recycled nylon uses fishing nets and carpet as feedstock. Fishing net collection programs are removing nets from the environment, and carpet take-back reducing land-fill. An overview of recycling nylon and polyester is included in table 4.

Recycled fibres save plastic bottles, fishing nets and carpets from land-fill. They produce up to 85% less air pollution, 34-58% less global warming and use 35-55% less energy.

Table 4. Basic process to produce recycled polyester and nylon fibre.

Material	Manufacture	Feedstock	Process
Polyester	Mechanical or Chemical	PET bottles 100% polyester fabric	• Separation from labels and caps. • Bottles processed into flakes • Mechanical: flakes melted then extruded into yarn. • Chemical: flakes chemically depolymerised, before re-polymerisation and transformation into yarn. • Yarns are spun, then woven.
Nylon	Chemical	Fishing nets Carpet fluff	• Cleaned, shredded, and compacted. • Depolymerisation (breakdown). • Polymerisation (reformed) • Transformation into yarn, spinning, weaving.

A hindrance to closed loop cycling of textiles is blending of fabrics, for example cotton blended with polyester, or nylon blended with elastane. In these instances, challenges in separating different materials may result in the loss of one or the other component[69,75]. As such presently recycled polyester and nylon products derive from pure sources only[69,72]. However, research by manufacturers continues, and in recent trials success in laboratory conditions was achieved degrading elastane, whilst retaining nylon using heat and ethanol[69].

Laundry trial including recycled fabric

A single published trial was found with results that could compare microfibre emissions from laundering recycled and conventional polyester jackets[18] (Table 5). Of the four polyester jackets tested, three were a *name* brand (two with recycled fibre content), the fourth a *budget* brand[18]. When washed as new jackets, the three branded jackets released smaller microfibres than the budget jacket, and the budget jacket produced 3.7-9.75 times the normalised mass of fibres of the branded jackets[76]. Additionally, both recycled jackets produced fewer microfibres than the comparable branded jacket (Table 5). When washed as aged garments, the branded 100% polyester jacket and the 85% recycled jacket produced a similar mass of microfibres to one another, with the budget jacket producing 1.5 times the proportionate mass of fibres [18]. All aged jackets produced larger proportions of larger microfibres than new jackets.

Table 5. Average fibre mass (mg) recovered per wash on 333 and 20 μm filters for four jackets (3 replicates) laundered in a front-loader washing machine [18,76].

Garment	NEW		Total	%	AGED		Total	%
	20 μm	333μm	(mg)	w/w	20 μm	333μm	(mg)	w/w
Recycled 85% polyester, 15% polyester, synthetic jumper	25	58	83	0.016	98	136	234	0.045
Recycled 63% polyester, 33% polyester, 3% elastane, mid-layer jacket	29	0	29	0.008	92	161	253	0.064
100% polyester, synthetic fleece jacket	122	0	122	0.021	92	139	231	0.040
100% polyester, budget brand, synthetic fleece	199	232	431	0.078	111	277	388	0.071

It is interesting to note that differences in quality of manufacture may correspond to improved durability of the product and a lower microfibre yield, suggesting not all synthetic textiles are equal. However, capture of larger microfibres should theoretically be easier than capture of very small fibres. It is also encouraging that use of recycled textiles may not correspond to a lower quality product or increased environmental foot-print. As synthetics are a product of non-renewable fossil-fuels, greater investment and research into recycled textiles is important. Further understanding could be obtained by laundering only fabric, as opposed to whole garments, to reduce variables and take into account an entire life cycle worth of washes, rather than simulating aging. Potential differences in quality at the polymer, fibre and textile level may provide greater opportunity to regulate microfibre release, than differences in brand[77]. However, there are of course opportunities to reduce microfibres from fashion through consumer education about laundering choices.

Additional uses of plastic in the fashion industry

With the globalisation of fashion, plastic has become ubiquitous within supply chains, in quantities greater than the plastic in product and packaging combined[63,78]. Based upon an estimated three trillion dollar fashion industry, present annual use of plastic within fashion supply chains is 14.1 million tonnes, 600,000 tonnes in packaging, and 9.9 million tonnes in product[63]. Garments are individually wrapped in plastic then packaged together in larger plastic bags for distribution. Apparel tags are coated, plastic stickers applied for hygiene, and garments hung on plastic hangers. In the case of mail order, apparel items are shipped in plastic packaging for protection. In brick and mortar stores, shoppers are offered branded plastic bags to carry their purchases. However, these are obvious sources of plastic within the life-cycle. Other areas are the textiles themselves, natural textiles blended with elastane, or 100% cotton garments sewn with polyester or nylon thread and a synthetic ‘satin’ care-tag applied to the garment, with a recommendation it be cut off after purchase (Figure 5), buttons, fastenings and embellishments. Alternatively, manufacturers label garments using screen/hot press printing, which may include plasticisers, phthalates, PVC, vinyl, or acrylic plastic[79]. Garments are also embellished with plastisol and acrylic inks. These inks do not last for the lifetime of the garment and can steadily wear off from UV degradation or surface contact, ultimately ending up in the environment (Figure 5).

Figure 5. Additional sources of plastic pollution from the fashion industry, including printing (hot-press/screen) separating from the garment, and entering the environment; and synthetic ‘satin’ tags sewn onto the garment with the scissor icon recommending removal.

5. LAUNDRY AS A SOURCE OF MICROPLASTIC FIBRES

Since the primary study linking environmental microplastic pollution to domestic laundry was published in 2011[4], a body of seven research trials into microplastic fibres in laundry waste water has grown. Although the focus has been on polyester fleece, limited fabric and garment selections have been included and physical characteristics of garments (age, cost, construction), in addition to washing machine centred variables such as mechanistic (top versus front loading), and chemical (detergent presence/absence, rinse conditioner) variables have been considered[9,10,14,18,19,55,64].

In reviewing these laundry trials, the consensus is that laundry is a significant source of microplastic pollution (Table 6). However, the myriad of laundry variables and imperative to address a significant environmental problem has resulted in data that is not always comparable, and knowledge gaps remain. It has been suggested there are as many chemical and mechanical variables as there are consumer choices that could affect microfibre yield, with seven mechanistic and five chemical variables when laundering alone[17]. However, this doesn't take into account the plethora of variables within the manufacturing life cycle of a garment, such as polymer, textile, weave, finishing processes, manufacture processes, and design concept (Figure 4). Variations in the trial methodology (e.g. filter types and sizes, sample sizes, whole garment, sub garment, *in vitro* or *in vivo*), and assumptions used (e.g. formulae for conversion of mass to fibre numbers) confound attempts to make comparisons between studies and, importantly, recommend management solutions to the problem. All previous trials have tested factors that derive from consumer choice, and consumer education will contribute to reducing the problem. However, improved manufacturing should coincide to create the greatest improvement.

> **Laundry is implicated as a significant source of microplastic pollution in oceans.**

It has been demonstrated that up to 90% of apparel degradation is imposed by laundering, rather than wear[80] and consequently garment life cycles are measured as the number of wash cycles in the usable life. There are more than 840 million domestic washing machines in operation worldwide[17], more than 7.5 million in Australia. Consumers tend to wash by habit not necessarily because clothes are dirty, often with machines at 75% capacity or less, from 2.5 - 5 cycles per week[65,68,81]. Whilst no study specifically addressing swim/active-wear laundry habits could be found, there are many examples of online recommendations to launder after every wear (Figure 6). Thus far, chemical variables such as effects of detergents and conditioners on fibre release have shown varying influence,[9,10] although this variable has been omitted in some trials due to the tendency to block fine micron filters[4,18]. However, there is agreement that top loading machines produce significantly greater microfibre yield than front loading machines,[14,18] with a study finding top load machines yield 430% more than front loading[18]. In addition to the central agitator on a top loading machine, the greater water use and longer cycle duration, could all contribute to the increased yield through weakening fibres[17,18].

> "But as a general rule of thumb, we recommend you wash sports bras after every wear to help ensure you get the longest life out of your garment possible."

"This is how often you really need to wash your sports bra" www.coach.nine.com.au

> "Most activewear has synthetic fibres meaning they dry fast so there isn't much of an excuse not to wash regularly," she said.

"Experts reveal how you should actually be washing your activewear" www.news.com.au

> "When we exercise, sweat pours out of the body carrying these odours and permeates into your active wear so my tip is keep it fresh and rotate your gym wardrobe daily," says Zack.
>
> "After all who wants to be seen in the same gym gear two days in a row?!"

"The five cardinal rules of washing your gym gear" www.coach.nine.com.au

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Figure 6. Examples of blogs recommending care for swim/active-wear garments.

An important variable that warrants more attention is the fabrics themselves and the fibre they are constructed from. The variability in garment manufacture is vast. From the construction of the monomer to build the polymer into a fibre, that is woven into a textile, to be then manufactured into apparel. There are a plethora of variations on fabric treatments, dyes, coatings, weaves, fasteners and quality of the equipment that do the task. Methodology that employs arbitrary selection of garments is inadequate to provide baseline answers to the problem. A current industry supported study is underway considering textiles at the polymer level[78]. Whilst this research is building on statements regarding fabric pilling,[10,18] it is investigating the regulator of the pilling, fibre tenacity. This is the first example of the apparel and science communities collaborating to seek remedies in manufacturing to reduce microplastic pollution from fashion. The complexity of factors that exist within this topic (Figure 3) requires a holistic approach that employs knowledge and experience from source to sink, which in this case is from polymer to the ocean, via a dynamic supply chain and life cycle.

This study aimed to minimise bias of external variables by focusing on fabric composition, which informed fabric selection. As the significant difference between front and top loading machines was already established[18] (Table 6), this study focused on front loader only. Filtration size was selected based upon previous studies. The majority of fibres collected from trials in front loader machines were from 20-333 μm[9,18], therefore this trial filtered as close to 20 μm as possible. As previous studies reported mixed results, whether presence/absence of detergent increased microfibre yield, this variable was included to ensure all aspects were considered[9,10,19]. This produced results relating to fabric fibre composition, reducing many of the variables in modern manufacturing.

Table 6. Research into microplastics from laundry effluent 2011-2017: summary.

Author	Focus	Method	Main findings
Browne *et al.*, 2011	Polyester blankets, fleeces, shirts. Forensic evaluation of sediments, reference and receiving sewage discharge.	• Water only (detergent blocked filters). • 3 different front loader machines. • Effluent filtered, microplastic counted. • Replicates unstated.	• Significant relationship between population and microplastic abundance. • Microplastics persist in sediment > decade. • Microplastic proportions mirror apparel. • A single garment can shed more than 1900 fibres per wash. • All garments released more than 100 fibres per wash. • Fleeces released 180% more fibres.
Dubaish & Liebezeit, 2013	Water sampling in Jade System, southern North Sea.	• Surface water sampling. • Informal laundry test	• Granular microplastics landward. • Fibrous microplastics seaward. • Mean items/L: granular 40, fibres 70, black carbon 30. • Laundry trial showed 220-260 mg fibres released from single 600 g polyester garment/wash (0.0004% w/w).
Karlsson, 2014	Micro-litter in sediment and biota.	• Sediment and surface water, invertebrate sampling: rivers, lakes, coast, harbours, canal. • Single mixed laundry trial.	• Fibres present in all sediment and water samples. • 2030 microparticles/kg sediment in rivers. • 51% all particles in waters were fibres. • 2 L washing machine effluent contained 1300 microplastic fibres.
Hartline *et al.*, 2016 **Bruce *et al.*, 2017** (report to Patagonia based on the same trial)	Microfibre masses from new/ aged garments, comparison of front and top loader machines, comparison of construction, brand vs off-brand. Fleeces: **See Table 4**	• Water only (detergent-free). • Front loader and top loader. • Sampled effluent – 5 L, filter 333 μm, then 20 μm. • 4 replicates. • Mechanically aged garments.	• Microfibre mass per garment ranged 0 to 2 g, > 0.3% of initial garment mass. • Top loader machine produced 7X microfibre mass than front loader. • Cheaper jacket yielded 41% more fibres. • Suggest laundry accounts for most microfibres entering the environment. • Model pop. 100,000 produce 1.02 kg fibres/day. • 333 μm filter caught more fibres than 20 μm (median 116 mg vs 94 mg). Not sig.
Pirc *et al.*, 2016	Long term fibre release from polyester fleece. Chemical: detergent & conditioner use.	• 6 polyester fleece blankets, 2 replicates. • Front loader washer. • 10 successive washes. • Filter all effluent 200 μm, stainless steel filter. • Calculate relative fibre release.	• Initial fibre loss 0.008-0.021 wt%, then stabilises at approx. 0.0012 wt%. • After 8 washes, release stabilised. • Release of fibres in tumble drying 3.5X higher than laundering. • Detergent & conditioner did not affect microfibre yield.
Napper & Thompson, 2016	Effect of fabric type and laundry conditions: 3 garment types selected from high-street retailers: 100% polyester; 100% acrylic; 65/35% polyester-cotton. Focus on fibre mass yield, not number.	• Factor 1: fabric type. • Factor 2: temperature. • Factor 3: detergent type. • Factor 4: conditioner. • 4 replicates: 20 x 20 cm • Considered long term yield, did not include wash 1-4 in results.	• Noted first 4 washes produce most fibres for 100% synthetics. • Estimate of microfibres released for 6 kg laundry load: more than 700,000 acrylic; 500,000 polyester; 138,000 poly-cotton blend. • Fibre release impacted by wash treatment, there are complex interactions.
Hernandez *et al.*, 2017	Mechanistic study comparing two fabric types: interlock (100% polyester), versus jersey knit (98% polyester, 2% spandex); comparing no detergent, liquid detergent, powder detergent.	• Textiles cut to same size (30x10 cm^2 ~ 7 g), tailored to seal edges. • Simulated laundry trial. • 3 replicates. 5 cycles. • 3 treatments: water, liquid, powder detergent. • Filtered 50, 100, 200 ml effluent 0.45 μm pore.	• Mass & length of microplastic fibres released dependent upon wash solution: water released least (0.0025%); no difference between liquid and powder detergent (0.01%), although greater than water. • No difference in microfibre release between jersey and interlock weave. • Majority fibres released 100-800 μm in length.

6. METHODS

A total of six laundry trials were conducted: 1-4 tested microfibre yield from stretch-performance fabrics; and, 5-6 test the capacity of laundry filter bags to restrict microfibres in laundry waste water.

Microfibre yield from synthetic fabrics

Fabric selection

To minimise differences resulting from fabric construction, three fabrics from a single textile house (A-C) were selected based upon their differences in base material (Table 7). A fourth fabric was selected from an alternative manufacturer.

Table 7. Fabrics selected for laundry trial to measure microfibre yield under domestic conditions, at 40 °C, 1200 RPM, 2 rinses, 56 minutes; August-December, 2017.

	Fabric	Composition	Colour
A	Recycled nylon blend	78% recycled nylon, 22% elastane	Blue
B	Conventional nylon blend-1	80% nylon, 20% elastane	Black
C	Polyester	100% polyester	Navy
D	Conventional nylon blend-2	80% nylon, 20% elastane	Black

Pretreatment of fabrics

All fabrics were cut to a similar 0.75 m^2 size (estimated as the amount of fabric in a garment), overlocked and hem-stitched to ensure no raw edges, with three replicates for each treatment. Fabric samples were gently shaken to remove superfluous fibres from manufacture and preparation immediately prior to first wash. Fabric replicates were all weighed individually before the first wash to 0.0001 g on an analytical balance.

Standardised laundry procedure

The laundry procedure was conducted in a domestic front-load washer. Immediately prior to trial commencement the machine was serviced, waste-water discharge hose was replaced and drum clean cycles run, to ensure any debris discharged was only from the trial. The wash cycle for all trials was a duration of 56 minutes, temperature 40 °C, 1200 rotations per minute (RPM), and two rinses. This cycle was selected due to its appropriate temperature for the fabric and feasibility for the study. A variable in the laundry procedure was presence/absence of liquid laundry detergent. The detergent volume used was 15 ml. A 25 µm filter bag was attached to the machine waste water hose to capture microfibres for each individual wash. Cross-contamination was minimised by running the washing-machine on a 15 minute, two rinse, 800 RPM cycle between trial washes with no fabric present, a white cotton lab coat and nitrile gloves was worn when handling fabrics to reduce cross contamination. The laundry order was maintained for the duration of the trial.

Filtration and data collection

Four trials were conducted for two sets of fabric (Table 8). Trials one to three used all four fabric types, for a total of fifteen washes per fabric piece. These trials incorporated two variables (presence/absence detergent and four fabric types) for a total of eight treatment conditions (4 x 2), with three replicates (total *n* = 24). Following data processing, a fourth trial was conducted for a fuller understanding of the microfibre yield in the first five washes. This trial used a new set of fabrics, the same three nylon fabrics, with three replicates, washed in detergent only (10 ml), (total *n* = 9).

To test the use of a filter bag on the waste water hose the same 25 µm filter bag, that was successfully used to capture microfibres for the trial, was also used with full domestic loads of laundry. In this instance, the bag regularly became clogged too quickly, and had the potential to cause laundry flooding. Management of the fibres was deemed too arduous for this to be a viable option to present to consumers. Consequently, an in machine laundry bag was made and a simple trial was run (trials 6 and 7, Table 8). The bag was made of 50 µm monofilament nylon, with all seams bound and a zip enclosure (Figure 7). Two trials were conducted to test the bag's ability to contain microfibres from aged polyester fleece jackets and aged recycled nylon swim-wear (Table 8).

Table 8. Experimental design for six laundry trials, of microfibre release, from synthetic swim/active-wear fabrics.

Trial	Fabrics	Wash conditions	No. of washes	Measurements
1	Recycled nylon + elastane Conventional nylon + elastane - 1 Polyester 100% Conventional nylon + elastane - 2	Water Detergent *Each piece individually washed*	1-5	• Fabric mass start • Fabric mass 1-5 washes • Microfibres per fabric after wash 5 (% w/w).
2	Recycled nylon + elastane Conventional nylon + elastane - 1 Polyester 100% Conventional nylon + elastane - 2	Water Detergent *All fabrics washed together for each treatment.*	6-10	• Fabric mass after 10 washes. • Mean microfibres combined per fabric after 10 washes (% w/w).
3	Recycled nylon + elastane Conventional nylon + elastane - 1 Polyester 100% Conventional nylon + elastane - 2	Water Detergent *Each piece individually washed*	11-15	• Microfibres per fabric after wash, (% w/w).
4	Recycled nylon + elastane Conventional nylon + elastane - 1 Conventional nylon + elastane - 2	Detergent *Each piece individually washed*	1-5	• Microfibres after every wash, washes 1-5 (% w/w).
5	Aged 100% polyester fleece X 2 washed together	No filter bag In filter bag	1-3	• Total microfibres in waste water (% w/w).
6	Aged 78% recycled nylon swim-wear	No filter bag In filter bag	1-3	• Total microfibres in waste water (% w/w).

Mass measurements were collected on an analytical balance to 0.0001g. However, it was not possible to analyse fibre size and composition, beyond a visual check under microscope at 32X magnification.

Figure 7. Laundry bag made from 50 µm monofilament nylon.

For each trial laundry cycle a nylon monofilament, 25 µm, 25x30 cm filter bag was attached to the grey-water discharge hose, one filter bag used per replicate. After laundering, the fabric was air dried, then placed in a drying cabinet for 24 hours at 45°C, before weighing. Fibres were extracted from the filter bags using distilled water and filtered through a 1.2 µm cellulose nitrate paper filter, using a filter housing and pump (Figure 8). Filter papers were weighed prior to filtration, and then the mass of fibres calculated after drying the filter and fibres in a drying cabinet.

Figure 8. Filtration equipment for laundry trial: 25 µm filter bag, filter housing, using 1.2 µm paper filters and pump.

Data analyses

All microfibre data was recorded and charted in Microsoft Excel 2010, and analysed for statistical significance using SPSS. In any data comparison, results were considered statistically different when *p* values were less than 0.05. All microfibre release calculations were normalised as percent weight for weight (% w/w) of initial fabric mass. Relationships in microfibre release were analysed using analysis of variance (ANOVA) per fabric, and *t*-test between laundry conditions.

7. RESULTS

Influence of trial washing order

To check washing order did not play a part in the microfibres captured, the interaction between wash order and microfibre release was investigated using a general linear model, and it was shown that microfibre yield was not influenced by wash order (p = 0.256).

Effect of detergent

The average microfibre mass released, when washing with detergent and in tap-water, was compared to determine if detergent effected microfibre release for washes 1 to 5, 6 to 10, and 11 to 15 (Figure 9, 10; Appendix 6: Figure A7-A9).

Washes 1 to 5

For washes 1 to 5 (from new), on average, significantly more microfibres (42%) were released by fabrics washed with detergent (average = 0.017 ± 0.006% w/w of initial) compared to fabrics washed in tap-water (average = 0.012 ± 0.004% w/w of initial), t (22) = -2.337, p = 0.029 (Figure 9). This release was apparent upon visual inspection of filters (Figure 10; Appendix 6, Figure A5), with fabrics washed with detergent also showing greater colour on the filters (Figure 10).

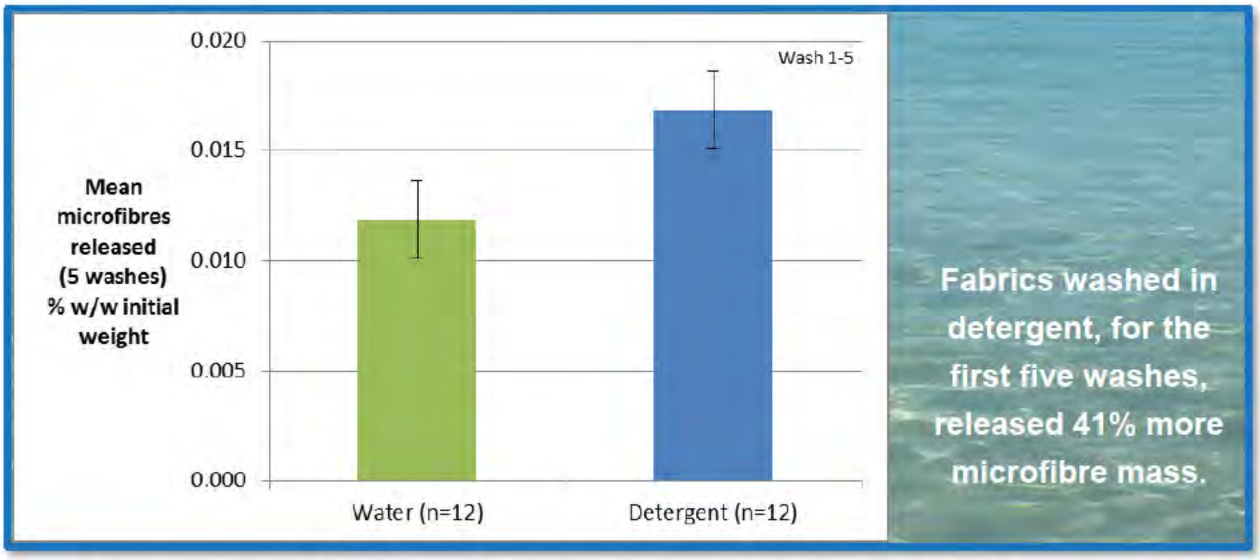

Figure 9. Comparison of washes 1 to 5 (from new), microfibres (% w/w) released from washing four types of swim/active-wear fabrics (3 nylon and 1 polyester) in detergent and in tap water, for five washes, in a front-load washing machine. Microfibres were captured in 25 µm filter bags, then filtered and weighed.

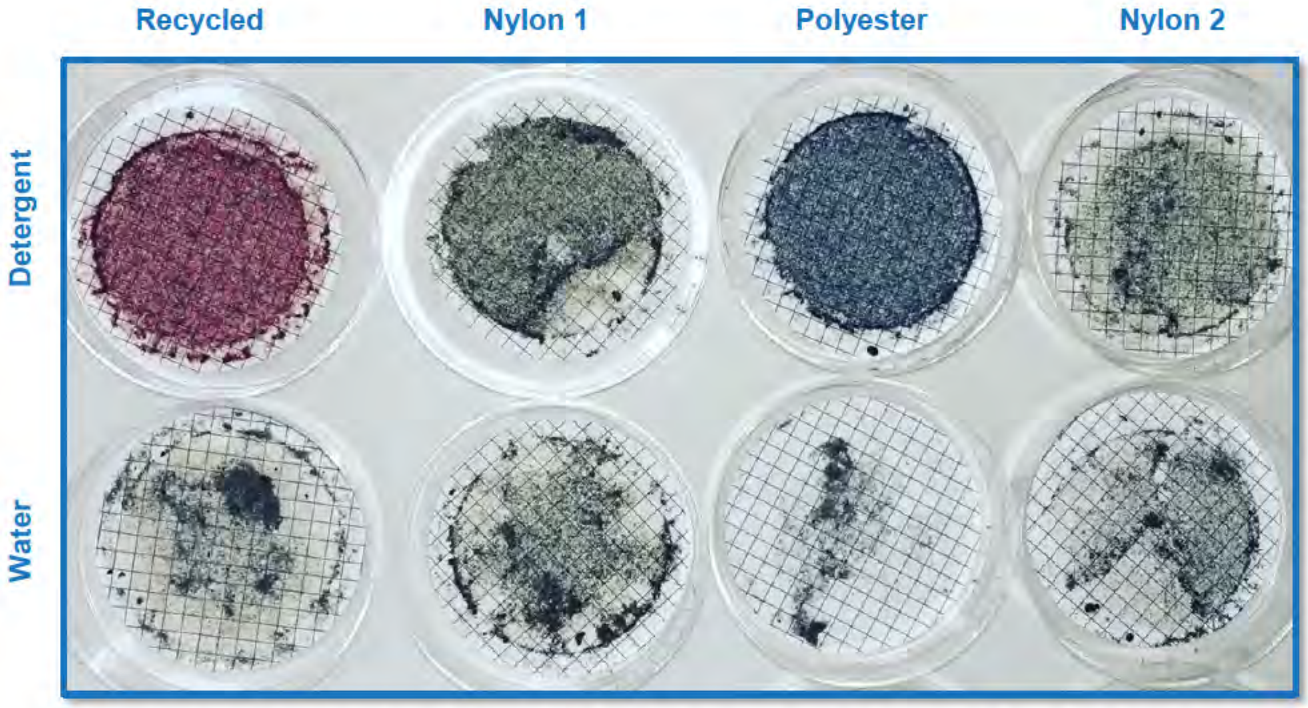

Figure 10. Visual comparison of microfibre filters after capturing microfibres from four types of swim/active-wear fabrics, for washes 1-5 (from new). Top row washed with detergent, bottom row washed in tap water only.

Washes 6 to 10

Due to time constraints, for washes 6 to 10 fabrics were washed together by treatment group, all water fabrics washed together five times, and all detergent fabrics washed together five times. The microfibre mass released was the same (Figure 11), although there were visual differences in the clumping of the microfibres (Figure 12).

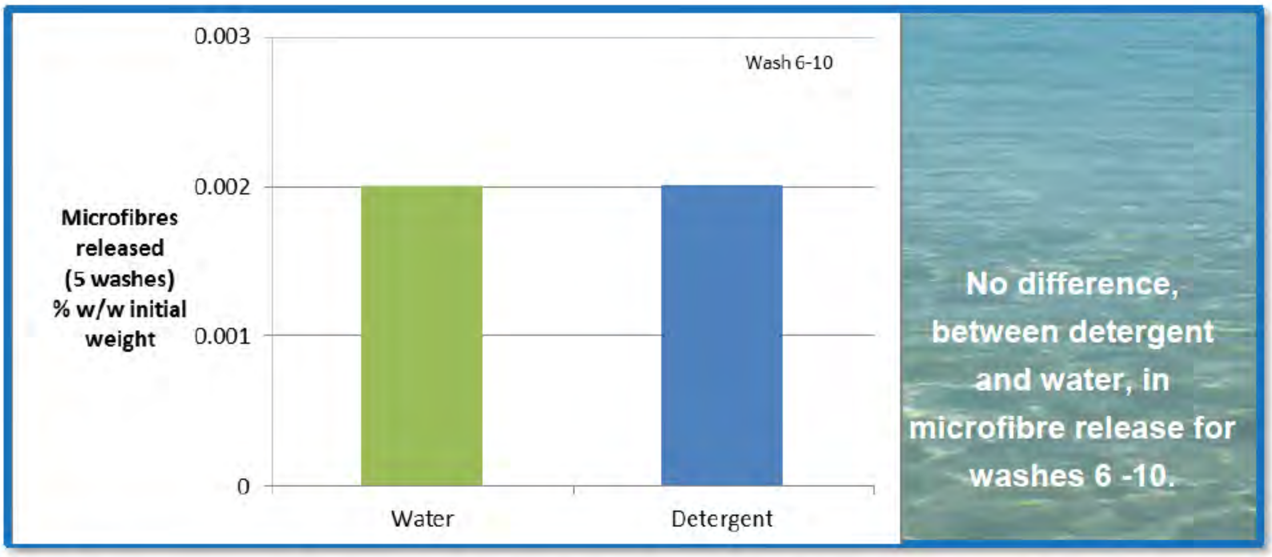

Figure 11. Comparison of washes 6-10, average microfibres (% w/w) released from combined washing of four types of swim/active-wear fabrics (3 nylon and 1 polyester) in detergent and tap water from, for five washes in a front-load washing machine.

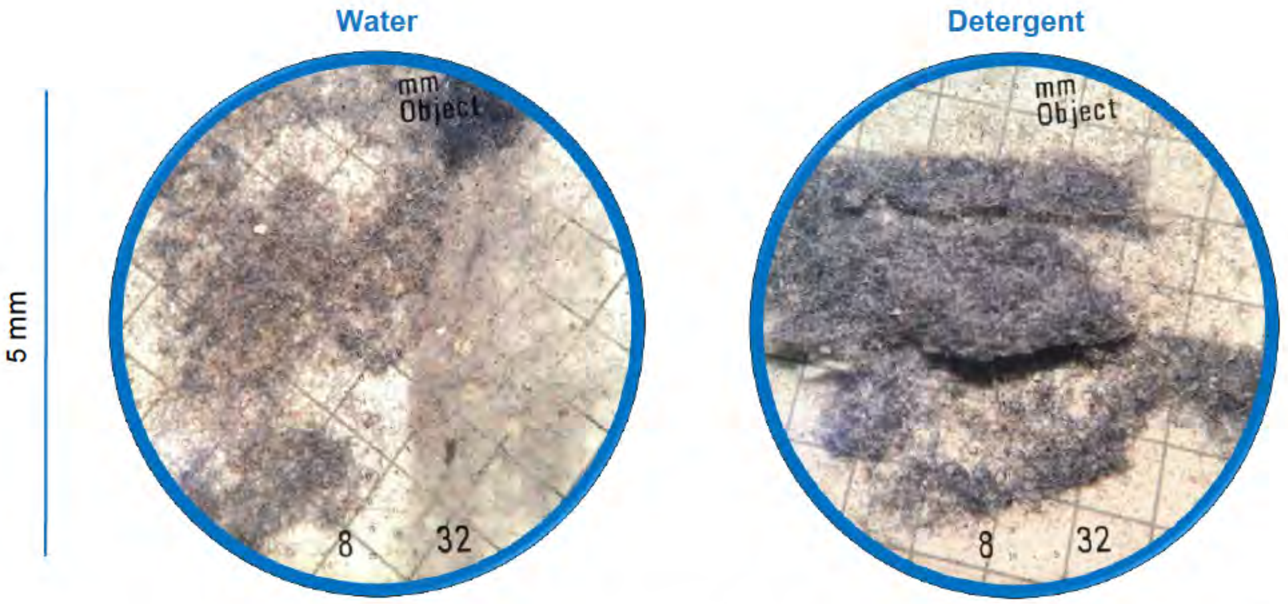

Figure 12. Visual comparison (8 X magnification) of microfibres captured from washes 6-10 of four types of swim/active-wear fabrics (3 nylon and 1 polyester). Fabrics were washed together for two separate treatments in tap water and with detergent, in a front-load washing machine.

Washes 11 to 15

On average, for washes 11 to 15, fabrics washed in detergent released 37% more mass than fabrics washed in tap-water (average = 0.032 and 0.023% w/w respectively), although this was not statistically significant (p = 0.107) (Figure 13). However, visual inspection of microfibres on filter papers showed more obvious fibre mass for water-only treatments, and excess detergent residue contributing to mass for detergent treatments (Figure 14; Appendix Figure A6).

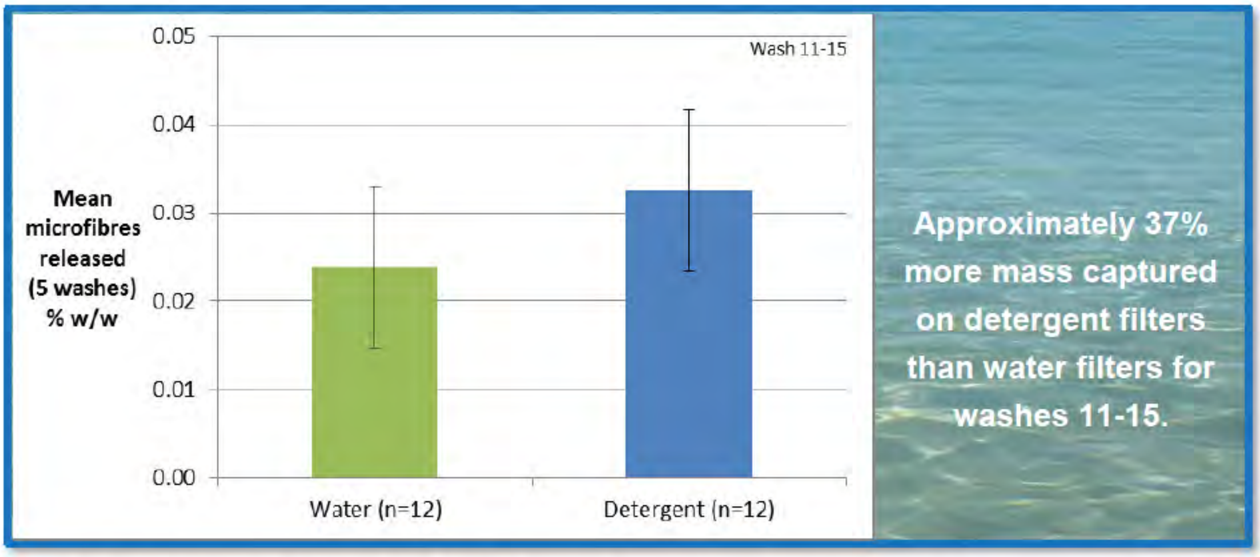

Figure 13. Comparison of washes 11-15, average microfibre release (% w/w) from washing four types of swim/active-wear fabrics (3 nylon and 1 polyester) in detergent and in tap water for five washes, in a front-load washing machine. Microfibres were captured in 25 µm filter bags, then filtered and weighed.

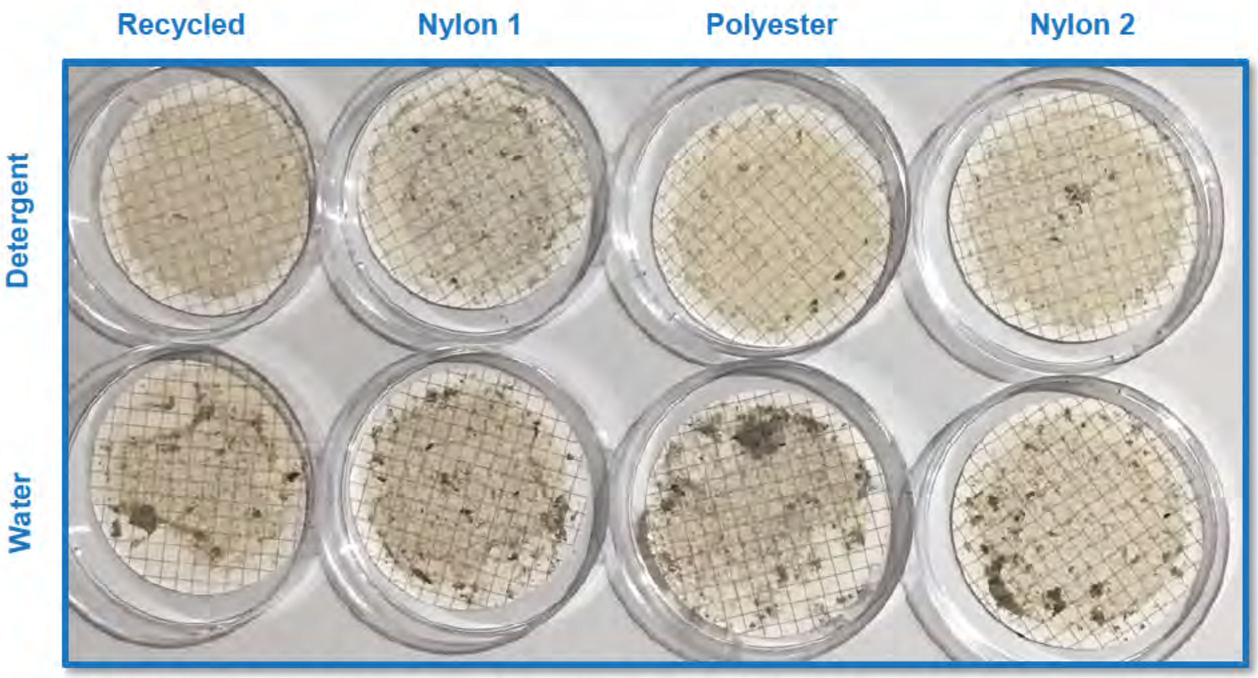

Figure 14. Visual comparison of washes 11-15, microfibre filters after capturing microfibres from swim/active-wear fabrics (3 nylon and 1 polyester). Top row washed with detergent, bottom row washed in tap water only.

Effect of age

To check if textile age influenced microfibre yield, the average microfibre mass released by all fabrics was compared by Independent Samples *t*-test for washes one to five, and washes 11 to 15. Due to the presence of detergent on filters for washes 11 to 15, the effect of age was compared for water washes only (Figure 14, Appendix 6, Figure A6). On average, washes 11 to 15 released 91% more microfibres (average = 0.023 $\pm$ 0.016%) than washes one to five (average = 0.012 $\pm$ 0.004% w/w), which was significant, t (22) = -2.389 $p = 0.026$ (Figure 15).

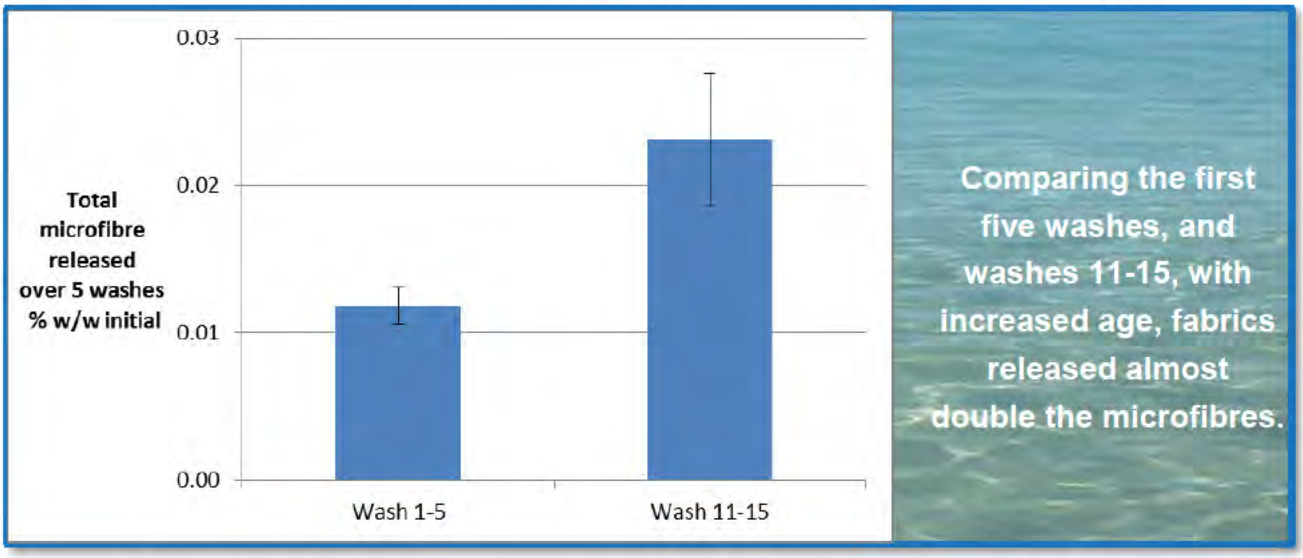

Figure 15. Comparison of fabric age, average microfibre release (% w/w) from washing four types of swim/active-wear fabrics (3 nylon blend, 1 polyester) in water for five washes (1-5 and 11-15) in a front-load washing machine. Microfibres were captured in 25 µm filter bags, then filtered and weighed.

Comparison of fabrics

To check if there were differences in microfibre release between fabric types, total microfibres released in washes one to five and 11 to 15 were compared for polyester, recycled nylon and conventional nylon (Figure 16). All three fabric types released similar amounts of microfibres, amounting to about 0.0035% w/w per wash.

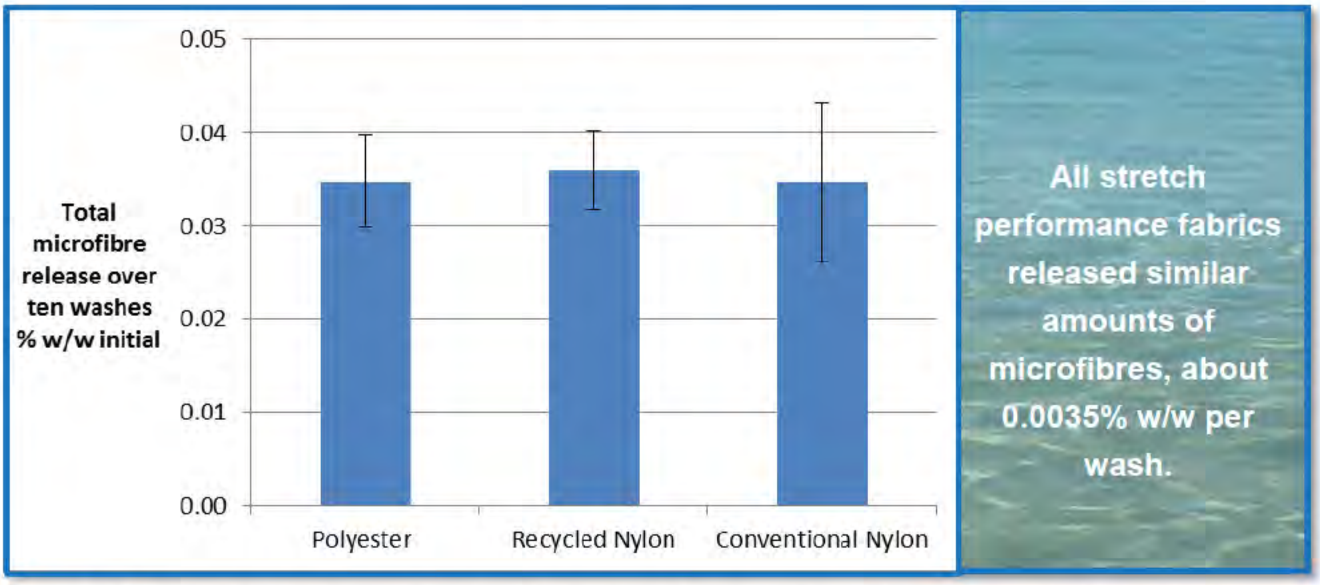

Figure 16. Comparison of average microfibre release from washing polyester, recycled nylon and conventional nylon swim/active-wear fabrics in tap water for ten washes (1-5 and 11-15), in a front-load washing machine. Microfibres were captured in 25 µm filter bags, then filtered and weighed.

Microfibre yield from first five washes (captured per wash)

To seek further information of microfibre yield from first washes, the trial was repeated for nylon fabrics only, washed with detergent (Figure 17). There was no significant difference in microfibre yield between the first five washes, although wash one released the greatest amount (on average 0.011% w/w). Additionally, there was no difference in microfibre yield between the nylon fabrics.

This method of capturing fibres from each individual wash (Trial 4) resulted in a larger microfibre mass captured, than accumulating fibres for five washes (Trial 1), on average 170% more (Trial 1: average = 0.015 $\pm$ 0.005% w/w; Trial 4: average = 0.041 $\pm$ 0.008% w/w; T-test t (16) = 7.896, p = <0.001).

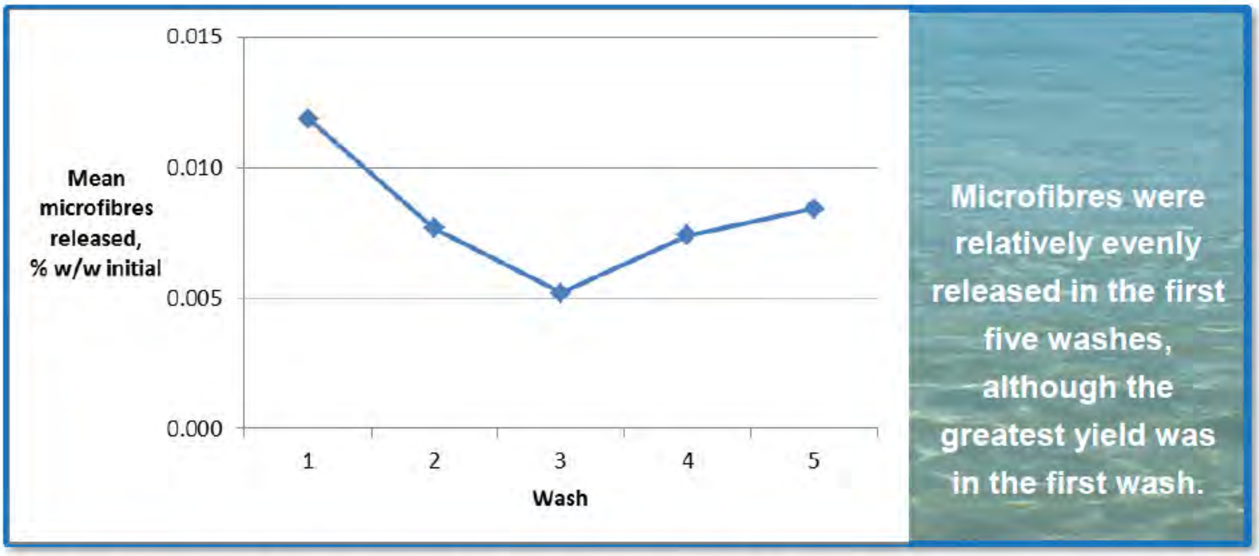

Figure 17. Microfibre yield per wash for the first 5 washes for 3 nylon fabrics (n=9) washed with detergent, in a front-load washing machine. Microfibres were captured in 25 µm filter bags per wash, then filtered and weighed.

Swim/active-wear versus fleece modelled microfibre release

To make comparisons between this data and previously published results, the average rate of microfibre release from trials one and three 0.0035% w/w was compared with a conservative stabilised microfibre mass release of 0.005% w/w for polyester fleece[9]. No published survey could be found as to the laundry habits for fleece or active-wear washing. However, fleeces have been modelled as washed eight times per year[9], and many are the online examples promoting wash and wear of active-wear (Figure 6). To provide a conservative comparison, both garment types were calculated as washed both 8 and 52 times per year, to demonstrate potential annual life cycle microfibre burden between the fabrics (Table 9). Garment mass was based on actual weights of fleece and active-wear sample items.

Table 9. Modelled microfibre release from fleece and active-wear garments, washed in detergent.

Garment	Mass (g)	Yield % w/w	Microfibres per wash (g)	Washes per year	Microfibres per year (g)
Women's fleece, Size 12	360g	0.005	.018	8	0.144
				52	0.936
Women's ¾ active-wear pants, Size 12	215g	0.0035	.007	8	0.056
				52	0.364
Men's fleece, Size L	525g	0.005	.026	8	0.208
				52	1.352
Men's swim vest, Size L	216g	0.0035	.007	8	0.056
				52	0.364
Child's fleece, Size 6	240g	0.005	.012	8	0.096
				52	0.624
Child's ¾ active-wear pants, Size 6	115g	0.0035	.004	8	0.032
				52	0.208

In each model scenario, washing both garments equal times, the fleece jacket will release 3-4 times the amount of microfibres. However, if comparing the jacket as modelled at 8 times per year[9], and active-wear as washed 52 times per year, active-wear releases 1.5-2.5 times the microfibre mass of a fleece jacket.

Mitigation of microfibres using a laundry filter bag

Based upon the evidence thus far, it was clear urgent remedies are required to limit microfibre pollution. As such the ability of a 50 µm, nylon-6, monofilament laundry bag to mitigate microfibre release in laundry waste water was tested, and compared with the waste water from laundry without the bag. When compared to laundering without a filter bag, for fleece jackets the bag restricted 91% of the microfibres, and for swim-wear the bag restricted 87% of the microfibres (Table 10, Figure 18). Additionally, the microfibres captured within the laundry bag amounted to 0.5% (jackets) and 4% (swim-wear) of the microfibres released when washed without a bag, meaning fewer microfibres were released from garments when washed inside the laundry bags.

Table 10. Comparison of microfibres released by fleece jackets and swim-wear in laundry with and without a nylon monofilament laundry bag.

Item	Treatment	Mass (g)	Average Microfibres released	% w/w
Jackets (X 2)	No bag (n=2)	714	0.2927	0.0416
Jackets (X2)	Washed In Bag (n=6)	714	0.0269	0.0038
	Plus fibres in laundry bag		0.0018	0.0002
	Total		0.0287	0.0040
Swim wear (X 2)	No bag (n=3)	291	0.0484	0.0166
Swim wear (X 2)	Washed In Bag (n=3)	291	0.0062	0.0021
	Plus fibres in laundry bag		0.0021	0.0007
	Total		0.0083	0.0028

A monofilament laundry bag restricted 87-91% of microfibres from fleece and swim/active-wear.

Figure 18. Image of microfibres released in laundry waste water for aged polyester fleece jackets and aged swim-wear when washed with and without a laundry bag, in a front loader machine. For fleece jackets microfibre yield was reduced 91%, for swim-wear microfibre yield was reduced 87%.

Potential microfibre burden from laundry into the environment

A calculation was completed to provide context for the quantity of microfibres that could be released into the environment from laundry in Australia per week (Table 11). This model was based on data from a 2016 waste water treatment plant study [8], which demonstrated waste water filtered in municipal secondary treatment can remove up to 98% of microplastics, and statistics on laundry from the Australian Bureau of Statistics, previous behavioural studies [68,81] and the average microfibre release for trials one and three in this study (0.0035%). By this calculation 62 kilograms of microfibres could be released from waste water treatment plants in Australia each week.

Table 11. Modelled microfibre burden into the environment from laundry, via waste water treatment plants in Australia each week.

Factor		Calculation
Average washer is used 3.5/week		3.5
Washer is ¾ full (average capacity 6.5 kg)	X	4.8 kg
70% of apparel made of synthetic fibres	X	0.7
Synthetic laundry per week, per washer	Sub-total	11.7 kg
7.6 Million washing machines in Australia	X	88,920,000 kg
Average 0.0035% w/w microfibre release	X	3112 kg/week
Filtration of secondary waste water treatment plant 98%	X	62 kg/week

Australia could be releasing **62** kgs microfibres per week into the environment. Globally the figure could be **6888** kgs per week.

8. DISCUSSION

Previous published studies, using similar methodology, found a proportionate microfibre release of 0.0012 to 0.078% w/w released from laundering synthetic fleece garments[9,14,18,76]. This study found synthetic swim/active-wear fabrics release between 0.0004 to 0.007% w/w of microfibres per wash depending upon the age of garment, washing conditions and fabric type.

Effect of detergent

The role of detergent is to decrease surface tension, increasing the ability of water to penetrate laundry, and dispersing grime from the laundry surface, holding it in the surrounding water. Detergent is an amphipathic substance, meaning it has a water-loving (hydrophilic) 'head' and water-repelling (hydrophobic) 'tail'. Different detergents are likely to have varied effects on different fabrics due to the fabric's basic chemical characteristics, in addition to their created characteristics such as coatings and lubricants in the manufacturing process. However, like attracts like, and having a hydrophilic and hydrophobic end, detergent is able to readily draw out both nylon (hydrophilic) and polyester (hydrophobic) microfibres.

Not all previous studies have tested the effect of detergent, with earlier trials finding challenges in filtration due to blocking of filters[4]. However, more recent trials that have successfully trialed detergents have produced varied results. A recent laboratory simulated washing trial found polyester fabrics (jersey versus interlock) released up to four times the amount of microfibres when washed in detergent, compared with water, filtering to 0.45 µm [19]. Whilst another trial found polyester fleece fabrics washed in water released 50% more microfibres than those washed in detergent for the first five washes, although the study also used mechanical drying in between washes and a larger filter pore size, possibly losing more in the drying process and missing capture of smaller fibres in the washing process (200 µm)[9]. A third trial using a domestic washing-machine showed acrylic, polyester and poly-cotton fabrics washed in detergent released significantly more microfibres, than those washed in water (p = 0.001) [11]. The most recently published trial also utilised laboratory simulation of acrylic and three brands of polyester fleece, finding increased microfibre yield in the presence of detergent for three out of four fabrics[84].

Washes 1-5

A significant effect of detergent was found for the first five washes of this trial, with fabrics washed in detergent releasing 41% more microfibres. The comparison of this trial with previous investigations highlights the fickle nature of testing microfibre release, particularly when images of the captured microfibres are also considered. It is apparent in images of filtered fibres for the first five washes that the mass contains more than just fibres, with colour prevalent in detergent washed samples (Figure 10), in addition to various unidentified substances accumulated on filters for both detergent and water washed fabrics. Other potential emissions include coatings, treatments and dyes used in manufacture and for protection of the fabric[82,83].

Washes 6-10

Intriguingly there was no effect of detergent on microfibre release for washes 6-10, with equal yield in water and detergent (0.0004% w/w per wash). Although methodology for these washes varied in that all 12 fabrics were washed together for each treatment. This may have decreased microfibre yield due to a fuller machine. Meanwhile, the image of the captured microfibres for water and detergent suggests there may be more chemical influence at play here. Observing Figure 12 there is an apparent separation of fibres for fabrics washed in water, with microfibres split by colour, possibly polyester/nylon to one side and elastane the other. Only one other study has washed fabrics ten times, although it also incorporated mechanical drying[9]. Whilst this may limit comparisons, the study found a similar significant reduction in microfibre yield after the first five washes, and surmised that at this point the release of microfibres had stabilised. However, results of this trial for washes 11-15 suggest that may not be the case.

Washes 11-15

Although the mass captured by filtering microfibres for washes 11-15 indicated detergent was still increasing microfibre release by on average 37%, inspection of the image of microfibres at 32 X magnification tells a different story (Figure 19, additional examples in Appendix 6, Figure A6). It appears for these washes part of the captured mass may be detergent, and visually there are similar amounts of fibres present for water and detergent washes, with both treatments having other substances present on the filter in addition to fibres (Figure 19). In this case consideration of mass only may be a diversion, as much of the mass appears to be detergent. This further accentuates the challenges in quantifying microfibre yield, particularly when using chemical variables. Potentially, there is simply a mass of microfibres a fabric will release in its usable life, which could be extended or reduced via laundering practices. Knowledge of the effect of laundry chemicals such as detergents and softeners, and physical variables such as temperature or top versus front loader machine, provides an opportunity to extend the life of a garment, and subsequently perceived quality of a brand. Slower fibre loss should equate to longer garment life. However, for the sake of understanding the potential microfibre pollution from a garment, it would be useful to quantify the amount of fibres a fabric will yield within its useful life.

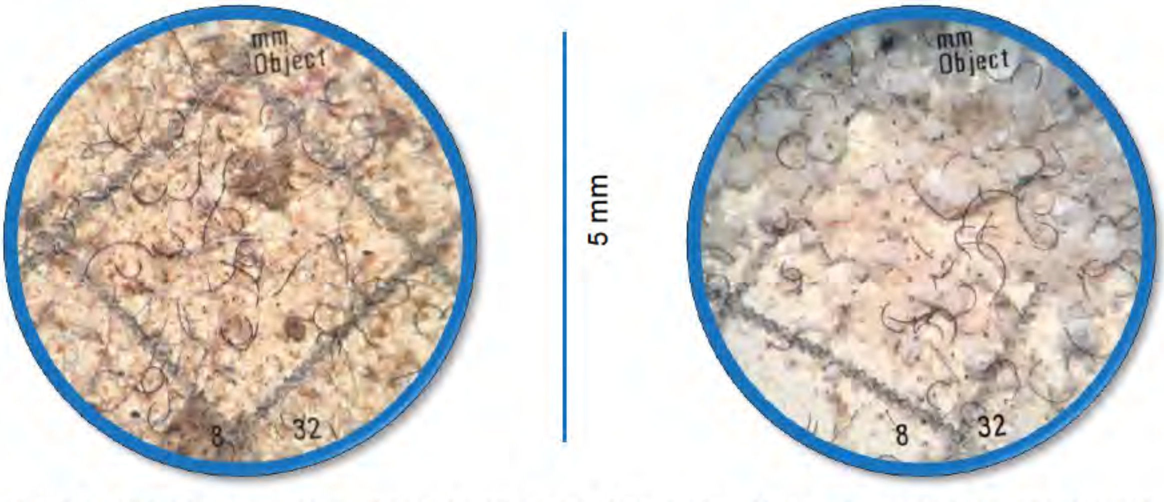

Figure 19. Single example of filtered microfibres for washes 11-16, conventional nylon/elastane blend 80/20%, washed in water (left), detergent (right), only part of filter shown, 32 X magnification.

Ultimately, detergent as a chemical variable is limited only by the number of detergents on the market and also to its efficacy depending on local water properties. Whilst detergent increased early microfibre yield, it is unclear whether it increased microfibre yield after ten washes. However, it is apparent that an opportunity exists for fabric and garment manufacturers to produce a detergent complimentary to extending the life of their product, whilst reducing polluting microfibre emissions.

An opportunity exists to produce a detergent, which extends the life of synthetic garments, whilst reducing microfibre pollution.

Effect of age

Within this trial washes 11-15 released almost double the microfibres of washes 1-5 (0.0046% w/w and 0.0024% w/w respectively, per wash) suggesting older garments yield more microfibres. Due to the apparent build-up of detergent on filters, this statistic is based upon water washes only. It would be invaluable to understand the total number of washes within a fabric's usable life to evaluate the life cycle of a garment and any opportunities to extend garment life and reduce microfibre emissions. The effect of garment age has been tested by some earlier trials, albeit through simulated aging[14,18,84], or to a maximum of ten consecutive washes[10]. Trials utilising simulated aging of garments all found significant increases (25-80%) in microfibres released for aged garments, and microfibres tended to be larger in size[14,18,84]. However, the only other trial to go as far as ten washes concluded microfibre yield was stabilising in washes 8-10 (0.0013% w/w from washing, plus 0.0041% w/w from mechanical drying per wash), after experiencing a large microfibre yield in the first five washes[10]. Although, the mechanical drying used in that particular trial may have inadvertently simulated aging.

Comparison of fabrics

This is only the second laundry trial to include recycled and conventional fabrics, and the first to compare polyester and nylon. Like the earlier study, recycled fabrics released comparable amounts of microfibres to conventional fabrics, and nylon and polyester fabric microfibre yield was also comparable. Meanwhile, the effect of detergent is worthwhile investigating further, due to differences in the amount of microfibres released when washing with detergent, and visual evidence on filters in this trial. Additionally, blended fabrics also warrant further investigation to elucidate which component is yielding the most microfibres. For example, figure 12 shows an intriguing difference in the distribution of microfibres on the filter for fabrics washed in water versus detergent. If the smaller component of blended fabrics, in this case 20% elastane, is responsible for a disproportionate amount of fibres, then future research should focus on improvements to this component.

Conventional fabrics and Recycled fabrics released comparable amounts of microfibres.

Microfibre yield for first five washes

To understand the dynamics of microfibre release in early washes, the trial was repeated with detergent, given this is the standard washing condition and had imparted the greatest microfibre yield for early washes. Had it been the case that the first wash produced far greater microfibre yield, this would have been an opportunity for manufacturers to capture a significant load of microfibres, by pre-washing garments before sale. Unfortunately, it was not the case for the nylon fabrics trialed, with a consistent release of microfibres for five washes. As suggested by previous trials[10 84], possibly the initial release of microfibres is dominated by relict fibres from manufacturing and the fabric coatings and dyes. Imaging of the filters showed fibres released in washes 1-4 were shorter, coloured fibres (Appendix A6: Figures A7-9). Whilst in wash 5, longer, uncoloured fibres became prevalent. In blended fabrics such as the nylons, the additional element of elastane may be the dominant fibre released in later washes, and the source of the clear strands. Given the broad inclusion of elastane in so many synthetic and natural fibre blends on the market from underwear to jeans and suits, it warrants greater focus within microfibre research.

Swim/active-wear versus fleece

The model comparing annual microfibre release between swim/active-wear and fleece emphasises the potential of the swim/active-wear market as a significant source of microfibres in laundry. Although such a model would vary from country to country due to weather and related clothing choices. Additionally, this model conservatively did not account for the fact that many active-wear users may wear synthetic fabrics on many days each week, being washed for each and every wear, as recommended by the manufacturers. Regardless, it is clear that the growing swim/active-wear market is likely a significant source of microfibres and presents an opportunity to reduce microfibre pollution, and enhance garment life through education of laundry care choices.

The growing active/swim-wear market presents an increasing source of microfibre pollution.

Mitigation of microfibres using a laundry filter bag

The scale of microfibre pollution from laundry requires urgent attention, akin to that received by microbead pollution from personal care products[40]. Unlike microbead pollution, microfibre pollution is more challenging to restrict at the source. Consequently, the onus is presently on consumers to restrict microfibres from their existing garments. Therefore, immediate mitigation needs to be affordable and accessible. After-market washing-machine filters are expensive and will take time to develop. Likewise, increased filtration to restrict microfibre pollution at municipal level will take time and investment.

No other study was found demonstrating the efficacy of a monofilament laundry filter bag to mitigate microfibres from synthetic garments. However, a commercially available nylon laundry bag published its efficacy in restricting microfibres from laundry waste water as 70-100%, comparable with the results from this study at 87-91%. Whilst a synthetic laundry bag potentially contributes to the problem of microfibre pollution in the long-term, in the shorter term even if it releases some fibres itself, the 87-91% reduction in microfibres in laundry waste water is preferable to no mitigation, and includes fibres released from the bag itself. However, for this reason it is important bags are properly constructed. Additionally, the combined microfibres captured within the bag and the waste water remained 84-90% less than when no laundry bag was used. It appears the laundry bag has an additional benefit of protecting the garments, reducing damage in laundry, meaning the garment life should be extended through using a laundry bag. An opportunity exists for brands to increase their eco-credentials by providing complimentary laundry bags with product, providing education within their marketing and consumer communication, and/or selling appropriate laundry bags that will also increase the life of their garments whilst restricting microfibre release into the environment.

Potential microfibre burden from laundry into the environment

> Microfibres equivalent to 7,750 plastic grocery bags may enter marine eco-systems in Australia weekly, or 44 million per year globally.

Deposition of microfibres into marine environments provides plastic pollution at a size that readily enters the food chain[38,42,51], in quantities already demonstrated to be significant in sediments[5]. Although conservative, the model calculated 62 kgs of microfibres could be released via laundry through waste water treatment plants, into marine eco-systems in Australia each week. It did not take into account the use of top-loader machines (demonstrated to release four times the microfibres of front-loaders[18]), and used average figures for microfibre yield from this study, which are low in comparison to some previous studies. Regardless, it is rather an abstract description to simply state 62 kgs of microfibres. To provide an everyday analogy for this figure, it is equivalent to 7,750 plastic grocery bags entering Australian oceans each week, in bite sized pieces to enter the food chain. An alternative visual is 11 million times the image in the top right of Figure 18 (p 33) each year. Further, this calculation is for Australia only, which operates less than one percent of all washing machines globally. Potentially, plastic microfibres equivalent to 861 thousand plastic grocery bags could be entering oceans worldwide weekly, or more than 44 million per year.

Future research recommendations

The question remains, what is the amount of microfibres a garment will yield in its usable life cycle, and does this vary depending upon fabric composition? This could be tested by washing fabrics a minimum of 50 times to replicate one year of use, recording microfibre loss per wash as feasible. Given the inclusion of elastane fabrics in performance swim-wear products, are these likely to degrade quicker than polyester and nylon, and could these contribute disproportionately to the issue of microfibre pollution? Further, do garments washed in laundry bags last longer? It would also be useful to research whether garment life could be extended, and microfibre emissions be decreased, through creation of detergents complimentary to specific fabric compositions. This would benefit the environment in reducing the number of garments produced, the consumer through longer lasting garments, and ultimately apparel companies, as reduced garment sales could be recouped in detergent sales and improved corporate and environmental responsibility.

Once a fuller understanding of garment life cycle is acquired, a benchmark for maximum microfibre yield could be set as a best practice guideline enabling fabric and garment manufacturers to minimise environmental impact. This could also provide a basis for a ratings system for fabrics, permitting consumers to select garments based upon their environmental impact. This would also aid legislation such as the recent California bill proposed to require warning labels on garments of 50 percent or more synthetic fibre. As consumer awareness of microfibre pollution grows, there will be pressure for manufacturers to research microfibre reduction in fabric production. Whilst many scientific studies into microfibre and plastic pollution are published in science journals, there is no reference to the issue in textile and fashion journals.

Conclusion

Whilst the problem of plastic microfibre pollution is well established in environmental and scientific circles, there is a dearth of acknowledgement and solution seeking in the textile, fashion and apparel realm. This trial demonstrated that laundering of swim/active-wear apparel provides yet another source of microfibre pollution. Additionally, the presence of detergent and increased age increased release of microfibres. Nylon, polyester and recycled nylon fabrics tested in this trial produced similar proportions of microfibres. Although swim and active-wear garments are generally made of lighter fabric than fleece garments, the wash and wear use of swim/active-wear may be a greater contributor to plastic microfibre pollution. However, widespread use of appropriate laundry bags could provide an interim reduction in microfibres released from laundering apparel. Although this raises the question of with whom responsibility lays, the consumer or the brand? At the very least, the consumer needs brands to produce appropriate laundry bags for them, and to educate them as to how and why they should be used. With global microfibre pollution from laundry conservatively estimated as equivalent to 44 million plastic bags entering oceans annually, it is vital the textile and fashion industry include solutions to this problem in their sustainability agendas.

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APPENDICES

Appendix 1

Global Plastic Production

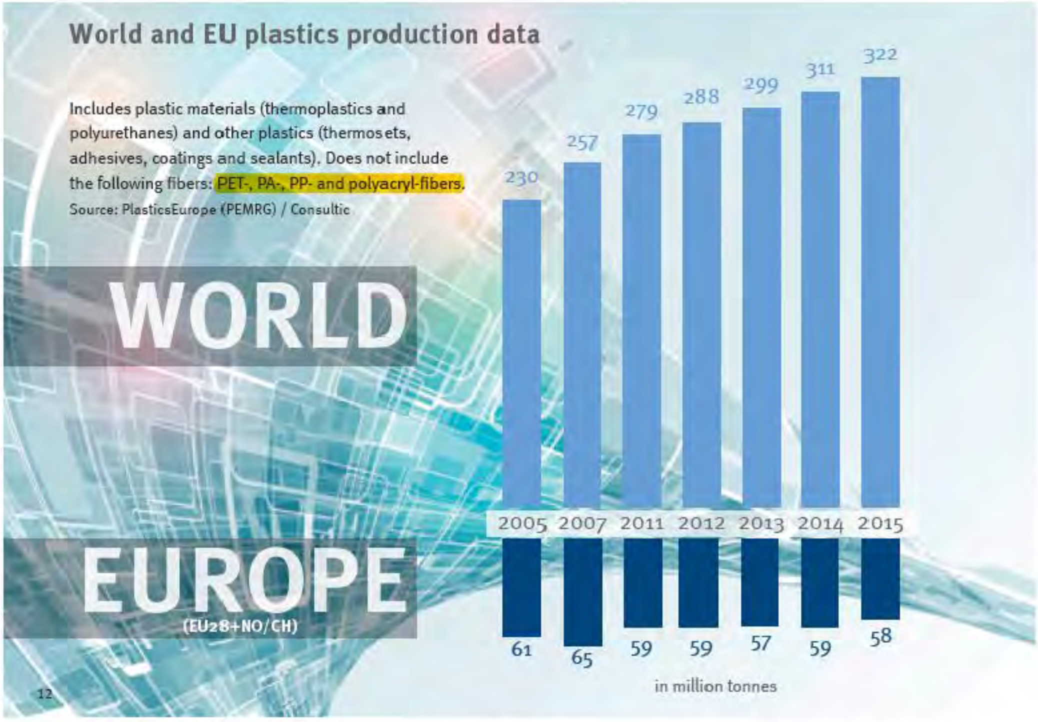

Figure A1. World plastic production per year in million tonnes, excluding fibres (Plastics Europe, 2016).

Appendix 2

2015 Global textile production

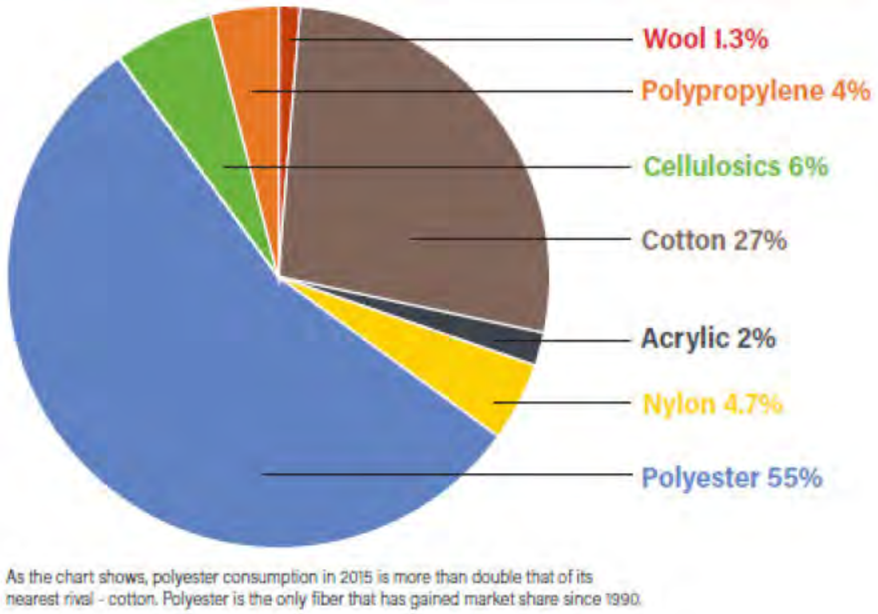

Figure A2. Global textile mill consumption of all major fibres in 2015 (Textile Exchange, 2016).

Appendix 3

Global Extent of Microplastics in Sediments

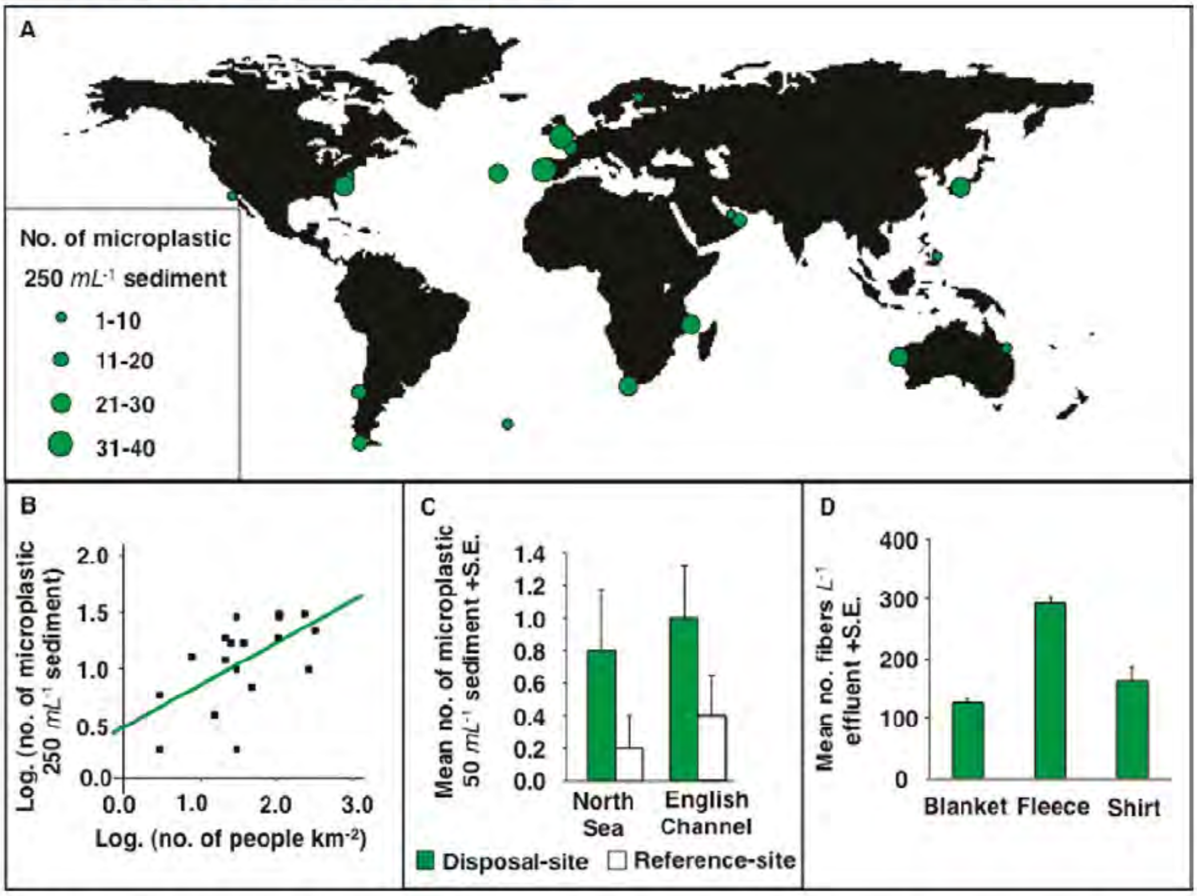

Figure A3. (A) Global extend of microplastic in sediments from 18 sandy shores, the size of filled-circles represents the number of microplastics found. (B) Relationship between population-density and number of microplastic particles in sediment from sandy beaches. (C) Number of particles of microplastic in sediments from sewage disposal-sites and reference-sites at two locations in UK. (D) Number of polyester fibres discharged into wastewater from using washing-machines with blankets, fleeces, and shirts (all polyester) (Browne *et al.*, 2011).

Appendix 4

Changes in fibre use for use for apparel 1992 – 2010 (FAO, 2013).

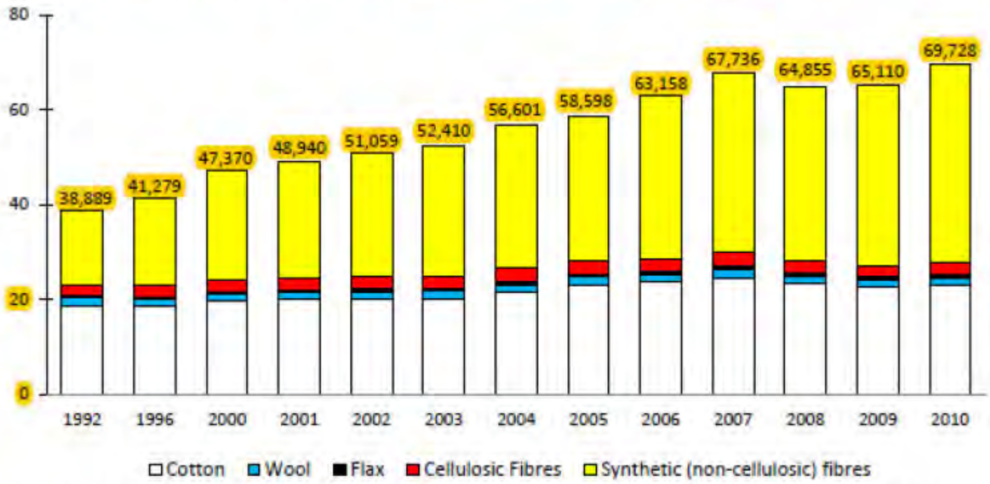

Figure A4. Evolution of world apparel fibre consumption, in million tonnes (FAO, 2013).

Appendix 5

Characteristics of nylon, polyester and elastane.

Table A1. Characteristics of polyamide, polyester and elastane within textiles that may be factors in microplastic fibre yield (Plastics Europe, 2016).

Property	Nylon	Polyester	Elastane
Base polymer	Polyamide 6	Polybutylene terephthalate + Polyester	Polyurethane
Water	Hydrophilic	Hydrophobic	Hydrophilic
Tenacity (tensile strength)	Excellent	Good to excellent	Poor
Abrasion resistance	Excellent	Good to excellent	Excellent
Sunlight/UV resistance	Poor	Good	Very good
Elasticity	Excellent	Fair to good	Excellent
Dying	Excellent	Fair to good	Poor
Chemistry	Aliphatic amide	Aromatic	Urethane linkage
Recyclability	Good to Excellent Chemical	Excellent Chemical	Poor – high chemical and energy inputs Mechanical
Recycling base stock	Fishing nets, carpets	Plastic PET bottles	Upcycled, not re-cycled

Appendix 6 *Magnified microfibre images*

Recycled nylon + elastane | **Conventional nylon + elastane - 1** | **Polyester 100 %** | **Conventional nylon + elastane - 2**

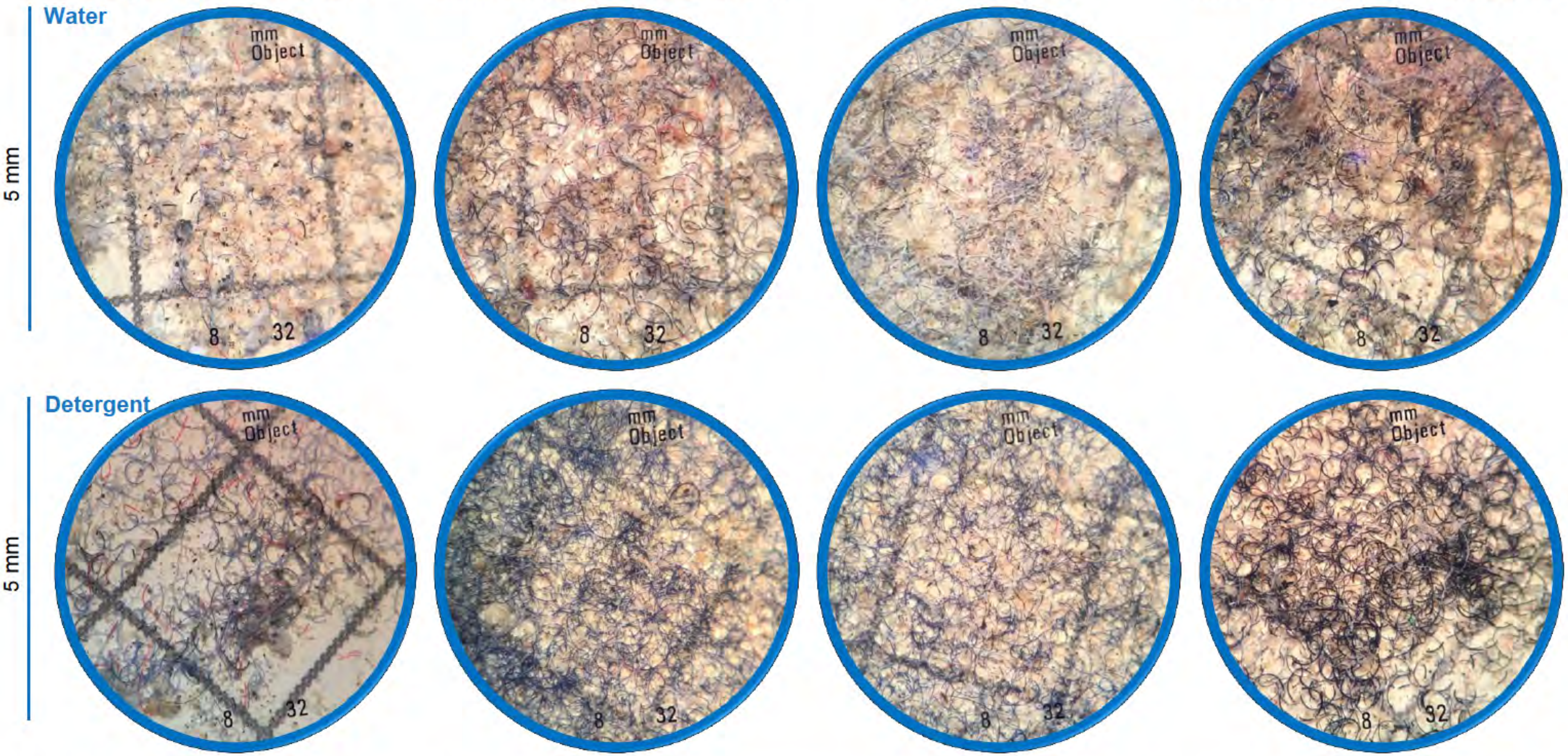

Figure A5. Trial 1: Washes 1-5; comparison of microfibre yield from synthetic swim/active-wear fabrics at 32 X magnification. Top row water, bottom row detergent.

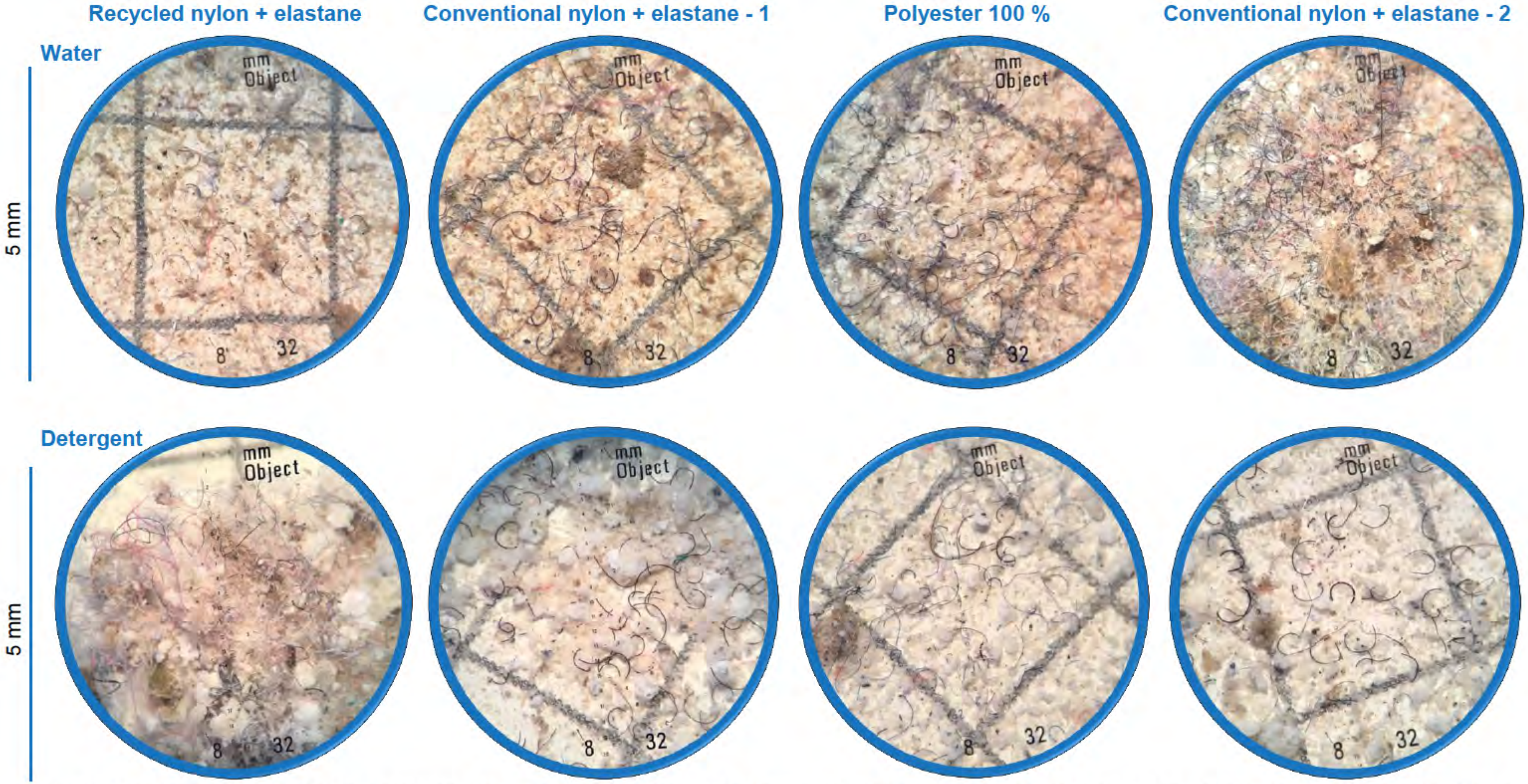

Figure A6. Trial 3: Washes 11-15; comparison of microfibre yield from synthetic stretch-performance fabrics. Top row water, bottom row detergent, only part of filter shown, 32 X magnification.

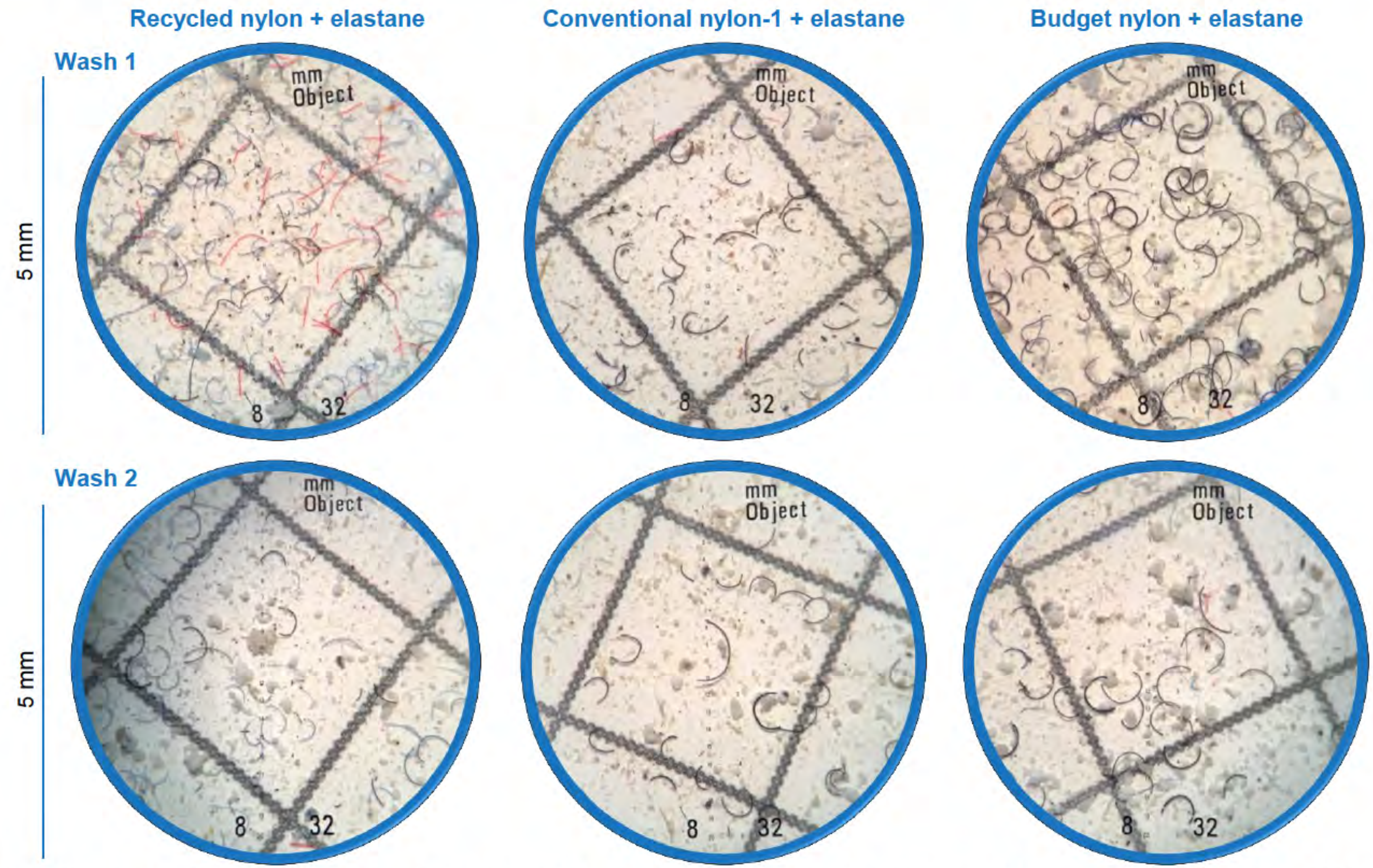

Figure A7. Trial 4: Washes 1 and 2; comparison of microfibre yield from nylon-elastane stretch-performance fabrics, washed in detergent at 32 X magnification, only partial filter shown.

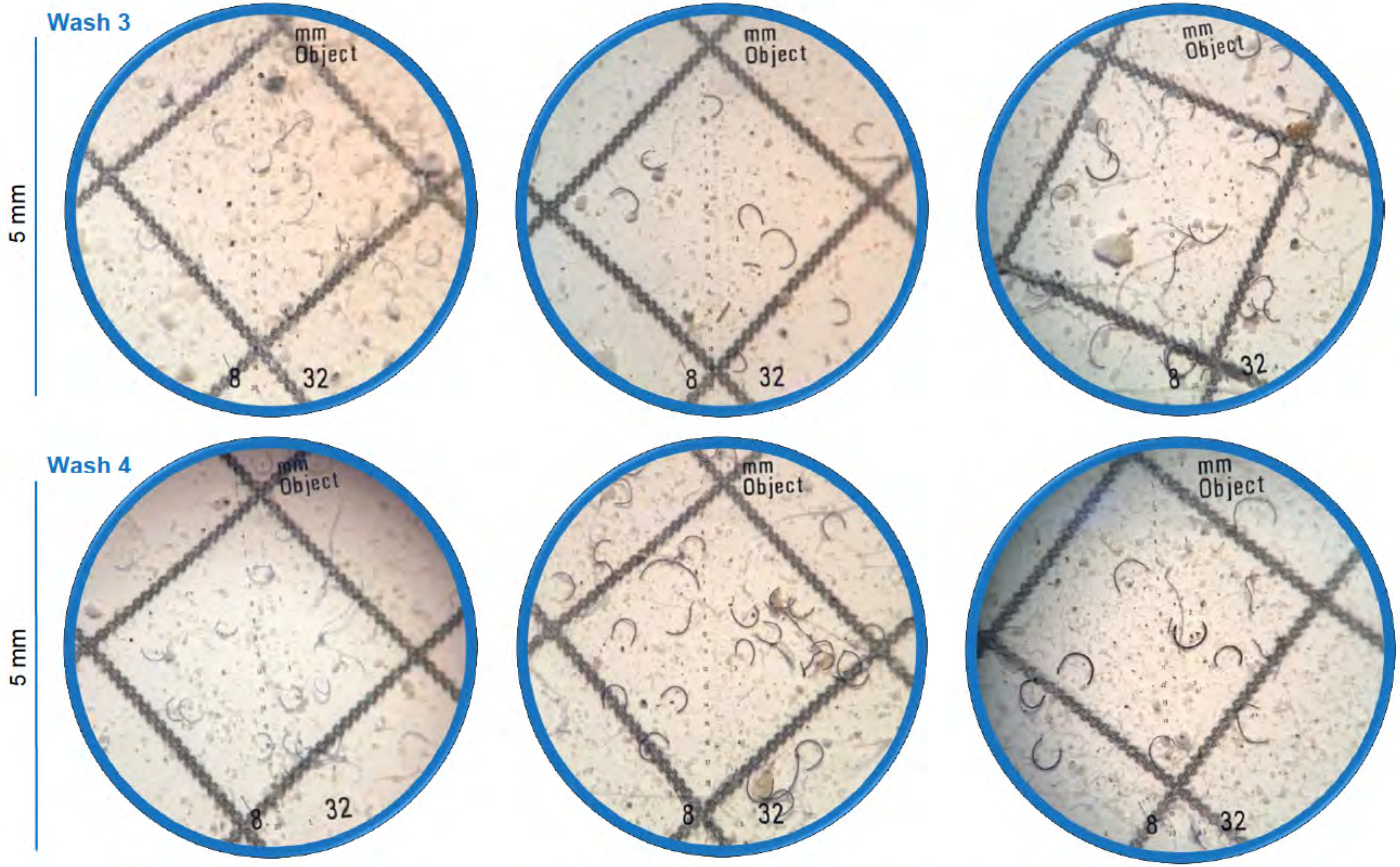

Figure A8. Trial 4: Washes 3 and 4; comparison of microfibre yield from nylon-elastane stretch-performance fabrics, washed in detergent at 32 X magnification, only partial filter shown.

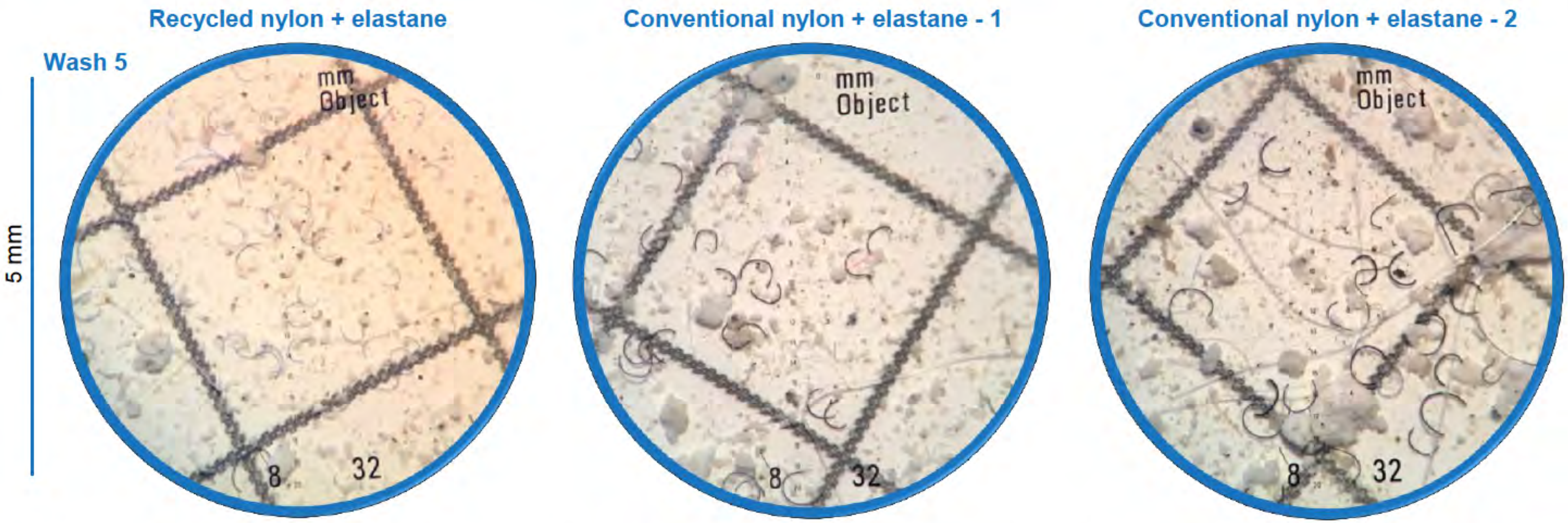

Figure A9. Trial 4: Wash 5; comparison of microfibre yield from nylon-elastane stretch-performance fabrics, washed in detergent at 32 X magnification, only partial filter shown.