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Microfibres from apparel and home textiles: Prospects for including microplastics in environmental sustainability assessment

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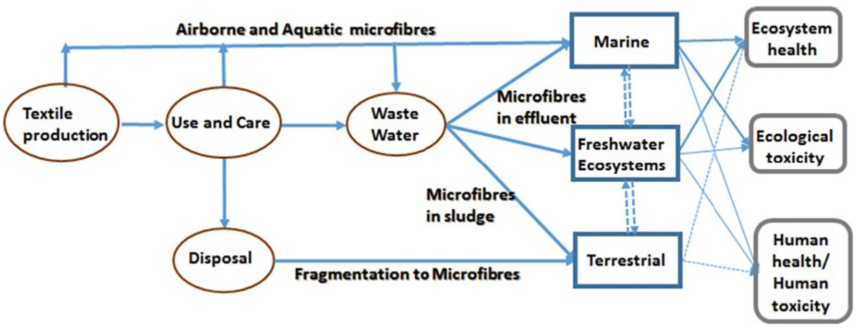
HIGHLIGHTS

- Accumulation of microplastic waste in ecosystems is a key global concern.
- A significant proportion of plastic pollution is microfibres from textiles.
- Environmental impacts of apparel and home textile microfibres are reviewed.
- Including loss of synthetic microfibres in sustainability assessment is recommended.
- Research priorities to improve microfibre monitoring and mitigation are identified.

GRAPHICAL ABSTRACT



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ABSTRACT

Textiles release fibres to the environment during production, use, and at end-of-life disposal. Approximately two-thirds of all textile items are now synthetic, dominated by petroleum-based organic polymers such as polyester, polyamide and acrylic. Plastic microfibres (<5 mm) and nanofibres (<100 nm) have been identified in ecosystems in all regions of the globe and have been estimated to comprise up to 35% of primary microplastics in marine environments, a major proportion of microplastics on coastal shorelines and to persist for decades in soils treated with sludge from waste water treatment plants. In this paper we present a critical review of factors affecting the release from fabrics of microfibres, and of the risks for impacts on ecological systems and potentially on human health. This review is used as a basis for exploring the potential to include a metric for microplastic pollution in tools that have been developed to quantify the environmental performance of apparel and home textiles. We conclude that the simple metric of mass or number of microfibres released combined with data on their persistence in the environment, could provide a useful interim mid-point indicator in sustainability assessment tools to support monitoring and mitigation strategies for microplastic pollution. Identified priority research areas include: (1) Standardised analytical methods for textile microfibres and nanofibres; (2) Ecotoxicological studies using environmentally realistic concentrations; (3) Studies tracking the fate of microplastics in complex food webs; and (4) Refined indicators for microfibre impacts in apparel and home textile sustainability assessment tools.

1. Introduction

Mass production of synthetic organic polymers, generically known as plastics, has seen remarkable growth from a modest annual output of 1.7 million tonnes in the early 1950s to almost 400 million tonnes

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in 2015 (Geyer et al., 2017) estimated using data from PlasticsEurope (2008), PlasticsEurope, 2016), Mills (2011) and The Fiber Year (2017). As a cheap, durable and versatile material that can be moulded, extruded, cast into shapes or films and drawn into filaments, plastic has come to dominate many domestic and industrial applications. The same properties that drive growth in consumption, however, underpin environmental concerns. The estimated 8300 million tonnes of virgin plastics manufactured from 1950 to 2015 have generated around 6300 million tonnes of plastic waste globally, with 79% of this amount remaining on the planet either in landfill or in the combined terrestrial, freshwater and marine environments (Geyer et al., 2017). Continuation of current production and waste management trends is projected to result in about 12 billion tonnes of plastic waste in landfill or across natural environments by 2050 (Geyer et al., 2017).

A significant use of plastic is in fibres to make the clothes we wear and the textiles that enhance the beauty and functionality of our homes. In 2016, 65 million tonnes of plastic was produced for textile fibres (The Fiber Year, 2017). Natural fibres of plant or animal origin, traditionally dominated by cotton and wool respectively, retain a share of total content, but production of synthetic fibres has led growth in textiles around the world (The Fiber Year, 2017). In recent decades, the rapid turnover in the 'fast fashion' sector has been a dominant factor in the growth in both production and waste (Cobbing and Vicaire, 2016).

The ever-increasing plastic waste in landfill and as litter visible on shorelines, coastal waterways and in oceans has emerged as a key global concern, particularly for the health of the marine environment (Jambeck et al., 2015). However, recognition that visible pieces of plastic represent only a small fraction, around 6%, of the total mass of plastic entering the oceans, is now redefining the plastic pollution problem (Eunomia, 2016); a problem that includes plastic particles and fibres <5 mm in size, commonly referred to as microplastics (GESAMP, 2015). Microplastics <100 nm may be distinguished as 'nanoplastics', with some research suggesting that this size class may be the most hazardous form of plastic pollution in aquatic environments (Koelmans et al., 2015). As much as 0.19 million tonnes of microfibres from the production and normal use of synthetic textiles, particularly domestic laundry of clothing, has been estimated to enter the marine environment alone annually (Eunomia, 2016), and as consumption continues to grow that figure seems set to rise further.

Over the past decade, expansion of research beyond coastal and marine habitats to include sampling of freshwater lakes and rivers (McCormick et al., 2014; Horton et al., 2017), terrestrial systems (Jambeck et al., 2015; Nizzetto et al., 2016; Machado et al., 2018) and atmospheric fallout (Dris et al., 2016; Dris et al., 2017; Gasperi et al., 2018) indicates that microplastis are now ubiquitous in global ecosystems. Although there remains limited understanding of the threat posed to ecosystems and human health (Carbery et al., 2018; Waring et al., 2018; Yu et al., 2018), reports on potential impacts are increasing.

In this paper, we review current understanding of emissions of microfibres from apparel and home textiles and their effects in the environment. We note that the term 'microfibre' has also been used to refer to fabrics of synthetic fibre finer than one denier or decitex, such as fine polyester or polyamides, but in this review, microfibre is used in the more contemporary context of <5 mm fibres. Used without a qualifier, we apply the term to plastic microfibres from synthetic textiles, with 'natural microfibres' and 'man-made microfibres' referring to fibres from textiles of, respectively, natural plant or animal origin (e.g. cotton and wool), and derived cellulosic sources (e.g. viscose/rayon[1]). The term 'textile' is applied generically for apparel, home textiles and other textile products (e.g. geotextiles, cloth automotive fittings), but our focus is on apparel and home textiles. The latter are important because of their global market share, contribution to microplastic pollution, and the strong interest in sustainability reporting by apparel and home textile industries and consumers (Islam and Khan, 2014, Laitala et al., 2018).

The objective of this paper is to evaluate whether it is yet possible to include a credible metric for microplastic pollution in tools used to assess the environmental performance of apparel and home textiles. We firstly review the methods used for identification and quantification of microplastic particles and fibres in global ecosystems and summarise current evidence for microplastic pollution. We then focus on issues specific to microfibres from textiles, including available evidence for their release and presence in aquatic and terrestrial habitats and in the air, and their ecological and human health impacts. The paper concludes by exploring an interim indicator to allow microplastic pollution to be included as an impact category in apparel and home textile product sustainability assessment, and identifying priority research areas to support more comprehensive accounting for microplastics in environmental management tools.

2. Microfibres in the environment

Microfibres enter the environment as both primary sources – fibres < 5 mm in size released during production and use of textiles – and secondary sources involving fragmentation of larger items such as discarded clothing. Fragmentation through chemical and physical forces, such as photodegradation and abrasion, reduces plastic polymer materials to increasingly smaller particles that persist but are difficult to detect and analyse (Bouwmeester et al., 2015). Plastics are generally resistant to biodegradation (Szostak-Kotowa, 2004). Emerging research is now beginning to engineer enzymes with enhanced capacity to degrade plastic polymers such as polyethylene terephthalate (PET), a form of polyester (Austin et al., 2018). However, at this time the lack of commercial-scale solutions means that plastics continue to accumulate in ecosystems where they remain for periods from a few decades up to thousands of years (Peng et al., 2017). In contrast, natural organic polymers are compostable and biodegrade in the presence of microorganisms (Pekhtasheva et al., 2011), with evidence of biodeterioration seen within a few days under warm moist conditions (Arshad et al., 2014). More research is needed to understand the rate of biodegradation of microfibres under various environmental conditions, including in marine habitats.

2.1. Methods for quantifying and identifying microplastics

Progress has been made in analytical methods for sampling, extraction and identification of microplastics in complex environmental media, but there are no standardised sampling or analytical protocols agreed for international use (Lambert and Wagner, 2016; Hermsen et al., 2018; Yu et al., 2018). Methods in use include optical microscopy (Gorokhova, 2015), scanning electron microscopy (Fries et al., 2013), Fourier transform infrared (FTIR) spectroscopy (Comnea-Stancu et al., 2017) and Raman spectroscopy (Lenz et al., 2015). Reference standards are often from artificially high laboratory libraries rather than samples from relevant environments such as sea, soil or ocean floor sediments.

Improved methods for detection of microplastics at environmentally relevant levels in biological samples are providing improved estimates of their prevalence (Hong et al., 2017) in a range of habitats and organisms. Sampling and analysis techniques developed for marine and freshwater ecosystems have more recently been applied to terrestrial and air samples. For example, detection of microplastics in soils has been adapted from marine sediment techniques, but the accuracy for soil samples and ability to differentiate microplastics and microfibres from different sources (plastic mulches, compost, irrigation with wastewater, and sewage sludge), has yet to be adequately tested (Bläsing and

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[1] In Europe, fibres and fabrics produced from regenerated cellulose became known as 'viscose', whereas in the United States they are termed 'rayon' (Comnea-Stancu et al., 2017). For consistency we use the term 'viscose' throughout this paper. Other derived cellulosic fibres include modal and lyocell.

Amelung, 2018). In all analyses, the issue of post-sampling contamination by small microplastics, especially airborne microfibres, is now widely recognised (Lachenmeier et al., 2015; Woodall et al., 2015; Hermsen et al., 2018), casting doubt on some early results. For example, studies identifying microplastics in beer (Liebezeit and Liebezeit, 2014) and honey (Liebezeit and Liebezeit, 2013) appear likely to be incorrect (Lachenmeier et al., 2015).

Progress in analytical techniques for characterisation of microplastics is indicating the prevalence of plastic fibres of both small micro (<100 μm) and nano (<100 nm) size classes (Mintenig et al., 2017), but more reliable data is needed to understand the quantity, sources, transfers and persistence of microfibres of different types. There is little reliable information on how chemical properties (e.g. plastic additives, dyes, flame-retardants) and an increasing range of synthetic and blended fibre types affect characterisation of microfibres. Comnea-Stancu et al. (2017) systematically examined the feasibility of using FTIR methods to distinguish man-made cellulosics such as viscose from natural cellulose fibres (e.g. cotton, hemp) to assess claims that cellulosics were a major fraction of microplastics in the deep sea (Woodall et al., 2014). Recommendations on how to unambiguously differentiate types of fibres (Woodall et al., 2015; Comnea-Stancu et al., 2017), and on avoiding contamination and achieving accurate characterisation (Hermsen et al., 2018) highlight the need for harmonised protocols for sampling, analysis and identification of microfibres. Until standards are adopted, the risk of false characterisation or inaccurate quantification must be considered in interpreting results of studies with a view to understanding potential environmental and human health impacts.

2.2. Microfibres in coastal and aquatic systems

Microfibres have been found in sediment samples from shorelines across a range of global locations (Browne et al., 2011). The proportional representation of the main synthetic fibres was polyester 56%, acrylic 23%, polypropylene 7%, polyethylene 6% and polyamide 3%. These proportions broadly reflected those in Waste Water Treatment Plant (WWTP) discharge, and reflected the relative amounts in textiles produced at the time of sampling (Oerlikon, 2009) – 79% polyester, 9% polyamide, 7% polypropylene, 5% acrylic. Together with an observed relationship between abundance and human population-density (Browne et al., 2011), these data led to the conclusion that effluent from the washing of textiles was a major source of microfibres in shoreline habitats. Possible contributing factors in the divergence from a simple proportional relationship between shoreline samples and annual production may include fibre and product properties, environmental influences such as rate of degradation or fragmentation, and methodology limitations. For example, higher representation of acrylic microfibres in point-in-time sediment samples (Browne et al., 2011) may relate to acrylic fibres generally having lower tenacity and breaking easier than polyamide and polyester (Gupta and Afshari, 2018), to their dimensions being less favourable to trapping in washing machine or WWTP filters or to sampling and FTIR characterisation techniques. Some recent reviews have questioned the effectiveness of microfibre identification, especially in the nanofibre size class as discussed in Section 2.1 (Comnea-Stancu et al., 2017; Yu et al., 2018).

While Browne et al. (2011) and later Murphy et al. (2016) found that differences in abundance of microplastics were correlated with regional human population density and sewage disposal, other studies (e.g. Mahon et al., 2016) did not find a comparable relationship. This possibly reflects variations in the efficiency of capture in WWTPs (Mahon et al., 2016). Across different countries, estimates of the efficiency of removal of microfibres in effluent were in the order of 95 to 99% (Peng et al., 2017). Despite high rates of capture, effluent discharge remains a significant source of microplastics due to the high volumes of discharge (Setälä et al., 2016). For example, wastewater discharged into the Gulf of Finland contained 4.9 ± 1.4 microfibres per litre, a concentration 25 times higher than in the receiving seawater (Talvitie et al., 2015). Similarly, analysis of samples from the Baltic Sea (Setälä et al., 2016) implicated fibres as the most abundant form of microlitter, with absolute results depending on how fine a filter was used e.g. 100 μm vs 300 μm. Assuming capture of 98.4% (based on Murphy et al., 2016), Hartline et al. (2016) extrapolated from fibre release rates from polyester fleece jackets to estimate that, for an indicative city population of 100,000, approximately 1.02 kg of microfibres per day is discharged in WWTP effluent. Importantly, not all wastewater goes through treatment plants and there is a dearth of data to quantify microfibre release directly to the environment from washing clothes, especially in developing countries.

On a global scale, Boucher and Friot (2017) estimated that of all primary microplastics in the world's oceans, 35% arise from laundry of synthetic textiles. Some estimates are lower, but even a value of 20% for 2014 as reported by Eunomia (2016) means that the equivalent to 0.19 million tonnes of textile microfibres enters the marine environment in a single year.

2.3. Microfibres in terrestrial habitats

Most studies on apparel and textile microfibres have focussed on shedding of fibres during washing and transfer to coastal and aquatic habitats. Sludge from WWTPs represents a valuable source of nutrients that is often applied to agricultural soils as a supplement to chemical fertilisers. While monitoring of hazardous substances in urban sourced sludge is regulated in most regions, microplastics are not currently included under such controls for application in agriculture, so there is less routine measurement. Nizzetto et al. (2016) conservatively estimated that approximately 50% of sewage sludge is applied to agricultural lands in Europe and North America. In European agricultural soils alone, this represents 125 to 850 tonnes microplastic per million inhabitants released annually, either directly or as added biosolids. Microplastics in soil may also derive from fragmentation of agricultural films and other materials (Zhang and Liu, 2018).

Plastic mulching is widely used in agriculture to gain higher yields and economic and efficiency benefits, with an estimated area of $4270 m^2$ of plastic mulching covered agricultural land in Europe alone in 2016 (Bläsing and Amelung, 2018). The contribution of plastic mulch to microplastics in soil globally is unknown. However, 100% agricultural soil samples from south-western China where use of plastic mulching is high (Espi, 2006), contained plastics particles mostly in the 1–0.05 mm range. On average, 92% were microfibres (Zhang and Liu, 2018). Sources of microfibres likely included use of water from clothes washing directly for irrigation and use of string or twine in vegetable growing (Zhang and Liu, 2018).

In the United States, analysis of soil samples from field sites to which waste water treatment sludge had been applied showed that textile fibres were present at higher concentrations than in untreated soils and that, even 15 years after application, they retained the characteristics of fibres in the applied sludge products (Zubris and Richards, 2005). The presence of synthetic fibres at depth and in horizons below the mixed layer suggested that there was potential for them to be translocated in the soils. Few vectors have been studied, but Rillig et al. (2017) demonstrated that earthworms have the capacity to significantly move microplastics from the soil surface to deeper layers. Transport via casts, burrows, egestion or adherence to the worm external surface would likely increase exposure of other soil biota and of organisms in deeper layers and potentially in groundwater. Little research has been conducted on possible harmful impacts due to release from plastics of chemical additives into the soil. However, it has been estimated that phthalate concentrations could be 74 to 208% higher in soils with plastic mulching compared to non-mulched soils in China (Kong et al., 2012).

In addition to sludge application and agricultural plastic use, potential sources of microplastics in terrestrial habitats include contaminated compost application, use of wastewater in irrigation, and fragmentation of garments discarded in landfill sites. Accurate statistics are not compiled globally, but the mass of discarded clothing is estimated to be in the order of millions of tonnes (Cobbing and Vicaire, 2016). In waste sites, synthetic textiles may degrade slowly over long periods producing smaller particles and eventually microfibres and nanofibres that are able to become airborne or be carried to aquatic systems via leachate, potentially depositing microfibres on land sites (Barnes et al., 2009).

2.4. Atmospheric transfer of microfibres

Microplastics have been detected in both indoor and outdoor air samples. In open environments, wind-blown debris from landfill sites may be a source of entrained microplastics, including microfibres from discarded textiles (Barnes et al., 2009) with deposition of airborne microplastics common because the density of plastic is greater than that of air (e.g. for polyester, approximately 1.39 g cm^{-3} at sea level and 15 °C).

Measurements indicate that microfibre concentrations are higher in air indoors than outdoors (Dris et al., 2017). Indoor and outdoor samples taken in Paris, showed 10 to 60 fibres m^{-3} and 0.3 to 1.5 fibres m^{-3}, respectively, with synthetic and natural textiles implicated as a major source (Dris et al., 2017). Similarly, Sundt et al. (2014) identified airborne textile microfibres in dust settling on household surfaces in Norwegian homes, and a review of geographically relevant studies indicated that the mass of textile fibres deposited on household surfaces was of the same order of magnitude as that emitted in laundry effluent. Compared to 0.12 kg per capita per year fibres in laundry effluent, there was 0.08 kg per capita per year in surface deposition. While Sundt et al. (2014) did not quantify the relative contribution of natural and synthetic fibres, Dris et al. (2017) reported that of the 190 to 670 fibres estimated in each mg of dust settling on household surfaces in a Paris apartment, 67% were of non-synthetic materials, primarily cellulosic, with the remaining 33% being petrochemical in origin. Using the term 'cellulosic', they did not distinguish natural vs derived man-made fibres. The dominant synthetic fibre was polypropylene, which is commonly used in carpet and other furnishings.

The presence of microplastics in drinking water has emerged as a human health concern for consumers (Kosuth et al., 2017). Of 159 samples of tap water from five continents, 83% contained plastic particles, while 93% of 259 samples of bottled water tested positive for microplastics (Kosuth et al., 2017; Mason et al., 2018). Whereas the microplastics in bottled water were predominantly particulate and matched materials in the bottle or its lid, 99.7% of the microplastics in tap water were microfibres. Fallout of airborne microfibres is a potential source of post-sampling contamination (Woodall et al., 2015). The possible contribution in published studies can be difficult to assess, but post-sampling contamination has been implicated as a possible factor in some reported data (e.g. for beer) by subsequent forensic analyses (Lachenmeier et al., 2015, Woodall et al., 2015, Rist et al., 2018). Based on analysis showing wool and cellulose fibres in laboratory control samples, Halstead et al. (2018) concluded that the presence of similar fibres in gut samples from Australian fish species caught in Sydney Harbour could be attributed to contamination during sample processing rather than ingestion during feeding. More detailed forensic studies using advanced analytical methods such as ATR-FTIR are needed to confirm this assumption.

2.5. Factors affecting release, accumulation and detection of textile microfibres

Experimental washing has been used to collect data on the number or mass of microfibres released from garments of different types and fibre content (Hartline et al., 2016; Napper and Thompson, 2016). Relating experimental test results to the wide range of real-life domestic or commercial laundry practices is difficult, and variations in conduct of the testing and in measurement techniques and protocols makes comparing outcomes of different experiments extremely complex (Laitala et al., 2017; Laitala et al., 2018). However, these tests do reveal some determinants of fibre shedding:

- Fibre loss is greater in top-loading (vertical axis) or industrial washing machines than front-loaders, assumed due to a more abrasive action (Hartline et al., 2016, De Falco et al., 2018).
- Fibre dimensions depend on the type of fibre and fabric characteristics (e.g. tightness of the weave). Fibres shed during washing varied from 11.9 to 17.7 μm in diameter and 5.0 to 7.8 mm in length across polyester, polyester/cotton blend and acrylic (Napper and Thompson, 2016).
- Release of fibres during tumble drying can be higher (up to 3.5 times) than during washing (Pirc et al., 2016). This practice very likely contributes to high indoor air concentrations of microfibres (Dris et al., 2017), but consumer behaviour will determine the fate of the remaining collected lint.

Hernandez et al. (2017) identified the main improvements needed in experiments to quantify microfibre pollution as:

- Use of standardised materials and equipment rather than commercially available textiles and household washing machines;
- Assessment of the size of fibres released across a statistically relevant sample size;
- Application of accurate measurement techniques to the large volumes of dischrged effluent to improve the precision of calculations of microfibre mass release; and
- Research on mechanistic properties of microfibre release.

Standardised testing demonstrated that use of detergent was a major determinant of the mass of fibres released from polyester fabric during machine washing regardless of detergent composition or dose (Hernandez et al., 2017). In this study fabric structure and wash cycle did not show a significant effect on shedding but wider testing is needed to evaluate whether these findings are more generally applicable to other fabric structures and wash cycles.

Sampling and monitoring of ecosystems to investigate broader factors that affect loss of microfibres has not provided clear evidence for causes of change or observed spatial and temporal variations. Contributions to differences in results may include:

- Variable assumptions on the efficiency of WWTP capture in different locations;
- Limited habitat sampling, with most reports examining marine ecosystems and fewer results available for freshwater rivers and lakes, terrestrial habitats and the atmosphere;
- Extrapolation of results to new locations or ecosystems for which they are not representative of microplastic sources and effects;
- Unknown transfer and dispersion characteristics in aquatic environments especially within oceans, including the ocean floor and sediments; and
- Lack of standardised environmental sampling and analysis protocols, including for detection of nano-sized particles and fibres. While individual measurement errors for concentration of microfibres or microplastics in a sample may be small, they can compound in extrapolating to larger areas and sites of high accumulation.

3. Environmental impacts of microfibres

The increase in public concern regarding the risks of microplastic pollution has outstripped the rate of growth in scientifically robust information on the extent and severity of potential effects, despite the rapid growth in scientific literature. do Sul and Costa (2014) estimated that >60% of found peer-reviewed papers on microplastic pollution had been published in the previous 5 years. Exposure to microplastics has escalated relatively recently (predominantly in the past 50 to 70 years) and, together with the enormous range of variables in magnitude and organism exposure parameters, this presents an enormous technical barrier to understanding and verifying long-term effects.

3.1. Exposure in different environments

Plastics continue to accumulate in the environment (Geyer et al., 2017). Rates of change and limited monitoring over extended time periods makes realistic dose-response studies on textile microfibres challenging. However, evidence of widespread exposure is growing even for remote locations. Sampling at depths of >2000 m shows that at least three major deep-sea floor dwelling phyla, which have different feeding mechanisms, are ingesting microfibres of polypropylene, viscose, polyester, and acrylic materials (Taylor et al., 2016).

As discussed in Section 2, exposure to microfibres is not limited to marine environments. Fig. 1 illustrates that release of microfibres can occur at multiple sites in the textile supply chain, and that transfers can occur between habitats, including through fallout of airborne microfibres and trophic transfers. Impacts on ecosystems and effects on human health are shown to be possible via a range of pathways in marine, freshwater and terrestrial environments. Understanding these pathways is relevant to the development of a metric in sustainability assessment tools that would be effective in monitoring and managing the risks of microfibre pollution from apparel and home textiles.

The mechanisms for ecological and human health effects of microplastics are generally poorly understood but are likely multifaceted. There is evidence for physical, chemical and biological mechanisms, acting individually or in combination. For example, in an experimental study of exposure of Eurasian perch larvae to polystyrene microplastics, Lönnstedt and Eklöv (2016) concluded that combined chemical and physical mechanisms were operating in the observed effects of inhibited hatching, decreased growth rates and altered feeding preferences. Changes were also observed in responses of the perch larvae to olfactory threat cues, which could translate to increased mortality from predator attacks in the wild. While recognising the complexity of mechanisms and their interactions it may be useful to initially consider the possible impacts separately.

3.2. Physical impacts

The major physical impact in organisms occurs through ingestion of microplastics. Ingestion has been observed in a wide range of filter feeders (Wright et al., 2013b) including marine megafauna (Germanov et al., 2018), and in a range of other species from zooplankton (Desforges et al., 2015; Jemec et al., 2016; Commonwealth of Australia, 2016) to vertebrates (Wright et al., 2013b; Mathalon and Hill, 2014; Vandermeersch et al., 2015). Transfer of ingested microplastics across trophic levels affects aquatic species such as salmon and other fish valued as human food, and birds such as shearwaters (Wright et al., 2013b; Carbery et al., 2018; Nelms et al., 2018). In general, intake of microplastics in place of feed has been reported to lead to false satiation and gastrointestinal blockages (Wright et al., 2013a, 2013b; Desforges et al., 2015). For example, exposure to environmentally relevant concentrations of microplastics resulted in up to 50% reduction in energy reserves, increased gut residence time of ingested material, and inflammation in the polychaete worm, *Arenicola marina* (Wright et al., 2013a).

Regular shaped microplastic particles may be easily egested (Nelms et al., 2018; Waring et al., 2018), but the smaller nanoplastics appear to be more readily absorbed, retained and accumulate in vital organs and other tissues of aquatic species and other organisms (Mattsson et al., 2017, Bhargava et al., 2018, Waring et al., 2018). Nanoplastics may affect the central nervous system and reproductive capacity resulting in behavioural disorders (Mattsson et al., 2017), potentially impacting whole ecosystem function (Waring et al., 2018). Foley et al. (2018) conducted a systematic meta-analysis of microplastic effects across a range of marine and freshwater taxa, and found the impacts of exposure to be

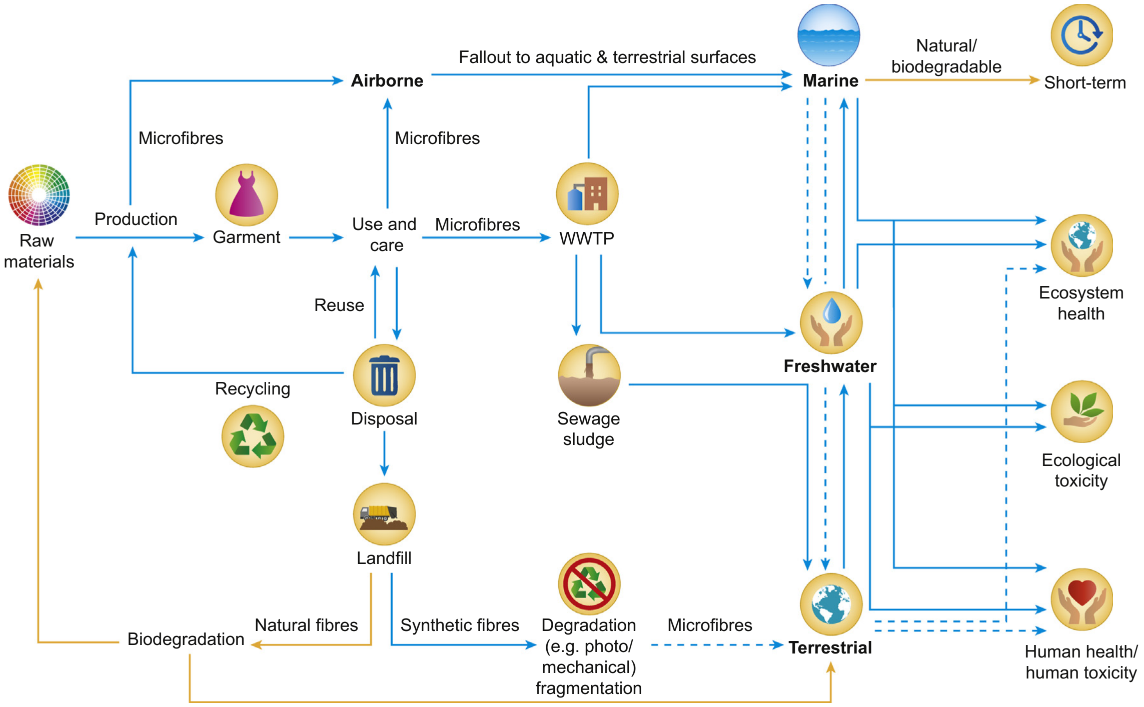

Fig. 1. Sites in the textile supply chain of potential release and transfers of microfibres, and indicative environmental impacts. Blue arrows indicate pathways for microfibres (broken arrows showing indirect or minor pathways); Yellow arrows show where natural biodegradable microfibre pathways deviate from those for the dominant synthetic fibres. (WWTP = Waste Water Treatment Plant). (Note that not all possible transfers are shown to maintain clarity on major pathways.)

variable across taxa, with a large number of neutral outcomes. The most consistent effect was a reduction in consumption of natural prey when microplastics were present and, in some cases, negative effects on growth, reproduction and even survival. Other studies, however, found that egestion of microplastic particles occurred more readily in some species and that, as a result of identified growth effects in sensitive species, more research is needed to understand the potential for changes in biodiversity (Redondo-Hasselerharm et al., 2018). The review by Foley et al. (2018) found that observed effects were stronger for lower trophic level organisms. These species are critical in food chains. Foley et al. concluded that there is sufficient basis for public concern regarding plastic pollution in aquatic ecosystems to warrant investment in research.

Better understanding is needed of differences in response due to the shape of microplastics and especially whether entanglement of fibre-shaped microplastics could exacerbate negative effects (Wright et al., 2013a; Jemec et al., 2016). In marine and freshwater systems, synthetic fibres appear to have a higher potential than other forms of microplastics to enter the food chain because their size and form allow them to be readily consumed by aquatic organisms and to be more prone to entanglement and gut retention. Jemec et al. (2016) found that while the majority of ingested fibres in *Daphnia magna* experimentally exposed to polyethylene terephthalate textile fibres were around 300 μm, some very large twisted microfibres around 1400 μm were present inside the gut. Even less is known about impacts in terrestrial situations, but microplastics introduced into agricultural soils, e.g. through application of sewage sludge, may interact with soil fauna and soil properties, altering soil microbial activity and potentially plant growth. Other possible effects such as altered soil bulk density and carbon content are poorly understood (Rillig, 2018).

3.3. Chemical impacts

Mechanisms potentially contributing to chemical impacts of microfibres in the environment include leaching of plastic additives such as antioxidants, dyes or fire retardants (Machado et al., 2018), and transfer of compounds such as persistent organic pollutants (POPs) and metals sorbed from aquatic environments (Rochman et al., 2014a). The capacity for microfibres with a high surface to volume ratio, to sorb a wide range of pollutants in solution (Besseling et al., 2013) raises the risk of enhanced bioavailability of toxic compounds. The effect on organisms of chemical contamination depends on the amount and nature of hydrophobic pollutants, extent of bioaccumulation, chemical release and onset of potential health effects in ingesting species.

The use of variable and high concentrations in experimental exposures may contribute to the inconsistency in results in published literature, but there is evidence for effects at environmentally relevant concentrations. Rochman et al. (2014b) demonstrated that the ingestion by adult fish of plastic debris at environmentally relevant concentrations in sea water is capable of altering endocrine system function. Under experimental exposure to polyethylene microplastics (< 1 mm) and associated chemicals, altered gene expression was observed in both male and female Japanese medaka (*Oryzias latipes*), and in female fish when exposed to virgin polyethylene or polyethylene deployed in sea water. However, a critical review of published studies and empirical evidence by Koelmans et al. (2016) concluded that the increase in exposure to hydrophobic organic chemicals due to ingestion of contaminated microplastics was not likely to significantly increase overall exposure and risk of harm in marine organisms, highlighting current uncertainty in impacts.

In terrestrial ecosystems, the risk to soil biota exposed to chemicals associated with microplastics as additives or through adsorption will likely depend on concentration-transport and size-selection mechanisms. In experimental exposures to microplastics at levels representative of those in agricultural soils receiving sewage sludge applications, survival and fitness of the earthworm, *Lumbricus terrestris* (Oligochaeta, Lumbricidae) were negatively affected (Huerta Lwanga et al., 2016). Research is needed to assess potential chemical impacts for food production of exposure for a wider range of soil biota and compounds carried in sludge or applied in agriculture.

3.4. Biological impacts

Microplastics provide new habitats for organisms and new sites for microbial colonisation. Microfibres and other microplastic particles passing through WWTPs may become enriched with pathogens (Kirstein et al., 2016) and subsequently disperse microbes in freshwater systems or, via sludge amendments, in soils. Sequencing of biofilms on microplastics in marine environments revealed the presence of potentially pathogenic organisms such as *Vibrio* spp. (Kirstein et al., 2016), implicating them as possible vectors for the dispersal of these pathogens (Reisser et al., 2014; Oberbeckmann et al., 2015).

Characterisation of organisms on the surface of small floating plastics (median length 3.2 mm) from Australia-wide coastal and oceanic sites recorded a biodiverse range of plastic colonisers (Reisser et al., 2014). Diatoms were the most diverse group (14 genera), but the study putatively identified bacteria, cyanobacteria, and fungi. Assessment of the risk of disease in 124,000 corals from 159 reefs in the Asia-Pacific region (Lamb et al., 2018) indicated an increase ranging from 4% to 89% in the likelihood of disease when corals were in contact with plastics. However, there is insufficient evidence at this time to determine whether microplastics pose an increased disease-risk more generally in ecologically and economically valuable marine ecosystems such as fisheries and coral reefs. Research is also needed to confirm whether colonisation of microfibres accelerates breakdown and to document the rates of biodeterioration for different fibre types since, from a variety of plastic surface microtextures in Australian marine samples, Reisser et al. (2014) inferred that colonising biota may play a role in plastic degradation at the sea surface. In summary, questions remain on the role of textile microfibres as pelagic microhabitats and as vectors in biofilm-associated disease risk, and additional research is needed on the scale of impacts, ecological impacts and potential implications for human health.

3.5. Impacts on human health

Research on potential impacts of exposure to microplastics on organisms has largely been confined to localised encounters over short time periods predominantly in aquatic habitats. Human effects are more likely to be a function of cumulative exposure from diffuse terrestrial sources (see Fig. 1). Microplastics have been reported in a wide range of human food and beverages, including seafood (Rochman et al., 2015), drinking water (Kosuth et al., 2017; Mason et al., 2018), beer (Liebezeit and Liebezeit, 2014), salt and sugar (Rist et al., 2018) and in the air (Dris et al., 2017), raising concerns about the threat to human health through ingestion and inhalation (Waring et al., 2018). Recognition of the risk of contamination of food and beverage samples (Rist et al., 2018) and uncertainty in analytical techniques have cast doubt on some earlier assessments of microplastic ingestion with food (Catarino et al., 2018). However, there is little doubt that a degree of chronic exposure is now an integral part of human life (Wright and Kelly, 2017). Nevertheless, a recent review of the available evidence by Waring et al. (2018) concluded that microplastic contamination of the food chain is unlikely to cause serious toxicity at current exposure levels and rates of uptake and translocation of microfibres and nanofibres via the gastrointestinal tract and/or in the lung. Waring et al. noted, however, that effects of accumulated high levels of contamination in human tissues and health conditions, such as a leaky gut, permeable blood-brain barrier or long-term ingestion of contaminated foodstuffs, require further research.

Research on humans is difficult, firstly because experimental studies are ethically controversial. In addition it is difficult, if not impossible, to find a control group that has not been exposed to microfibres, and distinguishing the impacts of individual elements in large population based studies is complex and costly. However, observational studies are beginning to examine evidence for potential effects of exposure to microplastics on human health. Impacts, as for other organisms, will likely reflect a combination of physical, chemical, and biological (e.g. transfer of pathogens) mechanisms. Major knowledge gaps include characterising the longer-term risk of exposure and understanding impacts of ingestion and inhalation of nanoplastics (Gasperi et al., 2018; Waring et al., 2018). Chronic exposure of humans to microfibres and nanofibres from textiles may result in a level of bioaccumulation (Revel et al., 2018; Waring et al., 2018). As for other organisms, these fibres may expose humans to chemicals such as unreacted monomers, additives, dyes, or finishes such as polybrominated diphenyl ethers (PBDE) that have been associated with toxicity, carcinogenicity and mutagenicity (Gasperi et al., 2018). This is in spite of most ingested microfibres likely passing harmlessly out of the body (Rist et al., 2018).

Airborne textile fibres are likely to be generally too large to be inhaled and smaller fibres, if inhaled, may be readily cleared (Dris et al., 2017). Nevertheless, both cellulosic and plastic microfibres have been observed in human pulmonary tissues (Pauly et al., 1998) indicating that some smaller fibres may enter respiratory passages and the lungs (Gasperi et al., 2018). In vitro tests (Gasperi et al., 2018) found evidence for the durability and biopersistence of plastic fibres in physiological fluid, with polypropylene, polyethylene and polycarbonate fibres having almost no dissolution or changes to surface area and characteristics in a synthetic extracellular lung fluid after 180 days (Gasperi et al., 2018). The nature and mechanism of possible toxicity impacts from chronic inhalation are uncertain, and care is needed in interpreting reports on effects of textile micro- and nanofibres that extrapolate from experience with inorganic or mineral fibre inhalation, such as asbestos.

In summary, limited research and observational evidence suggests that current levels of human exposure to microfibres from synthetic textiles are unlikely to cause serious toxicity. However, potential impacts of long-term chronic ingestion and inhalation of nanofibres, are unknown. Gaps in knowledge and public concern make these high priority research questions and indicate a case for limiting exposure to persistent plastic microfibres and nanofibres, as far as possible, especially for vulnerable groups. Reliable and consistent analytical standards are a priority to monitor exposure.

4. Natural and man-made textile microfibres

Potential environmental impacts of microfibres have been discussed as they relate to physical, chemical and biological aspects of exposure in aquatic and terrestrial habitats. Exposure is a function of the prevalence of microfibres, and their accumulation depends on their level of persistence in the environment. Few studies have described the prevalence and impacts of non-plastic fibres, and of these most have detected man-made cellulosics in microlitter (Halstead et al., 2018; Setälä et al., 2016; Remy et al., 2015; Dris et al., 2017). However, more comprehensive measurements are needed to confirm whether the apparent absence of natural fibres relates to use of analytical techniques targeting plastic polymers or to natural microfibres not being present in samples.

In summary, there are only limited data on the presence and persistence of natural and man-made cellulosic fibres and blends across a range of environmental systems. As described in Section 2.1, care is needed in interpreting results of studies quantifying presence of microfibre types because of the risk of post-sampling contamination. However, studies that took rigorous steps to avoid contamination provide more reliable indicative results. In marine samples handled so as to avoid post sampling contamination, Remy et al. (2015) found 27.6% of macrofauna had ingested viscose fibres, and Woodall et al. (2014), using a rigorous forensic approach described in Woodall et al. (2015), reported that viscose contributed 56.9% of total microfibres in deep sea sediments from the Atlantic Ocean floor, being more than twice as abundant as polyester, which was the dominant plastic fibre. Viscose is used in cigarette filters and personal hygiene products as well as clothing, and is introduced to marine habitats through a range of pathways, including sewage and litter. Microfibres of viscose have been reported in fish (57.8% of detected particles ingested) (Lusher et al., 2013) and in ice cores (54%) (Obbard et al., 2014), in similar proportions to those reported in Woodall et al. (2014). These studies took steps to avoid contamination.

Limited evidence on the fate of natural animal and plant fibres such as wool and cotton in the environment comes from studies showing that biodegradation occurs in soils in weeks to months (Arshad et al., 2014; Li et al., 2010; McNeil et al., 2007; Szostak-Kotowa, 2004). Laboratory and in-situ experiments from New Zealand concluded that wool fibre is also biodegradable in marine environments (Brown, 1994) under the action of the wool degrading bacteria of the genera *Alteromonas* and *Oceanospirillum*. Observations of textile-related marine debris in the United States (Ocean Conservancy, 2013) indicate that whereas a cotton T-shirt disappears in 2–5 months and a wool sock in 1–5 years, plastic fibres take decades (30–40 years for polyamide fabric) to hundreds of years (450 years for disposable diapers). Even if ingested, there is evidence that, unlike synthetics, natural fibres from textiles are broken down within organisms. Zhao et al. (2016) provided preliminary data that natural fibres accounted for 37.4% of the total microscopic litter in the digestive tract of terrestrial birds but that the proportion declined from the oesophagus to stomach to intestine suggesting that they are likely being digested. More robust data on the rate of biodegradation of textile fibres of different types in various climatic, environmental and biological conditions is a critical need.

Maximising the use of textiles made from biodegradable and renewable natural fibres has been proposed as a strategy to reduce the risks of textile microfibres (e.g. Henry et al., 2018). Research is needed to quantify resultant reductions in harmful impacts. Scientifically robust data on the fate and persistence of fibres of different origins and structure are required to support recommendations on minimising environmental threats. For example, durability will affect long-term exposure and the cumulative response of organisms in marine, freshwater and terrestrial habitats. Despite some uncertainty, the weight of evidence at present suggests that physical impacts of natural fibres are less likely to be of concern than those of more persistent man-made cellulosic or plastic synthetic fibres. However, Zhao et al. (2016) speculate that relatively rapid biodegradation of natural fibres may increase the bioavailability of chemical additives, e.g. dyes, if these microfibres are metabolized quickly once ingested. They urge more research in order to evaluate this potential risk of adverse effects.

5. Microfibres in sustainability assessment of textiles

The objective of product sustainability assessment is to provide a metric for managing and reporting environmental impacts of that product. These tools ideally include quantifiable indicators for all the important environmental impacts in order to avoid perverse outcomes arising from decisions or choices that reduce the impact for one category but inadvertently increase harm in an excluded category. With recent awareness of the potential environmental threat from microplastics, there is growing interest in including microplastic pollution as a new impact category in sustainability tools for assessing apparel and textiles (Laitala et al., 2018). However, the science and requisite data to underpin development of indicators is still evolving, and our literature search revealed no publications describing tools that included a quantifiable indicator for microfibre pollution from textiles. We examine this knowledge gap, and explore the potential for including an interim metric that will be effective in guiding sustainability decisions and monitoring progress towards lower risks, while allowing for refinement as scientific

Table 1
Preliminary indicative factors for microfibre shedding from garments during washing, showing relativity with fabric type, wash treatment and garment aging (Henry et al., 2018).

Study and treatment	Multiplier factor (No. of persistent/plastic fibres shed)	Multiplier factor (Mass of persistent/plastic fibres shed)	% mass shed per wash
Napper and Thompson (2016)			
Reference: Polyester garment in front-loading washer (# Fibres or mass fibres per 6 kg wash)	1 (496,030)	1 (1.04 mg)	0.02%
Acrylic garment	1.5	0.92	0.02%
Polyester-cotton (65%:35%) garment	0.3	0.39	0.01%
Hartline et al. (2016)			
Reference: New polyester jacket in top-loading washer (mass fibres/jacket/wash)		1 (1.8 g)	0.37%
New garment in front-loading washer		0.15	0.03%
Aged garment in top-loading washer		1.09	0.34%
Aged garment in front-loading washer		0.2	0.08%
Natural fibres (inclu. wool, cotton)[a]	0	0	0%
Cellulosic polymer (e.g. viscose)[a]	No data	No data	No data

[a] Data on persistence of natural fibres and man-made fibres are included based on assumptions and evidence for their biodegradability. The study by Napper and Thompson (2016) focussed on synthetic fibres.

methods and data develop to enable impacts to be more accurately quantified.

5.1. Quantifying microfibre shedding from clothing

Analysis of domestic effluent from washing machines provides clear evidence that all common household textiles shed fibres and that synthetic fabrics contribute to microplastic pollution. However, the lack of consistent test protocols leads to enormous variability in results and to the way they are reported (Jönsson et al., 2018). As illustrated for two example datasets, it also hampers comparisons and the development of representative results from different studies (Table 1). Consistent protocols are needed for quantifiable indicators of microfibre shedding that can reflect fibre type and wash conditions (See Section 2.5).

Henry et al. (2018) discuss issues for inclusion of microfibre pollution in textile product life cycle assessment (LCA) studies and indicate prospects for future refinement of an indicator for the effects of improved practices on impacts (Fig. 2).

5.2. Prospects for a meaningful indicator?

While research on the prevalence, fate and environmental and human health impacts of microplastics is evolving, knowledge gaps remain. Inclusion of preliminary indicators in management systems, such as LCA, would support industry sustainability objectives and reporting. LCA is the most common and most robust tool used to quantify and compare the environmental impact of apparel and textiles (e.g. Islam and Khan, 2014). With microplastics globally recognised as an environmental threat, omitting microfibres from apparel and textile sustainability assessments using LCA or equivalent tools means scores will have low credibility and fail to meet industry needs and community expectations. On the other hand, defining meaningful indicators for microfibre impacts within the existing LCA mid-point framework is

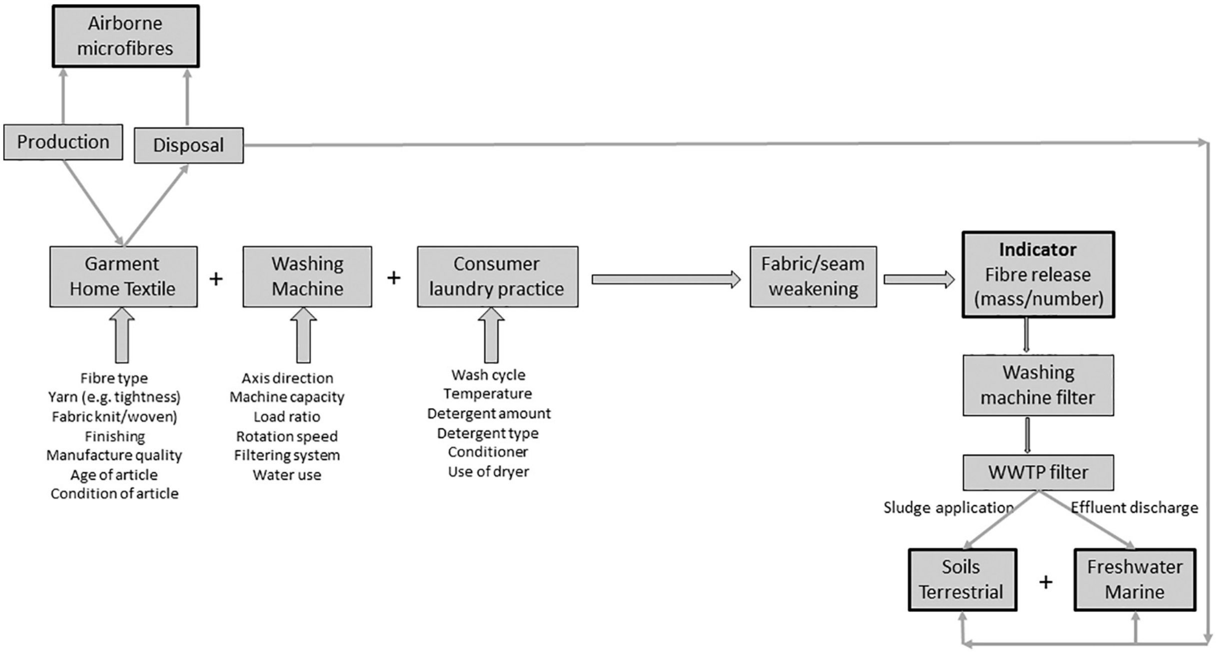

Fig. 2. Stages and factors affecting the release and emissions of microfibres from textiles.
Adapted from Cesa et al. (2017) and Henry et al. (2018).

Table 2
Summary of research and information requirements to address key gaps in knowledge on textile microfibre loss.

Knowledge gap	Information or research need
Terminology	— Clarification of key terms to aid data sharing and communication, including consensus definitions for
	— Microfibre and nanofibre
	— ‘primary’ and ‘secondary’ microplastics
	— ‘synthetic’, ‘man-made’, ‘natural’ fibres
Units for microfibre prevalence	— Comparison of research results requires common units e.g. mass per garment or per kg clothing [in wash] vs number of fibres per garment/kg clothing; kg/number per volume water/soil or per surface area
Measurement and sampling protocols	— Agreed and constantly updated protocols for sampling, analysis, characterisation of microfibres and nanofibres
	— Protocols for expressing confidence in detection (fibre size limits, instrument/technique uncertainty)
	— Protocols for experimental testing of fibre loss during wash cycles
Scale of loss of microfibres at all stages of textile life	— Relative loss to atmosphere during production, use, disposal
	— Relative exposure from airborne fallout vs WWTP effluent discharge to aquatic systems (freshwater, marine, coastal)
	— Discharge to aquatic systems that do not pass through a WWTP
	— Relative abundance from sewage sludge application to soils (natural or agricultural)
	— Contribution of fragmentation of textiles in landfill to atmospheric, water-borne or soil stocks of microfibres
Fate of microfibres once in the environment	— Rate of deposition from atmosphere
	— Transfer from river systems or land to coastal or marine habitats
	— Transfer from sea surface to deeper waters or to ocean floor
	— Trophic transfers in marine and land ecosystems
	— Rates of degradation and fragmentation of microfibres to nano-fibres
	— Rates of biodegradation in all environments (marine, freshwater, soil) by fibre type
Physical impacts of microfibres	— Occurrence and amount of ingested microfibres in organisms at all trophic levels
	— Rates of human intake of textile microfibres in food and beverage vs exposure to microplastics from general sources including packaging
	— Rates of human inhalation of textile fibres and potential health effects for micro- and nanofibres by fibre type
	— Presence and physiological location of microfibres in human systems
	— Rates of egestion of microfibres from organisms and humans
	— Impacts of ingested microfibres on growth, health, reproduction and survival of organisms by fibre type
Chemical impacts of microfibres	— Rates of leaching of harmful additives from textile microfibres
	— Rates of microfibre sorption of hydrophobic compounds and metals
	— Increase in exposure of aquatic organisms to harmful chemicals through microfibre ingestion over dissolved or floating sources
	— Evidence for impacts of sorbed chemicals on growth, health, reproduction and survival of organisms
Biological impacts of microfibres	— Extent of biocolonisation of microfibre surfaces in aquatic systems
	— Evidence of microfibre ‘rafting’ of harmful microorganisms to new habitats
	— Evidence for impacts of sorbed chemicals on growth, health, reproduction and survival of organisms
Mitigation strategies	— Sharing of information and technologies for best practice to minimise microfibre pollution throughout the apparel and textile supply chain
	— Protocols for monitoring prevalence and impacts to document effectiveness of practices and initiatives to manage microfibre loss

challenging due to the lack of consensus on methods and incomplete understanding of impacts.

It is not yet clear what properties of microfibres (and nanofibres) more closely determine ecological and human health impacts. Properties such as mass, number, dimensions, surface properties and persistence of microfibres could appropriately be included in a more credible indicator. However, exposure will strongly influence impacts and the accumulation of durable and persistent synthetic fibres are a determinant of exposure likely related to higher risk of environmental harm. Persistence is also a factor that distinguishes synthetic from biodegradable natural fibres, making it a credible interim modifier for an indicator of environmental impact assessment. Future improvement for more comprehensive and causal assessment of the impacts of textile microfibres from synthetic, man-made cellulosic and natural materials will require research on potential harm to the environment and human health through physical, chemical and biological mechanisms.

Research is also needed on factors affecting textile microfibre loss in less-developed countries. Large volumes of new and used textiles are transferred to these regions where laundry is more often done by hand-washing and waste water is not treated (Laitala et al., 2018). Efforts to develop better and more inclusive indicators and metrics for monitoring and managing microfibre pollution across apparel and home textile value chains can continue in parallel with education and implementation of practices that minimise risk based on an interim indicator such as mass or number of microfibres released.

In summary, a simple measure of microfibre shedding provides an interim indicator with some relevance to the range of potential areas of impact shown in Fig. 1. While limitations are acknowledged, standardised analytical methods and broader data collection will progressively improve understanding of impacts across global ecosystems. For example, in future a simple mass or number based indicator of persistent microfibre shedding could be combined with information such as the efficiency of washing machine and WWTP fibre capture and data on chemical additives and surface properties for different fibre types to quantify exposure and estimate physical and chemical threats. Data from research on factors that influence the rate of shedding (Fig. 2) may be applied to adjust the indicator to be responsive to practice change to reward mitigation options in the ‘sustainability score’ of products.

6. Knowledge gaps and conclusions

6.1. Summary of knowledge gaps

Table 2 summarises recommendations for research to address gaps in information and scientific knowledge to better understand the scale and nature of the threat of microfibre pollution.

6.1.1. Gaps specific to exposure

Research on the prevalence, fate and impacts of microplastics generally, and microfibres in particular, is a new area of science. Inconsistency in approach and variable results on exposure and impacts (e.g. see Foley et al., 2018) in published studies are, therefore, not unexpected. A high priority should be systematic trials to develop standardised analytical methods (e.g. FTIR with appropriate libraries) that reliably distinguish microfibres from synthetic, man-made cellulosic and natural fabrics. Another key knowledge gap is rates of biodegradation of different microfibres (including blends) in a range of climatic and environmental conditions and possible rates of breakdown following ingestion.

6.1.2. Gaps specific to impacts

Many laboratory ecotoxicological studies have used high concentrations of microplastics and these should be interpreted only as 'proof of concept' trials (Huvet et al., 2016). Studies seeking to understand the environmental threat of microfibres and impacts on organisms should ensure exposure trials use realistic concentrations and consider the statistical probabilities of organisms encountering or ingesting microfibres (Lenz et al., 2016). Another high priority is understanding the fate of microfibres and mixed contaminants through a complex marine food web using environmentally relevant concentrations. This knowledge would inform estimation of bioaccumulation through trophic transfers and assist in understanding chemical exposure in biota (Hong et al., 2017). Despite considerable speculation, robust evidence on any adverse effect on human health due to the consumption of marine organisms containing microplastics is limited, difficult to assess and still controversial.

6.1.3. Gaps specific to human health impacts

Priorities for resolving current conflicting evidence on the human health risks from exposure to microfibres include research on potential physiological impacts of nanofibres and investigation of whether chronic exposure may result in harmful cumulative levels of microplastics in the longer term (Waring et al., 2018). This research requires standardised sampling and analysis methods that minimise the risk of post-sampling contamination.

6.2. Conclusions

There is a poorly defined but potentially large and growing risk for ecological and human health problems associated with microplastics. We asked at the start of this article whether it is yet possible to include a credible metric for microplastic pollution in tools used to assess the environmental performance of apparel and home textiles. The answer to this question is a qualified yes. A preliminary mid-point indicator in sustainability assessment tools could be based on mass or number of textile microfibre loss, focussing initially on shedding during consumer care of microfibres that are not readily biodegraded. An indicator of this type, although uncertain, would potentially affect the ranking of textile fibres and consequently decisions that influence ongoing microplastic pollution. Accelerating investment in the research needed to develop more robust metrics is recommended. Progress towards managing the threat posed by microfibre emissions from textile supply chains, would be facilitated by periodic critical review of the rapidly expanding scientific literature on microplastic pollution and microfibre loss to the environment. Synthesis of experimental and observational results into a database to further develop and refine comprehensive indicators for sustainability assessment is also recommended. This will provide more confidence in mitigation options, e.g. the extent to which a strategy of increasing the share of biodegradable natural fibres in clothing may contribute to the solution to microplastic pollution. Taking a more strategic view, addressing fundamental questions on how we produce, use and dispose of clothing and other textiles in a more environmentally sustainable way may be more effective in reducing exposure to microfibres in the long-term.

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References

Arshad, K., Skrifvars, M., Vivod, V., Valh, J., Voncina, B., 2014. Biodegradation of natural textile materials in soil. Tekstilec 57 (2), 118–132. https://doi.org/10.14502/Tekstilec2014.57.118–132.

Austin, H.P., Allen, M.D., Donohoe, B.S., Rorrer, N.A., Kearns, F.L., Silveira, R.L., Pollard, B.C., Dominick, G., Duman, R., El Omari, K., Mykhaylyk, V., 2018. Characterization and Engineering of a Plastic-Degrading Aromatic Polyesterase. Proceedings of the National Academy of Sciences, p. 201718804 https://doi.org/10.1073/pnas.1718804115.

Barnes, D.K., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc. B 364 (1526), 1985–1998. https://doi.org/10.1098/rstb.2008.0205.

Besseling, E., Wegner, A., Foekema, E.M., Van den Heuvel-Greve, M.J., Koelmans, A.A., 2013. Effects of microplastic on fitness and PCB bioaccumulation by the lugworm *Arenicola marina* (L.). Environ. Sci. Technol. 47, 593–600. https://doi.org/10.1021/es302763x.

Bhargava, S., Chen Lee, S.S., Min Ying, L.S., Neo, M.L., Lay-Ming Teo, S., Valiyaveettil, S., 2018. Fate of nanoplastics in marine larvae: a case study using barnacles, *Amphibalanus amphitrite*. ACS Sustain. Chem. Eng. 6 (5), 6932–6940. https://doi.org/10.1021/acssuschemeng.8b00766.

Bläsing, M., Amelung, W., 2018. Plastics in soil: analytical methods and possible sources. Sci. Total Environ. 612, 422–435. https://doi.org/10.1016/j.scitotenv.2017.08.086.

Boucher, J., Friot, D., 2017. Primary Microplastics in the Oceans: a Global Evaluation of Sources. IUCN, Gland, Switzerland (43 pp).

Bouwmeester, H., Hollman, P.C., Peters, R.J., 2015. Potential health impact of environmentally released micro-and nanoplastics in the human food production chain: experiences from nanotoxicology. Environ. Sci. Technol. 49 (15), 8932–8947. https://doi.org/10.1021/acs.est.5b01090.

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.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R., 2011. Accumulation of microplastic on shorelines woldwide: sources and sinks. Environ. Sci. Technol. 45, 9175–9179. https://doi.org/10.1021/es201811s. doi:10.1021/es201811s.

Carbery, M., O'Connor, W., Palanisami, T., 2018. Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health. Environ. Int. 115, 400–409. https://doi.org/10.1016/j.envint.2018.03.007.

Catarino, A.I., Macchia, V., Sanderson, W.G., Thompson, R.C., Henry, T.B., 2018. Low levels of microplastics (MP) in wild mussels indicate that MP ingestion by humans is minimal compared to exposure via household fibres fallout during a meal. Environ. Pollut. 237, 675–684. https://doi.org/10.1016/j.envpol.2018.02.069.

Cesa, F.S., Turra, A., Baruque-Ramos, J., 2017. Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings. Sci. Total Environ. 598, 1116–1129. https://doi.org/10.1016/j.scitotenv.2017.04.172.

Cobbing, M., Vicaire, Y., 2016. Timeout for Fast Fashion. Published by Greenpeace e.v., Hamburg, Germany www.greenpeace.org/international/en/campaigns/detox/fashion (Accessed December 2016).

Commonwealth of Australia, 2016. The Senate Environment and Communications References Committee: toxic tide: the threat of marine plastic pollution in Australia. Published by Commonwealth of Australia, Canberra April 2016 (Note: clause 3.66).

Comnea-Stancu, I.R., Wieland, K., Ramer, G., Schwaighofer, A., Lendl, B., 2017. On the identification of rayon/viscose as a major fraction of microplastics in the marine environment: discrimination between natural and manmade cellulosic fibers using Fourier Transform infrared spectroscopy. Appl. Spectrosc. 71 (5), 939–950. https://doi.org/10.1177/0003702816660725.

De Falco, F., Gullo, M.P., GENTILE, G., Di Pace, E., Cocca, M., Gelabert, L., Brouta-Agnésa, M., Rovira, A., Escudero, R., Villalba, R., Mossotti, R., 2018. Evaluation of microplastic release caused by textile washing processes of synthetic fabrics. Environ. Pollut. 236, 916–925. https://doi.org/10.1016/j.envpol.2017.10.057.

Desforges, Jean-Pierre W., Galbraith, Moira, Ross, Peter S., 2015. Ingestion of microplastics by zooplankton in the Northeast Pacific Ocean. Arch. Environ. Contam. Toxicol. 69, 320–330. https://doi.org/10.1007/s00244-015-0172-5.

do Sul, J.A.I., Costa, M.F., 2014. The present and future of microplastic pollution in the marine environment. Environ. Pollut. 185, 352–364. https://doi.org/10.1016/j.envpol.2013.10.036.

Dris, R., Gasperi, J., Saad, M., Mirande, C., Tassin, B., 2016. Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? Mar. Pollut. Bull. 104 (1–2), 290–293. https://doi.org/10.1016/j.marpolbul.2016.01.006.

Dris, R., Gasperi, J., Mirande, C., Mandin, C., Guerrouache, M., Langlois, V., Tassin, B., 2017. A first overview of textile fibers, including microplastics, in indoor and outdoor environments. Environ. Pollut. 221, 453–458. https://doi.org/10.1016/j.envpol.2016.12.013.

Espi, E., 2006. Plastic films for agricultural applications. J. Plast. Film Sheeting (2), 85–102 https://doi.org/10.1177/8756087906064220.

Eunomia, 2016. Plastics in the Marine Environment. Eunomia Research & Consulting Ltd, Bristol, UK June 2016. www.eunomia.co.uk/reports-tools/plastics-in-the-marine-environment/, Accessed date: January 2018.

Foley, C.J., Feiner, Z.S., Malinich, T.D., Höök, T.O., 2018. A meta-analysis of the effects of exposure to microplastics on fish and aquatic invertebrates. Sci. Total Environ. 631, 550–559. https://doi.org/10.1016/j.scitotenv.2018.03.046.

Fries, E., Dekiff, J.H., Willmeyer, J., Nuelle, M.T., Ebert, M., Remy, D., 2013. Identification of polymer types and additives in marine microplastic particles using pyrolysis-GC/MS and scanning electron microscopy. Environ. Sci.: Processes Impacts 15 (10), 1949–1956. https://doi.org/10.1039/c3em00214d.

Gasperi, J., Wright, S.L., Dris, R., Collard, F., Mandin, C., Guerrouache, M., Langlois, V., Kelly, F.J., Tassin, B., 2018. Microplastics in air: are we breathing it in? Current Opinion in Environmental Science & Health 1, 1–5. https://doi.org/10.1016/j.coesh.2017.10.002.

Germanov, E.S., Marshall, A.D., Bejder, L., Fossi, M.C., Lonergan, N.R., 2018. Microplastics: no small problem for filter-feeding megafauna. Trends Ecol. Evol. https://doi.org/10.1016/j.tree.2018.01.005.

GESAMP, 2015. In: Kershaw, P.J. (Ed.), Sources, Fate and Effects of Microplastics in the Marine Environment: a Global Assessment. (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) https://doi.org/10.13140/RG.2.1.3803.7925 Rep. Stud. GESAMP No. 90, 96 p.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3 (7), e1700782. https://doi.org/10.1126/sciadv.1700782.

Gorokhova, E., 2015. Screening for microplastic particles in plankton samples: how to integrate marine litter assessment into existing monitoring programs? Mar. Pollut. Bull. 99 (1–2), 271–275. https://doi.org/10.1016/j.marpolbul.2015.07.056.

Gupta, S.B., Afshari, M., 2018. Polyacrylonitrile fibers. In: Bunsell, A.R. (Ed.), Handbook of Properties of Textile and Technical Fibers, 2nd ed. 2018. Woodhead Publishing, Oxford, UK, pp. 545–588 ISBN: (978-0-08-101272-7).

Halstead, J.E., Smith, J.A., Carter, E.A., Lay, P.A., Johnston, E.L., 2018. Assessment tools for microplastics and natural fibres ingested by fish in an urbanised estuary. Environ. Pollut. 234, 552–561. https://doi.org/10.1016/j.envpol.2017.11.085.

Hartline, N., Bruce, N., Karba, S., Ruff, E., Sonar, S., Holden, P., 2016. Microfiber masses recovered from conventional machine washing of new or aged garments. Environ. Sci. Technol. 50 (21), 11532–11538. https://doi.org/10.1021/acs.est.6b03045. doi:10.1021/acs.est.6b03045.

Henry, B., Laitala, K., Klepp, I.G., 2018. Microplastic pollution from textiles: a literature review. Project Report no. 1–2018. 2018. Consumption Research Norway - SIFO, Oslo , p. 49. http://www.hioa.no/eng/content/download/144803/4071096/file/OR1%20-%20Microplastic%20pollution%20from%20textiles%20-%20A%20literature%20review.pdf.

Hermsen, E., Mintenig, S., Besseling, E., Koelmans, A.A., 2018. Quality criteria for the analysis of microplastic in biota samples. Critical review. Environ. Sci. Technol. 52, 10230–10240. https://doi.org/10.1021/acs.est.8b01611.

Hernandez, E., Nowack, B., Mitrano, D.M., 2017. Polyester textiles as a source of microplastics from households: a mechanistic study to understand microfiber release during washing. Environ. Sci. Technol. 51 (12), 7036–7046. https://doi.org/10.1021/acs.est.7b01750.

Hong, S.H., Shim, W.J., Hong, L., 2017. Methods of analysing chemicals associated with microplastics: a review. Anal. Methods 9 (9), 1361–1368. https://doi.org/10.1039/c6ay02971j.

Horton, A.A., Walton, A., Spurgeon, D.J., Lahive, E., Svendsen, C., 2017. Microplastics in freshwater and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. Sci. Total Environ. 586, 127–141. https://doi.org/10.1016/j.scitotenv.2017.01.190.

Huerta Lwanga, E., Gertsen, H., Gooren, H., Peters, P., Salánki, T., van der Ploeg, M., Besseling, E., Koelmans, A.A., Geissen, V., 2016. Microplastics in the terrestrial ecosystem: implications for *Lumbricus terrestris* (Oligochaeta, Lumbricidae). Environ. Sci. Technol. 50, 2685–2691. https://doi.org/10.1021/acs.est.5b05478.

Huvet, A., Paul-Pont, I., Fabioux, C., Lambert, C., Suquet, M., Thomas, Y., Robbens, J., Soudant, P., Sussarellu, R., 2016. Reply to Lenz et al.: quantifying the smallest microplastics is the challenge for a comprehensive view of their environmental impacts. Proc. Natl. Acad. Sci. 113 (29), E4123–E4124.

Islam, M.M., Khan, M.M.R., 2014. Environmental sustainability evaluation of apparel product: a case study on knitted T-shirt. Journal of Textiles 2014. https://doi.org/10.1155/2014/643080.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347 (6223), 768–771. https://doi.org/10.1017/CBO9781107415386.010.

Jemec, A., Horvat, P., Kunej, U., Bele, M., Kržan, A., 2016. Uptake and effects of microplastic textile fibers on freshwater crustacean *Daphnia magna*. Environ. Pollut. 219, 201–209. https://doi.org/10.1016/j.envpol.2016.10.037.

Jönsson, C., Arturin, O.L., Hanning, A.C., Landin, R., Holmström, E., Roos, S., 2018. Microplastics shedding from textiles—developing analytical method for measurement of shed material representing release during domestic washing. Sustain. For. 10 (7), 1–17 (RePEc:gam:jsusta:v:10:y:2018:i:7:p:2457-:d:157886).

Kirstein, I.V., Kirmizi, S., Wichels, A., Garin-Fernandez, A., Erler, R., Löder, M., Gerdts, G., 2016. Dangerous hitchhikers? Evidence for potentially pathogenic *Vibrio* spp. on microplastic particles. Mar. Environ. Res. 120, 1–8. https://doi.org/10.1016/j.marenvres.2016.07.004.

Koelmans, A.A., Besseling, E., Shim, W.J., 2015. Nanoplastics in the aquatic environment. Critical review. Marine Anthropogenic Litter. Springer, Cham, pp. 325–340.

Koelmans, A.A., Bakir, A., Burton, G.A., Janssen, C.R., 2016. Microplastic as a vector for chemicals in the aquatic environment: critical review and model-supported reinterpretation of empirical studies. Environ. Sci. Technol. 50 (7), 3315–3326. https://doi.org/10.1021/acs.est.5b06069.

Kong, S., Ji, Y., Liu, L., Chen, L., Zhao, X., Wang, J., Bai, Z., Sun, Z., 2012. Diversities of phthalate esters in suburban agricultural soils and wasteland soil appeared with urbanization in China. Environ. Pollut., 161–168 https://doi.org/10.1016/j.envpol.2012.06.017.

Kosuth, M., Wattenberg, E.V., Mason, S.A., Tyree, C., Morrison, D., 2017. Synthetic Polymer Contaminating Global Drinking Water. https://orbmedia.org/stories/invisibles_final_report (Accessed 20 May 2018).

Lachenmeier, D.W., Kocareva, J., Noack, D., Kuballa, T., 2015. Microplastic identification in German beer-an artefact of laboratory contamination? Dtsch. Lebensmitt. Rundsch. 111 (10), 437–440.

Laitala, K., Klepp, I.G., Henry, B., 2017. In use phase of wool apparel: a literature review for improving lca. In: Bakker, C., Mugge, R. (Eds.), Product Lifetimes And The Environment - PLATE 2017, Delft, 9 November, 2017. Delft University of Technology and IOS Press, Delft , pp. 202–207. http://ebooks.iospress.nl/volumearticle/47870.

Laitala, K., Klepp, I.G., Henry, B., 2018. Does use matter? Comparison of environmental impacts of clothing based on fiber type. Sustain. For. 10 (7), 1–25.

Lamb, J.B., Willis, B.L., Fiorenza, E.A., Couch, C.S., Howard, R., Rader, D.N., True, J.D., Kelly, L.A., Ahmad, A., Jompa, J., Harvell, C.D., 2018. Plastic waste associated with disease on coral reefs. Science 359 (6374), 460–462. https://doi.org/10.1126/science.aar3320.

Lambert, S., Wagner, M., 2016. Characterisation of nanoplastics during the degradation of polystyrene. Chemosphere 145, 265–268. https://doi.org/10.1016/j.chemosphere.2015.11.078.

Lenz, R., Enders, K., Stedmon, C.A., Mackenzie, D.M., Nielsen, T.G., 2015. A critical assessment of visual identification of marine microplastic using Raman spectroscopy for analysis improvement. Mar. Pollut. Bull. 100 (1), 82–91. https://doi.org/10.1016/j.marpolbul.2015.09.026.

Lenz, R., Enders, K., Nielsen, T.G., 2016. Microplastic exposure studies should be environmentally realistic. Proc. Natl. Acad. Sci. 113 (29), E4121–E4122. https://doi.org/10.1073/pnas.1606615113.

Li, L., Frey, M., Browning, K.J., 2010. Biodegradability study on cotton and polyester fabrics. Journal of Engineered Fabrics & Fibers (JEFF) 5, 42–53.

Liebezeit, G., Liebezeit, E., 2013. Non-pollen particulates in honey and sugar. Food Addit. Contam., Part A 30 (12), 2136–2140. https://doi.org/10.1080/19440049.2013.843025.

Liebezeit, G., Liebezeit, E., 2014. Synthetic particles as contaminants in German beers. Food Addit. Contam., Part A 31 (9), 1574–1578. https://doi.org/10.1080/19440049.2014.945099.

Lönnstedt, O.M., Eklöv, P., 2016. Environmentally relevant concentrations of microplastic particles influence larval fish ecology. Science 352 (6290), 1213–1216. https://doi.org/10.1126/science.aad8828.

Lusher, A.L., Mchugh, M., Thompson, R.C., 2013. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. Mar. Pollut. Bull. 67 (1–2), 94–99. https://doi.org/10.1016/j.marpolbul.2012.11.028.

Machado, A.A.dS., Kloas, W., Zarfl, C., Hempel, S., Rillig, M.C., 2018. Microplastics as an emerging threat to terrestrial ecosystems. Glob. Chang. Biol. 24, 1405–1416. https://doi.org/10.1111/gcb.14020.

Mahon, A.M., O'Connell, B., Healy, M.G., O'Connor, I., Officer, R., Nash, R., Morrison, L., 2016. Microplastics in sewage sludge: effects of treatment. Environ. Sci. Technol. 51 (2), 810–818. https://doi.org/10.1021/acs.est.6b04048.

Mason, S.A., Welch, V., Neratko, J., 2018. Synthetic polymer contamination in bottled water. Available from Department of Geology and Environmental Sciences, Fredonia University, New York https://orbmedia.org/sites/default/files/FinalBottledWaterReport.pdf Accessed 23 March 2018.

Mathalon, A., Hill, P., 2014. Microplastic fibers in the intertidal ecosystem surrounding Halifax Harbor, Nova Scotia. Mar. Pollut. Bull. 81 (1), 69–79. https://doi.org/10.1016/j.marpolbul.2014.02.018.

Mattsson, K., Johnson, E.V., Malmendal, A., Linse, S., Hansson, L.A., Cedervall, T., 2017. Brain damage and behavioural disorders in fish induced by plastic nanoparticles delivered through the food chain. Sci. Rep. 7 (1), 11452. https://doi.org/10.1038/s41598-017-10813-0.

McCormick, A., Hoellein, T.J., Mason, S.A., Schluep, J., Kelly, J.J., 2014. Microplastic is an abundant and distinct microbial habitat in an urban river. Environ. Sci. Technol. 48, 11863–11871. https://doi.org/10.1021/es503610r.

McNeil, S.J., Sunderland, M.R., Zaitseva, L.I., 2007. Closed-loop wool carpet recycling. Resour. Conserv. Recycl. 51 (1), 220–224. https://doi.org/10.1016/j.resconrec.2006.09.006.

Mills, J., 2011. Polyester & cotton: unequal competitors. Tecnon OrbiChem presentation at Association Française Cotonnière (AFCOT), Deauville, France, 6 October 2011 http://www.coton-acp.org/modules/docpool/files/atelierspolyester-coton.pdf (Accessed 27 September 2018).

Mintenig, S.M., Int-Veen, I., Loder, M.G.J., Primpke, S., Gerdts, G., 2017. Identification of microplastic in effluents of waste water treatment plants using focal plane array based micro-Fourier-transform infrared imaging. Water Res. 108, 365–372. https://doi.org/10.1016/j.watres.2016.11.015.

Murphy, F., Ewins, C., Carbonnier, F., Quinn, B., 2016. Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. Environ. Sci. Technol. 50, 5800–5808. https://doi.org/10.1021/acs.est.5b05416.

Napper, I.E., Thompson, R.C., 2016. Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions. Mar. Pollut. Bull. 112 (1), 39–45. https://doi.org/10.1016/j.marpolbul.2016.09.025.

Nelms, S.E., Galloway, T.S., Godley, B.J., Jarvis, D.S., Lindeque, P.K., 2018. Investigating microplastic trophic transfer in marine top predators. Environ. Pollut. 238, 999–1007.

Nizzetto, L., Futter, M., Langaas, S., 2016. Are agricultural soils dumps for microplastics of urban origin? Environ. Sci. Technol. 50, 10777–10779. https://doi.org/10.1021/acs.est.6b04140.

Obbard, R.W., Sadri, S., Wong, Y.Q., Khitun, A.A., Baker, I., Thompson, R.C., 2014. Global warming releases microplastic legacy frozen in Arctic Sea ice. Earth's Future 2 (6), 315–320. https://doi.org/10.1002/2014EF000240.

Oberbeckmann, S., Löder, M.G., Labrenz, M., 2015. Marine microplastic-associated biofilms–a review. Environ. Chem. 12 (5), 551–562. https://doi.org/10.1071/EN15069.

Ocean Conservancy, N.O.A.A., 2013. Talking trash & taking action. Publication of the Talking Trash & Taking Action Educational Program of the Ocean Conservancy and National Oceanic and Atmospheric Administration Marine Debris Program. [Accessed January 2018]. https://marinedebris.noaa.gov/sites/default/files/publications-files/talking-trash-educational.pdf.

Oerlikon, 2009. The Fiber Year 2008/2009: A World Survey on Textile and Nonwovens Industry. Oerlikon, Switzerland https://www.oerlikon.com/ecomaXL/get_blob.php?name=Layout_Fibre_Year_08_09_290509__s_screen.pdf, Accessed date: 25 September 2018.

Pauly, J.L., Stegmeier, S.J., Allaart, H.A., Cheney, R.T., Zhang, P.J., Mayer, A.G., Streck, R.J., 1998. Inhaled cellulosic and plastic fibers found in human lung tissue. Cancer Epidemiol. Biomark. Prev. 7, 419–428. https://doi.org/10.1136/tc.11.suppl_1.i51.

Pekhtasheva, E.L., Neverov, A.N., Kubica, S., Zaikov, G.E., 2011. Biodegradation and biodeterioration of some natural polymers. Polymers Research Journal 5, 77.

Peng, J., Wang, J., Cai, L., 2017. Current understanding of microplastics in the environment: occurrence, fate, risks, and what we should do. Integr. Environ. Assess. Manag. 13 (3), 476–482. https://doi.org/10.1002/ieam.1912.

Pirc, U., Vidmar, M., Mozer, A., Krzan, A., 2016. Emissions of microplastic fibers from microfiber fleece during domestic laundry. Environ. Sci. Pollut. Res. 23, 22206–22211. https://doi.org/10.1007/s11356-016-7703-0.

PlasticsEurope, 2008. The compelling facts about plastics: an analysis of plastic production. Demand and Recovery for 2006 in Europe https://www.plasticseurope.org/application/files/2815/1689/9283/2006compelling_fact_PubJan2008.pdf, Accessed date: 27 September 2018.

PlasticsEurope, 2016. Plastics—the facts 2016: AN ANALYSIS of European plastics production, demand and waste data. https://www.plasticseurope.org/application/files/4315/1310/4805/plastic-the-fact-2016.pdf, Accessed date: 26 September 2018.

Redondo-Hasselerharm, P.E., Falahudin, D., Peeters, E.T., Koelmans, A.A., 2018. Microplastic effect thresholds for freshwater benthic macroinvertebrates. Environ. Sci. Technol. 52 (4), 2278–2286. https://doi.org/10.1021/acs.est.7b05367.

Reisser, J., Shaw, J., Hallegraeff, G., Proietti, M., Barnes, D.K., Thums, M., Wilcox, C., Hardesty, B.D., Pattiaratchi, C., 2014. Millimeter-sized marine plastics: a new pelagic habitat for microorganisms and invertebrates. PLoS One 9 (6), e100289. https://doi.org/10.1371/journal.pone.0100289.

Remy, F., Collard, F., Gilbert, B., Compère, P., Eppe, G., Lepoint, G., 2015. When microplastic is not plastic: the ingestion of artificial cellulose fibers by macrofauna living in seagrass macrophytodetritus. Environ. Sci. Technol. 49 (18), 11158–11166. https://doi.org/10.1021/acs.est.5b02005.

Revel, M., Châtel, A., Mouneyrac, C., 2018. Micro(nano)plastics: a threat to human health? Current Opinion in Environmental Science & Health 1, 17–23. https://doi.org/10.1016/j.coesh.2017.10.003.

Rillig, M.C., 2018. Microplastic disguising as soil carbon storage. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.8b02338.

Rillig, M.C., Ziersch, L., Hempel, S., 2017. Microplastic transport in soil by earthworms. Sci. Rep. 7 (1), 1362.

Rist, S., Almroth, B.C., Hartmann, N.B., Karlsson, T.M., 2018. A critical perspective on early communications concerning human health aspects of microplastics. Sci. Total Environ. 626, 720–726. https://doi.org/10.1016/j.scitotenv.2018.01.092.

Rochman, C.M., Hentschel, B.T., Teh, S.J., 2014a. Long-term sorption of metals is similar among plastic types: implications for plastic debris in aquatic environments. PLoS One 9 (1), e85433. https://doi.org/10.1371/journal.pone.0085433.

Rochman, C.M., Kurobe, T., Flores, I., Teh, S.J., 2014b. Early warning signs of endocrine disruption in adult fish from the ingestion of polyethylene with and without sorbed chemical pollutants from the marine environment. Sci. Total Environ. 493, 656–661. https://doi.org/10.1016/j.scitotenv.2014.06.051.

Rochman, C.M., Tahir, A., Williams, S.L., Baxa, D.V., Lam, R., Miller, J.T., Teh, F.C., Werorilangi, S., Teh, S.J., 2015. Anthropogenic debris in seafood: plastic debris and fibers from textiles in fish and bivalves sold for human consumption. Sci. Rep. 5, 14340. https://doi.org/10.1038/srep14340.

Setälä, O., Magnusson, K., Lehtiniemi, M., Norén, F., 2016. Distribution and abundance of surface water microlitter in the Baltic Sea: a comparison of two sampling methods. Mar. Pollut. Bull. 110 (1), 177–183. https://doi.org/10.1016/j.marpolbul.2016.06.065.

Sundt, P., Schulze, P.E., Syversen, F., 2014. Sources of Microplastic-Pollution to the Marine Environment. Mepex Report for the Norwegian Environment Agency www.miljodirektoratet.no/Documents/publikasjoner/M321/M321.pdf, Accessed date: March 2018.

Szostak-Kotowa, J., 2004. Biodeterioration of textiles. Int. Biodeterior. Biodegrad. 53 (3), 165–170. https://doi.org/10.1016/S0964-8305(03)00090-8.

Talvitie, J., Heinonen, M., Pääkkönen, J.P., Vahtera, E., Mikola, A., Setälä, O., Vahala, R., 2015. Do wastewater treatment plants act as a potential point source of microplastics? Preliminary study in the coastal Gulf of Finland, Baltic Sea. Water Sci. Technol. 72 (9), 1495–1504. https://doi.org/10.2166/wst.2015.360.

Taylor, M.L., Gwinnett, C., Robinson, L.F., Woodall, L.C., 2016. Plastic microfibre ingestion by deep-sea organisms. Sci. Rep. 6, 33997. https://doi.org/10.1038/srep33997.

The Fiber Year, 2017. The Fiber Year 2017: 2016 World Fiber Market. https://www.nonwovens-industry.com/contents/view_online-exclusives/2017-05-23/the-fiber-year-reports-on-2016-world-fiber-market, Accessed date: May 2018.

Vandermeersch, G., Van Cauwenberghe, L., Janssen, C.R., Marques, A., Granby, K., Fait, G., Kotterman, M.J., Diogène, J., Bekaert, K., Robbens, J., Devriese, L., 2015. A critical view on microplastic quantification in aquatic organisms. Environ. Res. 143, 46–55. https://doi.org/10.1016/j.envres.2015.07.016.

Waring, R.H., Harris, R.M., Mitchell, S.C., 2018. Plastic contamination of the food chain: a threat to human health? Maturitas 115, 64–68. https://doi.org/10.1016/j.maturitas.2018.06.010.

Woodall, L.C., Sanchez-Vidal, A., Canals, M., Paterson, G.L., Coppock, R., Sleight, V., Calafat, A., Rogers, A.D., Narayanaswamy, B.E., Thompson, R.C., 2014. The deep sea is a major sink for microplastic debris. Royal Society Open Science 1 (4), 140317. https://doi.org/10.1098/rsos.140317.

Woodall, L.C., Gwinnett, C., Packer, M., Thompson, R.C., Robinson, L.F., Paterson, G.L., 2015. Using a forensic science approach to minimize environmental contamination and to identify microfibres in marine sediments. Mar. Pollut. Bull. 95 (1), 40–46.

Wright, S.L., Kelly, F.J., 2017. Plastic and human health: a micro issue? Environ. Sci. Technol. 51 (12), 6634–6647. https://doi.org/10.1021/acs.est.7b00423.

Wright, S.L., Rowe, D., Thompson, R.C., Galloway, T.S., 2013a. Microplastic ingestion decreases energy reserves in marine worms. Curr. Biol. 23, 1031–1033. https://doi.org/10.1016/j.cub.2013.10.068.

Wright, S.L., Thompson, R.C., Galloway, T.S., 2013b. The physical impacts of microplastics on marine organisms: a review. Environ. Pollut. 178, 483–492. https://doi.org/10.1016/j.envpol.2013.02.031.

Yu, Y., Zhou, D., Li, Z., Zhu, C., 2018. Advancement and challenges of microplastic pollution in the aquatic environment: a review. Water Air Soil Pollut. 229, 140. https://doi.org/10.1007/s11270-018-3788-z.

Zhang, G.S., Liu, Y.F., 2018. The distribution of microplastics in soil aggregate fractions in southwestern China. Sci. Total Environ. 642, 12–20. https://doi.org/10.1016/j.scitotenv.2018.06.004.

Zhao, S., Zhu, L., Li, D., 2016. Microscopic anthropogenic litter in terrestrial birds from Shanghai, China: not only plastic but also natural fibers. Sci. Total Environ. 550, 1110–1115. https://doi.org/10.1016/j.scitotenv.2016.01.112.

Zubris, K.A.V., Richards, B.K., 2005. Synthetic fibers as an indicator of land application of sludge. Environ. Pollut. 138 (2), 201–211. https://doi.org/10.1016/j.envpol.2005.04.013.