Eionet Report - ETC/CE 2022/1

Microplastic pollution from textile consumption in Europe

February 2022

European Environment Agency
European Topic Centre
Circular economy and resource use

European Environment Agency
European Topic Centre on Waste and
Materials in a Green Economy

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Cover design: EEA
Cover photo © iStock Photo, picture by: robertsrob, reference: 519789072
Layout: ETC/CE

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Acknowledgements

This report has been produced within the task on ‘Microplastic pollution from textile consumption in Europe’ of the 2021 ETC/WMGE work program. Lars Mortensen (EEA) has been the project leader and Saskia Manshoven (ETC/WMGE) has been the task leader. The report was finalised and published under the 2022 work program of the successive, new ETC/CE.

The authors are grateful to the following experts and organisations for their comments that substantially improved the quality of the report: Paulo Da Silva (DG ENV), Carsten Wacholtz (The Ellen MacArthur Foundation), Sophie Mather (Microfibre Consortium), Valeria Botta (ECOS), Katy Stevens (European outdoor Group), Martina Luisa Martinez (The Policy Hub - Circularity for Apparel and Footwear) and Kristof Tirez (VITO). Bart Ullstein (BEC) provided careful editing of the report. Francesca Grossi (CSCP) and her team provided graphic design support.

1 Introduction

Plastics play an essential role in modern society. Their diversity and versatility make them indispensable materials used across all sectors from electronics and consumer goods, through building materials and synthetic textiles, to food packaging. In 2019, almost 370 million tonnes of plastics, plus around 70 million tonnes of synthetic fibre, were produced globally (Textile Exchange, 2020), of which 58 million tonnes originated in Europe (1) (Plastics Europe, 2020). However, since most plastics are made of fossil resources and persist in the environment for many years, their impact on the environment and climate is receiving increasing attention (EEA, 2021d).

Plastic waste released into the environment ends up in rivers, waterways and coastal waters, adding to the growing amount of marine litter that pollutes oceans and beaches worldwide. It is estimated that 6–15 million tonnes of plastics, representing 2-4 per cent of global production, enters the natural environment every year (Velis et al., 2017). Land-based sources, such as uncontrolled dumping of waste and littering, account for about 80 per cent of marine litter (Velis et al., 2017). Under the influence of sunlight, wind, waves and other mechanical action, this plastic debris can degrade into small fragments, so-called microplastics sized 0.001–5 millimetres (mm), or even smaller nanoplastics measuring < 0.001 mm (Velis et al., 2017). Additionally, some microplastics, such as microbeads in cosmetics or plastics granulates, are deliberately produced and are subsequently released in wastewater, intentionally or unintentionally. Others are formed during the use of products, such as tyre abrasion from road transport or microfibre release during the washing of synthetic textiles. These microplastics also end up in the ocean, through the runoff of city dust and the discharge of wastewater into rivers.

In recent years, concern about microplastic pollution has increased with research estimating that at least 14 million tonnes of microplastics have accumulated in the world's oceans (Barrett et al., 2020). According to the EU Strategy for Plastics in the Circular Economy (2019), the estimated release of microplastics to the environment in the EU is 75,000–300,000 tonnes each year (EC 2019).

While the washing of textiles is considered an important pathway of microfibre release (of both synthetic and natural origin), it is clear that microfibres are released from textiles throughout their entire lifecycles, from manufacturing, through use to waste treatment. Moreover, microfibres may also be released to air, for example, during the drying and wearing of garments (OECD, 2020a). Synthetic textiles are considered to be important source of plastic microfibres. It is estimated that synthetic textiles are responsible for the discharge of between 0.2 and 0.5 million tonnes of microplastics into the oceans each year (Ellen MacArthur Foundation, 2017; Eunomia, 2016).

Textiles and plastics are two of the key product value chains that are considered a priority in the EU Circular Economy Action Plan (EC, 2020a). As a result, the EEA has devoted specific attention to textiles and plastics in the circular economy, building the knowledge base on the textiles and plastics systems, their environmental and social impacts, and potential pathways to more sustainable and circular systems.

The briefing *Textiles in Europe's Circular Economy* (EEA, 2019) and its underpinning ETC report *Textiles and the environment in a circular economy* (ETC/WMGE, 2019) highlighted the sector's significant environmental impacts, ranking textiles as the fourth most significant in the use of primary raw materials and water – after food, housing and transport, and fifth for greenhouse gas (GHG) emissions. The study also highlighted that synthetic fibres have overtaken cotton in the production of clothing, household textiles and technical textiles. It is estimated that about 60 per cent of fibres used in clothing and 70 per cent used in household textiles are synthetic, with polyester being the most commonly used fibre. A follow-up briefing and report, *Plastics in textiles* (EEA, 2021c; ETC/WMGE, 2021c), examined the specific challenges posed by synthetic textiles and identified levers for circular economy solutions to reduce their

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[1] EU, Norway, Switzerland and the United Kingdom

environmental and climate impacts. The issue of microplastic release from synthetic textile production, washing and waste treatment was also briefly touched upon.

The EEA report *Plastics, the circular economy and Europe's environment – a priority to action* highlighted both the huge importance of plastics in our everyday lives (EEA, 2021d) and the enormous challenge of plastic waste entering the environment where it persists and can break down into microplastics. Many plastic products, such as packaging, are often only used once and are then discarded, often littered. This shows the need to move from the current linear plastics system to a more circular one, enabling longer use, reuse and recycling, thus reducing their environmental impacts. Textiles, being significant users plastics, are one of the areas of attention of the report.

While the emerging issue of microplastic pollution has gained a lot of attention from research and, to some extent, policy in recent years, there are still many unknowns and unsolved challenges. Estimating microplastic release and accumulation is challenging as measurement methods are still being developed. At the same time, factors determining the release of microplastics are still poorly understood and the long-term effects on ecosystems and human health are still unclear (Henry et al., 2019a; Salvador Cesa et al., 2017a).

The aim of this report is to contribute to an improved understanding of microplastics release from textiles, with a focus on European consumption, and to explore potential approaches to reduce their release from textiles. Chapter 2 presents current knowledge about microplastics sources and release mechanisms from a European perspective, focusing on the specific characteristics of microplastics originating from textiles and their release mechanisms across the textiles value chain. Chapter 3 focuses on the fate and impacts of microplastics on ecosystems and human health. Finally, Chapter 4 explores pathways to avoid, reduce or mitigate the release of microplastics from textiles in Europe, or reduce their environmental impact.

2 Sources of microplastic in the European environment

This chapter gives a general overview of the sources and release of microplastics in Europe and globally. It also describes the specific characteristics of microplastics originating from textiles and their release mechanisms across their value chain.

Plastics are ubiquitous in our everyday lives. In 2019, worldwide production of plastics amounted to around 370 million tonnes, plus about 70 million tonnes of synthetic fibre (Textile Exchange, 2020). Packaging, building materials and transportation are the three largest consumers of plastics. European (2) demand for plastics is almost 51 million tonnes (excluding textile fibres), 40 per cent of which is packaging, 20 per cent is construction materials and almost 10 per cent is used by the automotive sector (Plastics Europe, 2020). The European demand for synthetic textiles (3) is estimated at 8 million tonnes (ETC/WMGE, 2021c), representing almost 14 per cent of Europe's total plastic consumption.

2.1. Sources of microplastics

Microplastic formation and dispersion

Release of microplastics occurs throughout the plastics value chain, during production, transport, use and at the end of life. There are two major routes of microplastic formation, classifying microplastics into primary and secondary sources.

Primary microplastics are directly released into the environment in the form of plastic particles (Box 2.1). They can be deliberately added to a range of products, for example as abrasive microbeads, stabilisers or glitter in cosmetics, or as granular infill materials in artificial turf sports pitches. The European Chemicals Agency (ECHA) estimates that 145,000 tonnes of deliberately produced microplastics are used in the Europe (4) each year (ECHA, 2021). Primary microplastics can also be generated from spills during production, and from wear and tear of plastic products during their use, such as from the abrasion of shoe soles, car tyres and road markings; peeling and flaking paints and coatings; or textile microfibres released through washing. Most of these losses are accidental or unintentional, due to weathering, transport, use or in the recycling of plastic products. Only the release of microbeads from cosmetics can be considered as intentional, since these are added to the products and are meant to be discharged into wastewater (Boucher and Friot, 2017).

Once the microplastic particles have been released into the environment, they are dispersed through a number different routes, such as wind, road runoff, wastewater and surface water. The majority, from the abrasion of tyres, road markings and city dust, are spread in road runoff and those from textiles and personal care products in wastewater (Boucher and Friot, 2017). Atmospheric transport of microplastics is particularly relevant in densely populated areas, which generate higher concentrations of microplastics due to higher transport and car use and higher plastic consumption and waste generation. These urban microplastics are mainly transported through runoff and sewers into wastewater treatment installations or directly into rivers. Snow and ice sheets can also transport and deposit microplastics. All microplastics eventually end up in final deposits or sinks such as the ocean, soils and sediments, residual waste, or in sewage sludges resulting from wastewater treatment that are applied to agricultural land as fertilisers (Eunomia and ICF, 2018). It is estimated that about 48 per cent of primary microplastic is eventually

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[2] EU, Norway, Switzerland and the United Kingdom

[3] Estimate of textiles consumption is 26 kilograms per person. Assuming 60 per cent of total textile consumption to be synthetic results in a plastic fibre consumption of 8 million tonnes for the EU, Norway, Switzerland and the Unite Kingdom (527,642,683 inhabitants in 2019 according to Eurostat)

[4] EEA member countries

released into the ocean, while the remainder is trapped in soil, waste or sewage sludge (Boucher and Friot, 2017; Eunomia and ICF, 2018).

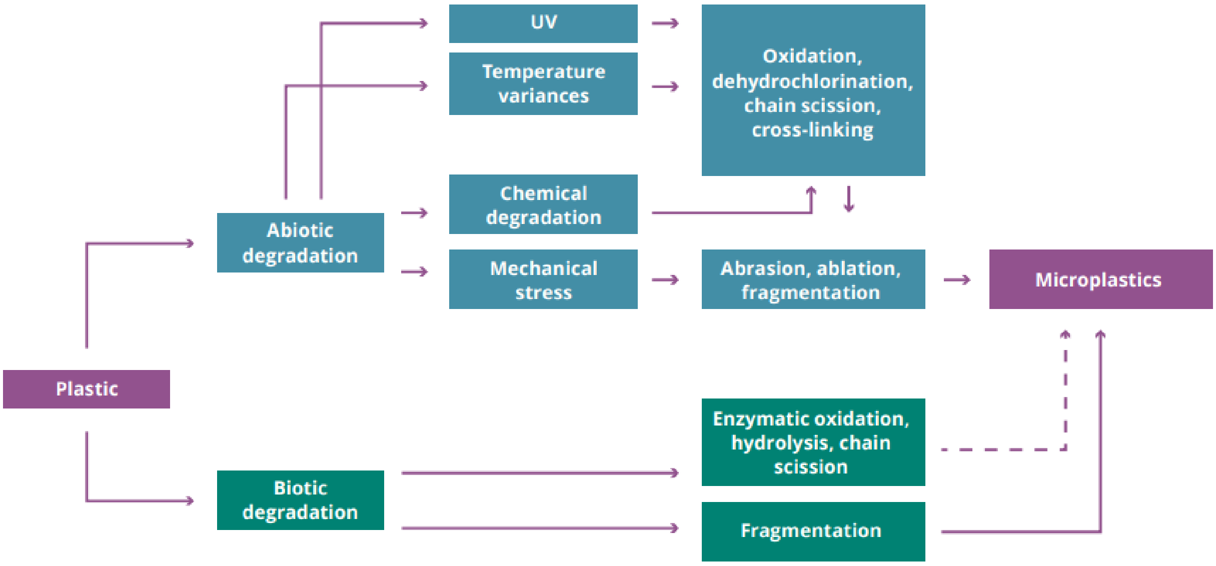
Box 2.1 Sources of primary microplastics

1. **Pellet losses:** most plastic products are made from industrial plastic pellets, which are typically 2–5 mm in diameter. Incidents during production, transport and recycling can cause accidental spills of pellets into wastewater or the environment.
2. **Tyres**: abrasion of vehicle tyres during driving releases rubber particles, consisting of a mix of natural and synthetic rubber – styrene butadiene rubber typically accounts for approximately 60 per cent of vehicle tyres. These particles can be washed off the roads by wind or rain, ending up in roadside soils, in wastewater or directly in surface waters.
3. **Road markings**: road markings – paint, thermoplastic, polymer tape and epoxy – can release microplastics as a result of weathering or abrasion by vehicles.
4. **City dust**: city dust is a generic name of microplastic losses that occur in urban environments due to the use and maintenance of objects and infrastructure, including abrasion of shoe soles, artificial turfs and sports pitches, and weathering of buildings and cables.
5. **Synthetic textiles**: washing synthetic textiles releases microplastic fibres, which are not retained by washing machines and end up in wastewater. These fibres typically consist of polyester, polyethylene, acrylic or elastane.
6. **Marine coatings**: protective coatings and paints are applied to the hull and equipment of vessels to prevent corrosion or biofouling. These coatings are made of polyurethane, epoxy or vinyl, releasing microplastic particles during boat building, cleaning, repair or use, either directly into surface waters or through runoff.
7. **Personal care products:** some personal care and cosmetic products contain plastic microbeads, which are intentionally added as, for example, sorbents, scrubbing agents and glitter. During and after use, these microplastic particles are discharged into wastewater.

Source: Boucher and Friot, 2017

Secondary microplastics are formed from the breakdown of larger plastic items, often called macroplastics, in the environment, typically mismanaged plastic waste such as discarded fishing gear, littered plastic packaging or losses from open landfills. Research shows that wind can mobilise and transport plastic waste from open dumpsites, and transport it to rivers up to 10 kilometres away (Parker, 2021). A recent study by Meijer et al. (2021) estimated that 80 per cent of global plastics emissions to the ocean is caused by the discharge of more than 1,000 rivers –small rivers that flow through densely populated urban areas, especially in Asia, are the most polluted by plastic waste. These emissions have caused plastic waste to be ubiquitous across the environment. Under the influence of mechanical stress caused by weathering by wind, erosion or wave action (mechanical degradation), and sunlight (ultra-violet (UV) degradation), this macroplastic waste degrades into smaller fragments, creating secondary microplastics or smaller nanoplastics. While mechanical stress and UV-induced degradation are predominant, several other plastic degradation pathways, including biological processes, can occur (Figure 2.1).

Figure 2.1 Overview of main degradation mechanisms and pathways to microplastics



Source: Modified from Zhang, et al. (2021)

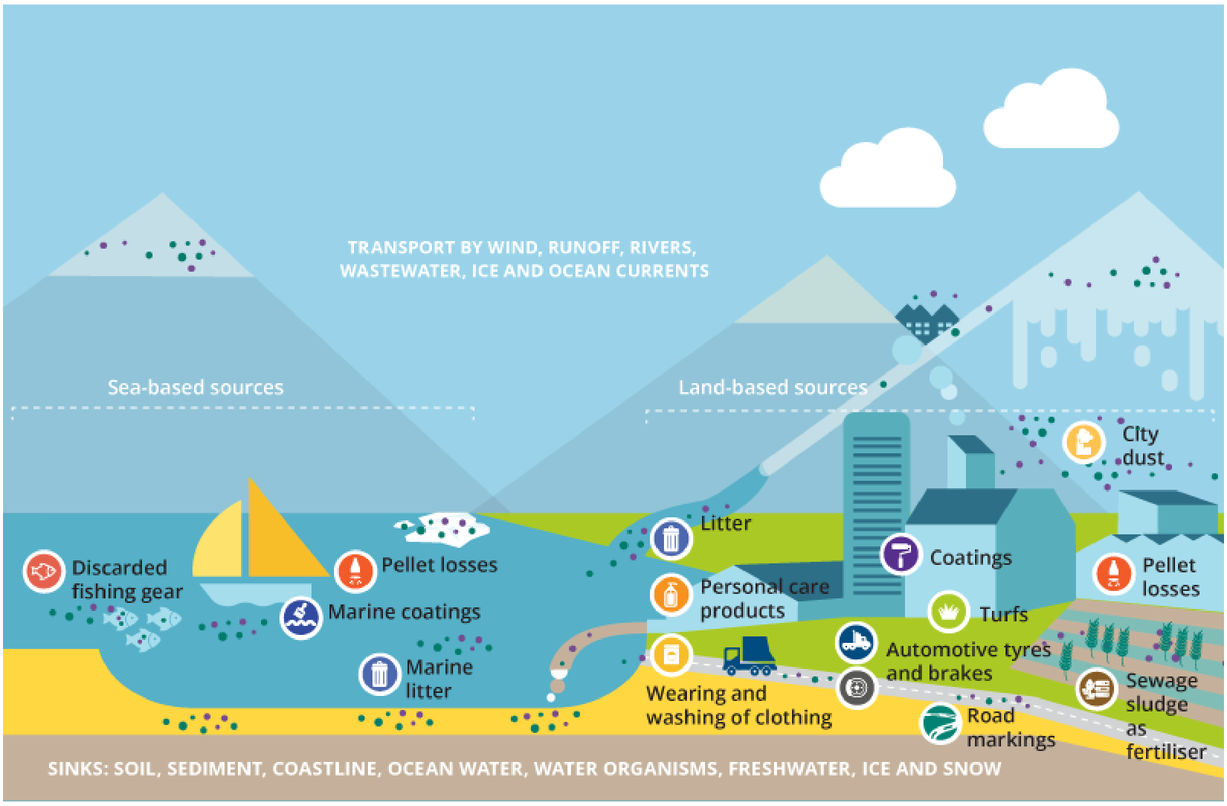
The majority of microplastic particles found in the marine environment consist of polypropylene (PP), polyethylene (PE) and polyethylene terephthalate (PET), also called polyester. These types of plastic are often used in consumer goods and packaging. Nylon is likely to originate from fishing nets, while polystyrene (PS) can be a result of the weathering of floats or styrofoam packaging. Fibre-shaped PET, nylon, acrylic and PP likely result from textile washing (De Falco et al., 2019b; UNEP, 2018).

The movement of microplastic particles in the environment is complex and driven by many factors including wind and sea currents, particle density, size and shape. Denser microplastics can accumulate in sediments on the ocean floor, which can lead to their accumulation in food chains (Boucher and Friot, 2017) (Box 2.2). As a result, microplastic pollution is globally distributed across rivers, water bodies and oceans, on river and sea shores and in animal species (Carney Almroth et al., 2018). It concentrates in some locations including ocean gyres and sediments (GESAMP, 2016).

Box 2.2 Microplastic on the ocean floor

While some plastic particles, such as PE, PP and expanded PS, float, most, including polyvinyl chloride (PVC), nylon and PET, sink to the ocean floor. It is estimated that 94 per cent of the plastic that enters the ocean ends up on its floor and in the sediment, amounting to an average quantity of 70 kilograms of plastic per square kilometre of sea bed (Eunomia, 2016). The sinking of plastics is due to the density of the polymer being greater than water's, but in the case of microplastics the density can be increased by the adsorption of heavy metals, which have a high affinity to organic polymers, from the environment (Brennecke et al., 2016). Especially in plastics used in electronics, electrical equipment, vehicles and construction, it is common to use brominated flame retardants as additives, which are relatively dense, heavy and known to be hazardous. Several studies have reported that microplastic particles can act as vectors for the transport of contaminants such as plasticisers and flame retardants, since these substances can be present as additives (De Falco et al., 2020).

Figure 2.2 Sources of microplastics, release routes and sinks



Source: illustration by CSCP

Global plastic and microplastic release

Microplastic release and formation is challenging to measure and estimate. Recent research estimates that at least 14 million tonnes of microplastics have accumulated in the world's oceans thus far (Barrett et al., 2020). Estimates on microplastics release and formation are, however, highly uncertain due to the myriad of primary and secondary sources and the lack of standardised sampling and measurement methods (Box 2.3). In literature, estimates differ in the scope they consider – source emissions ([5]), emissions to the environment ([6]), emissions to water/oceans, etc. Consequently, estimates of annual emissions vary considerably (Table 2.1).

Box 2.3 Sampling and analysis of microplastics

There are no standard procedures for sampling and analysing microplastics, which makes it challenging to compare the findings of different studies. Analysing microplastics in different media, such as water-based samples, sludges, sediments, compost, soil, air and animal tissue, typically requires different methods and modifications to established methods. Separation methods for microplastics typically include filtering or sieving, while identification and quantification is done using a broad range of chemical analyses. Sampling is challenging and the sensitivity of the studies typically depends on the ability to separate and identify the smallest particles. It can be cumbersome to accurately quantify and identify

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[5] Microplastic release from products, not taking into account capture by wastewater treatment

[6] Emissions to air, soil and surface water, taking into account capture by wastewater treatment

plastic particles, their type of polymer and potential source, especially when analysing challenging media, such as biofilms, that can cause interference in the detection method (WHO, 2019).

Currently, several CEN and ISO technical (sub-)committees and working groups on microplastics from textile sources are working on standards concerning (1) the determination of fibre loss from fabrics during washing and (2) qualitative and quantitative evaluation of microplastics.

A detailed study by the United Nations Environment Programme (UNEP) in 2018 found that about 3 million tonnes of primary microplastics are released annually into the global environment, on top of 5.3 million tonnes of macroplastics, mainly from mismanaged waste and litter, which in time will degrade and become potential sources of an unknown amount of secondary microplastics (UNEP, 2018). Others calculated similar estimates of 3.2 million tonnes of primary microplastics released by households and commercial activities annually, of which 1.5 million tonnes is released into the ocean (Boucher and Friot, 2017). This corresponds, on average, to a global release of 400 grams of primary microplastics released into the environment per person each year – the equivalent of 80 plastic grocery bags ([7]) – of which half ends up in the ocean.

The amount of secondary microplastics originating from mismanaged plastic waste is unclear. Estimates of mismanaged plastic waste, which can potentially degrade into secondary microplastics, ending up in the ocean cover a wide range, 1.15–12.7 million tonnes a year or up to 1.8 kilograms of plastic marine litter per person worldwide. Although many studies focus on microplastic release into the ocean, it is important to note that over half of microplastic releases end up in soils, due to runoff from roads, mainly particles from tyre abrasion and road markings, or the application of wastewater treatment sludge as fertiliser on fields, mainly from washing textiles (Eunomia and ICF, 2018; Boucher and Friot, 2017).

Table 2.1 Estimates of annual global plastic and microplastic releases into the environment

Source	Type of plastic release	Fate	Estimation (million tonnes)	Coverage
Global data				
UNEP, 2018	Mismanaged waste (macroplastics) Primary microplastics	To the environment To the environment	5.3 3.0	Global
Boucher and Friot, 2017	Mismanaged waste and fishing gear (macroplastics) Primary microplastics Primary microplastics	To rivers and the ocean To the environment To the ocean	10.5 3.2 (range 1.8–5.0) 1.5 (range 0.8–2.5)	Global
Jambeck et al., 2015	Mismanaged waste (macroplastics)	To the ocean	4.8–12.7	Global (coastal countries)
Lebreton et al., 2017	Mismanaged waste (macroplastics)	To rivers and the ocean	1.15-2.4	Global
Eunomia, 2016	Mismanaged waste (macroplastics) Primary microplastics	To the ocean To the ocean	12.2 0.5–1.4	Global
Meijer et al., 2021	Mismanaged waste (macroplastics)	To rivers and the ocean	0.8–2.7	Global

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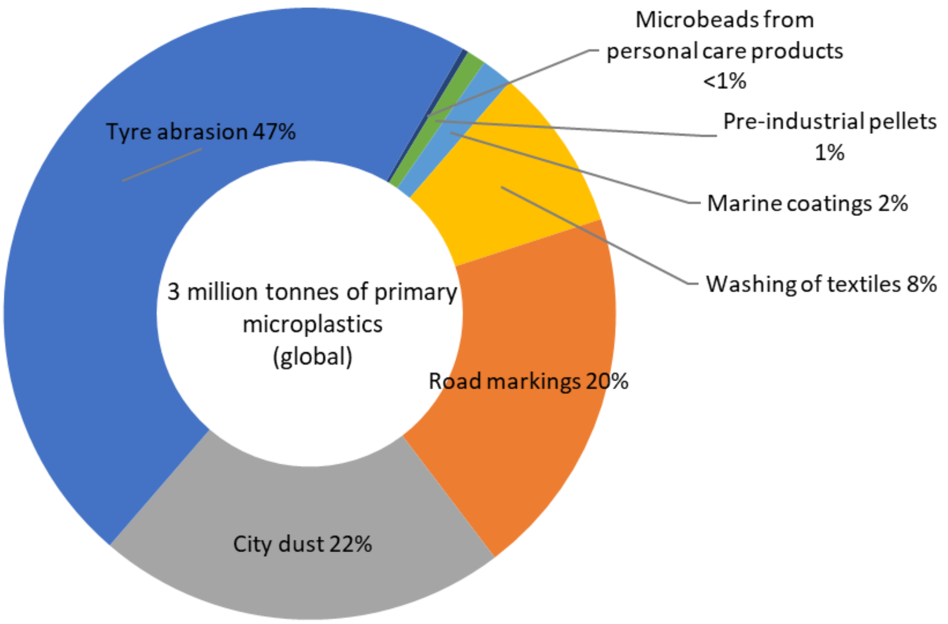
[7] Assumed weight of a plastic grocery bag: 5 grams

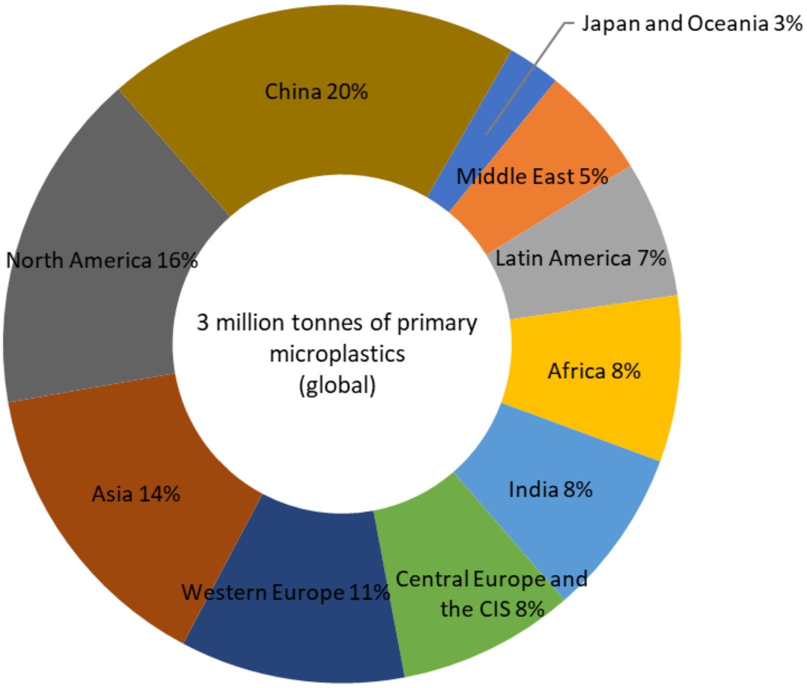
Abrasion of vehicle tyres is the predominant source of microplastic release, followed by road markings and city dust related to the built environment (Figure 2.3). The nature of plastic releases varies across global regions. For primary microplastics, population density and per-person plastic consumption are the main drivers of microplastic losses, making China, 20 per cent; North America, 16 per cent; Asia, excluding China, 14 per cent; and Western Europe, 11 per cent responsible for the majority of the microplastic release (Figure 2.4). In industrialised countries, the relative contribution of tyre abrasion and road infrastructure is higher than in developing countries, where city dust is the most important source of microplastics. In countries with inadequate waste management systems, such as open dumping and uncontrolled landfilling, mismanaged plastic waste is the main source of plastic release into the oceans, either directly or indirectly through rivers. Also, in regions where the share of households connected to wastewater treatment is low, microplastic release, for example from washing textiles, through wastewater discharge to the oceans is significant, while in regions where wastewater treatment is more common, a higher share of these microplastics are captured in wastewater treatment sludge (Boucher and Friot, 2017).

Figure 2.3 Sources of primary microplastic release to the environment, global, estimated yearly releases, per cent



Source: UNEP (2018)

Figure 2.4 Distribution of primary microplastic release to the environment, global, estimated yearly releases, per cent



Note: CIS = Azerbaijan, Belarus, Kazakhstan, Kyrgystan, Moldova, Russia, Tajikistan and Uzbekistan
Source: UNEP (2018)

Plastic and microplastic release in Europe

Several studies have estimated the release of microplastics in the European environment. The European Chemicals Agency (ECHA, 2021) calculated an annual release of 176,000 tonnes of unintentionally formed microplastics to European surface waters due to abrasion and weathering of plastic products. An additional 42,000 tonnes of microplastics deliberately added to products, such as granular infill material used on artificial turf pitches, the predominant source accounting for 16,000 tonnes, and additives to cosmetics, detergents and fertilisers, are discharged to the environment each year.

Detailed modelling by Eunomia and ICF (2018) estimated annual European primary microplastic emissions to surface water at 72,000–280,000 tonnes. Although actual source emissions of microplastics are estimated to be much higher at 670,000–940,000 tonnes per year, not all released microplastics end up in the ocean. A large share of them, for example from car tyres and roads, remain in the soil, although over time, they may be released to water, or are captured in sludges by sewage systems or wastewater treatment plants, which are then incinerated, landfilled or applied to agricultural land. Since waste management systems are well established across Europe, mismanaged plastic waste is not considered a major source of plastics in the European environment (UNEP, 2018). A recent study estimated that between 307 and 925 million items of litter are released annually into the ocean, 82 % of which is plastic (González-Fernández et al., 2021). Plastic leakage to the ocean originating from litter in Europe is estimated at 50,000–180,000 tonnes per year (Jambeck et al., 2015)..

Several studies assessed the microplastic release per person in a selection of European countries, yielding rough estimates of 1–5 kilograms per person per year (Table 2.2). Extrapolating these estimates to the entire EU population (8) yields an annual release of 0.5–2.2 million tonnes of microplastics to the environment.

Table 2.2 Estimates of annual plastic and microplastic releases into the environment in Europe

Source	Type of plastic release	Fate	Estimate	Coverage
Essel et al. (2015)	Litter (macroplastics) Primary microplastics	To the ocean To the environment	3.4–5.7 million tonnes (estimated as 6-10 per cent of total plastic production) 1.26 million tonnes (including tyre abrasion, pellet loss and textile washing)	Europe
Jambeck et al. (2015)	Litter (macroplastics)	To the ocean	50,000–180,000 tonnes	EU (23 countries)
UNEP (2018)	Primary microplastics Litter (macroplastics)	To the environment To the environment	570,000 tonnes 192,000 tonnes	Europe + CIS (9)
Eunomia and ICF (2018)	Primary microplastics	Total source emissions To surface water To soil	675,000–941,000 tonnes 72,000 - 280,000 tonnes 400,000 tonnes	EU, Norway, Switzerland and United Kingdom
ECHA (2021)	Primary microplastics	To the environment To surface water	42,000 tonnes (intentional) 176,000 tonnes (unintentional)	EEA-32 + UK
Country estimates				
Essel et al. (2015)	Primary microplastics	To the environment	2.2–5.1 kg/person	Germany
Bertling et al. (2018)	Macroplastics Primary microplastics	To the environment To the environment	1.4 kg/person 4.0 kg/person	Germany
Sundt et al. (2014)	Primary microplastics	Total source emissions To the sea after wastewater treatment	1.6 kg/person 0.8 kg/person	Norway
Magnusson et al. (2016)	Primary microplastics	To the sea after wastewater treatment (land-based sources)	4.1 kg/person	Sweden
Lassen et al. (2015)	Primary microplastics	Total source emissions	0.9–2.4 kg/person	Denmark

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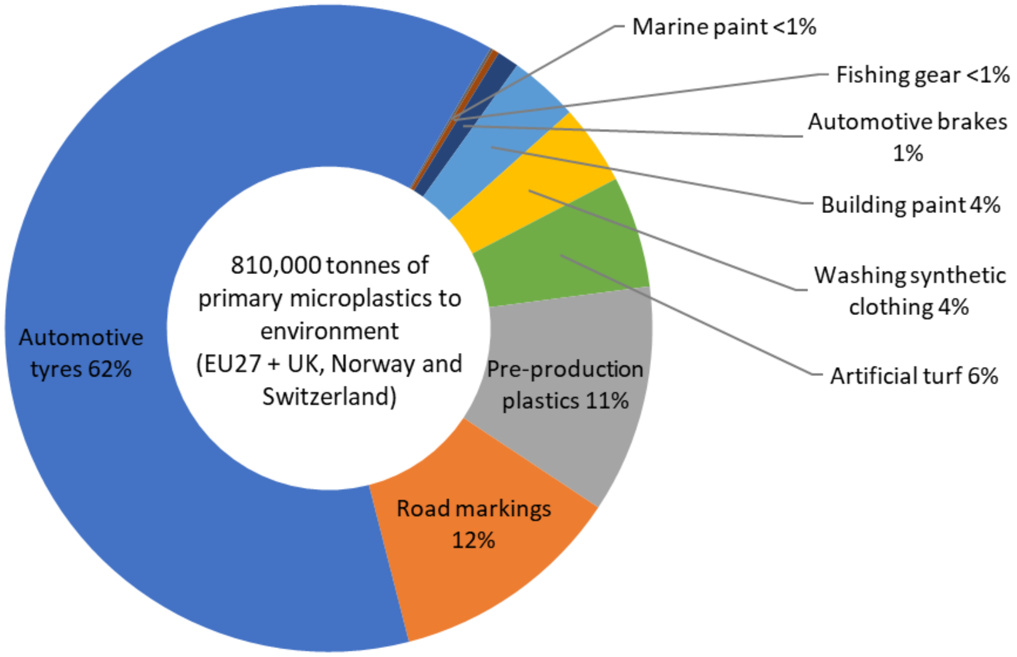
[8] EU population in 2020 was 448 million (Eurostat)

[9] CIS: Commonwealth of Independent States: Azerbaijan, Belarus, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan and Uzbekistan.

		To the sea after wastewater treatment	0.1–0.5 kg/person	

In Europe, 62 per cent of primary microplastic emissions are from tyre abrasion, 12 per cent come from abrasion of road markings and 11 per cent from the loss of plastic pellets; washing synthetic textiles only contributes around 4 per cent as a large share is captured by wastewater treatment (Eunomia and ICF, 2018) (Figure 2.5). About half of these emissions are released to air and deposited on soils, where they are retained. Of those that get washed out by road runoff, such as from tyre abrasion or building paint, a large share is captured in the sewage system, while those released in wastewater, such as from washing of textiles, are retained during wastewater treatment. Across Europe, most households are connected to wastewater treatment, where a large share of microplastics is retained (Box 5). During wastewater treatment, the retained microplastics are concentrated in sludge, half of which is applied on land, the other half is incinerated (Eunomia and ICF, 2018). Only around 20 per cent of microplastic source emissions, about 173,000 tonnes ([10]), end up in surface water (Figure 2.6).

Figure 2.5 Primary microplastics emissions to water, soil and waste management, EU27 + United Kingdom, Norway and Switzerland, estimated yearly emissions, per cent



Note: mean values of ranges are displayed (total may not sum due to rounding)
Source: Eunomia and ICF (2018)

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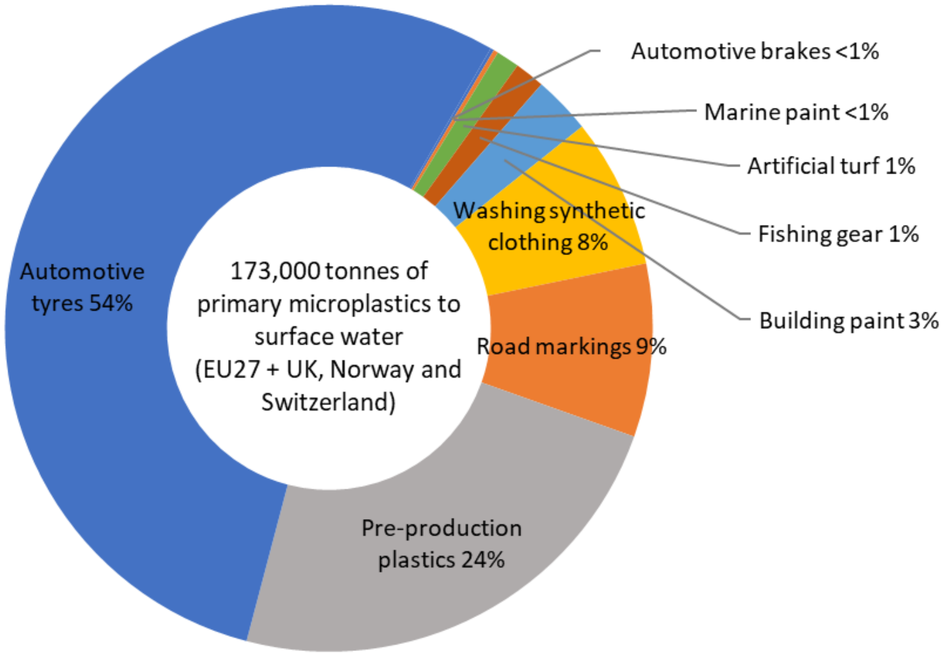
[10] Sum of mean values of all sources

Figure 2.6 Primary microplastics release to surface water after wastewater treatment, EU + United Kingdom, Norway and Switzerland, estimated yearly emissions, per cent

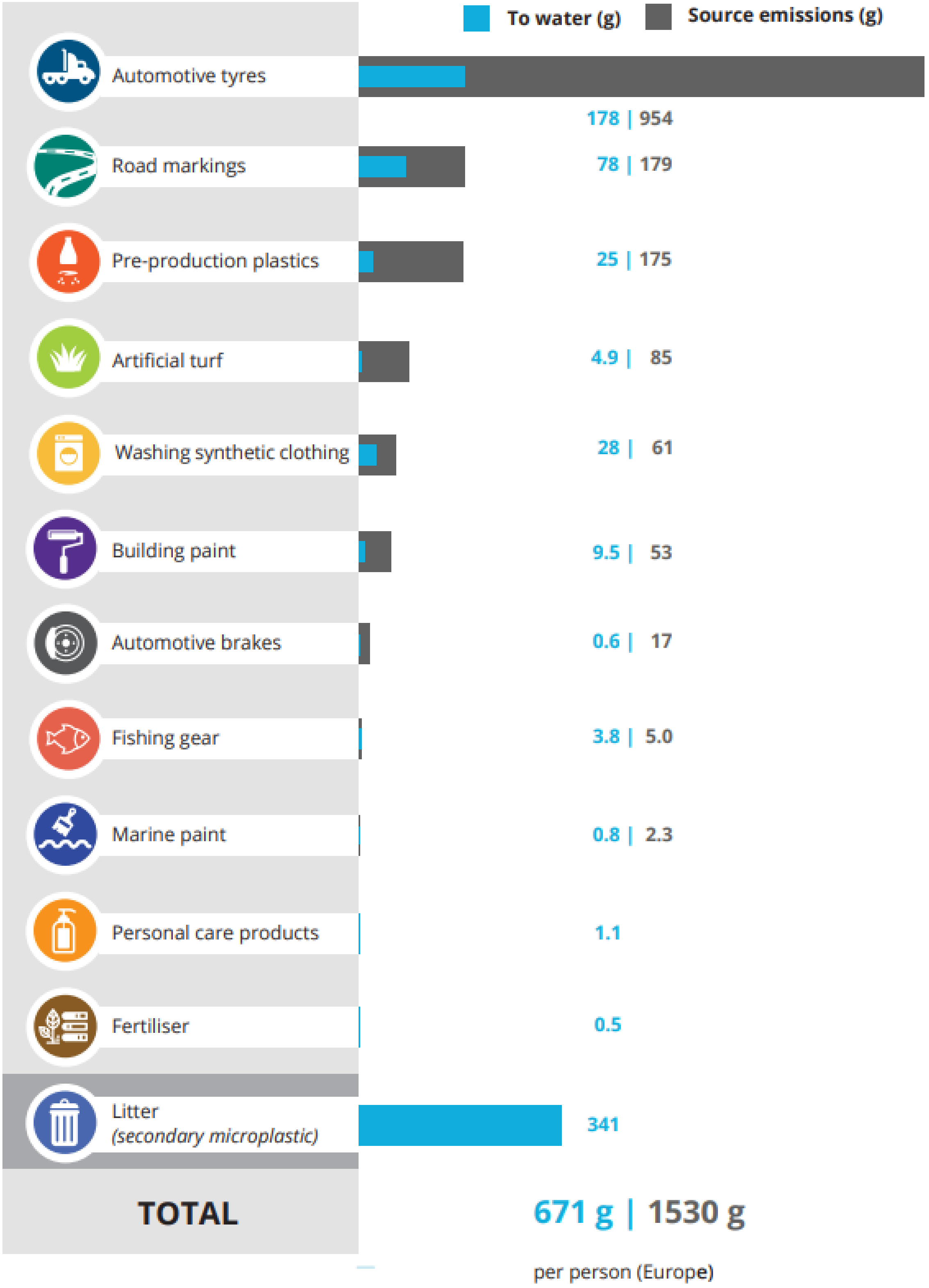


Note: mean values of ranges are displayed (total may not sum due to rounding)
Source: Eunomia and ICF (2018)

An overview of the estimated microplastic emissions per person is presented in

Figure 2.7.

Figure 2.7 Release of microplastics, EU27 + United Kingdom, Norway and Switzerland, estimated yearly releases, grams per person per year



Source: Eunomia and ICF (2018) and Jambeck et al. (2015)

2.2. Microplastic release from textiles

Microplastic release to water, air and soil

Textiles are recognised as one of the major sources of microplastic pollution. Microplastics originating from textiles typically have a fibre shape, which is why they are often referred to as microfibres (Roos et al., 2017). It should be noted, however, that textiles made of fibres from natural origin shed microfibres as well (Box 2.4) and that other shapes of microplastics from textiles can occur originating from different types of materials or accessories used in clothes and textile products, such as prints, coatings, buttons and glitter.

Box 2.4 Microfibres from natural origin

Not all microfibres released from textiles are made of plastic. An important share of microfibres from textiles is of natural origin. A distinction is to be made between man-made fibres of natural origin – like viscose and lyocell – and natural fibres – such as cotton, wool and silk. The former are made of natural substances such as wood pulp but artificially modified into cellulosic fibres to be used in garment production. Viscose, for example, is a versatile fibre that is extensively used in T-shirts, sportswear and dresses because it is lightweight, soft, breathable and has good moisture absorption and draping characteristics. Despite their natural origin these fibres can be considered semi-synthetic.

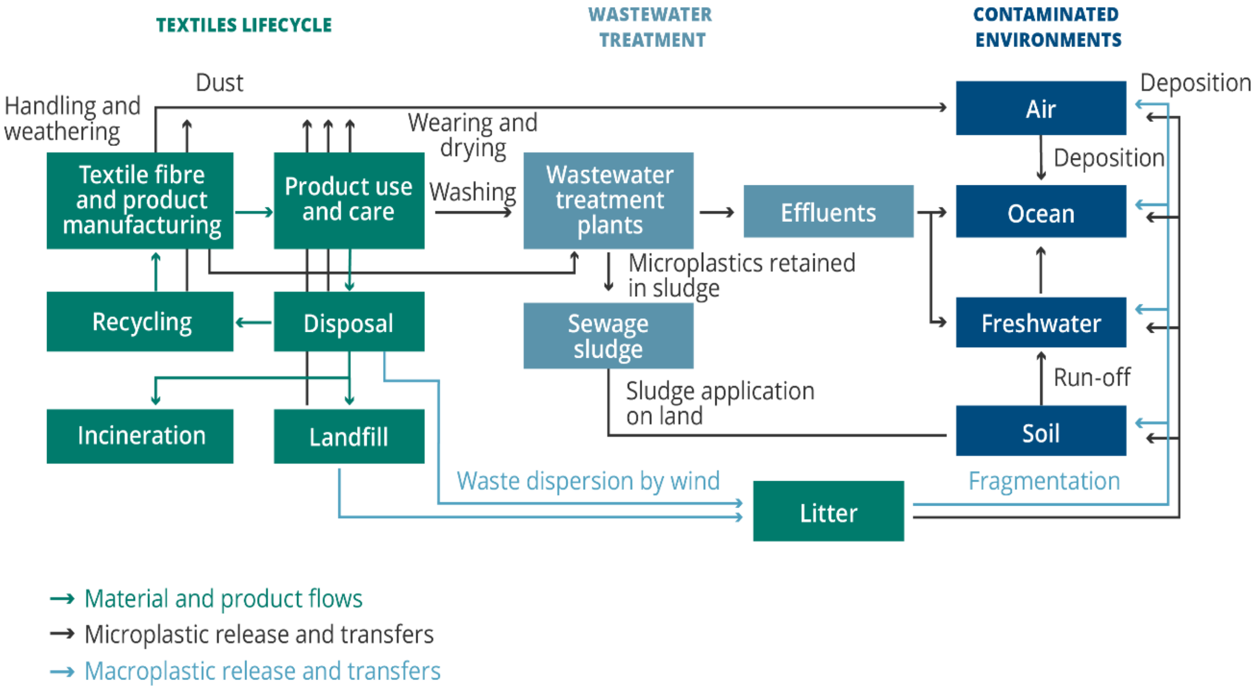
Limited evidence is available about the behaviour and fate of man-made cellulosics, but claims that they are biodegradable in sea water remain questionable (EDANA, 2020; Eunomia and ICF, 2018). Like microplastic fibres, they have been sampled in natural ecosystems and indoor air (Halstead et al., 2018; Dris et al., 2017; Remy et al., 2015), and are suspected to persist in the environment (Woodall et al., 2014; Lusher et al., 2013). Studies have illustrated the presence of viscose fibres in invertebrates and they have been reported to represent over 50 per cent of microfibres detected in deep sea sediments from the Atlantic Ocean floor, making them twice as abundant as polyester fibres (Remy et al., 2015; Woodall et al., 2014). It should be noted, however, that viscose is not only used in textile manufacturing, it is also widely present in cigarette filters and personal hygiene products. In this sense viscose microfibres are released into the environment from multiple sources and through a range of pathways, including sewage and litter. Moreover, viscose is easily confused with natural cellulose fibres such as cotton and hemp in environmental sampling, adding to the uncertainty in microfibre identification.

While being equally released into the environment, even less is known about the fate and persistence of natural fibres such as wool and cotton. They are believed to break down relatively fast compared to synthetic fibres, both in the environment (it takes a few weeks to months in soil) and when ingested (Henry et al., 2019a; Zhao et al., 2016). Nonetheless natural fibres undergo heavy processing, for example dyeing and finishing, similar to synthetic textiles which often involves the use of potentially hazardous chemicals. Although more extensive research is needed, the downside of the relatively rapid degradation of natural fibres may be the increased leaching of these chemicals to the environment (Henry et al., 2019b; Zhao et al., 2016). Additionally, due to their similar fibre shape, natural fibres may be equally effective as synthetic microfibres in adsorbing substances from the environment such as heavy metals, pharmaceuticals and other organic pollutants.

Microplastic fibres have been found everywhere on Earth, in sediments, in bottled drinking water and even in Arctic ice (UNEP, 2020). Fibres are the most common shape of microplastic found in wastewater effluent and typically consist of polyester, acrylics, nylon and polypropylene (Salvador Cesa et al., 2017b; Browne et al., 2011), which are the plastics most commonly used in clothing (ETC/WMGE, 2021c).

Microplastic release occurs throughout the textiles value chain (Figure 2.8). In most research, the focus is on microfibre release through the washing of synthetic textiles, considering wastewater as the predominant pathway for leakage into the aquatic environment (Boucher and Friot, 2017). Microfibres are, however, also emitted during textile manufacturing, garment wearing and end-of-life disposal, and are dispersed to water, air and soil (see following sections). Discarded fishing nets, estimated around 500,000 tonnes per year worldwide, are also a source of secondary microplastic directly emitted to the ocean (Boucher and Friot, 2017; UNEP, 2018).

Figure 2.8 Release and fate of microplastic fibres from textiles



Source: ETC/WMGE (2021c)

Release during textile manufacturing

Research on microplastic release from textiles typically focuses on the use phase, assuming that microplastic loss during manufacturing is generally low. Some losses of virgin plastic pellets that serve as a raw material for synthetic fibre production may occur as a result of accidental spills during transport and processing (UNEP, 2018).

Microfibre release during manufacturing occurs during yarn spinning, weaving and knitting, brushing and cutting of fabrics. Cai et al. (2020) studied the origin of microplastic fibres from polyester textile production and manufacturing processes. They showed that rotor-spun yarn showed higher microplastic fibre counts than other yarn types, which suggests that the rotor spinning may be a critical step responsible microplastic formation. On average, five times more microfibres were counted from textiles with processed surfaces, such as brushed fabrics in fleece, than with unprocessed surfaces. Reduced brushing leads to reduced fibre shedding (Roos et al., 2017). This indicates that abrasive friction during fabric production could be an important factor in microplastic formation (Cai, et al., 2020).

During cutting and sewing, it was shown that scissor-cut textiles produced a 3–31 times higher microplastic fibre count than laser-cut textiles (Cai, et al., 2020). This finding was also reported by Roos et al. (2017), who also mentioned ultrasound cutting being preferred to scissors.

Microfibres released to process water are most likely to end up in wastewater treatment, as industrial production plants are generally connected to wastewater treatment, especially in Europe. Even after high-performing wastewater treatment that removes more than 95 per cent of microfibres, however, the 5 per cent remaining in treatment effluent is significant because of the large wastewater volumes originating from textile production, and leads to considerable losses to the environment (UNEP, 2020).

Release during industrial and domestic washing of textiles

During washing, microfibres are released through abrasion wear and tear of the fabric due to clothes tumbling and rubbing against each other inside a washing machine. Many studies have attempted to identify the washing parameters affecting microfibre shedding, such as washing machine type, size of load, washing temperature, length of the wash cycle, spinning speed and detergent use (Lant et al., 2020; Carney Almroth et al., 2018; De Falco et al., 2018). While several studies report that polyester fleece releases the most microfibres (Carney Almroth et al., 2018; Roos et al., 2017), fabric construction appears to have a larger effect on shedding behaviour during washing than fibre type (Kärkkäinen and Sillanpää, 2021; Cai et al., 2020; Mermaids, 2019). Little evidence, however, is yet available on the mechanisms of microplastic release (Salvador Cesa et al., 2017c). A challenge when comparing results of different studies is that they all use different methodologies for experiments and different metrics and analysis methods to quantify results. Since microfibre research is relatively new, methodology has yet to be standardised.

Many studies have reported estimates of the microfibre emissions of synthetic textiles during machine washing. Microfibre shedding appears to be largest during early wash cycles, as loose fibres from manufacturing are released. Results vary considerably between studies and fabric types, showing estimates of 12–1,400 milligrams of microplastics emitted per kilogram of textiles per wash cycle – washing, rising and spinning (De Falco et al., 2019b; Eunomia and ICF, 2018; Pirc et al., 2016; Lassen et al., 2015; Sundt et al., 2014). In absolute fibre counts, this may represent 100,000–6 million microfibres per kilogram of textiles (Kärkkäinen and Sillanpää, 2021; Eunomia and ICF, 2018; De Falco et al., 2018). Additional fibres are shed during tumble drying (Kärkkäinen and Sillanpää, 2021). Over a textile product's lifecycle, this could add up to a microplastic loss of 1–5 per cent of a product's original mass (Boucher and Friot, 2017; Essel et al., 2015). Although microfibre shedding decreases over successive washes, wearing out of the fabrics again leads to an increase of microfibre shedding as garments age (Hartline et al., 2016).

As a result, fast fashion is particularly prone to high microfibre release, as it typically contains a high share of synthetic fibres, is only used for a short time having a high share of first washes, and tends to wear out quickly.

The shedding behaviour of garments made of recycled fibres are still unclear, with contradictory results provided by different sources (Box 2.5).

Box 2.5 How about shedding from recycled fibres?

While improved textile recycling and the use of recycled fibres in new textile products are often mentioned as a crucial pathway to improve the sustainability and circularity of synthetic textiles (ETC/WMGE, 2021c), some concerns have arisen recently about the release of microfibres from garments made from recycled yarns. There seems, however, to be conflicting evidence of shedding from recycled fibres.

An experiment studying microfibre release from knitted fabrics made of recycled (R-PET) and virgin polyester yarns was carried out by washing the fabrics three times under the same conditions (Özkan and Gündoğdu, 2021). Results showed that the R-PET fabrics released almost 2.3 times more fibers than the virgin polyester ones. The authors attribute this to R-PET having shorter fibres than virgin polyester.

On the other hand, when comparing the shedding of fleeces made of R-PET and virgin polyester, Roos et al. (2017) found lower shedding from those made of R-PET, and concluded that in the case of fleece material, which is usually made of recycled PET bottles and is often accused of being an important source of microfibre release, other elements, such as the brushing of fleece, could be more important determinants of shedding behaviour than the use of the recycled polyester.

De Falco et al. (2018) studied a variety of washing parameters, showing that the use of detergent increases microplastic shedding, possibly because the surfactants helps to lubricate loose fibres. Moreover, washing powder tends to induce more shedding than liquid detergent, possibly because the powder granules work as an abrasive, damaging the fibres. On the other hand, the use of fabric softener results in a lower microfibre shedding, possibly by reducing friction and fibre damage during washing. Long wash cycles increase wear and tear, while using higher temperatures tends to damage fabric structure, both resulting in higher microfibre releases.

The type of washing machine also has an influence on the rate of microfibre release, with top-loading models inducing significantly more shedding than front-loading ones, probably due to greater abrasion during tumbling (Hartline et al., 2016). Similarly, greater abrasion has also been raised as the explanation why half-load washing releases more microfibres than washing at full-load (Eunomia and ICF, 2018). Others point at the water-to-volume factor as the most influential reason for microfibre release, rather than agitation as such (Kelly et al., 2019). According to the latter research, a high water-to-volume ratio is responsible for the greater microfibre release in delicate laundry programmes.

In this way, the washing of synthetic textiles contributes significantly to microplastic releases in wastewater, surface water and the oceans. Estimates of the amount of microfibres released and their relative share vary greatly across literature sources, depending on geographical coverage, release pathways considered and whether microplastics removal by wastewater treatment is included (Table 2.3). According to Boucher and Friot (2017), approximately 35 per cent of global microplastic releases to oceans originate from washing synthetic textiles, while UNEP estimates a contribution of around 16 per cent ([11]) (UNEP, 2018). For Europe, where most households are connected to a sewage system and wastewater treatment, it is estimated that 13,000 tonnes of textile microfibres, or 25 grams per person, are released to surface water every year, accounting for 8 per cent of total primary microplastic releases to water (Eunomia and ICF, 2018).

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[11] UNEP (2018) estimates the contribution of washing textiles to releases to the environment at 9 per cent. If, however, it is assumed that 50 per cent of microplastics from tyre abrasion, road markings and city dust are trapped in soil, asphalt and on river banks, and thus do not reach the oceans, the share of textile microplastics discharges to the ocean increases to 16 per cent.

Table 2.3 Estimates of annual global microplastic releases to the environment from washing synthetic textiles

Source	Fate	Estimate	Grams/person	Coverage
Washing of synthetic textiles				
UNEP, 2018	To the environment	265,000 tonnes (9 % of total microplastic releases)	36	Global
		660,000 tonnes	16	Western Europe
		201,000 tonnes	52	Central Europe + CIS
	Source emissions to wastewater	497,000 tonnes	67	Global
		46,000 tonnes	107	Western Europe
		31,000 tonnes	78	Central Europe + CIS
Boucher and Friot, 2017	To the ocean	525,000 tonnes (35 % of total microplastic releases)	75	Global
Eunomia and ICF, 2018	Source emissions to wastewater	32,000 tonnes (4 % of total microplastic releases, range 18,000–46,000 tonnes)	61	EU + Norway, Switzerland and the United Kingdom
	To surface water	13,000 tonnes (8 % of total microplastic releases, range 4,000–23,000 tonnes)	25	
Essel, 2015		500–2,500 tonnes	5	Europe
		80–400 tonnes	1–6	Germany
Bertling et al. (2018)	To the environment		77	Germany
Discarded fishing nets				
UNEP, 2018	To the environment	600,000 tonnes		Global
Boucher and Friot, 2017	To rivers and the ocean	500,000 tonnes		Global

Currently, microfibres are not retained by washing machines; they are discharged together with the washing machine effluent. If no adequate sewage system and wastewater treatment are in place, the microplastics are emitted to the aquatic environment (Eunomia and ICF, 2018). Only about one third of the global population is connected to a wastewater treatment system, in Africa and Asia particularly shares of wastewater treatment are low (UNEP, 2018; Boucher and Friot, 2017). In most regions in Europe, however, effluent from industry and households passes through a wastewater treatment plants, where a large amount of the microfibres are retained, preventing them from being discharged to surface water and the ocean (Box 2.6) (UNEP, 2018). About 60 per cent of textile microplastic losses during washing, about 36 grams per person, are trapped in wastewater treatment sludge. However, since about half of wastewater sludges are applied as fertiliser to agricultural land, the microplastics contained in them are transferred to soil. The remainder is incinerated, destroying the microplastics (Eunomia and

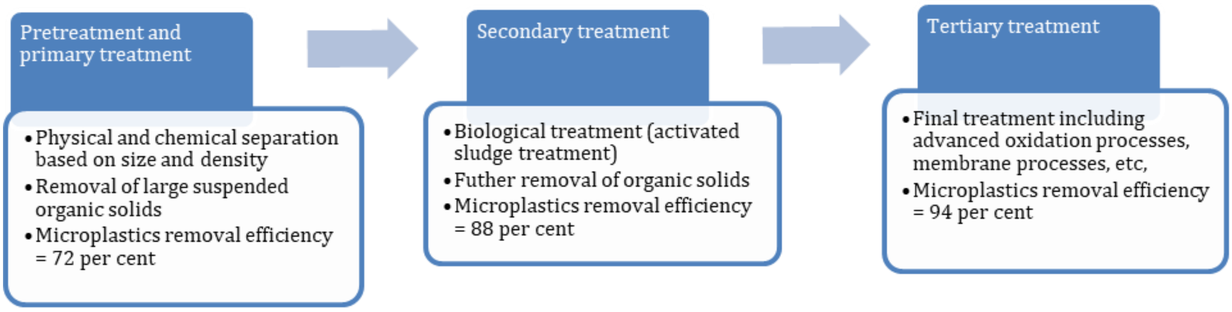
ICF, 2018). Currently, there is no technology to remove microplastics from sludge (Eunomia and ICF, 2018).

Box 2.6 Microplastic removal in wastewater treatment plants

Wastewater treatment technologies currently used in Europe are not specifically designed to capture microplastics. Nevertheless, microplastic retention rates can exceed 90 per cent, depending upon the technology used (Eunomia and ICF, 2018).

Wastewater treatment plants typically consist of pre-treatment, primary, secondary and possibly also tertiary treatment processes. Common pre-treatment and primary treatment remove larger plastic particles by a combination of screening, grease and grit removal, skimming and sedimentation processes. Secondary treatment operations are typically activated sludge processes entailing aeration and the action of micro-organisms. Secondary treatment further reduces the suspended and dissolved solids, and microplastics can be removed by entrapment, sedimentation or by ingestion by the micro-organisms. Tertiary treatments can consist of different filtration systems including biological, gravity, ultrafiltration and reverse osmosis technologies. Advanced treatment methods, including membrane bioreactors, are also used (Lares et al., 2018; Mintenig et al., 2017; Talvitie et al., 2017; Ziajahromi et al., 2017; Carr et al., 2016). Retention efficiencies for microfibres of wastewater treatment processes are on average 72 per cent for primary, 88 per cent for secondary and 94 per cent for tertiary treatment (Iyare et al., 2020). While some sources claim average microfibre removal across Europe exceeds 90 per cent (UNEP, 2018), lower retention rates of 53–84 per cent are calculated by Eunomia and ICF (2018), since only 56 per cent of the European population is connected to tertiary treatment.

Figure 2.9 Wastewater treatment steps to improve the removal of microplastics



Source: Liu et al. (2021); Wu et al. (2021); Iyare et al. (2020); Poerio et al. (2019)

Across the EU, different treatment plants’ retention rates have been studied. Magni et al. (2019) reported an 84 per cent retention rate in an Italian treatment plant. In Scotland, a 98.4 per cent retention rate was achieved using a grease removal process (Murphy et al., 2016). Leslie et al. (2017) concluded that the retention efficiency of Dutch wastewater treatment plants had a mean of 72 per cent retention efficiency of microplastics in the sewage sludge. In Finland, a 97 per cent retention rate was achieved during pre- and primary treatment, while an additional sieve-based system increased the retention even further (Talvitie et al., 2017). Overall, the retention rate depends on the technology and techniques used. It is important to also note that the accuracy of the measurement of microplastics and nanoplastics might affect the retention results – the results are only as good as the sampling, separation and identification methods – and the measurement methods are not standardised. A critical review by Elkhatib and Oyanedel-Craber (2020) analysed the methodologies and different techniques used to collect, quantify and characterise microplastics from both waste- and drinking water. There were significant discrepancies in reported concentrations, microplastic characterisation, quality control and assurance procedures. Disparities were also found for sample collection, sample processing, quality control, identification techniques and results (Elkhatib and Oyanedel-Craver, 2020). There is also a lack of harmonisation in the methodologies for sampling and analysis for micro- and nanoplastics, and there are limitations in the accuracy of detection of different sized particles – especially the smaller the particles get (Rios Mendoza et al., 2018).

Despite the majority of microplastics being retained during wastewater treatment, some are still discharged in effluents, meaning that wastewater treatment plants are significant sources of microplastics due to the high volumes of discharge (Henry et al., 2019a). Those microplastics that are retained end up wastewater treatment sludge, where concentrations of 1,000–179, 000 particles per kilogram (dry weight) have been reported in different studies and of which the majority of the microplastics, 63 per cent, were found to be microfibres (Iyare et al., 2020). Sludges are a good source of nitrogen, phosphorous and organic matter and are thus used in different land applications, such as for land remediation, and as soil improvers and fertilisers in agriculture. This is, however, another route for microplastics to enter the environment, in soils with the potential of further dispersion by runoff from fields. Some sludges are incinerated, which eliminates most microplastics, or dumped in landfills (UNEP, 2018).

As can be seen from the wide-ranging estimates in Table 2.3, estimating the amount of microfibres released into the environment is challenging. An additional hurdle in interpreting water samples from oceans and sediments is the difficulty in distinguishing between microfibres of natural and synthetic origin. In fact, many microfibres present in the aquatic environment have been found to be of natural origin, such as wool, cotton, natural or man-made cellulose, suggesting these natural fibres may degrade more slowly than expected and thus may pose the same risks to the environment as synthetic microfibres (Box 2.4).

Release during wearing and drying textiles

While wastewater is regarded as the predominant pathway for textile microfibre release (Boucher and Friot, 2017), textiles have also been reported to release microplastics to the air, which are then deposited in soil, during garment wearing (De Falco et al., 2020; Napper et al., 2020). The direct release of microfibres from garments through dry and wet atmospheric deposition is, however, not well studied. Wright et al. (2020) studied the deposition of microplastics from the air by analysing samples from rooftops in London. Samples contained 575–1,008 pieces of microplastic per square metre per day of which the majority, 92 per cent, were acrylic fibres, most likely connected to clothing (Wright et al., 2020). De Falco, et al. (2020) demonstrated that the direct release of microfibres to air due to garment wearing is of equal importance to microfibre releases to water from garment washing (De Falco et al., 2020). Furthermore, a study by the Organisation for Economic Co-operation and Development (OECD) suggested that up to 65 per cent of microplastics may be emitted to aerial environments during drying and wearing of garments (OECD, 2020b). Other studies indicate that the amount of microfibres deposited on household surfaces, from wearing of clothes as well as from the use of towels and household textiles, is of the same order of magnitude as those released through washing (Henry et al., 2019a).

Release during textile waste management

Leakage from textile waste management, including sludge application to land, is also likely to be a small but not insignificant source of microplastic releases to the environment (Eunomia and ICF, 2018). Literature on the subject is scarce, but landfills, open dumps and mismanaged municipal solid waste have been mentioned as potential sources of microplastic releases to air due to wind drift (UNEP, 2020; 2018). Waste textiles, such as used clothing, can be part of such mixed waste streams due to inadequate source separation or sorting losses. As dedicated textile collection schemes are in place across European countries, the share of textiles ending up in waste incineration or landfill should be limited. Europe, however, exports large amounts of used textiles for reuse and recycling and the fate of this waste is unclear. In developing countries connection to wastewater treatment plants is often not available and wastewater from textile washing is directly discharged into surface waters (Corcoran et al., 2009). Similarly, textile wastes are often landfilled or burnt, potentially releasing microplastics to soil and air.

Discarded fishing nets, estimated at around 500.000 tonnes per year worldwide, are also a source of secondary microplastics directly emitted to the ocean (UNEP, 2018; Boucher and Friot, 2017). Loss estimates are very uncertain and speculative, however, and microfibre loss from nets during fishing is not believed to be significant, as fishing nets are replaced before they are worn (Eunomia and ICF, 2018).

Microfibre degradation into nanofibres

Although available data concerning their environmental degradation is scarce, microfibres are expected to degrade into ever smaller particles and eventually into nanoparticles, similarly to other microplastics (Sait et al., 2021). These degradation processes increase the polymer surface area, which may increase leaching of chemicals (Box 2.7), and compromise their mechanical performance due to embrittlement by the mechanical forces of wind or waves, resulting in increasing fragmentation (Pinto da Costa et al., 2018; Gewert et al., 2015). Nanoplastic contaminants have particularly been shown to be released due to water fragmenting microplastics (Enfrin et al., 2019). In the case of textile washing and fragmentation, water's turbulence and pumping induce further fragmentation by crack propagation, which means that an initiated crack in/on the fibre particle will advance further. Photodegradation can also cause fragmentation, qualitative signs of which include polymer discoloration and surface cracking that can propagate further fragmentation (Pinto da Costa et al., 2018; Gewert et al., 2015). For example, PET and nylon microplastic fibres significantly fragment and undergo changes in their surface under the influence of UV exposure (Henry et al., 2019a).

Box 2.7 Chemical additives in textiles

During degradation, not only are plastic fragments released into the environment, but also the chemical additives present in these plastics. On average, 4 per cent of microplastics consist of additives such as brominated-based flame retardants or phthalate plasticisers which may be hazardous to the environment and human health. Additionally, due to their large surface area, microfibres can adsorb contaminants from the environment, causing accumulation of potentially harmful substances (Henry et al., 2019a).

Textiles can contain a wide variety of chemical additives. These are used in different production phases from pre-treatment, for example, bleaching, washing, scouring and colouring, to finishing for example, printing and applying finishes. Especially during finishing, additives are applied to improve, for example, protection against UV, water- and moisture resistance, oil-resistance or antistatic properties. About 3,500 substances are used in textile production, of which 750 have been classified as hazardous to human health and 440 as hazardous to the environment (Darbra et al., 2012).

Bisphenols, such as bisphenol A (BPA) and benzophenone UV (BP-UV) filters are two chemicals frequently used in textile and garment manufacturing. The first is used as a coating and features as an intermediate chemical in the manufacture of dyes, while BP-UV filters are used to reduce UV degradation and increase a product's lifetime (Sait et al., 2021). Other examples of potentially hazardous additives are perfluorocarbon compounds – water and oil repellent finishers; triclosan – antimicrobial finishers; and brominated-based flame retardants (Darbra et al., 2012). While most additives are not chemically bound to the plastic polymer, some, including flame retardants, are. Chemicals can also be added during the use and maintenance of textile products, for example, to renew water-repellent properties.

3 Environmental impacts and health effects of microplastics from textiles

It is clear that micro- and even nanoplastics from different sources, and of different shapes and compositions, are ubiquitous in the environment. They have been detected in seas and freshwaters, air and soil, living organisms, and drinking water and food for human consumption (SAPEA, 2019). While microplastics originate from a wide range of sources and estimates of their volumes across literature show a broad range (Table 2.3), it was found that in Europe about 8 per cent of the microplastics released to surface water originate from synthetic textiles (Eunomia and ICF, 2018). The predominant release route through which textile microfibres enter the environment is from the discharge of wastewater from laundry into freshwater and the marine environment, since wastewater treatment is currently not capable of completely capturing them. There are, however, other routes by which microfibre spread, such as to the air during textile manufacturing and from abrasion from wearing and drying textiles, or to soils from the application of wastewater treatment sludge on agricultural land. Wherever they end up, microplastics accumulate in natural ecosystems and remain there for decades, if not very much longer (Henry et al., 2019b). In recent years, concerns are rising about the environmental impacts and health effects associated with microplastic pollution. The role of microfibres from textiles, and the specific impacts related to their fibrous nature, is gaining attention in research (OECD, 2020a; Mermaids, 2019; Vesper, 2019a).

3.1. Fate, environmental impacts and health effects of microplastics

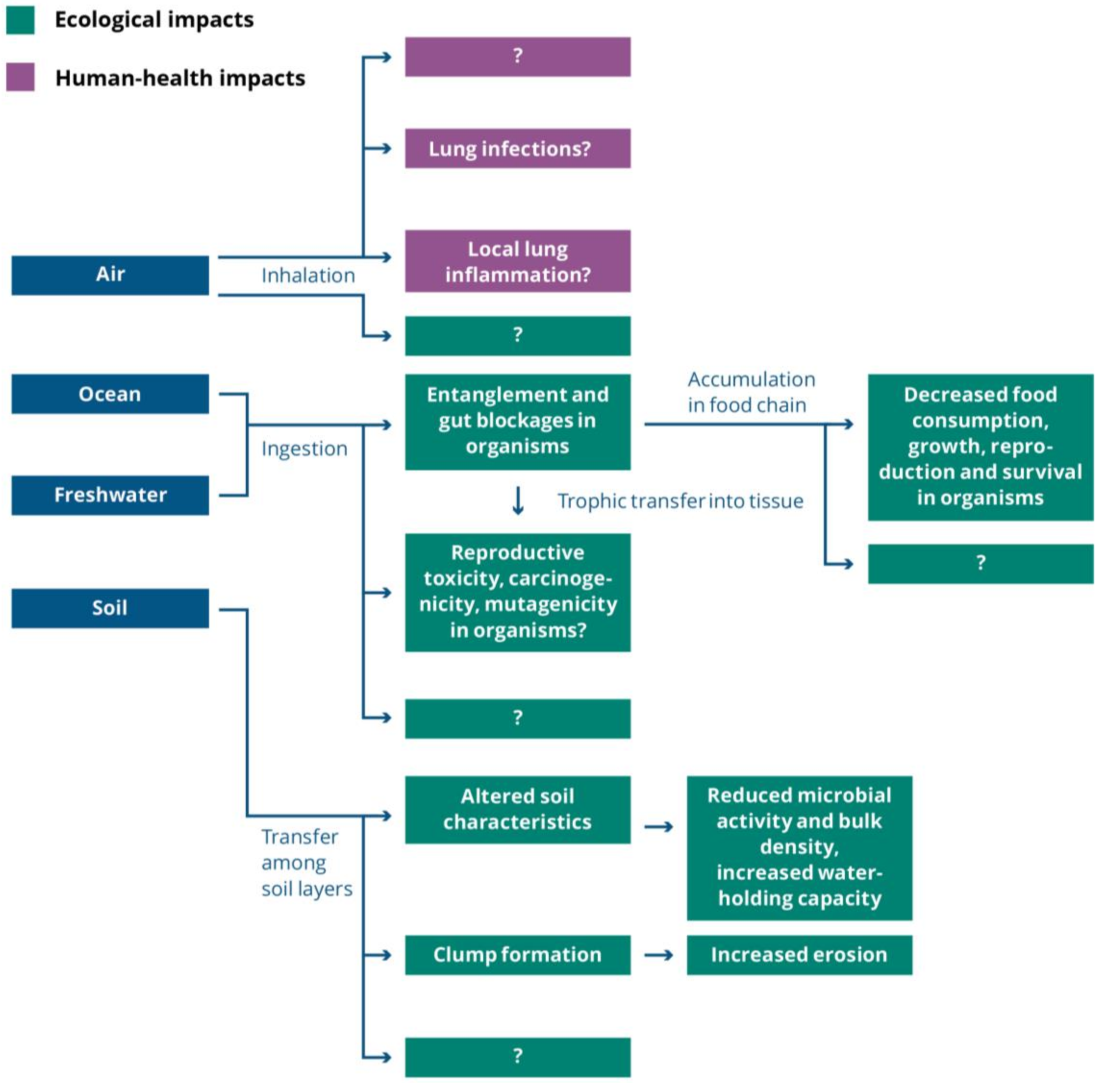
Due to their omnipresence, microplastics are ingested by all kinds of living organisms, ranging from plankton to fish and larger mammals in marine environments, and to land animals and humans. In addition to ingestion of microplastics from water and soil, airborne particles detected both in- and outdoors are inhaled (Henry et al., 2019a; SAPEA, 2019). Microplastics have been reported in a wide range of human food and beverages, including seafood, drinking water, beer, salt and sugar.

The World Health Organization (WHO) published a large study in 2019 on microplastics in drinking water, in which it reviewed existing studies that analysed microplastic particles in water, freshwater and both tap and bottled drinking water (WHO, 2019). Shruti et al. (2020) found that approximately 84 per cent of 57 samples of soft drinks, cold tea and energy drinks contained microplastics, with polyamides and polyester-amides the predominant polymer types. Glosh et al. (2021) found microplastics in the 10 commercial fish species they studied. Furthermore, there is limited evidence for the presence of microplastic particles in human placentas and stools (Ragusa et al., 2021; Schwabl et al., 2019).

It is safe to conclude that a certain degree of chronic exposure to microplastics is an integral part of contemporary life (OECD, 2020b; Henry et al., 2019a). It should therefore not come as a surprise that microplastics have become a topic of concern for both environmentalists and the general public. The potential ecological and health risks related to microplastics are determined by their intrinsic hazard on one hand, and exposure levels on the other (Gesamp, 2015). As often, effects depend on the dose. At high exposure levels microplastics are believed to induce inflammatory reactions and toxicity, and they can become a vector for the spread of pathogens and microbes (Henry et al., 2019a; SAPEA, 2019).

Unfortunately the long-term, chronic effects of microplastics on ecosystems and human health, as well as on the economic viability of agriculture, fisheries and other livelihoods, are largely unknown (OECD, 2020a; Gasperi et al., 2018; Waring et al., 2018). The effects of micro- and especially nanoplastic are rather recent areas of research, still surrounded by large degrees of uncertainty (SAPEA, 2019; Gesamp, 2015). There is a reasonable level of knowledge about microplastic concentrations and effects in freshwater and at the ocean surface, but little is known about concentrations and implications of micro- and nanoplastic in the air and soil or below the ocean surface (SAPEA, 2019). Compared to the increasing body of knowledge on the effects at the level of individual organisms, the large-scale effects of microplastics on species populations and at the ecosystem level remain largely unexplored, especially in the field (SAPEA, 2019). The high variability in physical and chemical properties, composition and concentrations of microplastics makes these risk assessments challenging (Koelmans et al., 2019) and there is concern that laboratory studies do not accurately reflect the natural environment (SAPEA, 2019). While many data gaps exist for microplastics in general, even less is known about the fate and effects of microplastics originating from synthetic textile sources. Due to their composition, fibrous shape with high surface to volume ratios, and product-specific additives, microfibres might induce a whole range of behaviours and impacts of their own (Henry et al., 2019a; Jemec et al., 2016). Unfortunately, to date this is largely unresearched.

Figure 3.1 Potential exposure routes and hazardous effects of microfibres on ecosystems and human health



Source: ETC/WMGE

Figure 3.1 shows the fate and effects of microplastics in both fresh and marine waters, and air and soil, which are discussed in detail in Sections 3.2 to 3.4 respectively. Attention is given to both ecosystem and human health impacts and textile-specific effects are included where there is a sufficient knowledge base. In the field of microplastic research there is a lot still to explore – the current data gaps are listed in Section 3.5.

3.2. Microfibres in water

Microplastic contamination of freshwater and marine environments is the result of both direct emissions to surface water and transport of particles through wind, runoff, wastewater and waste disposal. It is, however, currently unclear what levels of microplastic pollution can be considered acceptable – with a wide range of concentration levels, from 7,990 to 1,490,000 microplastic particles per cubic metre of water, being considered. Once these levels are exceeded, it is assumed that adverse effects will occur in ecosystem functions and structures, including alterations to species population levels, genetic diversity and evolutionary trajectories (Everaert et al., 2020). There is a high chance that, at current emission rates, an increasing number of (coastal) regions will exceed these thresholds within a century (SAPEA, 2019), with the Mediterranean Sea, among some others, already considered a contamination hotspot due to high population density and industrial activities concentrated on its coasts, combined with its enclosed nature limiting outflows of microplastics (Everaert et al., 2020; Llorca et al., 2020). The mass of macro- and microplastics released to the oceans is not on its own an appropriate indicator of environmental impacts as it does not reflect the actual damage to the environment (UNEP, 2018).

When exposed to microplastics, ingestion is considered a major entry pathway for aquatic organisms. This has been observed in a wide range of filter feeders, including marine megafauna, and in many other species ranging from zooplankton to vertebrates (Henry et al., 2019b). While floating plastics are more likely to be ingested by zooplankton and fish, organisms living in the sediment such as crabs, worms and mussels also ingest sedimental plastics (Wright et al., 2013). Microfibres, mainly originating from synthetic textiles, appear to have a higher potential than others to enter the food chain because their size and shape allow them to be readily consumed by aquatic organisms, as well as being more prone to entanglement into big clots inside the gut, causing blockages (Jemec et al., 2016). Sampling has demonstrated that multiple organisms living on the deep-sea floor ingest microplastics originating from textiles, such as fibrous polypropylene, viscose, polyester and acrylic particles (Henry et al., 2019a).

Apart from the physical effects of microplastics, another source of concern is the potentially toxic chemicals they contain – additives, monomers, catalysts and reaction by-products from manufacture. These can leach out once microplastics are released to the environment, with degradation and fragmentation of particles expected to further increase the potential for the leaching of chemicals (Wang et al., 2018). Unfortunately there have not been large-scale studies of what chemical concentrations are in plastics and in water, and how these concentrations change over space and time (SAPEA, 2019). For microfibres from synthetic textiles, the chemical additives include flame retardants, dyes and finishes such as polybrominated diphenyl ethers (PBDE). Apart from the chemicals present from manufacture, microfibres, with their high surface-to-volume ratios, are able to adsorb a wide range of other substances present in surrounding waters, such as heavy metals, pharmaceuticals and other organic pollutants (Hou et al., 2021). This concentrates toxic compounds and raises the risk of enhanced bioavailability through ingestion (Besseling et al., 2013).

Furthermore, microplastics provide habitats for pathogens and microbes, facilitating their transport, spread and ingestion by organisms. This can, for example, occur when microfibres pass through wastewater treatment where they collect contaminants and then disperse these in freshwater systems (Henry et al., 2019a; Kirstein et al., 2016). Whether microfibres have a higher chance of serving as such habitats is still a question as to date there is insufficient evidence that microplastics pose an increased disease-risk in ecologically and economically valuable marine ecosystems such as fisheries and coral reefs (Henry et al., 2019a).

Multiple laboratory studies have reported that when aquatic organisms are exposed to high levels of microplastics, there are significant negative effects on food consumption, growth, reproduction and survival for a range of species (Foley et al., 2018; Gerdes et al., 2018; Redondo-Hasselerharm et al., 2018). Some of the chemicals that can leach from textile microfibres (Section 3.1) have proven adverse effects on organisms and humans, such as reproductive toxicity, carcinogenicity and mutagenicity

(Gasperi et al., 2018; Linares et al., 2015; Lithner et al., 2011). Nevertheless, the uptake of chemicals through microplastic ingestion is still believed to be considerably lower than their uptake through other pathways, for example from food, prey or ambient water (Gesamp, 2015). When microplastic particles translocate from the outside of the body or the digestive system into tissue – also called *trophic transfer* – they can cause inflammatory reactions and cell damage (Browne et al., 2008).

It should be noted that is the lack of evidence that current laboratory studies reflect what happens in nature. Although there are uncertainties about what current environmental concentrations are and how these will evolve in the future, most of the studies are performed using concentrations way above those detected in nature, as well as small particle sizes on which limited exposure data is available. Furthermore, they tend to use spherical polystyrene particles, while polyester and polyamide particles in fibrous shapes, such as the ones from textiles, are underrepresented (SAPEA, 2019). Finally, exposure times are relatively short in the average laboratory studies.

To date it remains unclear whether and to what extent the inflammatory evidence found in animals translates to humans (SAPEA, 2019). Although there is clear evidence that microplastics occur in human food and drinks, evidence on the accumulation of microplastics in the food chain and human dietary intake is sparse. Nonetheless, this knowledge is crucial for determining the related effects on human health (OECD, 2020b; SAPEA, 2019). While some concern has been raised on the presence of microplastics in commercial seafood (Box 3.1) the degree of human toxicity and impacts of chemicals from environmental microplastics remain uncertain, and their relative contribution is expected to be small at current levels of exposure of uptake (Henry et al., 2019a; SAPEA, 2019).

Box 3.1 Microplastic contamination of commercial seafood

Commercial seafood is believed to be an important exposure pathway to microplastics for humans, especially when the food's digestive tracts – where most of the microplastics is found – are not removed (OECD, 2020). While this is usually done for larger fish and crustaceans, removing up to 90 per cent of the microplastics present (Devriese, et al., 2015), most smaller fish and shellfish are consumed whole. Limited numbers are available on the occurrence of microplastics in seafood. In fish, the average number of particles found per fish is between one and seven. In shellfish, the average number of particles is between 0.2 and four per gram, with shrimp having an average of 0.75 particles per gram (EFSA, 2016). Van Cauwenberghe and Janssen (2014) estimate that the annual dietary exposure for top consumers of shellfish in Europe can amount to 11,000 microplastics per year. Obviously, this number does not only depend on microplastic concentrations, but on the intake of seafood products as well.

Mussels appear to be particularly prone to microplastic accumulation. A worst case estimate is that the consumption of a portion of mussels of 225 grams would lead to the ingestion of 900 particles, around 7 micrograms of plastic (Lusher, et al., 2017). Nonetheless the European Food Safety Authority (EFSA) estimated that the consumption of one portion of mussels would, even under the worst case assumptions, contribute less than 0.2 per cent to the dietary exposure of well-known toxic chemicals like Bisphenol A, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) (EFSA, 2016). In this sense microplastic contamination of the food chain is unlikely to cause serious toxicity, affecting, for example, the central nervous and/or reproductive systems, unless exposure levels are very high and absorption rates are increased due to physiological aspects (Waring, et al., 2018).

3.3. Microfibres in the air

Although concentrations remain unclear, microplastics are proven to be present in both ambient and indoor air, with microfibres from textiles appearing to predominate (SAPEA, 2019; Gasperi et al., 2018; Dris et al., 2017). Higher levels are likely indoors (Dris et al., 2017), as some studies indicate that the amount of microfibres from, for example, wearing and drying clothes, as well as household textiles, deposited on household surfaces was of the same order of magnitude as that emitted when textiles are washed (Henry et al., 2019b). Apart from concentration levels, the size of inhalable particles also remains largely unknown which adds to the difficulty of estimating human daily intakes of airborne micro- and nanoplastics (SAPEA, 2019). Under regular circumstances, human ingestion of microplastics from the air is believed to be negligible (OECD, 2020b). The 2020 Covid pandemic has, however, led to the widespread use of nose and mouth masks, the potential effects of which are discussed in Box 3.2.

Box 3.2 Inhalation due to use of face masks in response of the COVID-19 pandemic

Wearing face masks has become the new normal worldwide due to the global spread of COVID-19. While several designs and material compositions are on the market, most single-use masks and some reusable masks are at least partly made of synthetic fabrics such as polyester (EEA, 2021b; ETC/WMGE, 2021b), so the risk of inhaling microplastics should be considered.

A study by Li et al. (2021) used different types of commonly used masks to conduct breathing simulation experiments and investigate microplastic inhalation risks (Li et al., 2021). Results showed that wearing masks considerably reduced the risk of inhaling spherical microplastics, which are present in the air, even when they are worn for an extended amount of time. N59 masks, however, prove effective in decreasing the inhalation of microplastic in fibrous shapes, while the same is true for surgical-A, cotton and fashion masks as long as they are not used for longer than seven days. For surgical-B and activated carbon masks an increased inhalation risk is detected, due to their often inferior quality. This implies that using masks for less than seven days does not increase the risk of microfibre inhalation, and the results suggest that the masks filter out most of microfibres from the air but only a limited number of those released from the masks themselves.

Many disinfection processes to support mask reuse can increase the risk of both spherical microplastic and microfibre inhalation. Ultraviolet disinfection has a relatively weak effect on microfibre inhalation, and thus, it can only be recommended if proven effective from a microbiological standpoint.

To date, only severe adverse health impacts from microfibre inhalation have been reported in the case of occupational exposure (Box 3.3). It is assumed that under normal circumstances the majority of inhaled microplastics are cleared from the body by excretion. Some may, however, persist in the lungs causing local inflammation, especially in individuals with compromised clearance mechanisms such as long-term smokers (Gasperi et al., 2018). Additionally, there is a concern that small-size microfibres might induce effects in human lungs similar to asbestos (SAPEA, 2019) although to date no widespread evidence is available.

Box 3.3 Flock workers' lung

Occupational exposure to microfibres can lead to (chronic) inflammation of lung tissue, causing irritation of the respiratory system, disturbed lung function and other conditions such as flock workers' lung (Warheit et al., 2001; Pimentel et al., 1975). This is a particular concern for nylon textile workers, who are exposed to high levels of inhalable-sized nylon flock – small fibres that are glued to a backing in order to create a velvety texture (Boag et al., 1999; Eschenbacher et al., 1999; Kremer et al., 1994). It has, however, also been reported for workers exposed to viscose fibres, although it is not of synthetic origin but a cellulosic man-made fibre (Centers for Disease Control and Prevention - National Institute for Occupational Safety and Health, 2019). Respiratory issues with flock workers were already connected to microfibre exposure in the early 1990's, but the disease was not formally described until 1998 (Turcotte et al., 2013). To date cases have been reported in Canada, Spain, Turkey and the United States.

Flock workers' lung is characterized by chronic and progressive respiratory symptoms and restrictive pulmonary function abnormalities, including crackling noises caused by fluid in the lungs, shortness of breath and coughing (Turcotte et al., 2013). Some also report chest pains. Symptoms typically disappear within days or weeks, although the long-term effects such as increased risk of lung cancer are still being researched (Kern et al., 1998).

Preventive measure can be taken in flocking plants to avoid these health issues. It is recommended that specific cutting systems for the nylon are used – guillotine rather than rotary cutting – and that workers wear respirators when performing high-exposure work. A final recommendation is not to use compressed air when cleaning the workplace to avoid the recirculation of particles (Centers for Disease Control and Prevention – National Institute for Occupational Safety and Health, 2019).

When airborne microplastics carrying microbial colonies are inhaled, there is a risk that these pathogens and microbes will infect lung tissue (Kirstein et al., 2016). Yet again, there are still many unknows with regard to these potential impacts. There is consensus that additional studies on airborne microfibres are required to extend the knowledge base in general.

3.4. Microfibres in soil

Next to aquatic and air environments, microplastics have been detected in terrestrial ecosystems. Many pathways lead to microplastics ending up in soil. Airborne microplastics, for example, from tyre abrasion, are deposited on roads and pavements, runoff then transports them to roadsides and sewers, and on to wastewater treatment plants, the sewage sludge from which is used as fertiliser on fields. Textile microplastics released through washing typically end up in wastewater treatment sludge, but they can also be spread by the use of contaminated wastewater in irrigation. Additionally, textile waste that is littered, for example, single-use face masks, ropes, tarpaulins and lost garments, or discarded in landfill sites can degrade and lead to microfibre leakage to soil (Henry et al., 2019b). All these are important microplastics exposure pathways (SAPEA, 2019) and it is assumed that organisms such as earthworms have the capacity to transport significant amounts of microplastics from the soil surface to deeper layers (Henry et al., 2019a).

The effects of microplastics in soil on terrestrial animals and plants remain largely unknown as they are yet to be systematically studied. Nonetheless de Souza Machado et al. (2018) state that key soil parameters might be affected by microplastics, resulting in reduced soil microbial activity, lower soil bulk density and increased water-holding capacity. This is especially the case for fibrous polyester and polyacrylic mircofibres from textiles. Microfibres also often form the skeletons of large clumps of soil, which might impact erosion processes. It might be their linear structure that implies a higher interaction potential with biophysical soil properties compared to microplastic beads and fragments, although there is no evidence of this (de Souza Machado et al., 2018). These changes in soil properties are likely to further impact a wide range of microbes present in soil and potentially root growth (SAPEA, 2019).

Whether and to what extent the presence of microplastics in soil and agricultural land impacts human health through their uptake in food is unclear.

3.5. Existing data gaps on environmental impacts and health effects

Although the scientific knowledge base is evolving quickly, a recurrent finding in previous sections is that the behaviour and impacts of microplastics in the environment are complex and still subject to many unknowns. This is particularly the case for the release and impacts related to microfibres from textile sources. Throughout this report their specific release mechanisms and environmental pathways have been discussed. Due to their composition, fibrous shape with a high surface-to-volume ratio and product-specific additives they might induce a wide range of behaviours and impacts of their own (Henry et al., 2019b; Jemec et al., 2016). Unfortunately, their specific fate and effects are currently largely unknown, which makes it hard to determine the severity of the issue and the required prevention and mitigation measures. Very little source-specific information is available for microplastics.

The most pressing data gaps that need to be filled to get a clear picture of the hazardous effects of the current and future accumulation of microplastics in general, and particularly of microfibres from textiles, on ecosystems and human health are listed below.

Microplastics concentrations and exposure levels

While a fair amount of information on the microplastic behaviour and contamination of freshwater systems and marine surfaces is available, this is definitely not the case for air, soil and the deeper ocean. For airborne microplastics, for example, it is still unclear how they interact with wind and rain, and what inhalable size fractions are (SAPEA, 2019). On land, little is known about microplastic concentrations in different types of ecosystem, especially forests, and what the contamination distribution is across continents (SAPEA, 2019). As hazardous effects are largely dependent on exposure levels, through their uptake in food and inhalation, and circumstances, concentration data are indispensable to determine microplastics impacts on ecosystems and humans (Henry et al., 2019a).

Accumulation in organisms and in the food chain

Although microplastics are expected to work their way up through the food chain once ingested by organisms, little evidence is available, especially for land species (SAPEA, 2019). Nonetheless concerns have been raised about contaminated seafood destined for human consumption. As most microplastics pass through the digestive system of aquatic organisms and fish, to be later excreted again, exposure to humans is believed to be minimal as long as the gastrointestinal tract is removed before the seafood is consumed. The European Food Safety Authority (EFSA) assumes that microplastic contamination is more likely to originate from seafood processing – processing aids, water, air or releases from machinery, equipment and textiles with which the food has been in touch – than from the food itself (EFSA, 2016). It did, however, conclude that more information is required on occurrence levels of microplastics in food.

Long-term chronic effects at population and community levels

To date one of the largest knowledge gaps in microplastic research concerns the long-term effects of microplastics exposure, both on the level of ecosystems and for human health (SAPEA, 2019). The main technical barrier for determining these effects is the fairly recent nature of the microplastic issue, which has only manifested in the past 50–70 years, as well as the vast variety in exposure levels and circumstances (Henry et al., 2019a).

Although quite some research has been done on the effects at the level of organisms or even organs and tissue, the extent to which these laboratory experiments correctly reflect realistic circumstances remains questionable, and far less is known about the effects at the scale of communities or entire populations (SAPEA, 2019). There is an urgent need more research to be able to determine the large-scale effects of microplastic contamination (SAPEA, 2019).

Chemicals from microplastics

It is acknowledged that microfibres contain chemicals and additives (Box 6) that can leach out, and that they take up other chemicals present in the environment (Gesamp, 2015). What is not known, however, is how these chemicals spread and evolve over time (SAPEA, 2019). The effect of particle degradation on chemical leaching is also not entirely understood. Conversely, it remains unclear how the use of chemicals and detergents impact the breakdown of microfibres. The huge variety in microplastic composition and added chemicals make it very hard to investigate these mechanisms (SAPEA, 2019). Finally, limited research has been carried out on the relative contribution of chemicals from microplastics to overall chemical exposure that organisms and humans face daily (SAPEA, 2019).

Human health impacts

While a fair amount of data is available on the hazardous effects of microplastic exposure on aquatic organisms, a major unknown is how this translates to land species and especially humans. Although to date it is stated that there is no evidence of widespread risks to humans and the monitoring of exposure and effects is increasing, the potential toxicity of the wide variety of microplastics to which people are regularly exposed remains insufficiently understood (SAPEA, 2019). The knowledge base on, for example, effects of the inhalation of microplastics, such as polyester microfibres from face masks, and the clearance mechanisms from people's lungs needs to be vastly increased (SAPEA, 2019; Gasperi et al., 2018).

Nanoplastics

Microplastics smaller than 0.001 millimetre in are considered to be nanoplastics (Velis et al., 2017). While data on the effects of microplastics is sparse, they are even more so for nanoplastics. While it is regularly stated that these are potentially more hazardous, no real evidence is available and even their occurrence in different ecosystems is hard to quantify. Furthermore, there is currently no evidence of nanoplastic contamination of drinking water and food (SAPEA, 2019). Bioaccumulation, where particles are retained in organs and other organisms' tissue, appears to take place more easily for smaller nanoplastics, potentially affecting the nervous system and reproductive capacity (Waring et al., 2018). Exposure levels remain entirely unclear (SAPEA, 2019). As nanoplastics may impact entire ecosystems in the long run, increased research efforts are needed to better understand their presence, behaviour, and short- and long-term effects (Gasperi et al., 2018; Waring et al., 2018).

Non-synthetic microfibres

As already touched upon in Box 2.4, more robust data is needed on the fate and persistence of natural and man-made cellulosic fibres and blends under varying conditions and across a range of natural ecosystems (Henry et al., 2019a). The behaviour and potential hazardous effects of man-made cellulose fibres, for example how they degrade in water and the leaching mechanisms of chemicals and additives, remain poorly understood. It might be that the same impacts described for synthetic microfibres also apply to natural ones, but additional research is needed (UNEP, 2020). The same holds for the risks of chemical leaching from natural fibres to the environment during degradation (Henry et al., 2019b; Zhao et al., 2016).

Table 3.1. Summary of knowledge on the fate and effects of microplastics in water, air and soil

	Microplastics in water	Microplastics in air	Microplastics in soil
What is certain	Freshwater and ocean surface contamination levels Transport and behaviour Ingestion by organisms	Textile origin of airborne microplastics	
What is somewhat certain	Effects on aquatic organisms Accumulation in the food chain Chemical bioaccumulation from leaching Trophic transfer (12)	Contamination levels Human health effects Clearance mechanisms of microfibres from lungs and trophic transfer (12)	Effects on soil biota and plants
What is uncertain	Deep ocean contamination levels Threshold levels for contamination Effects on population and large-scale ecosystems Long-term, chronic effects Human dietary intake Increased disease risk due to spreading of pathogens Nanoplastic exposure and effects	Inhalable size fractions Long-term, chronic effects Increased disease risk due to spreading of pathogens Nanoplastic exposure and effects	Contamination levels Nanoplastics exposure and effects Human health effects

Source: ETC/WMGE

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(12) *Trophic transfer* refers to the translocation of microplastic particles from the outside the body or the digestive system into tissue

4 Pathways to prevent or mitigate microplastics from textiles in Europe

Tackling the problem of microplastics discharge from textiles requires an interdisciplinary approach built around technical and social innovation, circular business models and sustainable behavioural changes as well as supporting policy measures.

The emerging issue of microplastics and the need to further investigate their sources and impacts was endorsed by the European Commission in the European Strategy for Plastics in a Circular Economy (EC, 2018). Subsequently, in the European Circular Economy Action Plan, specific points for action are proposed. In accordance with the recommendations from the European Chemicals Agency (2019), this includes a restriction on the use of intentionally added microplastics in products sold in the EU. Additionally, the unintentional release of microplastics needs to be better understood and prevented, including the development and harmonisation of measurement methods, the development of labels and standards, and measures to capture microplastics (EC, 2020b).

In 2020, the OECD organised a set of workshops to study the release of microplastics from tyres and textiles, and define their impacts on the environment and human health and the options for mitigating microplastic pollution from these sources (OECD, 2020b). To limit emissions from textiles, interventions at different stages of their lifecycle are needed. These include such interventions as amending textile product design to reduce shedding during wearing and washing, industrial pre-washing to capture microfibres at source, changing behaviour such as reducing washing frequency, and downstream measures including improving the capture of microplastics in washing machine filters and wastewater treatment.

Box 4.1 Private sector initiatives

In addition to public initiatives, private organisations from the clothing, soaps and detergents, and white goods industries have also taken initiatives to increase understanding and mitigate the challenge of microplastics release from textiles. Many of those initiatives are built on cross-industry collaboration. The following, non-exhaustive list provides some examples of private sector initiatives.

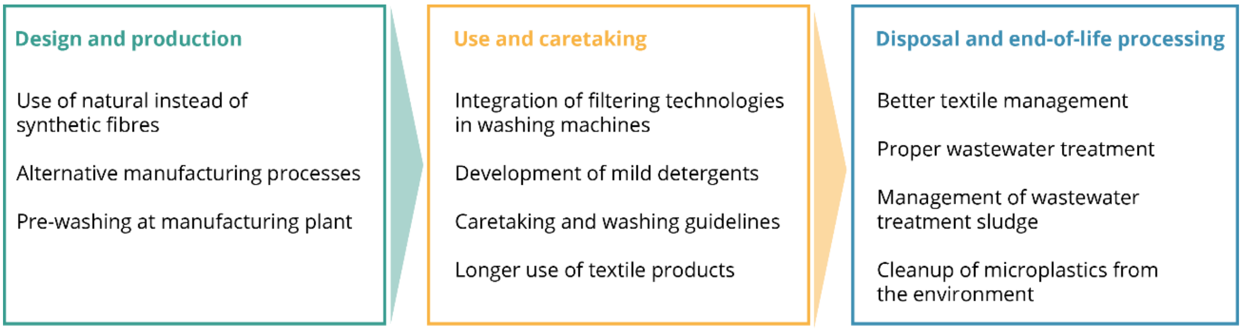
- The Cross Industry Agreement was founded early 2018, uniting a group of European industry associations from across the textile value chain. The aim is to tackle the issue of microplastics with a jointly developed harmonised test method, by sharing science-based knowledge, by fostering research studying the release of microfibres to the aquatic environment from garment washing, and searching for viable solutions.
- The Microfibre Consortium brings together a global network of industry and academia with the aim of developing solutions to minimise fibre fragmentation and release from textile manufacturing and use. This includes the development of an aligned and open test methodology, an aligned cross-industry topic roadmap with targets, a data portal, and best practice guidance for mitigation measures during manufacturing. In this way, the initiative aims to promote sustained action and the achievement of measurable impacts across the whole industry.
- The Policy Hub-Circularity for Apparel and Footwear was launched in 2019, uniting the apparel and footwear industries to speak with one voice and propose policies that accelerate circular practices. In total, its five partner organisations represent more than 500 apparel and footwear stakeholders including brands, retailers, manufacturers, and non-governmental organisations (NGOs).
- Textile Mission brought together nine organisations to pursue an interdisciplinary research approach to gain a better understanding of material flows, the fate of textile related microplastics in the environment, as well as the optimisation of wastewater treatment technology.
- Mistra Future Fashion, a joint research programme of three major Swedish companies to determine the relationship between textile construction parameters and shedding behaviours.
- Proctor and Gamble initiated and supported a number of research projects to understand the impacts of wash cycles, water volumes and washing habits on microfibre release.

Although domestic washing is estimated to be the largest contributor to the release of microfibres, public awareness of microplastic shedding from textiles and its relationship with the larger issue of microplastic pollution remains low (Herweyers et al., 2020). From a behavioural change perspective, this means that there is a great deal of potential in addressing microfibre release in the use, caretaking, and disposal stages of textiles. Such changes include, most notably, the adoption of more sustainable washing practices, including the use of filters, as well as more conscious disposal ones that prevent secondary microplastic release from the degradation of textile waste. In the EU, used textiles will have to be collected separately from 2025.

Long-term solutions to the issue of the shedding of microplastics from textiles are, however, likely to require more fundamental changes in behaviour, especially as they pertain to people's purchasing habits. Specifically, this means achieving overall reductions in consumption, thus challenging the fast-fashion paradigm, as well as increasing consumer preference for repurposed or recycled textiles (Henry et al., 2018). Such a shift could be facilitated by more circular business models which additionally have the potential to address microfibre release further upstream – at design and production stages.

In the following sections, options to reduce microfibre release are listed and explored. These are structured according to the textile lifecycle stage at which they can be applied (Figure 4.1). For primary microplastics, focus is on preventing emissions at source, while for secondary microplastics resulting from litter and unmanaged waste, measures focus on waste reduction and end-of-pipe measures such as improved waste management, wastewater treatment and cleanups (OECD, 2021). Finally, some thoughts are presented about the possibility of removing microplastics from the environment and the need for further research.

Figure 4.1 Reduction and mitigation pathways for microfibre release from textiles



Source: ETC/WMGE

4.1. Design and manufacturing

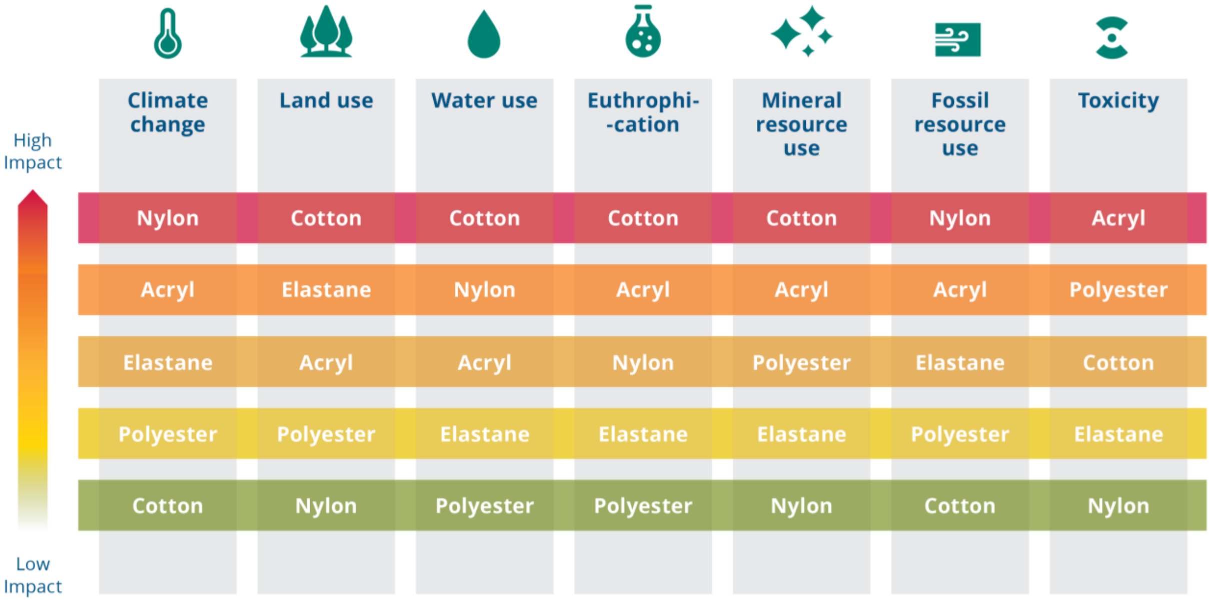
Several strategies for reducing microfibre release or avoiding shedding through the use of alternative fibres, alternative manufacturing techniques or the application of additional processing steps that prevent microfibre formation or their capture at source are considered.

Use of natural instead of synthetic fibres

Shifting consumption to textiles made from natural fibres is sometimes mentioned as a pathway for tackling microfibre shedding (Henry et al., 2019a). Questions can, however, be raised about whether such an approach delivers a viable alternative to synthetic fibres, which currently make up about 60 per cent of the textile fibres used (ETC/WMGE, 2021c). Not only would textile properties change considerably if natural fibres were used, but the substitution will not necessarily lead to a reduction in microfibre formation. Firstly, natural fibres also tend to shed microfibres as a result of wear and tear (Gesamp, 2015). Indeed, having analysed 2,000 microfibres drawn from six ocean basins, Suaria et al. (2020) found that only 8.2 per cent were synthetic – mainly polyester. Of the remainder, natural animal fibres, mainly wool, accounted for 12.3 per cent, and plant-based fibres, mainly cotton, made up 79.5 per cent. Although these fibres are expected to biodegrade within months or years (Henry et al., 2019a), they are, at least temporarily, present in the environment as microfibres and it is not clear what effects are related to exposure to them. While more research is needed to understand the large share of natural microfibres discovered and their perceived failure to degrade, possible explanations could be that wool and cotton fabrics release more fibres than polyester during laundering and that processing, dyeing and chemical coating of natural yarns slow down their biodegradation (Suaria et al., 2020). Secondly, some concerns prevail as to whether rapid biodegradation of natural fibres can lead to the release of chemical additives, such as dyes, and thus cause adverse effects (Henry et al., 2019a). Finally, it is important to note that not all microfibres made from natural resources are biodegradable. Bio-based polyester, for example, is chemically equivalent to fossil-based polyester and does not biodegrade, making it a contributor to the build-up of microfibres in the environment (ETC/WMGE, 2021c). Given the relatively high prevalence of microfibres in seas, a standard to determine the biodegradability of microfibres of various origins in marine environments is needed, as they already exist today for (an)aerobe environments, such as the European compostability standard EN 13432.

When comparing the respective merits of natural and synthetic fibers, it is also important to consider other environmental trade-offs beyond microfibre formation and degradation. As Stone et al. (2020) put it, "*both synthetic and more natural textiles present substantial challenges to the environmental quality and ecological health of freshwater across the world*", depending on the lifecycle stage and the environmental impact considered. Comparing wool and synthetic textiles, for instance, wool textiles pose most risks to freshwater ecosystems during their production phase, while PET textiles pose most risks during their use and disposal phases (Stone et al., 2020). Moreover, when considering the production phase, cotton has a much higher water and land use than polyester and nylon, while in terms of climate change the order is reversed (ETC/WMGE, 2021c). Ranking different fibres in terms of their environmental impact therefore requires nuance. According to Laitala et al. (2018), however, it is especially important to consider the use-phase of clothing when considering environmental impacts since use can vary so significantly as, for example, some people keep their clothes for a long time and others wear them only once, or not all, before disposing of them. Similarly, wool might generally be easier to keep clean, while synthetic fibres tend to become dirty faster and are therefore washed more frequently (Laitala et al., 2018). Ultimately, as the authors suggest, this complexity might suggest that reduction in overall consumption is the most effective solution for reducing the environmental impacts from textiles.

Figure 4.2 Comparison of the environmental impacts of the manufacturing of 1 kilogram of dyed, woven fabric
(red = worst, green = best)



Climate change	Land use	Water use	Euthrophi-cation	Mineral resource use	Fossil resource use	Toxicity
Nylon	Cotton	Cotton	Cotton	Cotton	Nylon	Acryl
Acryl	Elastane	Nylon	Acryl	Acryl	Acryl	Polyester
Elastane	Acryl	Acryl	Nylon	Polyester	Elastane	Cotton
Polyester	Polyester	Elastane	Elastane	Elastane	Polyester	Elastane
Cotton	Nylon	Polyester	Polyester	Nylon	Cotton	Nylon

Source: ETC/WMGE (2021)

Alternative manufacturing processes

The production processes of synthetic fibres, yarns, fabrics and products may be responsible for the increased release of microfibres during laundry. The application of abrasive friction during production is an especially important factor in microplastic formation (Cai et al., 2020). By using alternative production processes or textile construction methods, this microfibre release during use can be reduced. The EU Life project published a handbook for the textile industry detailing good practice (Mermaids, 2019) (Box 4.2).

Box 4.2 Production processes affecting microfibre release during washing

In fibre production, it is important to prevent fibre irregularities to reduce friction. Tensile strength of the resulting fibres should be preserved to prevent fibre breakage. This can be realised by melt spinning at lower and graduated temperatures, but this can increase production time.

Fibre fineness is important to reduce the tendency of fibres to stick out of the yarn. In spinning, the use of continuous fibres is preferred over staple fibres. When staple fibres are used, the cutting length should not be too low. Yarns that are plied or highly twisted tend to shed fewer microfibres (Mermaids, 2019). Rotor spinning should be avoided, as it was shown by Cai et al. (2020) to generate more microfibres.

In fabric construction, the knitting process is a key cause of fibre damage due to the mechanical action of the yarn carrier and needles. Similarly, during weaving, the movement of the thread transporters causes abrasion of the yarns. If the velocity of the knitting or weaving machines are reduced, fibre breakage can also be reduced. Fabric construction also plays a role. Fabrics with a tighter structure and higher density are less prone to microfibre release than low density fabrics, while fabrics with plain weave construction patterns shed fewer microfibres than those with twill weave (diagonal) patterns. Fabric finishing processes such as napping, shearing and brushing aim to alter the surface of the fabrics to produce a thick, soft and cuddly feel, as is common for fleece. After the napping, the fabric becomes woolly and needs to be sheared to assure equal thickness, and finally brushed. These processes involve revolving cylinders with bristles and can cause fibre damage. Adjusting the finishing processes to reduce fibre damage is needed to reduce microfibre shedding. Fibre waste from the shearing process needs to be removed and adequately treated –singeing the fabric surface is a good option to remove loose ends (Mermaids, 2019). Reducing or avoiding the use of brushed fabrics altogether and choosing unprocessed fabrics instead is also an option (Roos et al., 2017), but this fundamentally changes the fabrics' appearance and properties. Chemical finishes can improve fabric smoothness and protection against abrasion, which reduces microfibre release during use and washing (De Falco et al., 2019a; Mermaids, 2019).

During cutting and sewing of garments, ultrasound cutting and laser-cutting are to be preferred over cutting with scissors (Cai et al., 2020; Roos et al., 2017). Garment dyeing should be avoided, as it has more impact on microfibre release than yarn dyeing (Mermaids, 2019).

Using alternative production processes for fibres and fabrics may, however, increase production time or change mechanical properties of the resulting products, which may interfere with product requirements. Also, the use of chemical finishing agents to reduce fabric abrasion is not always compatible with other finishing treatments and may have environmental impacts of its own, for example, the leaching of chemicals in domestic wastewater (Mermaids, 2019).

Although much research is focused on microfibre release during washing, textile manufacturing processes are also a major source of microfibre pollution, especially if industrial wastewater treatment is inadequate. As shown by Chan et al. (2021), the industrial wastewater effluent from a textile processing mill in China showed a high concentration of microfibres – an average of 361.6 (± 24.5) microfibres per litre – emphasising the need for adequate wastewater treatment (Chan et al., 2021). Even if wastewater treatment is adequate, it is important to note that the resulting sludge is often applied on agricultural fields which releases the microplastics again, indicating the need to focus on reducing microplastics formation at source (section 4.3).

Industrial pre-washing at the manufacturing plant

Since synthetic fabrics tend to release the highest amount microplastics in the first 5–10 washes, pre-washing at the manufacturing plant could capture a large share of potential microfibre releases (OECD, 2020b; Mermaids, 2019; Roos et al., 2017). In industrial plants, microfibres released to process water are more likely to be captured, since the plants are generally connected to wastewater treatment, especially in Europe. Even after high-performing wastewater treatment (>95 per cent removal), however, the amount of microfibres remaining in treatment effluent is significant, taking into account the large wastewater volumes originating from textile production, which leads to considerable losses to the environment (UNEP, 2020). Moreover, if sludges are applied on soils, this presents another release pathway.

4.2. Use and care

Integration of filtering technologies in washing machines

With regard to washing-machine manufacture, one of the options is the re-engineer them to include filters to prevent microfibre release. In 2020, France was the first country to introduce an obligation for all washing machines to be equipped with a dedicated microfibre filter as of January 2025 (Sánchez, 2020).

Several filters are already on the market that are meant to provide consumers with an easy and effective way of filtering out microplastic during domestic washing (Herweyers et al., 2020; Napper et al., 2020). Two types can be distinguished. The first has to be inserted in the washing drum by the user during the washing cycle. These microfibre catchers include laundry balls and washing bags that collect microplastics (Coraball, 2021; Guppyfriend, 2021). Some clothing brands actively promote such devices in their stores (Patagonia, 2018). One key challenge these filters pose, however, is the risk of improper disposal and treatment of accumulated microfibres after washing (Roos et al., 2017) due to the current lack of consumer familiarity with these devices (Box 4.3). The second type of filter has to be fitted to the washing machine drainpipe to filter the effluent (Filtrol, 2021; PlanetCare, 2021; Xeros, 2020). Consumer behaviour is also important here to assure adequate maintenance and cleaning of the filter and disposal of the captured microplastics.

A study testing six filters at the UK's University of Plymouth showed that the release of microfibres can be reduced by up to 80 per cent (Williams, 2020). The best results were obtained with an external filter with the finest mesh of 60 micrometres (µm) ([13]) that also featured a motor-powered centrifugal separator to facilitate the flow of the wastewater through the mesh. It should, however, be noted that the energy efficiency of the washing machine and the duration of washing cycles might be influenced by the use of filters in washing machine outlets (OECD, 2020b).

Despite their smaller mesh size of 50 µm, in-drum devices only achieved microfibre emission reductions of 21–54 per cent (Napper et al., 2020). None of the tested filters was able to offer a complete solution: even in the best case, there was still a release of 0.10 grams of microfibre per wash. This clearly suggests that improving the quality of wastewater treatment remains a necessity.

Box 4.3 Consumer requirements from a microplastic filtering device for domestic washing

Based on survey data and interviews with Flemish consumers, Herweyers et al. (2020) identified key user requirements that microplastic filtering devices for consumers must meet in order to ensure long-term use. These include the following in descending order of importance.

1. **Effectiveness.** Notably, respondents not only wanted scientific proof but also needed to see fibres in the bag after use in order to be assured of the positive environmental impact and their own contribution to it.
2. **Durability**.
3. **Straightforward** and **easy** to use.
4. **Cost**. Although less frequently mentioned by respondents, cost remains a key aspect since microfibre pollution was seen as a collective challenge and thus filtering devices should be accessible to everyone – irrespective of their socio-economic status.
5. **Easy, fast and foolproof cleaning**. Especially important since the use of filtering devices constituted a new behaviour/habit to be learned. Overall, cleaning for 10 minutes after 15–17 washing cycles was considered tolerable.

Development of mild detergents

As discussed in Section 2.2, the use of detergent and fabric softeners have an effect on microfibre release. Detergent manufacturers can thus contribute to reducing microfibre shedding by developing liquid non-aggressive detergents that are effective at low temperatures and do not rinse off fabric finishes, some of which protect against fibre breakage. Powder detergents should be discouraged for use with synthetics since they increase friction, causing fibre breakage. Other laundry products, such as oxy

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[13] A micrometre is one millionth (10^{-6}) of a metre

agents, should also preferably be liquids. Fabric care additives, such as softeners, are capable of preventing fibres breakage (Mermaids, 2019).

Care and washing guidelines

With domestic washing estimated to be the largest contributor to microfibre release, one key area of attention has been consumers' laundry habits (Herweyers et al., 2020; Liu et al., 2019). A variety of research projects have studied the influence of laundry behaviour on microfibre shedding (Kelly et al., 2019; Vesper, 2019b; De Falco et al., 2018). This has led to a set of recommendations meant to help consumers reduce microfibre release during domestic washing and typically include a variation of the following aspects (Plastic Soup Foundation, 2021; Lant et al., 2020; OECD, 2020b; Yan et al., 2020; Vesper, 2019b; Henry et al., 2018; Hubbub, 2018):

1. carefully read and apply care instructions on labels;
2. wash less frequently;
3. use short, gentle cycles at lower temperatures;
4. use light-duty, liquid detergent; avoid the use of washing powder for synthetics;
5. use fabric softener to reduce friction;
6. wash full loads;
7. air dry clothes rather than using a tumble dryer.

This also points to the more general challenge of changing deeply embedded social norms – for example, washing clothes frequently at high temperatures – which makes them difficult to challenge and change (Harris et al., 2016).

Furthermore, while public awareness of the overall threat posed by microplastic pollution has risen in the last few years, awareness of the specific role textiles play in this has remained rather low (Herweyers et al., 2020; Yan et al., 2020). According to a poll conducted across the UK, for example, 44 per cent of respondents were unaware that microfibres were actually plastic and a key driver of microplastic pollution in the ocean (Hubbub, 2018). This is in line with results from a survey conducted in the Netherlands, where 68 per cent of respondents indicated awareness of the "*plastic soup problem*", but only 37 per cent knew of the existence of microfibres and their relation to the issue (Herweyers et al., 2020).

Yan et al. (2020) also found that there was some confusion around the use and meaning of the terms microplastic and microfibres and whether they meant the same. Findings such as these highlight a significant need for awareness raising and education as a basis for effective behavioural change around the issue of microplastic release from synthetic textiles (Box 4.4).

Box 4.4 Increasing consumer awareness on plastic microfibre pollution – two campaigns from the UK

What is in my wash?

This campaign was launched by Hubbub in 2018 to raise awareness about the impact of washing on microfibre pollution, engaging consumers through social media, campaign videos and pop-up installations. The campaign was covered more than 200 times in UK media and reached 3.4 million people on social media, while its campaign video was viewed nearly 77,000 times (WhatsInMywash, 2021).

Love your clothes

Started by WRAP in 2014, this campaign is part of the Sustainable Clothing Action Plan (SCAP) and aims to reduce the impact of clothing on the environment. Through its website ([14]), consumers are shown how to make more sustainable choices at each stage in the process, from buying to proper care, repair and disposal of clothes (LoveYourClothes, 2021).

Longer use of textile products

While largescale adoption of measures such as washing guidelines would unquestionably lead to significant reductions in microplastic shedding from textiles, solving the issue in the long term will likely require more far-reaching changes in consumer behaviour.

As many studies highlight, the release of microfibres is especially high during the first few washes of new clothes (Lant et al., 2020). Consequently, changes in consumer buying behaviour are needed along with an awareness of the impact that new clothing items have on microplastic pollution. Specifically, this means achieving reductions of clothing consumption overall, thus challenging the fast-fashion paradigm, as well as increasing consumer preference for reused or recycled textile items (Henry et al., 2018). Such a shift could be facilitated by more circular business models which additionally have the potential to address microfibre release at the design and production stage. A recent EEA Briefing and Eionet report (EEA, 2021a; ETC/WMGE, 2021a), discussed several business models for a more circular the textile system that can contribute to addressing the microfibre challenge.

Access-based models look to provide ways into services that meet a customer needs, without the necessity of owning the product itself. Services typically offer rentals or leasing, sometimes based on a pay-per-use principle. Complimentary services, such as maintenance or repair, are often included. To keep customers satisfied, companies have to ensure high levels of performance during the rental phase, creating a strong incentive for them to design highly durable and reparable products (ETC/WMGE, 2021a). Access-based models can, in theory, make several positive contributions to the microfibre challenge, most importantly, by enabling shared use and reuse, access-based models extend the active use phase of a product, thus potentially reducing the need for further consumption and decreasing waste generation overall. Furthermore, users who rent a textile items could be incentivised to return them unwashed in order to limit microfibre shedding associated with domestic laundering. On the other hand, it could be argued that customers' hygiene concerns could lead to additional and unnecessary washing at home. Similarly, if access-models, such as clothing libraries, were to become widely affordable, they could lead to additional rather than reduced consumption.

Some innovative models focus on providing long-lasting and durable products, with the aim of ensuring high customer satisfaction and loyalty. To offset increased costs related to production, products are usually premium branded and sold at higher prices. Complementary after-sales maintenance and repair services are often included in an attempt to support longer product lifetimes (ETC/WMGE, 2021a).

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[14] https://www.loveyourclothes.org.uk/

Business models around longevity and durability can, in theory, have similar positive impacts on microfibre shedding as models based on access. This is because, once again, they extend the active use phase of a product, thus potentially curtailing new purchases and waste generation overall. At the same time, longevity-and-durability based models run the specific risk that the higher initial purchase price of products, due to their higher quality, may make them less affordable to a wide range of consumers, thus limiting any potential positive impact on the microfibre challenge. Furthermore, while the notion of purchasing fewer but more durable items is promising, it runs contrary to the current fast-fashion paradigm. To be successful in the long run and make a significant impact on microfibre prevention, such a model would therefore have to go along with a broader cultural shift.

4.3. Disposal and end-of-life processing

Better textile waste management

Adequate textile waste collection and end-of-life treatment should prevent littering, mismanaged textile waste and wind blowing of textiles from open landfills that can be a source of macro- and microplastic environmental contamination. Although the effect of the use of recycled fibres in textiles is still unclear, recycling reduces overall environmental impacts of textile production and consumption. In the case of textile waste, a large share is exported from Europe for reuse or recycling. The eventual fate of those exported textiles, however, is unclear and many receiving countries do not possess high-quality waste management systems, posing a significant risk of microfibres spreading from washing reused garments through untreated wastewater, escapes from open landfills or inadequate disposal. Also, a growing number of receiving countries, such as Uganda, are starting to restrict imports of discarded textiles (Kuwonu, 2017).

Business models aimed at a better end-of-life management of used textiles (ETC/WMGE, 2021a) can also support efforts to reduce microplastics release from mismanaged textile waste.

Models based on collection and resale look to exploit the residual value of textile products by recycling them and/or preparing them for reuse. A general distinction can be made between selective take-back schemes and those that collect all textiles.

Once again, the main contribution of such models to the microfibre challenge lies in extending the use phase of a used product (ETC/WMGE, 2021a). As with the other business models, this could both decrease new purchases and waste generation overall, while also having the additional benefit that reused articles generally shed fewer microfibres when washed than new ones. Furthermore, preparing an old article for reuse requires fewer resources than the production of a new similar one, thus providing a further environmental benefit.

At the same time, mainstream acceptance of and even preference for previously used products is likely to require a fundamental shift in terms of social perception. As with other novel business models, there is also the risk that increased availability of previously used articles may actually result in more, or substituted, consumption by consumers. Furthermore, since collection and resale models rely on the active participation of consumers, a lack of transparency around donation and/or take-back schemes could create barriers to participation and thus limit any positive impact such models might yield in terms of limiting the release of microfibres.

Models based on recycling and upcycling look to turn products that cannot be reused for their original purpose into new raw materials for (re)manufacture (ETC/WMGE, 2021a). The key contribution of this model to microfibre challenges lies in reducing the need for virgin raw materials, thus decreasing textile waste generation overall and reducing the risk of microplastic shedding along the way. Similar to collection and resale models, however, these models require the active participation of consumers who once again could constitute a barrier. Furthermore, consumers might also be reluctant to buy recycled or upcycled products for a variety of other reasons, including but not limited to the lack of guarantees of quality, high prices, and/or limited options in terms of size and colour.

Proper wastewater treatment

Globally, 80 per cent of wastewater flows back into the wider environment without adequate treatment, contributing to a situation in which around 2.2 billion people do not have safely managed drinking water and sanitation services (UN-Water, 2017). During the past three decades, several physical, chemical and biological technologies have been used, both individually and in combination. Each treatment has its own advantages and disadvantages in terms of levels of investment and costs of operation, efficiency, feasibility and environmental impact. Currently, there is no single method capable of adequate treatment, mainly due to the complex nature of industrial effluents (Crini and Lichtfouse, 2018).

Removal efficiencies are dependent on the technology used and the properties of the microplastics including their form – fibre, granular, fragment, film or foam; particle size; mass; chemical composition – the commonest polymers are polyethylene (PE), polypropylene (PP) and polystyrene (PS) originating from plastic products and nylon (PA), PET and polyethersulfone (PES) from textiles and synthetic clothing; and concentrations. Emerging removal methods include advanced oxidation, adsorption on to non-conventional solids, biosorption, and biomass and nanofiltration (Crini and Lichtfouse, 2018).

Although conventional wastewater treatment plants are not equipped to entirely remove microplastics (Salvador Cesa et al., 2017a), technologies and techniques are available to improve wastewater treatment performance. By including primary, secondary and tertiary treatment steps in wastewater treatment (Box 4.5), it is estimated that up to 98 per cent of microplastics can be removed from effluents (Poerio et al., 2019), although actual retention efficiencies across Europe are likely to vary between 72–98 per cent.

It is, however, important to acknowledge that although micro- and nanoplastic sampling, detection, identification and separation is developing, it is currently not standard. Although wastewater treatment connection is widespread in the EU, tertiary treatment is still limited (Crini and Lichtfouse, 2018), with only about 56 per cent of households connected to tertiary treatment (Eunomia and ICF, 2018). Moreover, many challenges still need to be overcome if the last percentages of microplastics are to be filtered out (Box 4.5).

Particles which are not retained in common wastewater treatment plants, even after tertiary treatment, are generally smaller than 20 µm (Iyare et al., 2020) and typically originate from the fragmentation and degradation of larger polymer particles. These small micro- and nanoplastics are of particular concern because the risk of particles breaking through biological barriers is expected to increase with decreasing size (Boyle and Örmeci, 2020; European Commission, 2019; Al-Sid-Cheikh et al., 2018), while their high surface area ([15]) may increase bioavailability and the impact of chemicals (Henry et al., 2019a). Multiple studies have shown that fibre-shaped microplastics, mainly originating from domestic washing, are less likely in general to be retained than others. While more than 90 per cent of them are typically retained in preliminary and primary treatment, the removal efficiency for the remaining 10 per cent is low in secondary and even tertiary treatment processes and they are therefore highly likely to be present in the final effluents of the wastewater treatment plants.

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[15] Surface area is the area of all outside surfaces of material. As particle size decreases, a higher proportion of particles are at the surface of the materials. Increased surface area is typically linked to increased reactivity.

Box 4.5 Membrane processes for wastewater treatment – challenges

Conventional and established membrane processes, including microfiltration, ultrafiltration, reversed osmosis and membrane bioreactors, can play an important role in filtering out the last percentages of microplastics during tertiary wastewater treatment (Liu et al., 2021; Wu et al., 2021; Shen et al., 2020; Poerio et al., 2019). Nonetheless, the use of membrane processes comes with some challenges. Firstly, membrane fouling and cake layer formation, caused by the interactions between the membrane and suspended particles or organisms, can quickly reduce water flux and membrane performance. According to Li et al. (2020), fouling can be more severe with microplastic contamination, and is, in the case of small microplastics, irreversible. Therefore, a better understanding of microplastics' fouling mechanisms, antifouling strategies and cleaning procedures are crucial to retain membrane efficiency. Secondly, polymeric membranes, which are currently used in water treatment, can be a source of microplastics themselves. While membranes synthesised from biopolymers are sometimes mentioned as a solution, it is important to acknowledge that bio-based plastics form microplastics in a similar manner to conventional ones. A real solution could lie in the development of materials that do not shed microplastics, or, alternatively, monitoring microplastic release so the membranes can be replaced when shedding increases. Thirdly, concerns remain about the formation of nanoplastics, as a result of microplastic degradation. These nanoplastics are difficult to capture and are highly likely to be present in the remaining effluent.

Management of wastewater treatment sludge

It is important to note that the majority of the microplastics removed from wastewater end up in sewage sludge (Iyare et al., 2020). Multiple studies have shown that these dominate the microplastic composition of sewage sludge – 63–90 per cent of microplastics in sludge have been shown to be fibres (Iyare et al., 2020). This sludge, which is often used as an agricultural fertiliser across the EU, represents an important route for microplastics to enter aquatic and terrestrial ecosystems.

Alternative treatment methods for sewage sludge in Europe include landfilling, incineration and composting (Bianchini et al., 2016). Although incineration processes are expected to burn plastic particles, observations by Yang et al. (2021) in 12 waste incinerators suggest that they may not destroy plastic waste entirely, resulting in concentrations of microplastics remaining in incineration bottom ash, making it a potential source of microplastic release to the environment.

There is thus a need for additional knowledge of and regulations on the treatment and use of sludge that take the presence of microplastics into account. Innovative solutions to post-treat and deal with the sludges are needed, through which the nutrients can be recovered and the handling is neither chemical- nor energy intensive. As an example, a Finnish start-up provides thermal treatment solutions for wastewater sludges that enable the production of energy and the recovery of nutrients in the residual ash which can be used in fertilisers, while destroying medical residues and microplastics (Endev, 2021).

Clean-up of microplastics from the environment

A cost-effective technical solution for the large-scale removal of microplastics from the ocean seems unrealistic. In any case, as long as large quantities of plastics and microplastics continue to enter the ocean, clean-up activities would be in vain, which highlights the need for action that prevents the release of microplastics at source. Even if all losses of plastic into the environment were to stop immediately, however, continuing fragmentation of those (macro)plastics already present in the world's oceans will cause a further increase in the amount of microplastics in the ocean (GESAMP 2015).

4.4. Future research needs and policy options

Although textiles have recently been acknowledged as an important source of microplastics and many research efforts are targeted at investigating the issue, there are still many unknowns about the importance of difference factors affecting microfibre releases, release mechanisms, behaviour, associated ecosystem and health impacts and potential solutions that are scalable. Additionally, financial, regulatory or reputational incentives for manufacturers to design, produce and sell clothing that sheds fewer, or no synthetic microfibres, or to develop washing machines and filters that capture these fibres at source are lacking (Eunomia and ICF, 2018). There is also a lack of consumer awareness about measures that can be adopted at the level of households to limit microplastics release, such as reduced washing, carefully following washing instructions and longer use, avoiding fast fashion.

To further extend the knowledge of microfibres from textiles, some priority areas for further research include:

- the development of standardised sampling methods and metrics for the quantification and identification of micro- and nanofibres in environmental samples;
- the development of standardised research methods to study shedding behaviour from textile manufacturing, wearing, washing and waste treatment;
- research on innovative production processes and waste treatment technologies to prevent, reduce and capture microplastics across the lifecycle of textiles;
- studies clarifying environmental spread; contamination of air and soil; ecotoxicity and health effects of microfibre exposure, especially from accumulation in the food chain; long-term chronic effects; and the effect of textile chemicals that are released from microplastics;
- ways to stimulate sustainable consumption of textiles, including purchasing and use behaviour, washing habits and end-of-life management.

It is clear that continued governmental and industrial support is needed to advance research aimed at closing these knowledge gaps on the release, spread and impacts of nano- and microplastics. Also, a close interdisciplinary collaboration between technical, behavioural and regulatory measures is needed to address the complex issues associated with microfibre pollution from textiles.

The expected EU Textiles Strategy could be an important lever for more sustainable production, use and end-of-life management of textiles and a move away from fast fashion, short lifespans and waste generation. The EU Circular Economy Action Plan also targets microplastics by highlighting the need to tackle the unintentional release of microplastics by labelling and standardisation, and by harmonising measurement methods.

An overview of the main needs for research and supporting policy is given below.

Standardised sampling and measurement methods for identification and mapping

One of the most pressing issues is the current lack of standardised and harmonised methods to measure, quantify and identify micro- and nanoplastics concentrations in water, air and soil, and in biota (GESAMP, 2015). In particular, as wastewater is an important dispersion pathway, a standard test should be developed to identify and quantify, both in mass and number, the micro- and nanoplastics in the influent, effluent and sludge output of wastewater treatment plants, using filters able to capture the smallest particles, using sampling procedures that assure representativity and avoiding contamination by microfibres from other sources such as the air. The presence of chemical additives that can originate from plastic degradation or leaching also needs to be monitored in a more formalised manner.

Currently, several CEN and ISO technical (sub-)committees and working groups ([16]) on microplastics from textile sources are working on standards concerning (1) the determination of fibre loss from fabrics during washing and (2) qualitative and quantitative evaluations of microplastics. An additional test method on the measurement of microfibre emission from textile products during domestic washing is also under development (ISO/AWI 5228).

Standardised research methods to better understand shedding mechanisms and assess their impacts

More research is needed to quantify unintentional release of fibres across textile lifecycles and identify which different factors during production, use or disposal, such as fibre type, yarn composition, fabric construction, finishings, washing methods and detergents used, affect these release rates (The Policy Hub - Circularity for apparel and footwear, 2021). To structure such research and allow for a better comparison between different studies, standardised research methods are needed (Eunomia and ICF, 2018) and guidelines on experimental setup and reporting. For example, current studies typically use different textile items, washing machine models, washing programmes, spinning speeds, detergents, etc. – parameters which all have an impact on the results. The textile industry has now set up a cross-industry agreement and several research activities to work towards such a common measurement standard.

Similarly, methods to determine exposure and accumulation levels and assess potential impacts on ecosystems, biota and humans are lacking (SAPEA). In addition to risks related with the microplastics themselves, further measurement and assessment is also needed to quantify the potential risks associated with the plastic additives and finishing chemicals that can be released by microplastics.

The development of innovative production processes

As consumers only have a limited capability to prevent microplastics release during use, it is clear that the issue of microplastic release needs to be tackled at the design and manufacturing stage, by making sustainable products the norm. Source prevention measures are believed to be most cost-effective (Eunomia and ICF, 2018).

Research on innovative production processes that can reduce fibre shedding at source (prevention) and technologies to better separate and capture microfibers from wastewater (capture) at the industrial and household levels should be promoted (The Policy Hub - Circularity for apparel and footwear, 2021). Research routes include the development and use of alternative fibres with reduced fibre shedding, alternative fabric construction methods and pre-washing of textiles products at the manufacturing plant (section 4.1).

Firstly, textile designers and manufacturers should be made aware of the issue of microplastic shedding and of potential mitigation strategies that can be taken in product design and manufacturing to prevent and reduce microfibre shedding. Different product, industry, and environmental policy instruments could address the relevant parameters for textile design, such as fibre choice, fibre length, fabric construction, finishing treatments and dyeing processes. Research into biodegradable yarns could lead to alternative textile fibres, the microfibres of which would biodegrade in a relatively short period of time and not pose any environmental risk. The potential of industrial pre-washing of items could also be explored, as pre-washing would allow the collection and correct processing of the majority of released microfibres before textiles enter the use phase. In particular, standardisation on these aspects is key, including standardisation of testing protocols, harmonisation of measurement methods and common definitions.

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[16] CEN/ TC 248/ WG37 and ISO/ TC 38/ WG 34 "Microplastics from textile sources"

Voluntary approaches by industry are under development, such as under the Cross Industry Agreement for the prevention of microplastics release into the aquatic environment during the washing of synthetic textiles. Labelling of products according to their level of microplastics release would be an option. This does not, however, prevent fabrics and garments that emit a lot of fibres during washing from entering European markets, and puts the responsibility on consumers. Establishing a maximum threshold value for fibre release during washing, for example, would make low-emission products the norm, providing a strong incentive to manufacturers. Of course, such a threshold value would require a standard testing procedure for fabrics and products prior to market entry. There is a risk, however, that certain fibres or fabric types would not pass the test, which would lead to their banning.

Capturing of microplastics from wastewater

The emission of micro-plastics from the washing and drying of textiles can be reduced by applying filters or other technical solutions to washing machines, washer-dryers and tumble-dryers (section 4.2). More effective filters to remove microplastics at the level of the wastewater treatment plant should also be further investigated (Section 4.3), although whether a full removal of micro- and especially nanofibers by filtering systems will be possible can be questioned. Additionally, care has to be taken that microfibres, once collected in filters, are not -unwittingly- discharged in other sinks, showing the need for clear instructions for producers and consumers on how to safely dispose of captured microfibres and filters.

Moreover, as the application of wastewater treatment sludge on agricultural land represents an indirect source of microplastics pollution, technologies should be explored that avoid the mixing of microplastics with the sludge in wastewater treatment plants, or that are able to separate microplastics from sludge.

Advocating sustainable textiles consumption and behaviour

While consumers only have a limited influence on microplastic shedding, they can contribute to a reduction of microplastic release through more sustainable textiles consumption and appropriate washing behaviour. A change in consumer habits can be influenced by sustainable business models that promote sustainable products and policies that support sustainable behaviour with appropriate regulation. Labels could be developed that inform consumers on the risk of microfibre shedding and advise on washing procedures that reduce it. In this context, it is important to focus both on what information should be communicated as well as how and where. One key area to explore might be the testing of new care labels that provide specific microfibre (shedding) information and give further washing instructions that go beyond minimising harm to the clothing item (Salahuddin and Lee, 2020). Similarly, as more and more filtering devices come on to the market, it will be crucial to understand how their uptake and long-term use can be supported and guaranteed (Herweyers et al., 2020).

While labelling would increase consumer awareness about the microplastics issue, it is unlikely that purchasing behaviour will be significantly affected. Ultimately, one of the key questions requiring continuous research will also be how overall consumption can be reduced without compromising either consumer wellbeing or business viability. Phasing out fast fashion and encouraging consumers to use their clothes for longer and to reuse – i.e. buy second-hand clothes – would have an overall beneficial impact on the environmental impacts related to textile consumption, while also contributing to a reduction in microfibre release.

5 References

Al-Sid-Cheikh, M., et al., 2018, ‘Uptake, Whole-Body Distribution, and Depuration of Nanoplastics by the Scallop Pecten maximus at Environmentally Realistic Concentrations’, *Environmental Science & Technology* 52(24), pp. 14480-14486 (DOI: 10.1021/acs.est.8b05266).

Barrett, J., et al., 2020, ‘Microplastic pollution in deep-sea sediments from the Great Australian Bight’, *Frontiers in Marine Science* 7, 576170 (DOI: 10.3389/fmars.2020.576170).

Bertling, J., et al., 2018, ‘Kunststoffe in der Umwelt’, (DOI: 10.24406/UMSICHT-N-497117).

Besseling, E., et al., 2013, ‘Effects of Microplastic on Fitness and PCB Bioaccumulation by the Lugworm Arenicola marina (L.)’, *Environmental Science & Technology* 47(1), pp. 593-600.

Bianchini, A., et al., 2016, ‘Sewage sludge management in Europe: a critical analysis of data quality’, *International Journal of Environment and Waste Management* 18, p. 226 (DOI: 10.1504/IJEWM.2016.10001645).

Boag, A. H., et al., 1999, ‘The Pathology of Interstitial Lung Disease in Nylon Flock Workers’, *The American Journal of Surgical Pathology* 23(12), p. 1539.

Boucher, J. and Friot, D., 2017, *Primary microplastics in the oceans*, International Union for the Conservation of Nature (https://www.iucn.org/content/primary-microplastics-oceans) accessed 21 May 2021.

Boyle, K. and Örmeci, B., 2020, ‘Microplastics and Nanoplastics in the Freshwater and Terrestrial Environment: A Review’, *Water* 12(9), p. 2633 (DOI: 10.3390/w12092633).

Brennecke, D., et al., 2016, ‘Microplastics as vector for heavy metal contamination from the marine environment’, *Estuarine, Coastal and Shelf Science* 178, pp. 189-195 (DOI: 10.1016/j.ecss.2015.12.003).

Browne, M. A., et al., 2008, ‘Ingested Microscopic Plastic Translocates to the Circulatory System of the Mussel, Mytilus edulis (L.)’, *Environmental science & technology* 42, pp. 5026-5031 (DOI: 10.1021/es800249a).

Browne, M. A., et al., 2011, ‘Accumulation of Microplastic on Shorelines Woldwide: Sources and Sinks’, *Environmental Science & Technology* 45(21), pp. 9175-9179 (DOI: 10.1021/es201811s).

Cai, Y., et al., 2020, ‘The origin of microplastic fiber in polyester textiles: the textile production process matters’, *Journal of Cleaner Production* 267, 121970 (DOI: 10.1016/j.jclepro.2020.121970).

Carney Almroth, B., et al., 2018, ‘Quantifying shedding of synthetic fibers from textiles; a source of microplastics released into the environment’, 25(2), pp. 1191-1199.

Carr, S. A., et al., 2016, ‘Transport and fate of microplastic particles in wastewater treatment plants’, *Water Research* 91, pp. 174-182 (DOI: 10.1016/j.watres.2016.01.002).

Centers for Disease Control and Prevention - National Institute for Occupational Safety and Health, 2019, ‘Respiratory Diseases: Occupational Risks’ (https://www.cdc.gov/niosh/programs/resp/risks.html) accessed 14 June 2021.

Chan, C. K. M., et al., 2021, ‘Microplastic fibre releases from industrial wastewater effluent: a textile wet-processing mill in China’, *Environmental Chemistry* (DOI: 10.1071/EN20143).

Coraball, 2021, ‘Cora Ball - The World’s First Microfiber Catching Laundry Ball’, Cora Ball (https://coraball.com/) accessed 24 June 2021.

Corcoran, P. L., et al., 2009, ‘Plastics and beaches: a degrading relationship’, *Marine Pollution Bulletin* 58(1), pp. 80-84 (DOI: 10.1016/j.marpolbul.2008.08.022).

Crini, G. and Lichtfouse, E., 2018, ‘Wastewater treatment: an overview’, in: Crini, G. and Lichtfouse, E. (eds), *Green adsorbents for pollutant removal: fundamentals and design*, Environmental Chemistry for a Sustainable World, Springer International Publishing, Cham, pp. 1-21.

Darbra, R. M., et al., 2012, ‘Additives in the Textile Industry’, in: Bilitewski, B. et al. (eds), *Global Risk-Based Management of Chemical Additives I: Production, Usage and Environmental Occurrence*, The Handbook of Environmental Chemistry, Springer, Berlin, Heidelberg, pp. 83-107.

De Falco, F., et al., 2018, ‘Evaluation of microplastic release caused by textile washing processes of synthetic fabrics’, *Environmental Pollution* 236, pp. 916-925 (DOI: 10.1016/j.envpol.2017.10.057).

De Falco, F., et al., 2019a, ‘Novel finishing treatments of polyamide fabrics by electrofluidodynamic process to reduce microplastic release during washings’, *Polymer Degradation and Stability* 165, pp. 110-116 (DOI: 10.1016/j.polymdegradstab.2019.05.001).

De Falco, F., et al., 2019b, ‘The contribution of washing processes of synthetic clothes to microplastic pollution’, *Scientific Reports* 9(1), p. 6633 (DOI: 10.1038/s41598-019-43023-x).

De Falco, F., et al., 2020, ‘Microfiber release to water, via laundering, and to air, via everyday use: a comparison between polyester clothing with differing textile parameters’, *Environmental Science & Technology* 54(6), pp. 3288-3296 (DOI: 10.1021/acs.est.9b06892).

de Souza Machado, A. A., et al., 2018, ‘Impacts of Microplastics on the Soil Biophysical Environment’, *Environmental Science & Technology* 52(17), pp. 9656-9665 (DOI: 10.1021/acs.est.8b02212).

Dris, R., et al., 2017, ‘A first overview of textile fibers, including microplastics, in indoor and outdoor environments’, *Environmental Pollution* 221, pp. 453-458 (DOI: 10.1016/j.envpol.2016.12.013).

EC, 2018, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions — A European strategy for plastics in a circular economy (COM(2018) 28 final).

EC, 2020a, ‘A new Circular Economy Action Plan For a cleaner and more competitive Europe. COM(2020) 98 final’ (https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF) accessed 26 March 2020.

EC, 2020b, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions — A new circular economy action plan: for a cleaner and more competitive Europe (COM(2020) 98 final).

ECHA, 2019, ‘microplastics - Registry of restriction intentions until outcome - ECHA’ (https://echa.europa.eu/registry-of-restriction-intentions/-/dislist/details/0b0236e18244cd73) accessed 2 June 2021.

ECHA, 2021, ‘Microplastics’, European Chemicals Agency (https://echa.europa.eu/hot-topics/microplastics) accessed 25 May 2021.

EDANA, 2020, ‘Nonwoven industry’s response to the Eunomia study on the plastics definition under the Directive (EU) on the reduction of the impact of certain plastic products on the environment’, edana.org (https://www.edana.org/about-us/news) accessed 3 June 2021.

EEA, 2019, *Textiles in Europe’s circular economy*, EEA Briefing No 10/2019, European Environment Agency (https://www.eea.europa.eu/publications/textiles-in-europes-circular-economy) accessed 26 March 2020.

EEA, 2021a, *A framework for enabling circular business models in Europe*, EEA Briefing, European Environment Agency (https://www.eea.europa.eu/publications/a-framework-for-enabling-circular) accessed 31 May 2021.

EEA, 2021b, *Impacts of COVID-19 on single-use plastic in Europe’s environment — European Environment Agency*, Briefing (https://www.eea.europa.eu/publications/impacts-of-covid-19-on) accessed 24 June 2021.

EEA, 2021c, ‘Plastic in textiles: towards a circular economy for synthetic textiles in Europe’ (https://www.eea.europa.eu/publications/plastic-in-textiles-towards-a) accessed 28 April 2021.

EEA, 2021d, ‘Plastics, the circular economy and Europe’s environment’ (https://www.eea.europa.eu/publications/plastics-the-circular-economy-and/) accessed 14 April 2021.

EFSA, 2016, ‘Presence of microplastics and nanoplastics in food, with particular focus on seafood’, *EFSA Journal* 14(6), p. e04501 (DOI: https://doi.org/10.2903/j.efsa.2016.4501).

Elkhatib, D. and Oyanedel-Craver, V., 2020, ‘A Critical Review of Extraction and Identification Methods of Microplastics in Wastewater and Drinking Water’, *Environmental Science & Technology* 54(12), pp. 7037-7049 (DOI: 10.1021/acs.est.9b06672).

Ellen MacArthur Foundation, 2017, ‘Circular Fashion - A New Textiles Economy: Redesigning fashion’s future’ (https://www.ellenmacarthurfoundation.org/publications/a-new-textiles-economy-redesigning-fashions-future) accessed 5 February 2019.

Endev, 2021, ‘https://www.endev.fi/en/front-page/’ (https://www.endev.fi/en/front-page/) accessed 24 June 2021.

Enfrin, M., et al., 2019, ‘Nano/microplastics in water and wastewater treatment processes – Origin, impact and potential solutions’, *Water Research* 161, pp. 621-638 (DOI: 10.1016/j.watres.2019.06.049).

Eschenbacher, W. L., et al., 1999, ‘Nylon Flock–Associated Interstitial Lung Disease’, *American Journal of Respiratory and Critical Care Medicine* 159(6), pp. 2003-2008 (DOI: 10.1164/ajrccm.159.6.9808002).

Essel, R., et al., 2015, *Sources of microplastics relevant to marine protection in Germany*, No (UBA-FB) 002147/E, Umwelt Bundesamt, Dessau-Roßlau (https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_64_2015_sources_of_microplastics_relevant_to_marine_protection_1.pdf).

ETC/WMGE, 2019, *Textiles and the environment in a circular economy*, Eionet Report No ETC/WMGE 2019/6, European Topic Centre for Waste and Materials in a Green Economy (https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-reports/textiles-and-the-environment-in-a-circular-economy) accessed 26 March 2020.

ETC/WMGE, 2021a, *Business models in a circular economy*, Eionet Report — ETC/WMGE 2021/2, European Topic Centre on Waste and Materials in a Green Economy (https://www.eionet.europa.eu/etcs/etc-wmge/products/business-models-in-a-circular-economy) accessed 26 November 2021.

ETC/WMGE, 2021b, *Impact of COVID-19 on single-use plastics and the environment in Europe* (https://www.eionet.europa.eu/etcs/etc-wmge/products/impact-of-covid-19-on-single-use-plastics-and-the-environment-in-europe) accessed 24 June 2021.

ETC/WMGE, 2021c, *Plastic in textiles: potentials for circularity and reduced environmental and climate impacts*, Eionet Report — ETC/WMGE 2021/1, European Topic Centre on Waste and Materials in a Green Economy (https://www.eionet.europa.eu/etcs/etc-wmge/products/plastic-in-textiles-potentials-for-circularity-and-reduced-environmental-and-climate-impacts) accessed 28 April 2021.

Eunomia, 2016, *Plastics in the Marine Environment* (https://www.eunomia.co.uk/reports-tools/plastics-in-the-marine-environment/) accessed 21 May 2021.

Eunomia and ICF, 2018, *Measuring the impacts of microplastics* (https://www.eunomia.co.uk/case_study/measuring-impacts-of-microplastics/) accessed 21 May 2021.

European Commission, 2019, *Environmental and health risks of microplastic pollution.*, Publications Office, LU.

Everaert, G., et al., 2020, 'Risks of floating microplastic in the global ocean', *Environmental Pollution* 267, p. 115499 (DOI: 10.1016/j.envpol.2020.115499).

Filtrol, 2021, 'The Filtrol | Washing Machine Microfiber and Lint Filter | Stop Plastic Microfiber Pollution' (https://filtrol.net/) accessed 24 June 2021.

Foley, C. J., et al., 2018, 'A meta-analysis of the effects of exposure to microplastics on fish and aquatic invertebrates', *Science of The Total Environment* 631-632, pp. 550-559 (DOI: 10.1016/j.scitotenv.2018.03.046).

Gasperi, J., et al., 2018, 'Microplastics in air: are we breathing it in?', *Current Opinion in Environmental Science & Health* 1, pp. 1-5 (DOI: 10.1016/j.coesh.2017.10.002).

Gerdes, Z., et al., 2018, 'A serial dilution method for assessment of microplastic toxicity in suspension', *bioRxiv*, p. 401331 (DOI: 10.1101/401331).

Gesamp, 2015, *Sources, fate and effects of microplastics in the marine environment: a global assessment*, Gesamp Reports and Studies No 90, Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (http://www.gesamp.org/publications/reports-and-studies-no-90) accessed 25 January 2021.

GESAMP, 2016, *Sources, Fate and Effects of Microplastics in the Marine Environment (Part 2)*, GESAMP Reports and Studies No #93, Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (http://www.gesamp.org/publications/microplastics-in-the-marine-environment-part-2) accessed 25 January 2021.

Gewert, B., et al., 2015, 'Pathways for degradation of plastic polymers floating in the marine environment', *Environmental Science: Processes & Impacts* 17(9), pp. 1513-1521 (DOI: 10.1039/C5EM00207A).

Ghosh, G. C., et al., 2021, 'Microplastics contamination in commercial marine fish from the Bay of Bengal', *Regional Studies in Marine Science* 44, 101728 (DOI: 10.1016/j.rsma.2021.101728).

González-Fernández, D., et al., 2021, ‘Floating macrolitter leaked from Europe into the ocean’, *Nature Sustainability* 4(6), pp. 474-483 (DOI: 10.1038/s41893-021-00722-6).

Guppyfriend, 2021, ‘Guppyfriend Washing Bag Online Shop’, Guppyfriend Shop | Europe | Global (https://en.guppyfriend.com/) accessed 24 June 2021.

Halstead, J. E., et al., 2018, ‘Assessment tools for microplastics and natural fibres ingested by fish in an urbanised estuary’, *Environmental Pollution* 234, pp. 552-561 (DOI: 10.1016/j.envpol.2017.11.085).

Hartline, N. L., et al., 2016, ‘Microfiber masses recovered from conventional machine washing of new or aged garments’, *Environmental Science & Technology* 50(21), pp. 11532-11538 (DOI: 10.1021/acs.est.6b03045).

Henry, B., et al., 2018, *Microplastic pollution from textiles: A literature review*, Consumption Research Norway SIFO, Oslo, Norway (https://fagarkivet.oslomet.no/bitstream/handle/20.500.12199/3859/OR1%20-%20Microplastic%20pollution%20from%20textiles%20-%20A%20literature%20review.pdf?sequence=1&isAllowed=y) accessed 30 March 2021.

Henry, B., et al., 2019a, ‘Microfibres from apparel and home textiles: prospects for including microplastics in environmental sustainability assessment’, *Science of the Total Environment* 652, pp. 483-494 (DOI: 10.1016/j.scitotenv.2018.10.166).

Henry, B., et al., 2019b, ‘Microfibres from apparel and home textiles: Prospects for including microplastics in environmental sustainability assessment’, *Science of The Total Environment* 652, pp. 483-494 (DOI: 10.1016/j.scitotenv.2018.10.166).

Herweyers, L., et al., 2020, ‘Consumers’ Perceptions and Attitudes toward Products Preventing Microfiber Pollution in Aquatic Environments as a Result of the Domestic Washing of Synthetic Clothes’, *Sustainability* 12(6), p. 2244 (DOI: 10.3390/su12062244).

Hou, L., et al., 2021, ‘Conversion and removal strategies for microplastics in wastewater treatment plants and landfills’, *Chemical Engineering Journal* 406, p. 126715 (DOI: 10.1016/j.cej.2020.126715).

Hubbub, 2018, *Change your laundry habits if you don’t want to eat your clothes: #WhatsInMyWash campaign shares tips to make your washes more eco-friendly and help clothes last longer*, Hubbub, London.

Iyare, P. U., et al., 2020, ‘Microplastics removal in wastewater treatment plants: a critical review’, *Environmental Science: Water Research & Technology* 6(10), pp. 2664-2675 (DOI: 10.1039/D0EW00397B).

Jambeck, J. R., et al., 2015, ‘Plastic waste inputs from land into the ocean’, *Science* 347(6223), pp. 768-771 (DOI: 10.1126/science.1260352).

Jemec, A., et al., 2016, ‘Uptake and effects of microplastic textile fibers on freshwater crustacean *Daphnia magna*’, *Environmental Pollution* 219, pp. 201-209 (DOI: 10.1016/j.envpol.2016.10.037).

Kärkkäinen, N. and Sillanpää, M., 2021, ‘Quantification of different microplastic fibres discharged from textiles in machine wash and tumble drying’, *Environmental Science and Pollution Research* 28, pp. 1-11 (DOI: 10.1007/s11356-020-11988-2).

Kelly, M. R., et al., 2019, ‘Importance of Water-Volume on the Release of Microplastic Fibers from Laundry’, *Environmental Science & Technology* 53(20), pp. 11735-11744 (DOI: 10.1021/acs.est.9b03022).

Kern, D. G., et al., 1998, ‘Flock worker’s lung: chronic interstitial lung disease in the nylon flocking industry’, *Annals of Internal Medicine* 129(4), pp. 261-272 (DOI: 10.7326/0003-4819-129-4-199808150-00001).

Kirstein, I. V., et al., 2016, 'Dangerous hitchhikers? Evidence for potentially pathogenic Vibrio spp. on microplastic particles', *Marine Environmental Research* 120, pp. 1-8 (DOI: 10.1016/j.marenvres.2016.07.004).

Koelmans, A. A., et al., 2019, 'Microplastics in freshwaters and drinking water: Critical review and assessment of data quality', *Water Research* 155, pp. 410-422 (DOI: 10.1016/j.watres.2019.02.054).

Kremer, A. M., et al., 1994, 'Airway hyper-responsiveness and the prevalence of work-related symptoms in workers exposed to irritants', *American Journal of Industrial Medicine* 26(5), pp. 655-669 (DOI: 10.1002/ajim.4700260508).

Kuwonu, F., 2017, 'Protectionist ban on imported used clothing', Africa Renewal (https://www.un.org/africarenewal/magazine/december-2017-march-2018/protectionist-ban-imported-used-clothing) accessed 30 September 2021.

Laitala, K., et al., 2018, 'Does Use Matter? Comparison of Environmental Impacts of Clothing Based on Fiber Type', 10(2524), pp. 1-25 (DOI: http://dx.doi.org/10.3390/su10072524).

Lant, N. J., et al., 2020, 'Microfiber release from real soiled consumer laundry and the impact of fabric care products and washing conditions' Annamalai, P. K. (ed.), *PLOS ONE* 15(6), e0233332 (DOI: 10.1371/journal.pone.0233332).

Lares, M., et al., 2018, 'Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology', *Water Research* 133, pp. 236-246 (DOI: 10.1016/j.watres.2018.01.049).

Lassen, C., et al., 2015, *Microplastics. Occurrence, effects and sources of releases to the environment in Denmark*, Danish Environmental Protection Agency (https://mst.dk/service/publikationer/publikationsarkiv/2015/nov/rapport-om-mikroplast/) accessed 25 June 2021.

Lebreton, L. C. M., et al., 2017, 'River plastic emissions to the world's oceans', *Nature Communications* 8, 15611 (DOI: 10.1038/ncomms15611).

Leslie, H. A., et al., 2017, 'Microplastics en route: Field measurements in the Dutch river delta and Amsterdam canals, wastewater treatment plants, North Sea sediments and biota', *Environment International* 101, pp. 133-142 (DOI: 10.1016/j.envint.2017.01.018).

Li, L., et al., 2020, 'Performance evaluation of MBR in treating microplastics polyvinylchloride contaminated polluted surface water', *Marine Pollution Bulletin* 150, p. 110724 (DOI: 10.1016/j.marpolbul.2019.110724).

Li, L., et al., 2021, 'COVID-19: Performance study of microplastic inhalation risk posed by wearing masks', *Journal of Hazardous Materials* 411, p. 124955 (DOI: 10.1016/j.jhazmat.2020.124955).

Linares, V., et al., 2015, 'Human exposure to PBDE and critical evaluation of health hazards', *Archives of Toxicology* 89(3), pp. 335-356 (DOI: 10.1007/s00204-015-1457-1).

Lithner, D., et al., 2011, 'Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition', *Science of The Total Environment* 409(18), pp. 3309-3324 (DOI: 10.1016/j.scitotenv.2011.04.038).

Liu, J., et al., 2019, 'Microfibers: a preliminary discussion on their definition and sources', *Environmental Science and Pollution Research* 26(28), pp. 29497-29501 (DOI: 10.1007/s11356-019-06265-w).

Liu, W., et al., 2021, ‘A review of the removal of microplastics in global wastewater treatment plants: Characteristics and mechanisms’, *Environment International* 146, p. 106277 (DOI: 10.1016/j.envint.2020.106277).

Llorca, M., et al., 2020, ‘Microplastics in Mediterranean coastal area: toxicity and impact for the environment and human health’, *Trends in Environmental Analytical Chemistry* 27, p. e00090 (DOI: 10.1016/j.teac.2020.e00090).

Lusher, A. L., et al., 2013, ‘Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel’, *Marine Pollution Bulletin* 67(1-2), pp. 94-99 (DOI: 10.1016/j.marpolbul.2012.11.028).

Magni, S., et al., 2019, ‘The fate of microplastics in an Italian Wastewater Treatment Plant’, *Science of The Total Environment* 652, pp. 602-610 (DOI: 10.1016/j.scitotenv.2018.10.269).

Magnusson, K., et al., 2016, ‘Swedish sources and pathways for microplastics to the marine environment’, , p. 87.

Meijer, L. J. J., et al., 2021, ‘More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean’, *Science Advances* 7(18), eaaz5803 (DOI: 10.1126/sciadv.aaz5803).

Mermaids, 2019, *Handbook for zero microplastics from textiles and laundry — good practice guidelines for the textile industry*, EU Life Project (https://www.oceancleanwash.org/wp-content/uploads/2019/08/Handbook-for-zero-microplastics-from-textiles-and-laundry-developed.pdf) accessed 4 June 2021.

Mintenig, S. M., et al., 2017, ‘Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-Fourier-transform infrared imaging’, *Water Research* 108, pp. 365-372 (DOI: 10.1016/j.watres.2016.11.015).

Murphy, F., et al., 2016, ‘Wastewater Treatment Works (WwTW) as a Source of Microplastics in the Aquatic Environment | Environmental Science & Technology’, 50(11), pp. 5800-5808.

Napper, I. E., et al., 2020, ‘The efficiency of devices intended to reduce microfibre release during clothes washing’, *Science of the Total Environment* 738, 140412 (DOI: 10.1016/j.scitotenv.2020.140412).

OECD, 2020a, *Workshop on Microplastics from Synthetic Textiles: Knowledge, Mitigation, and Policy*, OECD.

OECD, 2020b, *Workshop on microplastics from synthetic textiles: knowledge, mitigation, and policy — summary note*, 11 February 2020, OECD Headquarters, Paris, Organisation for Economic Co-Operation and Development (https://www.oecd.org/water/Workshop_MP_Textile_Summary_Note_FINAL.pdf) accessed 26 November 2021.

Özkan, İ. and Gündoğdu, S., 2021, ‘Investigation on the microfiber release under controlled washings from the knitted fabrics produced by recycled and virgin polyester yarns’, *The Journal of The Textile Institute* 112(2), pp. 264-272 (DOI: 10.1080/00405000.2020.1741760).

Parker, L., 2021, ‘Plastic gets to the oceans through over 1,000 rivers’, *National Geographic*, 30 April 2021 (https://www.nationalgeographic.com/environment/article/plastic-gets-to-oceans-through-over-1000-rivers) accessed 21 May 2021.

Patagonia, 2018, ‘An Update on Microfibre Pollution’ (https://eu.patagonia.com/de/en/stories/an-update-on-microfiber-pollution/story-31370.html).

Pimentel, J. C., et al., 1975, 'Respiratory disease caused by synthetic fibres: a new occupational disease.', *Thorax* 30(2), pp. 204-219 (DOI: 10.1136/thx.30.2.204).

Pinto da Costa, J., et al., 2018, 'Microplastics in soils: assessment, analytics and risks', *Environmental Chemistry* 16(1), pp. 18-30 (DOI: 10.1071/EN18150).

Pirc, U., et al., 2016, 'Emissions of microplastic fibers from microfiber fleece during domestic washing', *Environmental Science and Pollution Research* 23(21), pp. 22206-22211 (DOI: 10.1007/s11356-016-7703-0).

PlanetCare, 2021, 'PlanetCare | The Most Effective Solution To Stop Microfiber Pollution', PlanetCare (https://planetcare.org/) accessed 24 June 2021.

Plastic Soup Foundation, 2021, 'Ocean Clean Wash: Solutions for Consumers' (https://www.oceancleanwash.org/solutions/solutions-for-consumers/) accessed 20 April 2021.

Plastics Europe, 2020, *Plastics - the facts 2020* (https://www.plasticseurope.org/application/files/5716/0752/4286/AF_Plastics_the_facts-WEB-2020-ING_FINAL.pdf) accessed 12 May 2021.

Poerio, T., et al., 2019, 'Membrane processes for microplastic removal', *Molecules* 24(22), 4148 (DOI: 10.3390/molecules24224148).

Ragusa, A., et al., 2021, 'Plasticenta: First evidence of microplastics in human placenta', *Environment International* 146, p. 106274 (DOI: 10.1016/j.envint.2020.106274).

Redondo-Hasselerharm, P. E., et al., 2018, 'Microplastic Effect Thresholds for Freshwater Benthic Macroinvertebrates', *Environmental Science & Technology* 52(4), pp. 2278-2286 (DOI: 10.1021/acs.est.7b05367).

Remy, F., et al., 2015, 'When Microplastic Is Not Plastic: The Ingestion of Artificial Cellulose Fibers by Macrofauna Living in Seagrass Macrophytodetritus', *Environmental Science & Technology* 49(18), pp. 11158-11166 (DOI: 10.1021/acs.est.5b02005).

Rios Mendoza, L. M., et al., 2018, 'Micro(nanoplastics) in the marine environment: Current knowledge and gaps', *Current Opinion in Environmental Science & Health* 1, pp. 47-51 (DOI: 10.1016/j.coesh.2017.11.004).

Roos, S., et al., 2017, *Microplastics shedding from polyester fabrics*, Mistra Future Fashion Report No 2017:1, SEREA (http://mistrafuturefashion.com/wp-content/uploads/2017/06/MFF-Report-Microplastics.pdf) accessed 26 November 2021.

Sait, S. T. L., et al., 2021, 'Microplastic fibres from synthetic textiles: Environmental degradation and additive chemical content', *Environmental Pollution* 268, p. 115745 (DOI: 10.1016/j.envpol.2020.115745).

Salvador Cesa, F., et al., 2017a, 'Synthetic fibers as microplastics in the marine environment: A review from textile perspective with a focus on domestic washings', *Science of The Total Environment* 598, pp. 1116-1129 (DOI: 10.1016/j.scitotenv.2017.04.172).

Salvador Cesa, F., et al., 2017b, 'Synthetic fibers as microplastics in the marine environment: A review from textile perspective with a focus on domestic washings', *Science of The Total Environment* 598, pp. 1116-1129 (DOI: 10.1016/j.scitotenv.2017.04.172).

Salvador Cesa, F., et al., 2017c, 'Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings', *Science of the Total Environment* 598, pp. 1116-1129 (DOI: 10.1016/j.scitotenv.2017.04.172).

Sánchez, L. D., 2020, 'France is leading the fight against plastic microfibers', Ocean Clean Wash (https://www.oceancleanwash.org/2020/02/france-is-leading-the-fight-against-plastic-microfibers/) accessed 24 June 2021.

SAPEA, 2019, 'A scientific perspective on microplastics in nature and society', Science Advice for Policy by European Academies (https://www.sapea.info/topics/microplastics/) accessed 6 February 2020.

Schwabl, P., et al., 2019, 'Detection of Various Microplastics in Human Stool: A Prospective Case Series', *Annals of Internal Medicine* 171(7), p. 453 (DOI: 10.7326/M19-0618).

Shen, M., et al., 2020, 'Removal of microplastics via drinking water treatment: Current knowledge and future directions', *Chemosphere* 251, p. 126612 (DOI: 10.1016/j.chemosphere.2020.126612).

Sherrington, C., 2016, *Plastics in the marine environment*, Eunomia, Bristol, UK (https://www.eunomia.co.uk/reports-tools/plastics-in-the-marine-environment/) accessed 25 March 2020.

Shruti, V. C., et al., 2020, 'First study of its kind on the microplastic contamination of soft drinks, cold tea and energy drinks — future research and environmental considerations', *Science of The Total Environment* 726, 138580 (DOI: 10.1016/j.scitotenv.2020.138580).

Stone, C., et al., 2020, 'Natural or synthetic – how global trends in textile usage threaten freshwater environments', 2020(718), pp. 1-10 (DOI: https://doi.org/10.1016/j.scitotenv.2019.134689).

Suaria, G., et al., 2020, 'Microfibers in oceanic surface waters: A global characterization', *Science Advances* 6, p. eaay8493 (DOI: 10.1126/sciadv.aay8493).

Sundt, P., et al., 2014, *Sources of microplastic pollution to the marine environment* (https://www.miljodirektoratet.no/globalassets/publikasjoner/M321/M321.pdf) accessed 25 June 2021.

Talvitie, J., et al., 2017, 'Solutions to microplastic pollution - Removal of microplastics from wastewater effluent with advanced wastewater treatment technologies', *Water Research* 123, pp. 401-407 (DOI: 10.1016/j.watres.2017.07.005).

Textile Exchange, 2020, *Preferred fiber & materials. Market report 2020* (https://textileexchange.org/2020-preferred-fiber-and-materials-market-report-pfmr-released/) accessed 25 May 2021.

The Policy Hub - Circularity for apparel and footwear, 2021, 'EU Textile Strategy - Position Paper.' (https://assets-global.website-files.com/5dcda718f8a683895d9ea394/610a5d4b0631e6180d3a9e79_30072021_Policy%20Hub_Position%20Paper_EU%20Textile%20Strategy.pdf) accessed 22 September 2021.

Turcotte, S. E., et al., 2013, 'Flock Worker's Lung Disease: Natural History of Cases and Exposed Workers in Kingston, Ontario', *Chest* 143(6), pp. 1642-1648 (DOI: 10.1378/chest.12-0920).

UNEP, 2018, *Mapping of global plastics value chain and plastics losses to the environment: with a particular focus on marine environment*, United Nations Environment Programme (http://www.unep.org/pt-br/node/27212) accessed 6 May 2021.

UNEP, 2020, *Sustainability and Circularity in the Textile Value Chain* (https://www.oneplanetnetwork.org/sites/default/files/unep_sustainability_and_circularity_in_the_textile_value_chain.pdf) accessed 5 June 2021.

UN-Water, 2017, *The United Nations world water development report, 2017: Wastewater: an untapped resource* (https://unesdoc.unesco.org/ark:/48223/pf0000247552) accessed 30 September 2021.

Velis, C., et al., 2017, *Prevent marine plastic litter — now!*, International Solid Waste Association, Vienna (https://marinelitter.iswa.org/fileadmin/user_upload/Marine_Task_Force_Report_2017/ISWA_report170927_interactive_lowres.pdf) accessed 30 April 2021.

Vesper, H., 2019a, 'Microplastics – challenges and requirements for sustainable solutions', presentation given at: TextileMission Workshop, Brussels, 12 October 2019.

Vesper, H., 2019b, 'Microplastics – challenges and requirements for sustainable solutions', presentation given at: TextileMission Workshop, Brussels, 12 October 2019.

Wang, F., et al., 2018, 'Interaction of toxic chemicals with microplastics: a critical review', *Water Research* 139, pp. 208-219 (DOI: 10.1016/j.watres.2018.04.003).

Warheit, D. B., et al., 2001, 'Potential Pulmonary Effects of Man-Made Organic Fiber (MMOF) Dusts', *Critical Reviews in Toxicology* 31(6), pp. 697-736 (DOI: 10.1080/20014091111965).

Waring, R. H., et al., 2018, 'Plastic contamination of the food chain: a threat to human health?', *Maturitas* 115, pp. 64-68 (DOI: 10.1016/j.maturitas.2018.06.010).

WHO, 2019, *Microplastics in drinking-water*, World Health Organization, Geneva (https://www.who.int/water_sanitation_health/publications/information-sheet190822.pdf) accessed 26 November 2021.

Williams, A., 2020, 'Study shows devices can reduce fibres produced in laundry cycle by up to 80%', University of Plymouth (https://www.plymouth.ac.uk/news/study-shows-devices-can-reduce-fibres-produced-in-laundry-cycle-by-up-to-80) accessed 29 April 2021.

Woodall, L. C., et al., 2014, 'The deep sea is a major sink for microplastic debris', *Royal Society Open Science* 1(4), p. 140317 (DOI: 10.1098/rsos.140317).

Wright, S. L., et al., 2013, 'The physical impacts of microplastics on marine organisms: A review', *Environmental Pollution* 178, pp. 483-492 (DOI: 10.1016/j.envpol.2013.02.031).

Wright, S. L., et al., 2020, 'Atmospheric microplastic deposition in an urban environment and an evaluation of transport', *Environment International* 136, p. 105411 (DOI: 10.1016/j.envint.2019.105411).

Wu, M., et al., 2021, 'Fate and effects of microplastics in wastewater treatment processes', *Science of The Total Environment* 757, p. 143902 (DOI: 10.1016/j.scitotenv.2020.143902).

Xeros, 2020, 'Xeros Technology' (https://www.xerostech.com/technology#xfiltra) accessed 9 June 2020.

Yan, S., et al., 2020, 'Sustainable knowledge from consumer perspective addressing microfibre pollution', *Journal of Fashion Marketing and Management: An International Journal* 24(3), pp. 437-454 (DOI: 10.1108/JFMM-08-2019-0181).

Yang, Z., et al., 2021, 'Is incineration the terminator of plastics and microplastics?', *Journal of Hazardous Materials* 401, p. 123429 (DOI: 10.1016/j.jhazmat.2020.123429).

Zhang, Y.-Q., et al., 2021, 'Microplastics from textile origin – emission and reduction measures', *Green Chemistry* 23(15), pp. 5247-5271 (DOI: 10.1039/D1GC01589C).

Zhao, S., et al., 2016, ‘Microscopic anthropogenic litter in terrestrial birds from Shanghai, China: Not only plastics but also natural fibers’, *Science of The Total Environment* 550, pp. 1110-1115 (DOI: 10.1016/j.scitotenv.2016.01.112).

Ziajahromi, S., et al., 2017, ‘Impact of Microplastic Beads and Fibers on Waterflea (*Ceriodaphnia dubia*) Survival, Growth, and Reproduction: Implications of Single and Mixture Exposures’, *Environmental Science & Technology* 51(22), pp. 13397-13406 (DOI: 10.1021/acs.est.7b03574).

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