Textile derived microfibre release: Investigating the current evidence base

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Executive summary

Textiles-derived microfibre pollution encompasses all fibres less than 5mm in size, which are formed and shed during the processing, production, use and disposal of textiles. Their presence has been recorded in both terrestrial and aquatic environments as a proportion of airborne dust and waterborne microplastics, and additionally as a hazard in textile manufacture. However, many of these observations in the environment to date have been incidental, and studies of their formation and shedding have been biased toward synthetic fibres. The effect in terms of quantitative environmental impact metrics such as ecotoxicity has not been determined, so although it is possible to estimate the volume of microfibres produced, it is not currently possible to quantify the true effect they may have.

In this report, we approach the formation of textiles-derived microfibres from a life cycle perspective, assessing microfibre formation and shedding during textiles production and processing, the use phase, and disposal at the end of life.

The analysis carried out in this project of the mass loss throughout the life cycle of textiles indicates that up to 168,432 tonnes may be lost during processing and production; 1,300 tonnes lost during domestic machine washing and tumble drying; and over 350,000 tonnes are sent to residual waste at end of life. However, it is unclear what proportion of these are microfibres, since the losses reported are the total mass which can include other waste products, intermediates, long fibres or textile offcuts.

The manufacture of clothing and flat textiles is a complex, multi-stage process which varies heavily in relation to the fibre utilised and the garment construction and finishing processes, which are dictated by the requirements of the product. As a result, developing a single estimate for the formation and shedding of microfibres is challenging. More investigation has taken place for the production phase of natural fibres than for synthetic, due to the higher quantities of loss, and a natural drive to increase productivity by reducing waste. From the available data, it is often difficult to distinguish the mass of microfibres from that of impurities or other waste, or to calculate what proportion of waste is directed into other value chains and what proportion is discarded.

In the use phase, studies of the formation of microfibres are predominantly focussed on the breakdown of synthetic garments during machine washing. A great emphasis has been put on the susceptibility of certain garments, such as fleeces, to contribute to marine microplastic pollution; however, there is very little available data on the contributions made by natural fibres, and what effect they may have on the environment. Due to the rapid simultaneous development of similar research projects across different institutes, several studies have been published in a short period, but due to variation in methodology these are mostly incomparable with each other. However, it is clear that variation in the methods of washing and drying clothing and flat textiles results in high variation in the mass of fibres produced. The volume of microfibre leakage in the use phase is comparatively lower than in the production phase, but it is thought to be more likely to enter the marine environment due to the volume of fibres entering wastewater from washing.

Textiles may take a number of routes at the end of life, and the route taken will have a marked effect on potential microfibre formation, although very little data is available to quantify this. Re-use, either in the UK or overseas may extend shedding in the use phase, whereas recycling of materials may result in microfibre shedding as textiles are cleaned and prepared. Finally, textiles sent to residual waste may be sent to landfill, resulting in potential degradation to microfibre over an extended period and an unknown quantity of leakage.

Due in part to the emphasis currently placed on microfibres as a subset of microplastic pollution, and again with the growing interest in the impacts of the textiles industry, emphasis has been placed on reducing and mitigating the impacts of microfibre formation. Promotion of this issue by a range of conservation bodies, special interest groups and a wider community of environmental NGOs, has resulted in increased awareness of the issue of microfibres in the general public. This in turn has led to investment in engineering and behavioural solutions developed to combat microfibre formation. However, the effectiveness of these mitigation methods is currently unquantified.

Actions to mitigate the impacts of microfibre generation throughout the life cycle should be considered where the greatest volumes of waste are being generated. Hence, the upstream processing and production stages should be an initial point of focus. UK producers and importers of textiles should investigate their supply chains, whether domestic or overseas, to ensure that waste management procedures are rigorous and designed to prevent the release of microfibres to the environment.

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Glossary

Animal fibre, any fibre originating from animal products, such as wool, hair and silk

Bast, fibre derived from the inner bark surrounding the plant phloem

Bleaching, pre-treatment, to improve textile whiteness

Carding, straightening fibres and pulling them to parallel alignment

Charity shop grade textiles, used clothing and household textiles of UK origin

Combing, removal of short fibres

Cutting, trimming fabric to the pattern

De-sizing, pre-treatment, removing “sizing” starch from the fabric

Decitex, a unit of fibre measurement expressed in grams per 10 km

Degumming, pre-treatment, the removal of sericin proteins from natural silk

Double knitted, knitted from two sets of yarns

Dyeing, application and fixing of a dye to the textile fibre

Fibre fly, fluff or fibre dust generated during processes such as knitting and napping

Fibril, fine fibre approximately 1 nm in diameter

Fibrilisation, the formation of fibrils

Filament fibre, long, continuous fibres such as synthetics

Finishing, processes to improve the look performance and feel of a textile

Flat textiles, for the purposes of this report: bedlinen, bathroom linen and table linen

Greige fabric, un-bleached woven or knitted fabric

Hairiness, the degree to which fibre ends protrude from a yarn

Interlock, fabric made by inter-knitting two fabrics each made from a single yarn

Knitting, interlocking loops of yarn to form a fabric

Napping, the process of drawing out fibre ends to give a “hairy” surface of the textile

NACE, statistical classification of economic activities in the European Community

Mercerizing, pre-treatment of cellulosic yarns to swell fibres

Pilling, the formation of surface defects, balls of fibres or “pills”, as a result of wear

Plucking, removal of unwanted non-lint or trash

Regenerated Cellulosic, any fibre formed of regenerated natural materials such as rayon, viscose and modal

Retting, the separation of bast fibres by decomposition of the surrounding vegetal material

Scouring, pre-treatment, removing fats and other impurities

Scutching, the separation of impurities from raw vegetable fibres

Singeing, pre-treatment, removal of surface fibres

Single knitted, consecutive rows of intermeshed loops

Sizing, starches or polymers applied to protect yarn from abrasion

Spinning, the twisting of fibres to form yarn

Sliver, a bundle of parallel fibres from which yarn is spun

Staple fibre, short lengths of fibre such as wool, cotton and synthetics

Synthetic fibre, any fibre of polymer construction, such as Acrylic, Polyamide/Nylon (PA),

Polyester (PET), Polyurethane/Elastane, or Polypropylene

Textile derived microfibres (TDMF), any fibre of textile origin which is below 5mm in its longest axis, whether intentionally formed or created through secondary process during production, processing, use or disposal

Textile derived fibre (TDF), any fibre of textile origin which exceeding 5mm its longest axis, whether intentionally formed or created through secondary process during production, processing, use or disposal. This will include mesofibres 5-10mm, and larger fibres

Trash, non-fibrous waste of the combing and carding process

Vegetal fibre, any plant-based fibre such as cotton, flax, jute, ramie and hemp

Warping, arranging parallel threads on a beam prior to weaving

Weaving, production of fabric by interlacing warp and weft yarns

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1.0 Background

1.1 What are microfibres?

Microfibres are formed from the fragmentation of longer fibres in apparel and other textile goods. Despite the recent publicity regarding the impact of microfibres, a universally accepted definition has yet to be agreed upon. Much of the ongoing research into microfibres as an environmental risk relates to recent emphasis on the formation of microfibres as a subset of microplastic pollution. In this context, microfibres are characterised as fibrous material less than 5mm in length. However, this emerging definition differs from that currently in use in the textiles industry, in which a microfibre is described as a fibre intentionally manufactured below ten micrometres in diameter and less than one decitex. A range of staple fibre lengths are used in industry, which can typically be between 25-32mm. These would require further fragmentation following shedding to be classified in the definition of microfibre as reported in other studies. Whilst we will attempt to quantify the generation of microfibres at all stages, many studies enumerate all fibres generated in their analyses. As a result, fibre shedding observations may include textile derived fibres of up to 70mm in length.

In addition, the term microfibre has become synonymous with synthetic microfibres of a multitude of sources such as tyre wear and fibreglass, rather than those formed from textiles. Whilst some groups, such as the outdoor clothing company Patagonia, aim to make this partition clear by highlighting the issue as "synthetic microfibres", this distinction is not made consistently across the field.

For the purposes of this report, the authors use the following standard definition for textile derived microfibres (TDMF):

'Any fibre of textile origin which is below 5mm in its longest axis, whether intentionally formed or created through a secondary process during production, processing, use or disposal.'

1.2 What are the impacts of microfibres?

Microfibres (or micro-fibres) have gained a great deal of public interest over the past decade as a result of concerns over marine pollution and the wider impacts of fashion and the textiles industry. Concerns include the high occurrence of plastic marine pollution and the potential for microfibres to exist for long periods of time, gradually accumulating while remaining undetected in the environment, and becoming pervasive in the food chain. The issue of microfibres and their potential effects in the environment have been widely documented in the media. Primary focus has been placed on the production of synthetic textile fibres, however, new evidence suggests that natural fibres may represent a significantly higher proportion of both airborne and water pollution than previously thought[1].

To date, the range of recorded impacts of microfibre formation and shedding have been varied. For example, during textile processing, the negative impacts of fibre shedding and build up during textile manufacture may include reduction in production efficiency, increased fire risk and impacts on worker health. Health issues linked to the production of textiles include

[1] *Stanton, Thomas, Matthew Johnson, Paul Nathanail, William MacNaughtan, and Rachel L. Gomes. "Freshwater and airborne textile fibre populations are dominated by 'natural', not microplastic, fibres." Science of The Total Environment 666 (2019): 377-389.*

respiratory conditions such as Flocker's Lung[2], resulting from exposure to nylon flock, and byssinosis[3], experienced by workers exposed to cotton, flax, hemp, or jute dust. Whilst the size fractions of fibres at the root of these disorders is not made apparent, the proximity and level at which textile workers are exposed far exceed those in typical ambient air. Migration of microfibers from manufacture to the environment has yet to be quantified, and the scale of these releases in comparison to that lost during the use-phase are unquantified.

During the use stage, microfibres may contribute to airborne dust and local deposition, or may be transported to the marine environment by wastewater systems. Finally, transport to the aquatic environment has been seen to result in the uptake of synthetic microfibres by a range of species, although the impacts of ingestion and inhalation are yet to be fully investigated.

1.2.1 How are microfibres shed?

Formation of TDMF may occur at any stage of the textile lifecycle as individual microfibres are lost from staple yarns; the fabrics, clothing and flat textiles derived from them; or are otherwise formed as microfibres and fibrils broken from continuous filaments and their by-products. Whilst degradation of textiles may be the result of numerous factors such as UV damage or the action of biological substances, the shedding of fibres is predominantly the result of abrasion forces either deliberately applied, such as the carding or combing of natural fibres, or accidentally occurring, such the processing of textiles and their day to day use, including machine washing and drying. Microfibres formed may be lost immediately to the environment, or released during subsequent processes, such as laundry.

Although currently understudied, the degradation of apparel and flat textiles ending in residual waste (going to landfill or incineration) will also result in the formation of microfibres. The period over which these textiles degrade may be over a greater timescale than the other processes discussed in this report, and the influence of landfill conditions on factors such as light availability, temperature and pH suggest that the rate of degradation and fibre formation are subject to high variability.

1.3 Purpose of this report

1.3.1 Scope of research

This report aims to determine the extent of available information on the formation and shedding of TDMF throughout the lifecycle of clothing (household and commercial) and flat textiles placed on the market in the UK. It collates evidence from past and ongoing research, identifies key evidence gaps and identifies mitigation actions currently under research. This research attempted to provide an estimate of the scale of the impact, however, it became clear during the process that data to support these estimates is not presently robust. As a result, in addition to quantifying TDMF formation and shedding where data is available, emphasis is placed on highlighting the current knowledge and data gaps which reduce our ability to determine the scale and likely impact of TDMF releases.

The manufacture of clothing and flat textiles is a complex, multistage process which varies heavily in relation to the fibre utilized, the garment construction and finishing processes, dictated by the requirements of the product. As a result, developing a single estimate for the production of microfibres is challenging, and must incorporate a high level of variability. Additionally, few studies of wastage in the textile production chain highlight the mass of material lost as microfibre. In addition, it is often difficult to distinguish the mass of TDMF from

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[2] Eschenbacher, William L., et al. "Nylon flock–associated interstitial lung disease." American journal of respiratory and critical care medicine 159.6 (1999): 2003-2008.

[3] Zuskin, Eugenija, et al. "Byssinosis in carding and spinning workers: prevalence in the cotton textile industry." Archives of Environmental Health: An International Journal 19.5 (1969): 666-673.

that of impurities, or to calculate what proportion of 'waste' is directed into other value chains and what proportion is discarded.

In some specific areas, such as for blended fabrics containing multiple fibre types, or mixed material garments made up of a range of different textiles, data was not available to support the separate estimation of the release of microfibres from these scenarios.

In order to maximise the applicability of available data, the work identifies TDMF production at three levels, as shown in Figure 1:

1. TDMF arising from all clothing and flat textiles;
2. TDMF arising from vegetal fibres, animal fibres, regenerated cellulosic fibres and synthetic fibres; and
3. TDMF arising from cotton, silk, wool, flax/linen, viscose/Lyocell, polyester, acrylic, polyamide/nylon, polyurethane/polypropylene/elastane.

Figure 1 Hierarchy of textile fibre characterisation

1.3.2 Objectives

The report seeks to estimate the mass of TDMF produced during the processing of textile fibres and the production of UK-sold garments and flat textiles, as well as the formation and loss of TDMF during use and at end of life in the UK. It is the intention that the outcomes of this report should steer future work to be undertaken with findings compatible with WRAP's SCAP Footprint calculator and other future modelling.

Using the mass of textiles consumed data, and currently reported proportions of textile and fibre loss, percentages of TDMF at key stages in the textile life cycle have been identified.

The report addresses the proportion of total TDMF production for each of these stages – processing, production, use, and end of life – and seeks to identify where actions may be most effective in reducing both the formation of TDMF and their loss to the environment.

Finally, the report explores the fate of these fibres, their route to the environment and impacts therein, as well as the potential for their minimisation and mitigation.

2.0 Textile derived microfibre formation and shedding during production and processing

The 2012 Valuing our Clothes report suggests that, of the 1.76 million tonnes of raw material entering the clothing industry, one third became waste[4]. However, not all of this waste may be classed as TDMF, and some may be returned to the textile value chain.

The processing and production of garments and flat textiles is a complex multi-stage process, which varies greatly in relation to the fibre type used, fibre length, construction and end use of the product. For example, natural staple fibres may pass through a range of carding, combing and wet processing steps not applicable to synthetic filament fibres. Additionally, some processes may be applied at different points during manufacturing, such as the dyeing of yarns vs the dyeing of fabrics, which may result in different proportions of TDMF being formed.

A greater amount of information is available on the reduction in weight during processing of vegetal and animal fibres in comparison to synthetic fibres. This may be the result of the level of processing required to produce natural fibres, leading to greater mass loss during this stage than for synthetic fibres. The comparative strength and smoothness of synthetic fibres typically results in a smaller proportion of mass loss during processing, so this has been a lower priority for research and optimisation.

However, it is important to highlight that the mass lost and waste produced during many processes, particularly during bleaching and scouring of natural and regenerated cellulosic fibres is not necessarily the result of TDMF formation and shedding, much of the observed loss is the result of the removal of impurities or the degradation of constituents of the fibre. For example, mercerization of ramie fibres results in the removal of hemi-cellulose and ∝-cellulose, which may result in over 60% weight loss[5]. Similarly, weight loss associated with scouring of cotton is linked to the removal of non-cellulosic material such as proteins[6]. Unfortunately, the literature currently available does not address the composition of the material lost, but rather focusses on the quality of the retained fibre or fabric.

The mass loss figures shown in the following sections are comparative figures based on the total input materials minus the mass loss arising, regardless of whether this is TDMF or not. The proportion of the waste arising which is TDMF is discussed where insight is available, but mostly this has not been quantified in the available research.

2.1 Textile derived microfibre formation and shedding during the production of animal and vegetal yarns, and staple fibres

For all fibre types, TDMF may be formed during the spinning process, however, the production of vegetal and animal yarns has much higher potential to result in the formation of TDMF than regenerated cellulosic and synthetic yarns. This is because the pre-treatment and processing of natural fibres such as cotton, flax, silk and wool require several cleaning and sorting steps. These techniques may result in the shedding of fibres, as well as mass loss as a result of the removal of dirt, proteins, oils and other unwanted material.

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[4] *WRAP (2012). Valuing Our Clothes: The true cost of how we design, use and dispose of our clothing in the UK. A report for WRAP: London.*

5 (Qin, Chen, et al. "The effect of fibre volume fraction and mercerization on the properties of all-cellulose composites." Carbohydrate Polymers 71.3 (2008): 458-467.

6 Lin, Chien-Hua, and You-Lo Hsieh. "Direct scouring of greige cotton fabrics with proteases." Textile Research Journal 71.5 (2001): 425-434.

2.1.1 Scouring, degumming, and bleaching

Scouring, degumming and bleaching are all processes which may result in the loss of TDMF along with proteins and organic material. The processes of scouring and bleaching may occur prior to spinning or be applied to greige fabric. Scouring processes aim to remove non-essential dirt, fats and proteins from fibres, whereas bleaching is applied to improve optical brightness of the fibre. Many studies report mass loss as a result of both methods, and the degree of mass lost can be highly variable.

This variability is apparent in the range of methods employed during the bleaching of natural and regenerated cellulosic fibres. Hydrogen peroxide bleaching of cotton has been observed to cause a mass loss between 3.9% and 6.9% depending on pH and liquor concentration[7]. Similarly, bleaching of wool may result in weight loss of 5.16% to 10.17%[8], and bleaching of jute has been seen to result in weight loss of between 0.8% and 12.9%, affected by chlorite concentration, temperature, treatment time, yarn/liquor ratio, and pH[9].

Scouring has also been observed to have variable effects depending on fibre origin, variety and method, with a maximum weight reduction during the scouring of cotton between 4.9% and 10% (minimum between 3.8% and 5%)[10]. Non-chemical approaches may not necessarily result in reduced weight loss, for example, enzymatic bleaching of cotton has been seen to cause up to 12.65% [11] and bio-scouring has been linked to up to 11.7% of initial weight loss[12].

Silk fibres must go through a process of degumming before use to remove sericin. During this process, initial material may be reduced by between 0.63% and 23.55% of the original weight[13]. As mentioned above, much of the mass loss resulting from bleaching, scouring and degumming is the result of the removal of fats and other solids rather than of individual fibres.

Whilst evidence may suggest large reductions in material mass as a result of the above processes, there is no available literature on the proportion of these losses which may result in TDMFs. Analytical studies of waste water may assist in establishing the proportion of this loss that is fibre and that which may be intercepted or reused.

2.1.2 Ginning, carding, combing, retting, and scutching

Carding and combing of natural fibres is essential to remove non-textile waste from materials, eliminate irrevocably tangled and very small fibres, and align fibres prior to spinning. In cotton,

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7 Abdel-Halim, E. S., and Salem S. Al-Deyab. "One-step bleaching process for cotton fabrics using activated hydrogen peroxide." Carbohydrate polymers 92.2 (2013): 1844-1849.

8 Chen, Weiguo, Dongzi Chen, and Xungai Wang. "Surface modification and bleaching of pigmented wool." Textile Research Journal 71.5 (2001): 441-445.

9 Sarkar, P. B., and H. Chatterjee. "24—THE BLEACHING OF JUTE WITH CHLORITE." Journal of the Textile Institute Transactions 39.8 (1948): T274-T281.

10 Aly, A. S., A. B. Moustafa, and A. Hebeish. "Bio-technological treatment of cellulosic textiles." Journal of Cleaner Production 12.7 (2004): 697-705.; Karmakar, Samir Ranjan. Chemical technology in the pre-treatment processes of textiles. Vol. 12. Elsevier, 1999; Lin, Chien-Hua, and You-Lo Hsieh. "Direct scouring of greige cotton fabrics with proteases." Textile Research Journal 71.5 (2001): 425-434.

11 Buschle-Diller, Gisela, Xiang Dong Yang, and Ryohei Yamamoto. "Enzymatic bleaching of cotton fabric with glucose oxidase." Textile Research Journal 71.5 (2001): 388-394.

12 Lin, Chien-Hua, and You-Lo Hsieh. "Direct scouring of greige cotton fabrics with proteases." Textile Research Journal 71.5 (2001): 425-434.

13 Gulrajani, M. L., Ritu Agarwal, Amrit Grover, and Mona Suri. "Degumming of silk with lipase and protease." (2000); Gulrajani, M. L., Shailja Vaidya Gupta, Abhilasha Gupta, and Mona Suri. "Degumming of silk with different protease enzymes." (1996).

early observations of carding were seen to remove up to 8% of the initial weight[14]. More recently, this has been seen to equate to 2.70% of the initial weight, however, the proportion of this which is fibre accounts for only 1.08% when the weight of trash is removed[15]. In the production of flax fibres, retting may reduce the initial weight of material by between 31.98% and 63.91%[16], although other studies suggest lower figures of up to 10% initial material losses as a result of dew retting, and 16% form scutching. In hemp, the retting and scutching process may reduce the initial yield by up to 25%, resulting in the formation of long fibres (9%), short fibres known as scutching tow (23%), and the shives, particles of the woody plant core (40%). In bio-retting and green scutching, the reduction in mass may increase to 30%, with over 94% of the remaining material classified as long fibre[17]. The same is also apparent in animal fibres. In wool, loss from carding has been seen to reach up to 13.5% of the initial weight[18], and combing in 17% initial weight loss[19]. Whilst there is very little information available on the size distribution of this waste, Bogan indicates that around 33% of carding waste is motes and fly[20].

2.1.3 Spinning and winding

Very little information is available regarding the mass of fibre lost during spinning and winding, however, spinning of cotton has previously been seen to result in up to 19.07% initial weight loss[21], however blending cotton with synthetic fibres such as polyester can reduce this loss to 1.29%. In addition, transfer of dyed fibres to undyed sections of yarns has shown the potential for microfibre formation and transfer during winding[22].

In hemp, the hackling process, proportion of sliver to hackling tow ranges between 40:50 and 50:40 dependent on the earlier retting and scutching methods employed. Short fibres produced at this stage may be diverted to other short-fibre spinning activities, however, this is poorly quantified. Drawing out of this silver to 'rove' may result in further fibre losses of up to 5%. In flax, 65% of the original mass may become sliver, and around 25% hackling tow[23].

2.2 Textile derived microfibre formation and shedding during the production of synthetic and regenerated cellulosic yarns, filaments, and staple fibres

Virgin synthetic and regenerated cellulosic fibres are usually formed through the production of polymers or regenerated cellulosic material, melting, and extrusion through a spinneret to form filaments. Where staple fibres are required, filaments are cut to the appropriate length for

14 Bogdan, J. F. "The Control of Carding Wastes." Textile Research Journal 25.5 (1955): 377-385.

15 Halimi, Mohamed Taher, Mohamed Ben Hassen, and Faouzi Sakli. "Cotton waste recycling: Quantitative and qualitative assessment." Resources, Conservation and Recycling 52.5 (2008): 785-791.

16 Sharma, H. S. S., G. Faughey, and G. Lyons. "Comparison of physical, chemical, and thermal characteristics of water-, dew-, and enzyme-retted flax fibers." Journal of Applied Polymer Science 74.1 (1999): 139-143.

17 van der Werf, Hayo MG, and Lea Turunen. "The environmental impacts of the production of hemp and flax textile yarn." Industrial Crops and Products 27.1 (2008): 1-10.

18 Robinson, G. A. "High-speed Carding of Wool." Journal of the Textile Institute 80.1 (1989): 147-157.

19 Belin, R. E., and D. S. Taylor. "The Influence of Hooked Fibers on Cotton Comber Waste." Textile research journal 36.6 (1966): 542-546.

20 Bogdan, J. F. "The Control of Carding Wastes." Textile Research Journal 25.5 (1955): 377-385.

21 Kalliala, E M 'The Ecology of Textiles and Textile Services - A LCA Assessment Study on Best Available Applications and Technologies for Hotel Textile Production and Services', Tampere University Technology Publications 214, 1997, Finland, p117.

22 Rust, J. P., and S. Peykamian. "Yarn hairiness and the process of winding." Textile research journal 62.11 (1992): 685-689.

23 Turunen, Lea, and Hayo MG van der Werf. "The Production Chain of Hemp and Flax Textile Yarn and Its Environmental Impacts." Journal of Industrial Hemp 12.2 (2007): 43-66.

later spinning. Further descriptions of the potential for TDMF formation at the processing and yarn production stages are outlined in the subsections below. The level of information regarding the loss of staple fibre mass during the spinning of staple synthetic fibres is not well reported in the literature.

2.3 Textile derived microfibre formation and shedding during knitting and weaving

Material mass loss is observed during both the construction and finishing of fabrics. Due to the abrasion forces involved, the generation of TDMF during knitting and weaving is very apparent; conversely, mass lost during finishing procedures may be the result of removal of sizing, and impurities.

2.3.1 Fibre fly generation during knitting

One well documented area of fibres formed during textile production is that of fibre fly; short fibres shed during knitting. These processes are studied intensively due to their capacity to influence production efficiency and fabric quality, as well as for their potential as a fire and health risk. As with wet processing, the variability observed is very high, and is dependent on a range of factors including pre-treatment and fibre characteristics. For example, shorter fibres are more easily shed[24], and hairier yarns produce more fly. As a result, un-sized yarns shed more than sized yarns[25].

Yarn hairiness and associated lint generation varies in relation to the type of yarn and the knitting process for which they are developed. For example, TDMF formation is higher in ring yarns than compact and rotor yarns[26], and carded yarns shed more than combed yarns[27]. As a result, ring spun carded yarn produces more shedding than open-end spun and ring spun combed fibres respectively[28].

The proportion of fibre fly that is classed as microfibres is highly variable, sitting between 52%[29] and 98%[30]. One analysis of the dimensions of cotton fibre fly formed during the ringspun knitting process revealed that 24.5% of fibres were approximately 1mm in length, 20% were 3mm in length and 18.5% were of 5mm in length. Just 7% were over 5mm in length[31]. Similarly, during weft knitting, the highest mean percentage of microfibres (>5mm) was just 72%[32]. Longer fibres tend to be produced in the guide zone, and shorter fibres in the unwinding and knitting zones; mean fibres in the knitting zone have been seen to have a mean

24 Lawrence, C. A., and S. A. Mohamed. "Yam and Knitting Parameters Affecting Fly During Weft Knitting of Staple Yarns." Textile research journal 66.11 (1996): 694-704.

25 Basu, Arindam, and Rajanna L. Gotipamul. "Lint shedding propensity of cotton and blended yarns." (2003).

26 Basu, Arindam, and Rajanna L. Gotipamul. "Lint shedding propensity of cotton and blended yarns." (2003).

27 Lawrence, C. A., and S. A. Mohamed. "Yam and Knitting Parameters Affecting Fly During Weft Knitting of Staple Yarns." Textile research journal 66.11 (1996): 694-704.

28 Ruppenicker, George F., and John T. Lofton. "Factors affecting the lint shedding of cotton knitting yams." Textile Research Journal 49.12 (1979): 681-685.

29 Kumar, Alok, Niranjan Bhowmick, and Subrata Ghosh. "Characterisation of Fibre Lengths and Breakage Behaviour of Cotton Fly in Knitting Process." Tekstilec 61.4 (2018); Lawrence, C. A., and S. A. Mohamed. "Yam and Knitting Parameters Affecting Fly During Weft Knitting of Staple Yarns." Textile research journal 66.11 (1996): 694-704.

30 Bhowmick, N., and S. Ghosh. "Fibre Shedding from Cotton Spun Yarn-A Serious Indoor Air Pollution in Knitting Industry." (2007).

31 Bhowmick, N., and S. Ghosh. "Fibre Shedding from Cotton Spun Yarn-A Serious Indoor Air Pollution in Knitting Industry." (2007).

32 Brown, Peter. "A preliminary study of the fiber-length distribution in fly produced during the weft knitting of cotton yarns." Textile Research Journal 48.3 (1978): 162-166.

length of between 2.9mm and 2.7mm, whereas those in the guide zone had a mean length between 9.4mm and 9.5mm[33], exceeding that of TDMF.

Fibre shedding can be reduced by blending hairy natural fibres with comparatively smooth synthetic fibres. For example, blending cotton and polyester reduces lint shedding[34]. When comparisons were made between lint shedding in cotton, staple fibre polyester and blends of both, the shedding of pure polyester was over an order of magnitude less than that of cotton. The reduction in shedding is increased in blends of higher thread count. Lint shedding reduced by 0.5µg/m for every 10% increase in polyester in 40s polyester-cotton yarn and by 0.25µg/m for every increase 10% in polyester in 60s polyester-cotton yarn[35].

Whilst very few studies discuss TDMF formation in the spinning of synthetic and regenerated cellulosic fibres, there are incidental comments that illustrated reduced TDMF forming potential. For example, knitting efficiency of polyester filament yarns on a circular knitting machine is 95%, but only 75%-80% when knitting cotton yarns[36].

2.3.2 Fibre fly generation during weaving

Fibre fly generation is also reported from weaving operations. Studies of the fly generation from cotton during warp production indicated fly generation between 0.18% and 0.6% [37]. In acrylic yarns, this was between 0.42% and 1.70%[38]. As with knitting, fly generation was affected by yarn construction, weaving method, and atmospheric conditions.

2.3.3 Finishing

Textile fibres may pass through a number of finishing processes which aim to improve the look, feel or functionality of the end product, such as dyeing, printing, washing and drying. Loss of textile mass has been reported for a number of these processes, including de-sizing, singeing, and chemical treatment of synthetic materials. De-sizing is the process by which the size, or sizing, added to protect fibres is removed. De-sizing of cotton has previously been seen to result in between 0.5% and 5.0% reduction in initial weight, with the application of ultrasound increasing this loss to 9.4%[39]. In a broader study of vegetal fibres, Niaz et al.[40] indicate a mass loss at de-sizing of between 7.84% and 8.94%. Whilst most of the mass removed will be that of the sizing, there is currently no information as to the composition of the wastes produced, and TDMF may make up a proportion of what is removed.

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33 Ruppenicker, George F., and John T. Lofton. "Factors affecting the lint shedding of cotton knitting yams." Textile Research Journal 49.12 (1979): 681-685.

34 Ruppenicker, George F., and John T. Lofton. "Factors affecting the lint shedding of cotton knitting yams." Textile Research Journal 49.12 (1979): 681-685.

35 Basu, Arindam, and Rajanna L. Gotipamul. "Lint shedding propensity of cotton and blended yarns." (2003).

36 Basu, Arindam, and Rajanna L. Gotipamul. "Lint shedding propensity of cotton and blended yarns." (2003).

37 Yuksekkaya, Mehmet E. "Fiber fly generation of 100% cotton yarns during warp preparation." The Journal of The Textile Institute 101.3 (2010): 270-275.

38 Yuksekkaya, Mehmet E. "Fiber Fly Generation of 100% Acrylic Yarns during Weaving." Textile Research Journal 80.6 (2010): 508-515.

39 Thakore, K. A., and Bademaw Abate. "APPLICATION OF ULTRASOUND IN THE PRETREATMENT OF COTTON FABRIC." CELLULOSE CHEMISTRY AND TECHNOLOGY 51.9-10 (2017): 983-992.

40 Niaz, Ahmad, Qaiser Jawed Malik, Sher Muhammad, Tahir Shamim, and Shoaib Asghar. "Bioscouring of cellulosic textiles." Coloration Technology 127, no. 4 (2011): 211-216.

Singeing is the removal of surface fibres from a garment or fabric. In this process, the fabric surface is burnt to improve evenness. Mass loss as a result of the singeing of cotton has been recorded between 2.8% and 12.8%[41]. In jute this has been reported as between 1.9% and 9.7%[42] and in wool at 0.43 and 0.89 grams per yard[43]. In a more general study of textiles, Lopez-Amo and Serrano suggest boundaries between 5.8 and 15.4%[44].

A range of finishing processes are also applied to synthetic and regenerated cellulosic fibres. For polyester, aqueous sodium hydroxide is used to smooth the surface of the fabric. This process has been shown to reduce fibre diameter and can result in chain scission of the polymer in the surface layers[45]. Caustic treatment of polyester has been seen to cause mass loss between 2 and 37% dependent on the conditions to which the fibres are exposed, however, the authors indicate a reasonable expectation of 16% loss during optimised processing[46]. Similar alkali treatments of regenerated cellulosic Lyocell result in fibrilization, the formation of small surface fibres which are more susceptible to subsequent breakage and shedding.

Whilst mass losses are routinely recorded for these processes, the proportion of TDMF formed or shed is very likely to be negligible, and these processes are not included in our calculations of TDMF formation.

2.4 Textile derived microfibre formation and shedding during the production of whole garments

The production of whole garments may include pattern cutting, sewing, overlocking, and a range of finishing processes. The level of waste generated at these stages is poorly documented and may exhibit great variability in relation to the manufacturing steps employed. In addition, the proportion of the mass lost that is less than 5mm in length and that which is over this is undocumented. Thus, the proportion of overall production that may be attributed to TDMF is not calculable.

Observations of wastes produced throughout the garment production stages have indicated that up to 15% of the initial textile material may not be included in the final garment. However, much of these wastes are reclaimed and diverted into other production streams rather than being sent to landfill or incineration. The potential for TDMF production is largely dependent of the manner in which waste materials are handled. Those broken down for recycling may pass through a secondary carding, spinning and knitting or weaving or be incorporated into other production streams which would prevent the passage of microfibres to the environment. Unfortunately, values for the annual proportion of waste material which

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41 Pillay, K. P. R., N. Viswanathan, and M. S. Parthasarathy. "The structure and properties of open-end yarns: Part I: A study of fiber configurations and migration." Textile Research Journal 45.5 (1975): 366-372; ; Xia, Zhigang, Xin Wang, Wenxiang Ye, Weilin Xu, Jianxiang Zhang, and Haito Zhao. "Experimental investigation on the effect of singeing on cotton yarn properties." Textile research journal 79, no. 17 (2009): 1610-1615.

42 Ghosh, S. N., G. K. Bhattacharyay, N. K. Sil, and B. N. Mukhopadhyay. "Hairiness of Jute Yarn: Part II-Effects of Linear Density, Twist Multiplier, Spinning Draft and Piling Period." (1987).

43 Boswell, H. R., and P. P. Townend. "11—SOME FACTORS AFFECTING THE HAIRINESS OF WORSTED YARNS." Journal of the Textile Institute Transactions 48.5 (1957): T135-T142.

44 López-Amo Marín, Federico, and José Antonio Serrano Moreno. "A contribution to the study of the villus of the threads." (1958).

45 Zeronian, S. Haig, and Martha J. Collins. "Surface modification of polyester by alkaline treatments." Textile Progress 20.2 (1989): 1-26.

46 Bajaj, P. "Ecofriendly finishes for textiles." (2001).

is treated in this manner is low, however, the HMRC database indicates that large volumes of waste material are imported and exported annually.

2.4.1 Calculating potential textile derived microfibre formation for processing and production

In order to calculate the mass of TDMF formed during the manufacture of clothing and flat textiles, the proportion of material lost during key processing and production steps was calculated. The median reported mass lost by each fibre type was taken from all available studies, and an average for all clothing calculated using the proportions of animal, vegetal, regenerated cellulosic and synthetic fibres used in the clothing industry. These figures were then applied to the annual consumption of textiles, to determine upstream losses during the manufacturing process.

As stated above, many of the manufacturing stages result in the loss of impurities and the breakdown of organic components resulting in difficulties in calculating the mass of TDMF generated. To avoid overestimation, only activities likely to result in a high proportion of TDMF, such as processing to fibre, spinning and winding, weaving and knitting and garment construction, are included in the final figures. Other processes will be discussed in the following subsections, in which their potential to result in TDMF formation and shedding will be discussed.

The diagram below illustrates the mass of material lost at key stages in the production and processing of textiles (Figure 2). For an annual figure of 1,130,000 tonnes of clothing consumed in the UK, an estimated 168,452 tonnes of textile mass is lost. Over 70,000 tonnes of this loss is the result of the stages of processing to fibre (4.1% of the original weight), spinning and winding (1.2% of the original weight), and weaving and knitting (0.2% of the original weight). Most of this mass is likely to be TDMF. However, the proportion of mass lost during garment construction that may be attributed to TDMF is currently unquantifiable and additional research is required.

It is important to note that the percentages given are applied sequentially and are not cumulative, for example for 100 kg of cotton, 5% loss during carding and 15% loss during bleaching does not equal a loss of 20 kg, but a loss of 19.25% (5% of 100Kg + 15% of 95kg).

In addition to the mass of completed clothing and flat textiles purchased each year, the UK both imports and exports large volumes of fibres, yarns and textiles, the handling of which may affect our annual TDMF outputs. Table 1 illustrates the known mass of textiles imported and exported at each of the key production and processing stages, with upstream losses calculated as above. While the volumes reported are much lower from those on annual clothing consumption, at just 11,300 tonnes, they do help to illustrate the TDMF losses as a result of the UK textile manufacturing chain. These numbers include all textile manufacture, and not just that of clothing.

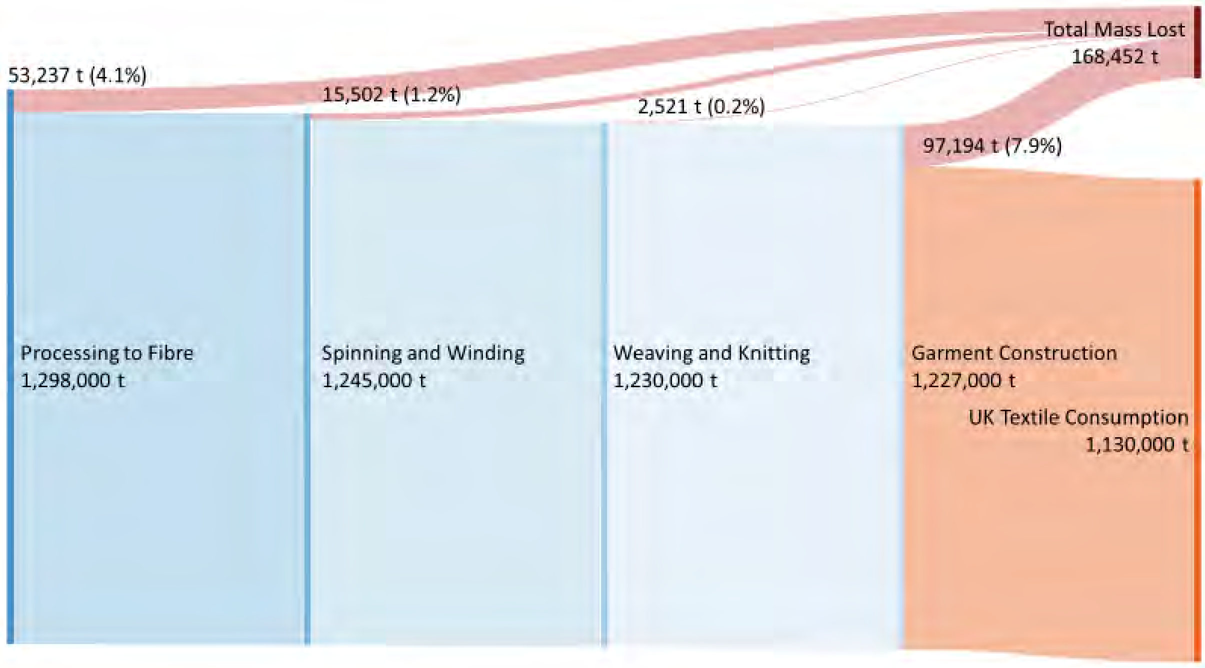

Figure 2 Estimating the Annual Mass of Textiles Lost During Processing and Production

	Production to Fibre			**Spinning and Winding**			**Knitting and Weaving**		
	Total (tonnes)	Estimated loss %	Estimated loss (tonnes)	Total (tonnes)	Estimated loss %	Estimated loss (tonnes)	Total (tonnes)	Estimated loss %	Estimated loss (tonnes)
Animal	6,100	12	833	21,500	--	--	17,400	--	--
Vegetal	46,800	15.2	8,397	3,400	19	808,364	20,200	0.02	4.046
Regenerated Cellulosic	5,200	--	--	1,100	1.29	14,497	8,900	1.7	0.150
Synthetic	73,400	--	--	64,400	1.29	842,630	118,800	0.205	244.045

Table 1 Estimating the Mass of Textiles Lost during Processing and Production in 2017

2.4.2 Key data deficiencies in production and processing

The current level of information regarding the production of TDMF during processing and production is limited. For key processes such as production to fibre, spinning and winding and knitting and weaving, much of the mass lost is likely to be predominantly microfibres. However, there is very little available detail on the size of the fibres released. During garment construction, the mass lost is likely to be above the size range for TDMF, however, subsequent processing may result in additional fibre formation.

Studies of wet processing do not currently address the loss of fibres, despite the potential for abrasion to cause the formation of TDMF. Waste water from processes such as dyeing are often subject to waste water treatment, a process known to reduce microfibre releases to aquatic environments.

Substantial research is required to identify the points at which TMDF may be produced and, equally importantly, released to the environment. This is of particular importance in finishing techniques during which a degree of mass loss or gain is predicted.

3.0 Textile derived microfibre formation and shedding during use

Recent figures place UK clothing consumption at 1.1 million tonnes (Mt), with an additional 16,000 tonnes of corporate wear, and 295,000 tonnes of table and bed linen[47]. However, the pool of 'active' textiles is generated over several years' consumption and it is estimated that only 3.6 Mt of that is in active use[48]. These textiles may form and shed TDMF over the course of their useful life.

3.1 Microfibre shedding during daily wear

The use of textiles both in the home and in commercial and industrial settings results in daily abrasion and wear, however the relative strength of our studied fibre types is highly variable, being influenced by the structure of the textiles as well as the fibre used. The effort needed to break vegetal fibres is between 6% and 38% lower than that of animal and synthetic fibres[49]. The shedding of pills may be reduced by the blending of natural and synthetic fibres which form stronger anchor points which prevent pills being shed.

The abrasive forces to which textiles are exposed may result in the formation of individual fibres or the formation of pills on the fabric surface. The prevalence of daily shedding can be observed in studies of fibre transfer in forensic science. The movement of fibres from donor garments to recipients can be observed from contact as fleeting as a hug[50].

Daily use of apparel and flat textiles, results in high ambient TDMF concentrations. Comparisons of airborne fibre concentrations in indoor (two homes and one office) and outdoor environments have demonstrated elevated concentrations of between 1 and 60 fibres per cubic meter inside and just 0.3 and 1.5 fibres per square meter outside. Inside, over two thirds of fibres recovered are natural fibres, and the settlement rate reached up to 11,130 fibres per square meter per day[51]. The elevated indoor concentrations are believed to be the result of numerous sources and reduced transport in enclosed spaces.

Despite this understanding of the issue of fibre shedding, reliable estimates of day to day TDMF loss from in use textiles have not been developed. However, we can observe the period between washes over which TDMF may form. If excluding regularly washed items such as underwear and sportswear, the average number of wears between washes may fall between 2 and 5.5[52]. If we assume the daily wear time is 16 hours, garments may experience 88 hours of diffuse shedding between washes.

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[47] WRAP, 2016, Textiles market situation report

[48] WRAP, 2017, Valuing our Clothes: the cost of UK fashion

49 Laitala, Kirsi, Ingun Klepp, and Beverley Henry. "Does use matter? Comparison of environmental impacts of clothing based on fiber Type." Sustainability 10.7 (2018): 2524.

[50] Palmer, Ray, Kelly Sheridan, Jemma Puckett, Naomi Richardson, and Wing Lo. "An investigation into secondary transfer—The transfer of textile fibres to seats." Forensic science international 278 (2017): 334-337

51 Dris, Rachid, Johnny Gasperi, Cécile Mirande, Corinne Mandin, Mohamed Guerrouache, Valérie Langlois, and Bruno Tassin. "A first overview of textile fibers, including microplastics, in indoor and outdoor environments." Environmental Pollution 221 (2017): 453-458.

[52] Laitala, Kirsi, Ingun Klepp, and Beverley Henry. "Does use matter? Comparison of environmental impacts of clothing based on fiber Type." Sustainability 10.7 (2018): 2524.

3.2 Microfibre shedding during laundry

The current emphasis on the release of microfibres to the aquatic environment has resulted in increased concern regarding the shedding of microfibres from textiles during washing, in particular, domestic washing. This interest has resulted in an increasing number of studies by materials scientists, environmental scientists and industry bodies, however, there are currently large discrepancies in the way microfibre shedding during clothes washing is measured and reported, and there is a lack of consideration for natural and regenerated cellulosic fibres.

Testing has been carried out on both whole garments and prepared textile samples, pre-treated and not and on varied washing machines and programmes. The preparation of fabric samples, for example laser cutting or overlocking sample edges, may greatly influence fibre production. Comparisons between results are further complicated by inconsistencies in the reporting methods employed. The units of measure reported by studies vary between number of fibres produced per unit area, number of fibres produced per weight of fabric, and mass of fibres produced per mass of fabric.

Even within studies, the number or weight of fibres produced has been seen to be highly variable. Polymer type, fibre type, fabric construction and finishing each influence the rate of fibre formation. For example, polyester fleece and microfleece have been seen to release microfibres at a much higher level than knitted/woven fabrics. This is perhaps unsurprising when comparing the shedding rates of filaments and staple fibres and the effects of fibre length and hairiness as outlined in the previous section. The number of prior washes may also reduce the total volume of TDMF produced. Hernadez et al suggest that TDMF released in the wash is predominantly short fibres produced during manufacture, but still present within the finished garment[53]. As these fibres are eliminated, the rate of TDMF release should be reduced.

The interactions between these factors can be observed in Table 2. Experimental inconsistencies and variation as a result of fabric properties may result in a large range of potential shedding rates for each polymer.

Microfibres may also be formed during both machine and air drying. However, whilst the issue of dryer-lint is widely recognised, the rate of microfibre formation, their primary sources and composition are poorly understood. Observations of the drying of polyester fleece have indicated reductions in mass of up to 0.02%, although subsequent repeated drying cycles resulted in losses of around 0.003%[54].

It is important to note that many of these studies establish total fibre generation by number rather than just the weight of microfibres produced. An unknown proportion of fibres generated at this stage will be above 5mm in length.

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[53] Hernandez, Edgar, Bernd Nowack, and Denise M. Mitrano. "Polyester textiles as a source of microplastics from households: a mechanistic study to understand microfiber release during washing." Environmental science & technology 51.12 (2017): 7036-7046.

[54] Pirc, U., M. Vidmar, A. Mozer, and A. Kržan. "Emissions of microplastic fibers from microfiber fleece during domestic washing." Environmental Science and Pollution Research 23, no. 21 (2016): 22206-22211.

Table 2 Factors affecting the production of TDMF during washing

Tested Fibres	Effect of fibre type	Effect of fabric construction	Effect of washing machine type	Effect of detergent	Effect of temperature	Effect of cycle length	Effect of repeat washing	Author
Polyester jersey and interlock		No significant difference in TDMF production between jersey and interlock knits		Higher TDMF production with liquid and powder detergent than DI water alone	No significant effect of temperature	Np effect of cycle length	No effect of repeat washing	Hernandez et al., 2017[55]
Polyester fleece				Higher TDMF production with detergent than with DI alone (less elevated in the presence of detergent and fabric softener)			Reduction in releases of up to an order of magnitude after 10 washes (0.027%-0.005%)	Pirc et al, 2016[56]
Polyester-cotton, Polyester, Acrylic	Acrylic> Polyester> Polyester-Cotton			Higher TDMF production with bio-detergent than with DI alone Polycotton produced least fibres in DI and most in Bio-detergent	Polyester releases more fibres at 40 than 30		Reduction in releases in pure synthetics, no reduction in releases from blends	Napper et al., [57]2016

[55] *Hernandez, Edgar, Bernd Nowack, and Denise M. Mitrano. "Polyester textiles as a source of microplastics from households: a mechanistic study to understand microfiber release during washing." Environmental science & technology 51.12 (2017): 7036-7046.*

[56] *Pirc, U., M. Vidmar, A. Mozer, and A. Kržan. "Emissions of microplastic fibers from microfiber fleece during domestic washing." Environmental Science and Pollution Research 23, no. 21 (2016): 22206-22211.*

[57] *Napper, Imogen E., and Richard C. Thompson. "Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions." Marine pollution bulletin 112, no. 1-2 (2016): 39-45.*

Tested Fibres	Effect of fibre type	Effect of fabric construction	Effect of washing machine type	Effect of detergent	Effect of temperature	Effect of cycle length	Effect of repeat washing	Author
Polyester Fleece, Nylon Shell			Significantly higher TDMF production in top-loading machines					Hartline et al., 2016[58]
Polyester, Nylon, Acrylic		No significant difference in TDMF production by fleeces than by knitted or woven fabric		Higher TDMF production with detergent than with DI alone			Reduction in fibres after repeat washing is dependent on the fabric construction	Almroth et al, 2018

[58] Almroth, Bethanie M. Carney, Linn Åström, Sofia Roslund, Hanna Petersson, Mats Johansson, and Nils-Krister Persson. "Quantifying shedding of synthetic fibers from textiles; a source of microplastics released into the environment." Environmental Science and Pollution Research 25, no. 2 (2018): 1191-1199.

3.3 Domestic washing

International figures suggest that clothes are washed once every one to ten wears, that woollen and cotton sweaters are washed least frequently, and underwear, socks and sportswear are washed most frequently[59]. The Women's Institutes' In a Spin report indicates that 54% of the clothes washed in the UK contain less than 30% synthetic and regenerated cellulosic fibres (are over 70% animal or vegetal fibres). The average household reported carrying out 2.5 loads of washing per week, equating to 68 million loads per week across the UK[60], or 3.54 billion loads per year. This number is lower than that previously reported in between approximately 274 washing loads per annum (5.27 loads per week) reported by UK Energy Research Centre Energy Data Centre[61] or 7.45 billion loads. The average load capacity of a domestic washing machine is approximately 5.58 kg[62] but even assuming just a 4 kg load as a part-filled machine, this would amount to 14.14 Mt to 29.82 Mt of washed textiles.

The production of TDMF during washing has been studied in a range of laboratory trials. Garments and test fabrics are exposed to a range of washing conditions and the mass or number of TDMF produced is determined (Table 2). The proportion of TDMF produced ranged between 0.002%[63] and 0.3%[64] of the original garment weight, with that produced by fleeces around 10 times that of other knitted and woven garments. Most of the available data concerns synthetic fibres or synthetic fibre blends and the proportion of TDMF formed during the washing of natural fibres has yet to be established. Due to the known level of variation in TDMF formation for synthetic fibres, and the unknown effects of washing on natural fibres, the minimum level of fibre formation has been used in the calculations reported here.

Clothing has an average lifespan of 3.3 years[65]. Over this period, items such as jeans, t-shirts and socks may be washed between 30 and 62 times[66], losing a minimum of 0.002% of their weight with each cycle.

WRAP's Valuing our Clothes – the cost of fashion report from 2017 states that tumble drying is carried out at a rate of approximately 26% of total washes. Thus, the annual weight of tumble drying has been calculated as 26% of that being washed; 3.68 – 7.75 Mt. Only one study was found that examined the impact of tumble drying on TDMF production, in which

59 Laitala, Kirsi, Ingun Klepp, and Beverley Henry. "Does use matter? Comparison of environmental impacts of clothing based on fiber Type." Sustainability 10.7 (2018): 2524.

60 NFWI, 2018, In A Spin: How Our Laundry is Contributing to Plastic Pollution

61 DECADE and Fawcett, T., Lane K., Boardman, B., et al, 2000, Lower Carbon Futures for European Households, Environmental Change Institute Oxford - Appendix F, UK 1 Table 1 (using data from the English Housing Condition Survey)

62 DECADE and Fawcett, T., Lane K., Boardman, B., et al, 2000, Lower Carbon Futures for European Households, Environmental Change Institute Oxford Appendix F, UK 1 Table 1 (using data from the English Housing Condition Survey)

63 *Hernandez, Edgar, Bernd Nowack, and Denise M. Mitrano. "Polyester textiles as a source of microplastics from households: a mechanistic study to understand microfiber release during washing." Environmental science & technology 51.12 (2017): 7036-7046.*

64 *Sillanpää, Markus, and Pirjo Sainio. "Release of polyester and cotton fibers from textiles in machine washings." Environmental Science and Pollution Research 24.23 (2017): 19313-19321.*

65 *WRAP's 2015 Sustainable Clothing Guide*

66 *WRAP, 2015,* Sustainable clothing guide

the mass of TDMF produced ranged between 0.003% and 0.027% of the original garment weight[67].

3.4 Hospitality

The serviced accommodation industry in the UK may also contribute to the mass of TDMF produced annually. There are around 337,000 B&Bs, guest houses and hotels, with 1,769,000 bed spaces in England alone[68]. Reports of the number of visitors to destinations in Great Britain in 2017 indicate 39.2 million international visitors and over 120.7 million domestic tourists.

Tourism and additional non-tourism related stays accounted for 491,144,000 nights spent in serviced accommodation between January and October in 2017[69]. It is estimated that the average mass of laundry created per room per night is between 2.8 kg and 4 kg[70]. At the lowest estimate, the mass of laundry produced by people using the serviced accommodation industry in 2017 would exceed 1.375 Mt.

3.5 Medical laundry

Washing of clothing and flat textiles used in hospitals, care homes and other health facilities also has the potential to contribute large volumes to the mass of textiles washed annually. For example, the Raigmore Hospital reported a weekly wash pattern equating to 6,250 individual 5.44kg domestic laundry loads in 2012. Whilst the weekly value of washing generated by the NHS and private practice is not well documented, estimates place the average laundry of a 600-bed hospital at 30,000 items per week[71]. In England, the number of NHS hospital beds in December 2018 was 127,589. Using the figures provided by Barrie (1994), the number of items washed by English NHS hospitals each week could equal 6,379,450.

3.6 Uniforms and other commercial laundry

A 2012 estimate of uniforms and commercial laundry in the UK suggested that 39.2 million corporate wear garments were provided to the 11.6 million staff members in the UK[72]. In a more recent report of the European textiles and workwear market, it is suggested that the weight of workwear consumption in the UK may be closer to 16,617 tonnes[73]. A previous study of US commercial laundry facilities receiving uniforms and workwear revealed that these facilities may take in between 9.8 and 48 tonnes of textiles per day, although these were not all clothing. Garments were washed in machines of between 181 kg and 408 kg capacity[74].

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[67] Pirc, U., M. Vidmar, A. Mozer, and A. Kržan. "Emissions of microplastic fibers from microfiber fleece during domestic washing." Environmental Science and Pollution Research 23, no. 21 (2016): 22206-22211.

[68] *Visit England 2016*

[69] *Source:* Eurostat (online data code: tour_occ_nim)

70 Styles, David, Harald Schoenberger, and José Luis Galvez-Martos. "Water management in the European hospitality sector: Best practice, performance benchmarks and improvement potential." Tourism Management 46 (2015): 187-202.

71 Barrie, D. "How hospital linen and laundry services are provided." Journal of Hospital Infection 27, no. 3 (1994): 219-235.

[72] *Bartlett, Caroline, Dan Eatherley, and Clare Hussey. "A review of UK corporatewear arisings and opportunities."*

[73] *Sustainable Global Resources Ltd (2017) ECAP European Textiles and Workwear Market: the role of public procurement in making textiles circular, Rijkwaterstaat*

[74] *Cartwright, Jane, J. Cheng, J. Hagan, C. Murphy, N. Stern, and J. Williams. "Assessing the environmental impacts of industrial laundering: life cycle assessment of polyester/cotton shirts." Bren School of Environmental Science and Management, University of California, Santa Barbara; Mission Linen Supply (2011).*

3.7 Waste water treatment

After leaving the washing machine, most laundry effluent water travels through sewers to waste water treatment plants (WWTPs) or is discharged to a septic tank. The waste sludge from septic tanks is later removed and subjected to WWTP processing[75]. In a small proportion of cases – some 300,000 homes in the UK – effluent pipes are wrongly connected to surface water sewers, resulting in the direct release of fibres and detergents to the environment.

Effluent directed to WWTPs is subjected to screening, settling and digestion designed to prevent the passage of solid wastes and reduce the concentration of key nutrients. Current WWTPs are not designed to remove TDMF or other micro-pollutants such as pharmaceuticals and microplastics, however, studies of the effectiveness of secondary treatment plants (those with screening, settlement and biological processing) in removing microplastics including synthetic microfibres have indicated between 95% and 98% removal[76]. Despite these high levels of filtration, millions of synthetic microfibres per treatment plant may still be released to the environment each year.

It is important to note that not all WWTPs have the same level of treatment. Small communities discharging into 'less sensitive' environments may only pass through primary, or even preliminary, treatment. Additionally, the fibres trapped as part of the treatment process may subsequently be released to the environment. Sewage sludges may be sent for anaerobic digestion and subsequently be spread over terrestrial environments.

3.8 Calculating potential textile derived microfibre formation for washing and drying

In order to determine the weight of TDMF produced by domestic machine washing and drying of clothing and flat textiles, the mass of clothing washed and dried each year was calculated and adjusted using the percentage mass lost in laboratory studies. The weight of clothing machine washed each year was calculated in the earlier section by multiplying the number of reported washes per annum by the number of households in the UK, between 14.14 Mt to 29.82 Mt of textiles. The mass of TDMF formed was then calculated as 0.002% of this figure; a minimum of 282.88 tonnes (Figure 3). However, this figure is derived from a minimum load size of 4 kg, if increasing the average washing load to 10 kg, the minimum number of fibres produced would range from 1,379 tonnes to 1,491 tonnes. This latter figure is similar to that reported in previous estimates of microfibre releases for Friends of the Earth[77].

WRAP's Valuing our Clothes – the cost of fashion report from 2017 states that tumble drying is carried out at a rate of approximately 26% of total washes. Thus, the annual weight of tumble drying has been calculated as between 3.68 Mt and 7.75 Mt. Again, the proportion of TDMF formed was determined as 0.003% of the mechanically dried mass, or 364 tonnes (Figure 3).

When considering the effectiveness of WWTPs in removing TDMF from solution, a conservative estimate of 95% effectiveness has been applied. When applied to the figures for annual TDMF formation from domestic laundry and textiles derived from serviced accommodation, between

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[75] Environment Agency Regulatory position statement (2012) https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/297800/RPS_007_Disposal_of_septic_tank_sludge.pdf

76 Murphy, Fionn, Ciaran Ewins, Frederic Carbonnier, and Brian Quinn. "Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment." Environmental science & technology 50, no. 11 (2016): 5800-5808.

[77] Hann et al, 2018, Reducing Household Contributions to Marine Plastic Pollution. Report to Friends of the Earth

294.86 tonnes and 592.54 tonnes may be retained in sewage sludge and between 15.52 tonnes and 31.19 tonnes may be released to aquatic environments (Figure 3).

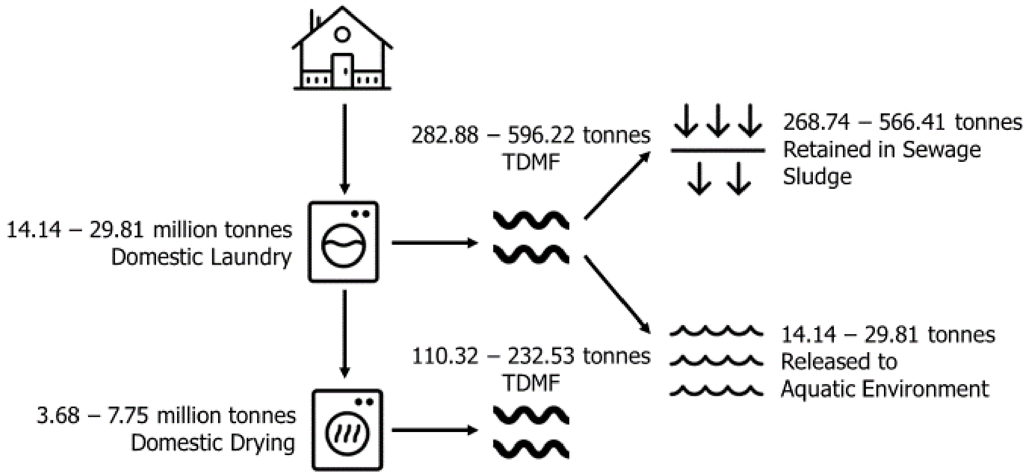

Figure 3 Estimating the Annual Formation of TDMF as a Result of Domestic Machine Washing and Tumble Drying

The same method was used to estimate the mass of TDMF produced by the serviced accommodation industry in 2017. Using an estimated textile mass of 1.375 Mt, the mass of TDMF formed could exceed 27.50 tonnes (Figure 4).

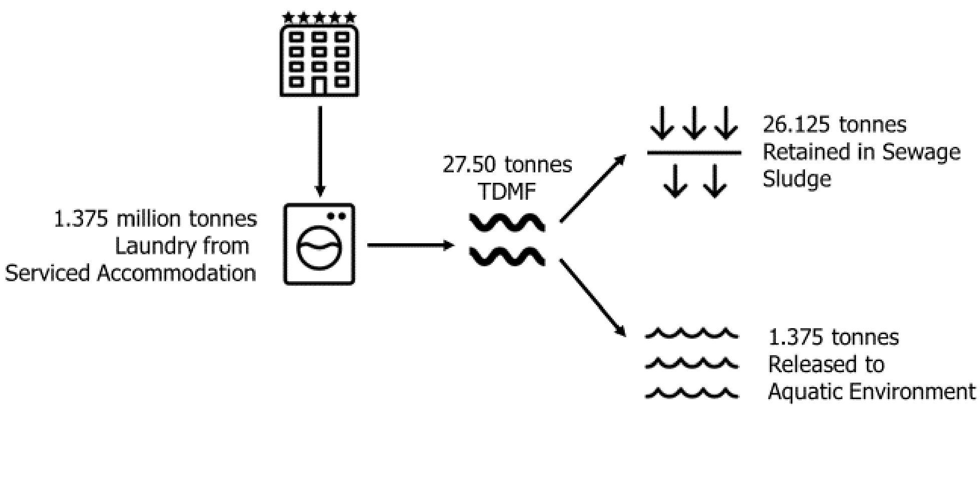

Figure 4 Estimating the Annual Formation of TDMF as a Result of Serviced Accommodation

3.9 Key data deficiencies in use

Attempts to calculate the proportion of TDMF formed during the use phase are hampered by the lack of information regarding the day to day shedding of fibres during the use of garments and flat textiles. Individual studies have shown reported some data for the losses of fibre due to abrasion, and for the mechanisms of fibre shedding such as pilling. These studies have made some comparative conclusions amongst varying fibre types but drawing an absolute value for fibre loss in the use of textiles based on the experiments carried out is not currently possible.

There is currently a bias toward synthetic fibres in the study of formation and shedding during mechanical washing and drying due to their perceived effects in the environment. Although some fibre types and formats have been investigated, the methodology for determining and measuring losses has not been standardised. Due to the huge range of fibre/fabric types and combinations, the tests which have been carried out can only represent a small proportion of overall textiles in use.

The lack of information regarding the losses from hand washing also limits the development of robust estimates of total TMDF production, especially since hand washing is being recommended as a mitigation measure.

Estimates are not available for the mass of textiles sent to dry cleaning or arising from healthcare due to lack of data, hence their contributions are not presented here.

4.0 Microfibre formation and shedding at end of life

As mentioned above, the useful lifespan of our textiles is highly variable. Recent surveys suggest that 65% of adults dispose of between 1 and 20 items of clothing a year and 22% dispose of between 21 and 40 items of clothing per year[78], and there are many routes by which textiles may be disposed of at end of life. When the Women's Institute questioned their members as to the primary route by which they disposed of their clothing, 90% stated that they sent their clothes to charity, 3.7% was sold independently, given to friends or used for a different purpose, 1.8% reported taking their clothes to designated recycling centres and just 1.7% reported sending most of their clothes to residual waste[79]. In the 2015 Textiles Market Situation Report, 7% of respondents reported putting most of their unwanted clothing in the bin. Across the UK, this would represent between 489,600 and 1,904,000 homes sending all their waste clothing direct to residual waste.

Estimation of the mass of textiles in household residual waste presents numerous challenges. Breakdown of waste according to NACE economic activity suggested that the volume of textiles from households to landfill was 138,302 tonnes in 201480. In the same year, the total waste arising from households was over 27.7 Mt, placing textile wastes at just under 0.05% of total production. In addition to this, a further 107,848 tonnes were produced from non-household sources, 43,295 tonnes of which originated during the "manufacture of textiles, wearing apparel, leather and related products". However, more in-depth estimation places the value arising from households at 300,000 tonnes, with a further 119,000 tonnes of flat non-clothing textiles [81].

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79 NFWI, 2018, *In A Spin: How Our Laundry is Contributing to Plastic Pollution*

80 [DEFRA, 2018]

[81] *Resource Futures, 2016, 'National Estimates for Household Textiles in Residual Waste' (unpublished research for WRAP)*

The Valuing our Clothes report from 2012 indicates that around 48% of our textiles are sent for reuse, 14% are recycled, 7% are incinerated and 31% are sent to landfill[82]. Whilst a large proportion (70%) of textiles for reuse are sent overseas, there are also numerous routes for Charity Shop Grade textiles processed in the UK. Of the estimated 349,948 tonnes arising, 40% go to rag merchants, 55% are sold through charity shops, and 5% is directed to landfill. Over the same period, the total dry recycling produce by UK households was 6 million tonnes, of which 120,000 tonnes (2%) was made up of textiles (including shoes)[83].

The creation of TDMF at end of life may occur as a result of fragmentation on disposal or through handling and processing as part of the recycling process. As a result, the mass of textiles directed to residual waste and recycling respectively were explored; overall figures for mass to each disposal route are shown in Figure 5.

When considering textiles in landfill as a source of TDMF it is important to consider that the formation of fibres will vary greatly in relation to the fibre type and the conditions to which they are exposed. Natural and regenerated cellulosic textiles may shed fibres and degrade at a faster rate than synthetic textiles. For example, degradation studies of wool[84] and sisal in relation to synthetic fibres has seen a much greater rate of degradation in natural fibres[85]. As a result, the abundance of natural TDMF will increase and decay comparatively rapidly whereas a slow increase in synthetic TDMF would be observed followed by an extended degradation period. Substantial research is needed to understand the potential for TDMF production under landfill conditions and the potential for microfibre release to the environment.

Route		Mass (tonnes)
Landfill	Household	300,000
	Manufacture of textiles	43,295
Recycling		120,000
UK Reuse	*Rag merchants*	*139,980*
	Diverted to landfill	17,498

Figure 5 Disposal of Clothing at End of Life

4.1 Key data deficiencies in end of life calculations

Establishing the formation of TDMF at end of life is as challenging as during the production and processing and use stages. Whilst figures exist for the route of textile disposal at end of life, there is a lack of information as to the rate of degradation in both aquatic and terrestrial environments. There is a need for comparative studies exploring the effect of temperature, pH and light penetration, as well as the effects of microbial action on the degradation of textile degradation under marine, freshwater and terrestrial conditions, including those typical of landfill and composting facilities.

5.0 Overview of microfibre formation and shedding

Figure 6 provides an overview of the mass of textiles lost during the use phase (laundry and drying) and at disposal. As noted in Section 2, the estimated mass of textiles lost during production and processing were calculated as upstream losses from annual textile

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[82] *WRAP, 2012 Valuing our clothes*

83 (DEFRA)

[84] *Brown R.M. (1994). The Microbial Degradation of Wool in the Marine Environment. Thesis for the degree of Master of Science in Microbiology, University of Canterbury, New Zealand*

[85] *Welden, Natalie A., and Phillip R. Cowie. Degradation of common polymer ropes in a sublittoral marine environment."Marine pollution bulletin 118, no. 1-2 (2017): 248-253.*

consumption. Losses as a result of machine washing and tumble drying were calculated from the annual losses calculated in Section 3, multiplied by a 3.3-year average use phase. Finally, the remaining mass was divided according to the proportions of textiles diverted to residual waste, incineration, reuse and recycling set out in Section 4.

The results indicate that the maximum estimated mass of TDMF generated during the domestic cleaning of clothes is 1,298 tonnes (3.3 years use). Whereas an estimated 168,454 tonnes of mass were lost during manufacture, and 350,187 tonnes were diverted to residual waste (Figure 6). It is important to note that the mass of textiles lost during production and processing is uncertain regarding the proportion of mass losses which may be classed as TDMF, and the proportion of these that make it to the environment or residual waste. It is often difficult to separate the loss of fibres from that of impurities or additives from the fabric, and there are large disparities regarding the availability and reliability of information for each fibre type. However, if just 10% of this may be classed as TDMF or TDMF parent material, then the mass of TMDF formed during production and processing would be around four times that formed during machine washing.

When comparing the potential for different fibre types to produce TDMF, the largest amounts of natural TDMF appear to be produced during fibre processing and during knitting and weaving, whereas most regenerated cellulosic and synthetic TDMF appear to be produced during the use phase – this is particularly apparent in fabrics of susceptible construction, such as fleeces.

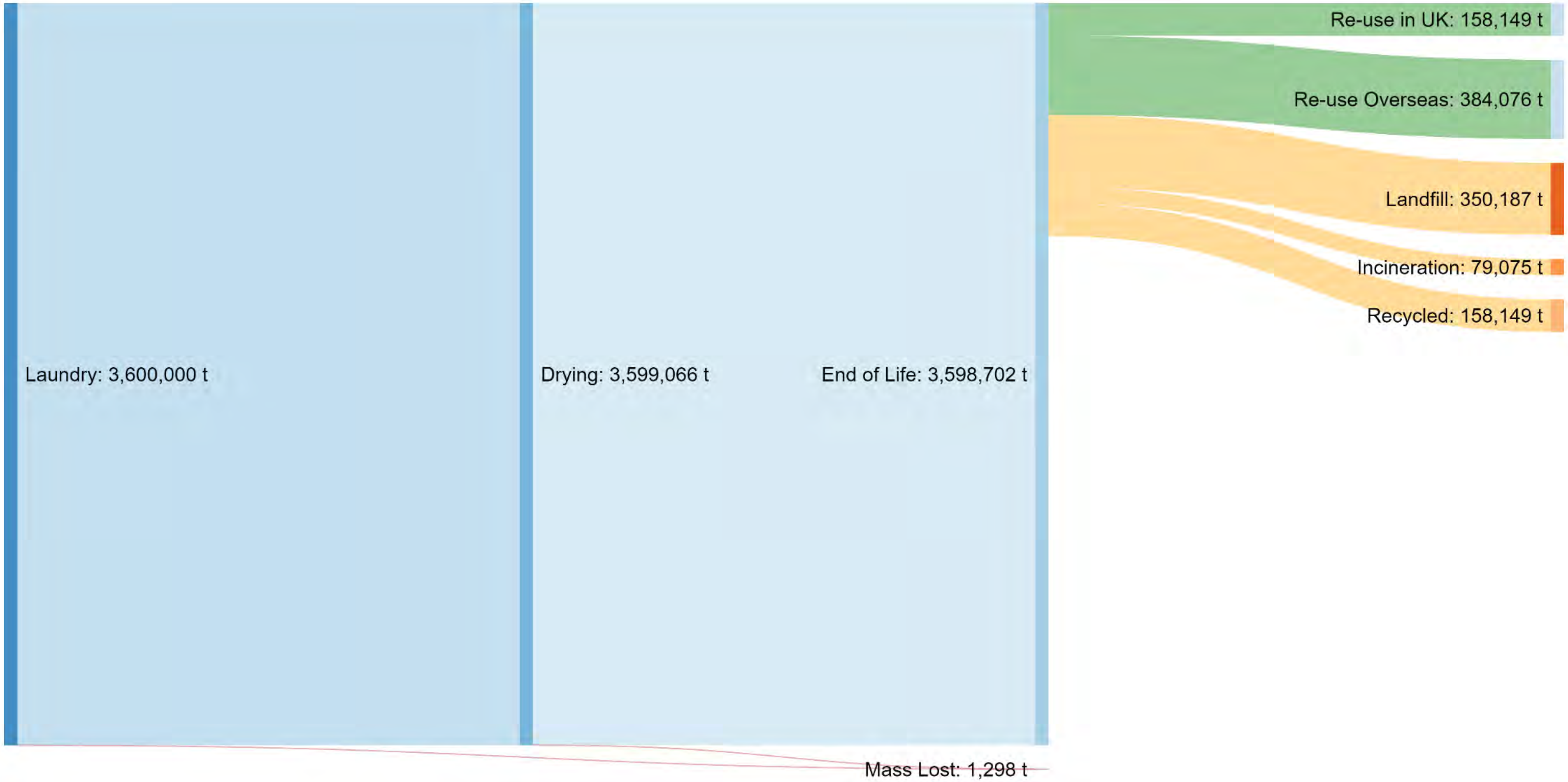

Figure 6 Estimating the Mass Loss Generated During the Clothing Lifecycles of Use Phase and Disposal

6.0 Environmental implications

6.1 Distribution

The movement of TDMF both into and through the environment is a complex process governed by the origin, composition and properties of the fibres, the location in which they are formed, and the route by which they are lost. In addition, the duration over which fibres may remain in any environment will be related to the properties of the receiving medium. For example, microfibres could be incorporated into sandy sediments, or lie on top of a solid surface. Microfibres on the latter may be more susceptible to being carried away on wind currents whereas those on the former may only be moved through sediment by heavy rainfall or the action of animals.

Degradation rates are also believed to vary greatly within and between natural fibres, regenerated cellulosic fibres and synthetic fibres, with long chain synthetic materials potentially persisting for decades. Temperature, light penetration, pH, abrasion as a result of sediment, and the action of organisms and enzymes will all act to influence degradation rates, and thus predicting the breakdown of TDMF is a challenging task.

6.1.1 Terrestrial distribution

Accumulation of TDMF in the terrestrial environment may occur as a result of the shedding and airborne transport of in-use textiles, as well as by the spreading of anaerobically digested sludges produced during water treatment. While some estimates suggest that the release of plastics to land may be between 4 and 23 times that released to the marine environment[86], the sources of these microplastics are highly diverse and the proportion of microfibres may be lower than that observed in aquatic habitats.

Comparisons of atmospheric fallout of microplastics in urbanised and sub-urban areas of Paris over periods of up to a year have revealed large proportions of microfibres. This is perhaps unsurprising considering the surface area to volume ratio of these fibres. Of the recovered fibres 50% were natural and 21% were regenerated cellulosic. The level of fallout varied between 2 and 355 particles per square meter per day[87].

Observations of land treated with sewage sludge have shown the presence of plastic up to 15 years after application. After 5 years, soils treated with a variety of sludge products were seen to contain on average between 0.58 and 1.21 fibres per gram of soil[88].

6.1.2 Freshwater distribution

Rivers may receive high levels of TDMF as a result of receiving WWTP effluent. Transport of TDMF and other debris in riverine environments is primarily one way, following the current downstream; however, fibres may be held up by aquatic plants or become entrained in sediments, resulting in locally increased levels of contamination. In the Solent Estuary,

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86 Horton, Alice A., Claus Svendsen, Richard J. Williams, David J. Spurgeon, and Elma Lahive. "Large microplastic particles in sediments of tributaries of the River Thames, UK–Abundance, sources and methods for effective quantification." Marine Pollution Bulletin 114, no. 1 (2017): 218-226.

87 Dris, Rachid, Johnny Gasperi, Mohamed Saad, Cécile Mirande, and Bruno Tassin. "Synthetic fibers in atmospheric fallout: a source of microplastics in the environment?." Marine Pollution Bulletin 104, no. 1-2 (2016): 290-293.

88 Zubris, Kimberly Ann V., and Brian K. Richards. "Synthetic fibers as an indicator of land application of sludge." Environmental pollution 138, no. 2 (2005): 201-211.

plankton net surveys of microplastic from surface waters of the Rivers Hamble, Itchen and Test as well as Southampton Water revealed between 114 and 959 fibres per five-minute trawl[89].

Sites along the River Thames revealed an average of between 12.1 and 22.3 synthetic microfibres per 100 grams of sediment (121 to 223 microfibres per kilogram of sediment). Fibres were the dominant type of microplastics recovered at all locations but one. The high number of fibres observed at The Cut Site 2 were believed to be the result of sewage effluent input[90]. Conversely, a larger study of 14 river catchments in North West England revealed that microfibres make up an average of just 9% of recovered microplastics before flood events, and 3% after flood events, although the level of variation is substantial (0-582 fibres per kilo of sediment at Urmaston on the Mersey). More importantly, these low proportions still equate to billions of fibres per river[91].

Studies have also indicated that synthetic fibres may also be transported to lakes and ponds. Sediment sampling in Edgbaston Pool near Birmingham revealed that synthetic microfibres were the most abundant form of microplastic recovered. Microfibre concentrations were between 0.5 and 8 fibres per 100 grams, with increased concentrations generally seen in shallower water[92]. Unfortunately, as in many other studies the presence of natural and regenerated cellulosic fibres was not recorded.

6.1.3 Marine distribution

It has been estimated that around 34.8% of the releases of primary microplastics are the result of washing of synthetic textile fibres[93]. In the marine environment, the transport and aggregation of synthetic fibres is influenced by an interaction between proximity to a source, fibre density, salinity, local and global currents, wind and weather patterns and the shape of our coastlines and the seabed. A comparison of the degradation rates of natural and synthetic rope fibres on the seabed has indicated that sisal fibres may be completely degraded after 2 months, whereas nylon, polyethylene and polypropylene remain comparatively unchanged after 12 months of exposure.

In their 2004 paper, Thompson et al. report increasing concentrations of microfibres in seawater, from 0.01 per m^3 in the 1960's to 0.08 fibres in the 1990's. In the same study, contemporary fibre contamination of marine sediments from around Portsmouth was seen to range between 0.5 fibres per 50 ml of sediments to over 6 fibres per 50 ml of sediment.

In wider Europe, the contamination of sediments recovered from the Noderney Coast was recorded at between 27 – 238 fibres per kilo of dry sediment[94]. Whereas, along the German

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89 Gallagher, Anthony, Aldous Rees, Rob Rowe, John Stevens, and Paul Wright. "Microplastics in the Solent estuarine complex, UK: an initial assessment." Marine pollution bulletin 102, no. 2 (2016): 243-249.

90 Horton, Alice A., Alexander Walton, David J. Spurgeon, Elma Lahive, and Claus Svendsen. "Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities." Science of the total environment 586 (2017): 127-141. (Horton et al., 2017)

91 Hurley, Rachel, Jamie Woodward, and James J. Rothwell. "Microplastic contamination of river beds significantly reduced by catchment-wide flooding." Nature Geoscience 11, no. 4 (2018): 251.

92 Vaughan, Rebecca, Simon D. Turner, and Neil L. Rose. "Microplastics in the sediments of a UK urban lake." Environmental Pollution 229 (2017): 10-18.

[93] Boucher and Friot (2017). Primary Microplastics in the Oceans: A Global Evaluation of Sources. Gland, Switzerland: IUCN. 43pp.

94 Dekiff, Jens H., Dominique Remy, Jörg Klasmeier, and Elke Fries. "Occurrence and spatial distribution of microplastics in sediments from Norderney." Environmental Pollution 186 (2014): 248-256.

Baltic coasts, these concentrations were as low as 2 to 11 fibres per kilogram[95]. Synthetic fibres in the water column were observed to number between 0.43 and 5 fibres per litre in waters sampled of the German Baltic coasts[96]. Further south, synthetic microfibre concentrations recorded in Belgian marine sediments were between 41.2 and 134.3 fibres per kilo in harbours, 42.7 to 132 in coastal areas, and between 46.0 and 237.3 fibres in sediments on the continental shelf[97].

6.2 Uptake and impacts

Most of our awareness of the ingestion, inhalation and effects of microfibres is the result of the study of microplastic pollution. These studies have highlighted the uptake of both synthetic and, to a lesser extent, regenerated cellulosic microfibres, however, the uptake of natural fibres is very poorly understood. Due to the early focus of microplastic studies in the marine environment, the majority of these observations stem from marine organisms.

Uptake of synthetic microfibres has been recorded in a range of marine organisms, from the foundation of the food chain up. In zooplankton species, *Neocalanus cristatus* and *Euphasia pacifica*, have been seen to readily ingest fibres, (43.9% and 68.3% of ingested microplastics respectively) with decreasing proportions of fibres recorded with increasing distance from shore[98]. Similarly, microplastic uptake by sea cucumbers in laboratory trials ingested up to 517 fragments of nylon line per individual.

Microfibres have been seen to represent over 97% of microplastics ingested by Langoustine[99], and 82.1% of fish [100] from Scottish waters. In the English Channel, fibres represented 68.3% of the microplastics recovered[101].

Studies of synthetic microfibre uptake also exist in fresh and brackish waters. Observations of microplastic uptake by Roach sampled from the River Thames revealed that 75% of the synthetic particles ingested were microfibres. Uptake was seen to correlate with distance from source[102]. Further down the Thames, European Flounder and Smelt were also seen to ingest fibres, 75% of particles ingested by flounder were fibres, and just 20% by smelt[103].

95 Stolte, Andrea, Stefan Forster, Gunnar Gerdts, and Hendrik Schubert. "Microplastic concentrations in beach sediments along the German Baltic coast." Marine Pollution Bulletin 99, no. 1-2 (2015): 216-229.

96 Stolte, Andrea, Stefan Forster, Gunnar Gerdts, and Hendrik Schubert. "Microplastic concentrations in beach sediments along the German Baltic coast." Marine Pollution Bulletin 99, no. 1-2 (2015): 216-229.

97 Claessens, Michiel, Steven De Meester, Lieve Van Landuyt, Karen De Clerck, and Colin R. Janssen. "Occurrence and distribution of microplastics in marine sediments along the Belgian coast." Marine pollution bulletin 62, no. 10 (2011): 2199-2204.

98 Desforges, Jean-Pierre W., Moira Galbraith, and Peter S. Ross. "Ingestion of microplastics by zooplankton in the Northeast Pacific Ocean." Archives of environmental contamination and toxicology 69, no. 3 (2015): 320-330.

99 Welden, Natalie AC, and Phillip R. Cowie. "Environment and gut morphology influence microplastic retention in langoustine, Nephrops norvegicus." Environmental pollution 214 (2016): 859-865.

100 Murphy, Fionn, Marie Russell, Ciaran Ewins, and Brian Quinn. "The uptake of macroplastic & microplastic by demersal & pelagic fish in the Northeast Atlantic around Scotland." Marine pollution bulletin 122, no. 1-2 (2017): 353-359.

101 Lusher, A. L., Matthew Mchugh, and R. C. Thompson. "Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel." Marine pollution bulletin 67, no. 1-2 (2013): 94-99.

102 Horton, Alice A., Monika D. Jürgens, Elma Lahive, Peter M. van Bodegom, and Martina G. Vijver. "The influence of exposure and physiology on microplastic ingestion by the freshwater fish Rutilus rutilus (roach) in the River Thames, UK." Environmental pollution 236 (2018): 188-194.

103 McGoran, A. R., P. F. Clark, and D. Morritt. "Presence of microplastic in the digestive tracts of European flounder, Platichthys flesus, and European smelt, Osmerus eperlanus, from the River Thames." Environmental pollution 220 (2017): 744-751.

Currently, few studies exist which examine the effects of fibres on marine organisms; however, examination of the impacts of synthetic rope derived microfibres on langoustine after eight months of exposure has indicated reduced feeding, growth and energy reserves[104].

7.0 Ongoing action, research, and mitigation methods

7.1 Ongoing research

The current emphasis on the potential negative implications of TDMF to the environment and public concern regarding issues of food safety and human health have resulted in a range of ongoing projects exploring the causes and implications of TDMF production. In the UK, established research groups exist at the University of Plymouth, as part of larger work on the environmental effects of microplastics in the marine environment, and the University of Leeds, as part of the work of the School of Design.

Internationally, work is underway at the University of Gothenburg's Department of Biological and Environmental Sciences, the University of California's Bren School of Environmental Science and Management, and Finnish Environment Institute. The work of these groups is primarily linked to ongoing work on the environmental impacts of microplastics,

Additional input to research is provided by textile producers and NGOs, outlined below.

7.2 Government action

Appreciation of the production of TDMF through clothes washing has resulted in a number of potential legislative responses. For example, California's recent legislation which requires that any garment containing 50% or more polyester should carry a care label suggesting that the garment be handwashed to prevent the formation of microfibres. However, there is currently no evidence to indicate that the formation of fibres is reduced by washing clothes in this manner and further research is clearly needed to establish the effectiveness of this measure, and other potential approaches to reduce microfibre formation from laundry.

7.3 Textile production chain

In response to initial indications of the scale of TMDF pollution released from clothes, a number of producers, such as Patagonia, have been instrumental in driving and shaping the microfibre research agenda. Furthermore, a number of active groups have formed which bring together researchers with producers and retailers of apparel and other consumer textiles to explore the issue of TDMF. To date, the focus of these groups has primarily been on the formation of synthetic microfibres during laundry processes, seeking to highlight inconsistencies in research methodology and drive for wider research on understudied fibres and other sources of variation; however, there is ongoing work by Consiglio Nazionale delle Ricerche, Italy, which aims to develop a pectin-based coating to reduce microfibre shedding.

In addition to these microfibre focussed initiatives, broader industry objectives regarding the sustainable production of textiles have very much to offer in terms of reducing TDMF pollution. Advancements in dyeing and finishing processes which have reduced the level of abrasion to which textiles are subjected may also limit the rate of microfibre formation. In addition, by minimising the volume of textiles sent to landfill, recycling and cradle-to-cradle design approaches reduce the mass of parent stock in landfill from which TMDF may be

104 Welden, Natalie AC, and Phillip R. Cowie. "Long-term microplastic retention causes reduced body condition in the langoustine, Nephrops norvegicus." Environmental pollution 218 (2016): 895-900.

formed. However, more work is required to understand the potential effects of textile reuse, for example comparative analyses to establish the potential shedding rates of recycled fibres over virgin textiles.

Notable examples of interested bodies and working groups include the European Outdoor Group, the Microfibre Consortium, and the Cross-Industry Agreement a "voluntary collaboration for the prevention of microplastic release into the aquatic environment during the washing of synthetic textiles".

7.4 Mitigation methods

To date, a number of design solutions to the issue of laundry-based shedding of TDMF have been identified. These primarily relate to using in-wash solutions such as bags (Guppy Friend)[105], capture devices (Cora Ball)[106] to retain shed fibre within the wash, or built-in, add on and external washing machine filters (PlanetCare)[107]. Examples of current research work in this area include:

- Inheriting Earth Ltd and Beko, supported by the University of Glasgow;
- the Rozalia Project[108], with Cora Ball;
- STOP! Micro Waste[109], with the guppy friend; and
- Planet Care[110].

Uptake of these physical methods is thought to be low but rising and the level of comparable data on the efficiency of mitigation methods is limited. Until robust comparative studies of the effectiveness of these solutions are carried out, their potential to interrupt the flow of microfibres cannot be quantified. Furthermore, there are currently no recommended routes for the disposal or reuse of TDMFs caught.

7.5 NGOs

The issue of microfibre pollution has been highlighted through the work of numerous environmentally focused NGOs with the driving force being the observed proliferation and impacts of microplastic pollution in the marine environment. In the UK, the impact of textiles as a source of microfibres has been highlighted by Hubbub, as part of their #Whatsinmywash initiative and by the National Federation of Women's Institutes' 2017/18 campaign to 'End Plastic Soup'. Internationally, the topic has been highlighted by Flora and Fauna International, the Marine Conservation Society, the Plastic Soup Foundation, the Plastic Pollution Coalition and many others.

7.6 Consumers

Consumer awareness of the microfibre issue is increasing and campaign focus has been placed on behavioural change around buying choices and laundry practices. As mentioned above, fibre production can be affected by washing conditions. In the results of the In a Spin report, The National Federation of Women's Institutes state that over 95% of the respondents regularly wash the clothes at 40°C or less, with just 32.1% using powder

[105] *GuppyFriend, http://guppyfriend.com/en/*

[106] *Cora Ball, https://coraball.com/*

[107] *PlanetCare, https://planetcare.org/en/*

[108] *Rozalie Project, https://rozaliaproject.org/*

[109] *STOP Micro Waste https://www.stopmicrowaste.com/*

[110] *Planet Care, https://planetcare.org/en/*

detergent over liquids and liquid pods[111]. In addition to this, 62% of respondents indicated undertaking some sort of behavioural change in their washing habits as a result of the campaign. Reported changes included washing at a lower temperature, reducing the number of washes, washing at capacity and reducing wash cycle length. In addition, over 14% reported changing their clothes buying habits.

Additional suggestions to reduce the impact of domestic laundry include:

- Extending the product's lifespan (Patagonia's 'just keep using it' campaign);
- Investing in frontloading washing machines, seen to produce fewer fibres per wash;
- Washing clothing less often;
- Use of liquid detergents and fabric softeners;
- Reduced cycle length and spin speeds; and
- Air drying of clothing.

Whilst these suggestions appear to be logical, there is little data to confirm their efficacy.

8.0 Conclusions

Analysis of the mass of fibres lost throughout the lifecycle of clothing indicates that up to 168,452 tonnes may be lost during processing and production, 1,300 tonnes lost during domestic machine washing and tumble drying, and over 349,000 tonnes are sent to residual waste at end of life. However, comparative analysis of the formation of TMDF at each stage of the project life cycle was made challenging by the lack of data during the production stage, inconsistencies in reporting, bias toward synthetic fibres during washing and drying, and lack of understanding regarding the breakdown and migration of textile fibres in residual waste. However, a number of factors have become apparent even from the conservative estimation process used in this report.

Whilst the generation of microfibres from textiles during the use phase is comparatively low, the potential for TDMF to be leaked into the environment is potentially higher than during production or disposal, as microfibres formed during washing are predominantly directed to waste water treatment. Whilst the majority of these fibres are retained by WWTPs, many tonnes may be released to the aquatic environment each year. In contrast to washing, it is believed that large proportions of TDMF captured during tumble drying are directed to residual waste.

The current focus of efforts to prevent the release of microfibres to the environment has been in relation to the control of microfibres formed during machine washing. However, the effectiveness of the methods being commercialised is unknown, and the most suitable waste stream for the captured fibres has yet to be identified.

The waste materials arising from the disposal of garments and flat textiles has been estimated, showing that many textiles are exported for subsequent reuse overseas. It has not been possible to estimate the downstream effect of these materials and their next use-phase, but it should be assumed that the impact will be similar if not worse than the UK based estimates. Those textiles not exported at the end of life may be reused within the UK, disposed to recycling, incineration or landfill. The potential for microfibre production through these stages is not well understood, and the long term effects of disposal to landfill have not been quantified.

The findings of the research have indicated that there are presently many data gaps and significant uncertainties in the evidence base regarding the losses of microfibres over the life

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[111] *WI*

cycle specific to different types of fibres and fabrics. Moreover, there is presently early understanding of the types of damage microfibres have on the environment and wildlife. Whilst we understand Society of Environmental Toxicology and Chemistry (SETAC) and the UN are presently enhancing life-cycle based toxicity methods to consider the burden associated with microfibres, the impacts associated with microfibres are just beginning to be understood.

Actions to mitigate the impacts of microfibre generation throughout the lifecycle should be considered where the greatest volumes of waste are being generated. Hence, the upstream processing and production stages should be an initial point of focus. UK producers and importers of textiles should investigate their supply chains, whether domestic or overseas, to ensure that waste management procedures are rigorous and designed to prevent the release of microfibres to the environment. During the use phase, the effectiveness of current mitigation measures is yet to be fully understood, but it is certain that the effect of microfibres being captured in sewage sludge and its onward use in digestate should be investigated due to this being the predominant route for the volume of fibres released from laundry. At the end of life, the various routes of disposal should be considered for their potential for leakage, so that measures for improvement can be proposed.

9.0 Further research

9.1 Development of the evidence base

The results of this research have shown significant data gaps across the life cycle of textiles in the UK. The following are suggestions for further research:

- The impact of microfibres on the environment – by fibre type, in various aquatic and terrestrial situations, and the relationship with specific environmental impact metrics such as ecotoxicity
- A breakdown of textiles in use; fibre type, use/purpose, fibre type category (animal, synthetic), etc.
- An understanding of the distribution of fibre types and their processing by various stages, e.g. bleaching, degumming etc. What volume goes through each of these?
- Losses during production and processing for natural compared to synthetic fibres. Particular importance in finishing stages.
- Losses in place of production, by country and fibre type i.e. what practices are commonplace and what end of life routes are used across the supply chain
- In-use losses: abrasion from use phase results in unknown levels of microfibre formation. Trials could be carried out to investigate the losses through use, and their end destination. How much enters the atmosphere, the terrestrial env., and how much is retained on the garment and then washed off in laundry?
- Laundry losses – a wider study is needed of a wider range of fibre types and fabric configurations, with a range of washing procedures, detergents etc.
- Commercial and industrial washing - more accurate quantification of the volume and likely losses from this sector.
- Mitigation methods – an evaluation of the effectiveness of current and emerging mitigation methods and feasibility for scale up.
- Greater understanding of how microfibres behave in WWTPs.

9.2 Development of the clothing footprint calculator (SCAP)

The original brief for this research stated that if suitable data are available, WRAP may include microfibres in its clothing footprint calculator in the future as an additional metric.

In the meantime, taking a precautionary principle view and accepting the level of uncertainty in the evidence, WRAP could readily enhance the clothing footprint calculator to provide a quantity/inventory/count of harmful microfibre losses, alongside the carbon, water and waste metrics that are already provided.

This could help inform SCAP's signatories over the scale of the potential losses of microfibres associated with different clothing and fibre types. The tool could be enhanced to provide default improvement opportunities which show the areas for microfibre reduction over the life cycle. In time, given an acceptable level of data robustness, impact reduction targets for microplastics could even be set for signatories and monitored using the tool.

Using the research findings compiled here, combined with future research findings covering the most significant gaps, research data on losses could be readily integrated into the tool. At each life cycle stage an estimate for microfibres could be calculated using the background data and process (mass) losses for each fibre already available in the tool. The laundry module in the tool could also be enhanced to estimate losses by wash frequency. Estimates for end of life losses could also be gained from insights on how exported second-hand clothing is washed and managed.

10.0 Appendix A: Quantitative outputs related to the SCAP tool categories

The following table attempts to illustrate the spread of data which was found during this project and how it relates to the SCAP tool input categories. The data which was found during the course of the research was found to be highly variable and dispersed amongst a range of very specific processes and sub-processes. It is not possible to infer average values for mass loss for each fibre type based on the data which was found, due to the unknown distribution of textile products in the UK amongst these processes and scenarios during their average use. For example, for the cotton fibre type, a range of studies were found which show mass loss during specific sub-processes, e.g. biopolishing. Data is not available on the proportion of total UK cotton textiles which undergo this or any other process, so it is not possible to say how much of UK cotton textiles is lost through the mass loss as a result of biopolishing. The data found was also often a result of various testing procedures and methodologies and is not always comparable even within a single process. In addition, a variety of units was found in the reporting of losses, including both mass and number of fibres, and a conversion factor between the two is not known.

Table 3 – Quantitative Outputs Related to the SCAP Tool Categories

		Production & Processing	Use	Disposal
How much material	Clothing	1.8Mt input 1.1Mt output 1,143,080 tonnes total mass of fibre sold (2013)	2.5Mt in use	1.1Mt end of life
	Flat textiles	?		
Cotton	Mass	Mass of fibre sold (2013): 491,507 tonnes		
	Mass lost	Data found for ~18 individual sub-processes, e.g. spinning Of the studies found, a median maximum value of 5.75% mass loss was reported Some individual sub-processes were reported to have mass loss of up to 40%	Data found in 5 studies which show up to 4% mass loss from abrasion in use, and up to 1,146 fibres released per cm²	
	Micro fibre quantity			
Polyester	Mass	Mass of fibre sold (2013): 182,886 tonnes		
	Mass lost	Data found for ~5 individual sub-processes, e.g. spinning was reported to have a mass loss of 1.27%	A number of studies for washing which show approx. 0.2% mass loss.	

		Some individual sub-processes were reported to have mass loss of up to 47% (alkali treatments)	Fewer studies for wear, with up to approx. 80 microfibres per cm².	
	Micro fibre quantity			
Viscose (regenerated cellulosic)	Mass	Mass of fibre sold (2013): 102,874 tonnes		
	Mass lost	Data not found for fundamental stages of production and processing Some data found for post-processing such as mercerising and alkali treatment, with mass loss up to 30% reported in individual sub-processes.	One study for loss during wear, suggesting up to 140 microfibres per cm².	
	Micro fibre quantity			
Acrylic	Mass	Mass of fibre sold (2013): 102,874 tonnes		
	Mass lost	Only one study found, for biopolishing, with an upper mass loss reported of 1.7%	Few studies for the use phase of acrylic, which show around 0.05 microfibres per cm²	
	Micro fibre quantity			
Other fibre types. Wool, silk, flax, linen, polyamide, polyurethane etc.	Mass	Mass of fibre sold (2013): 102,874 tonnes		
	Mass lost	Silk: up to 23.55% mass loss in some individual sub-processes was reported Wool: up to 17% mass loss in some individual sub-processes was reported Flax/linen: up to 71% mass loss in some individual sub-processes was reported	Very few studies for fibres in the 'other category', including a max mass loss for wool fabric as a result of abrasion of 3.11%.	
	Micro fibre quantity			
TOTAL	Mass			

	Mass lost	Processing to fibre 10.25% Spinning and winding 1.245% Knitting and weaving 0.205% Garment production 7.92% Cutting and sewing 15.74%		Overall figures suggest mass losses of: Laundry 0.002% per cycle Drying 0.003-0.027% per cycle See Table 2 for a more detailed and comparative view of the losses during washing of the fibre types.	
	Micro fibre quantity				
	Potential reduction % (from standard to best practice)				
	Most impactful mitigation measures				
	Most significant evidence gaps				

11.0 Appendix B: Overview of academic papers

The following is a non-exhaustive list of data sources which were drawn upon for the data in this report.

Table 4: Data Sources for Production and Processing

Fibre	Process	Minimum%Loss	Maximum%Loss	Source	Notes
Cotton	Cleaning	0.2025	0.8955	Halimi et al, 2008	0.43-1.99% (Only 45% of this is fibres)
Cotton	Carding	4	8	Bogdan 1955	
Cotton	Carding	0.792	1.08	Halimi et al, 2008	1.98-2.70%(56-65% trash)
Cotton	Spinning	19.07	19.07	Kalliala, 1997	
Cotton	De-sizing	0.5	5	Thakore and Abate 2017	
Cotton	Ultrasound and de-sizing	6.5	9.4	Thakore and Abate 2017	
Cotton	De-sizing, scouring and bleaching	10	12.65	Thakore and Abate 2017	
Cotton	Scouring	4.5	4.9	Aly et al., 2004	
Cotton	Scouring	5	10	Karmakar, 1999	
Cotton	Scouring	3.8	5.7	Lin and Hsieh 2001	
Cotton	Singeing	5.98	12.82	Xia et al., 2009	
Cotton	Singeing	2.8	5.5	Pillay et al., 1975	
Cotton	Ultrasound Bleaching	0.2	5	Bahtiyari et al, 2011	

Fibre	Process	Minimum%Loss	Maximum%Loss	Source	Notes
Cotton	Bleaching	4	4	Abdel-Halim 2012	
Cotton	Bleaching	8	8	Abdel-Halim and Al-Dayeb 2013	
Cotton	Bleaching, De-sizing	9.80	9.80	Buschle-Diller et al., 2001	
Cotton	Bleaching, De-Sizing and scouring	12.4	12.4	Buschle-Diller et al., 2001	
Cotton	Bleaching	5.5	5.8	Aly et al., 2004	
Cotton	Biopolishing	3	6	Bajaj 2001	
Cotton	Bioscouring	0.72	3.9	Aly et al., 2004	
Cotton	Bioscouring	2.3	11.7	Lin and Hsieh 2001	
Cotton	Biopolishing	1.84	4.8	Aly et al., 2004	
Cotton	Biobleaching	3.3	6.2	Aly et al., 2004	
Cotton	Mercerizing	0	40	Haga and Takagashi 2001	
Yarn production		1.2	1.2	Cartwright et al 2011, mission linen supply report	
Cotton	Ring spun knitting	0.5	1	Bhowmick and Ghosh 2007	
Cotton	Knitting			Basu and Gotipamul, 2003	16um/m
Cotton	Weft knitting	0.207048458	0.207048458	Brown 1978	
Cotton	Weft Knitting	0.203	0.203	Lawrence and Mohamed, 1996	

Fibre	Process	Minimum%Loss	Maximum%Loss	Source	Notes
Cotton	Knitting			Ruppenicker and Lofton, 1979	400mg/g
Silk	Biopolishing	7.69	7.69	Gulrajani et al., 1998	
Silk	Degumming	1.7	2.70	Freddi et al., 2003	
Silk	Degumming	15.45	23.55	Gulrajani et al., 2000	
Silk	Degumming	0.63	3.08	Gulrajani and Gupta	
Jute	Singeing	1.85	9.7	Shosh et al, 1897	
Jute	Bleaching	1.58	7.77	Chattopadhyay et al., 1999	
Jute	Bleaching	0.8	12.9	Sarkar and Chatterjee, 1948	
Wool	Singeing			Boswell and Townend 1957	0.43-0.89g/yard
Wool	Bleaching	5.15	5.15	Chen et al., 2001	
Wool	Bleaching	3.71	3.71	Cardamone et al., 2005	
Wool	Enzyme	5.8	6.2	Chikkodi et al 1995	90% wool, 10% cotton
Wool	Comber	7	17	Belin and Taylor 1966	
Wool	Carding	3.44	13.5	Robinson 1989	

Fibre	Process	Minimum%Loss	Maximum%Loss	Source	Notes
Flax/Linen	Alkali treatments	3.34	24.9	Bhattacharya and Shah, 2004	
Flax/Linen	Retting	31.98	63.91	Sharma et al., 1999	
Flax/Linen	Preparation	5	71	Akin et al 2005	
Lyocel/Tencel/Rayon	Mercerizing	2.5	13	Chae et al, 2003	
Lyocel/Tencel/Rayon	Alkali treatments	0.98	4.9	Shin et al, 1999	
Lyocel/Tencel/Rayon	Alkali treatments	2	8	Kasahara et al., 2001	
Lyocel/Tencel/Rayon	Alkali treatments	4	30	Zhang et al., 2005	
Polyester	Mercerizing - Caustic Soda	2	37	Bajaj 2001	2-37% (16% reasonable)
Polyester	Knitting			Basu and Gotipamul, 2003	0.3um/meter
Polyester	Spinning	1.29	1.29	Kalliala, 1997	
Polyester	Yarn	1.09	1.09	Cartwright et al., report to mission linen supply	
Polyester	Alkali treatments		47	Zeronian et al., 1989	Aqueous NaOH
Polyester	Alkali treatments	20	30	Fukuhara 1993	
Acrylic	Biopolishing	0.7	1.7	McCloskey and Jump, 2005	Cutinase
Polyamide/Nylon	?				
Polyurethane/Polypropylene/Elastane	?				
Vegetable Fibres	De-sizing	7.84	8.94	Niaz et al., 2011	

Fibre	Process	Minimum%Loss	Maximum%Loss	Source	Notes
Vegetable Fibres	Bleaching	11.62	12.49	Niaz et al., 2011	
Vegetable Fibres	Biopolishing	3.92	4.98	Niaz et al., 2012	
All	Singeing	5.8	15.4	Lopez-Amo and serrano 1958	
All	Cutting and sewing	15.74	15.74	Kasemset et al., 2015	End product wastes - may be sent to recycling
polycotton	Weaving	0.08	0.08	Cartwright 2011, report to mission linen	
polycotton	finishing	0.03	0.03	Cartwright 2011, report to mission linen	
polycotton	Cutting and sewing	0.1	0.1	Cartwright 2011, report to mission linen	

Table 5: Data Sources for the Use Phase

Fibre	Test	Minimum%Loss	Maximum%Loss	Minimum fibres/CM2	Maximum fibres/CM2	Minimum mg fibres/cm2	Maximum mg fibres/cm2	Source
Vegetable Fibres	Abrasion	6	9.7					Nergis and Beceren, 2008
Cotton	Abrasion	2	4					Kaynak and Topalbekiroglu, 2008
Polyester	Washing			0.03	0/21			Almroth et al., 2018
Polyester	Washing			1.106	1.106			Almroth et al., 2018
Polyester	Washing	0.2	0.2					Hartline et al 2016
Polyester	Washing	0.002	0.015					Hernandez et al., 2017
Polyester	Washing	0.025	0.23					Sillanpaa and Sainio 2017
Polyester	Washing	0.03	0.3					Sillanpaa and Sainio 2017
Polyester	Washing					0.0625	0.1375	Napper et al., 2016
Polyester	Wear			*712*				Palmer et al. 2017 (during wear)
Polyester	Wear			*10.3*	*79.5*			Salter et al., 1984 (during wear)

Polyester	Washing			3.162790698	29.75581395			Jonsson et al, 2018
Visoce	Wear			*20*	*140.5*			Salter et al., 1984 (during wear)
Nylon	Washing			0.03	0.03			Almroth et al., 2018
Acrylic	Washing			0.05	0.05			Almroth et al., 2018
Acrylic	Washing					0.05	0.12	Napper et al., 2016
Cotton	Washing					0.025		Napper et al., 2016
Cotton	Wear			*621*				Palmer et al. 2017 (during wear)
Cotton	Wear			*95.3*	*1146.2*			Salter et al., 1984 (during wear)
Cotton	Washing	0.07	0.25					Sillanpaa and Sainio 2017
Wool	Abrasion	1.73	3.11					Onal et al., (2006)
Wool	Wear			*1.9*	*93*			Salter et al., 1984 (during wear)