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Review

# Microfibers: Environmental Problems and Textile Solutions

Judith S. Weis <sup>1</sup> and Francesca De Falco <sup>2,\*</sup><sup>1</sup> Department of Biological Sciences, Rutgers University, Newark, NJ 10023, USA<sup>2</sup> International Marine Litter Unit, School of Biological and Marine Sciences, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK

\* Correspondence: francesca.defalco@plymouth.ac.uk

**Abstract:** Microplastics have become a topic of considerable concern and intensive study over the past decade. They have been found everywhere in the oceans, including the deepest trenches and remotest parts of the Arctic. They are ingested by many animals and some are incorporated into tissues. There is considerable effort in studying what effects they have on marine life. It has become clear that when water samples are collected in ways that prevent most long thin particles from escaping through pores of a net, the most abundant type of microplastics found in water and sediments are microfibers (fibers with dimensions less than 5 mm). The major source of these pollutants is synthetic textiles, such as polyester or polyamides, which shed microfibers during their entire life cycle. Microfibers are released during textile manufacturing, everyday activities (e.g., washing, drying, wearing) and final disposal. The complexity of microfiber release mechanisms and of the factors involved make the identification and application of ways to reduce the inputs of microfibers very challenging. A comprehensive approach is strongly needed, taking into account solutions at a number of levels, such as re-engineering textiles to minimize shedding, applying washing machine filters, developing advanced wastewater treatment plants and improving the management of textile wastes. To harmonize and make mandatory the solutions identified, a variety of potential government policies and regulations is also needed.

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**Keywords:** microfibers; microplastics; textiles; washing machine; filter; wastewater

## 1. Introduction

In the years since the discovery of microplastics (small pieces ranging from 5 mm in size down to micron sizes), there has been considerable attention devoted to studying the problems. As with larger plastic pieces, microplastics are made of different polymers, such as polyethylene, polystyrene, etc. Some of them are the result of fragmentation of large pieces of plastic, while others are released into the environment as micro-sized pieces (nurdles, microbeads). They are found in a variety of shapes, including spheres, fragments, films and fibers. In the past decade, there has been a great amount of study on their locations, their sources, how organisms interact with them, and effects they may have on organisms and the ecosystem. These studies have focused mainly on the marine environment since that is where they were initially detected, but they have subsequently been found to be abundant in freshwater and terrestrial environments and in the air as well as water. They have been found in the deepest ocean trenches as well as remote mountain tops. The purpose of this article is not to be a comprehensive review of what is known about microfibers, but (1) to demonstrate that evidence shows that microfibers from textiles are the most abundant type of microplastics in the environment and in aquatic animals and (2) to discuss ways in which these inputs to aquatic systems can be reduced by modifying the manufacture, labelling, washing and disposal of textiles.

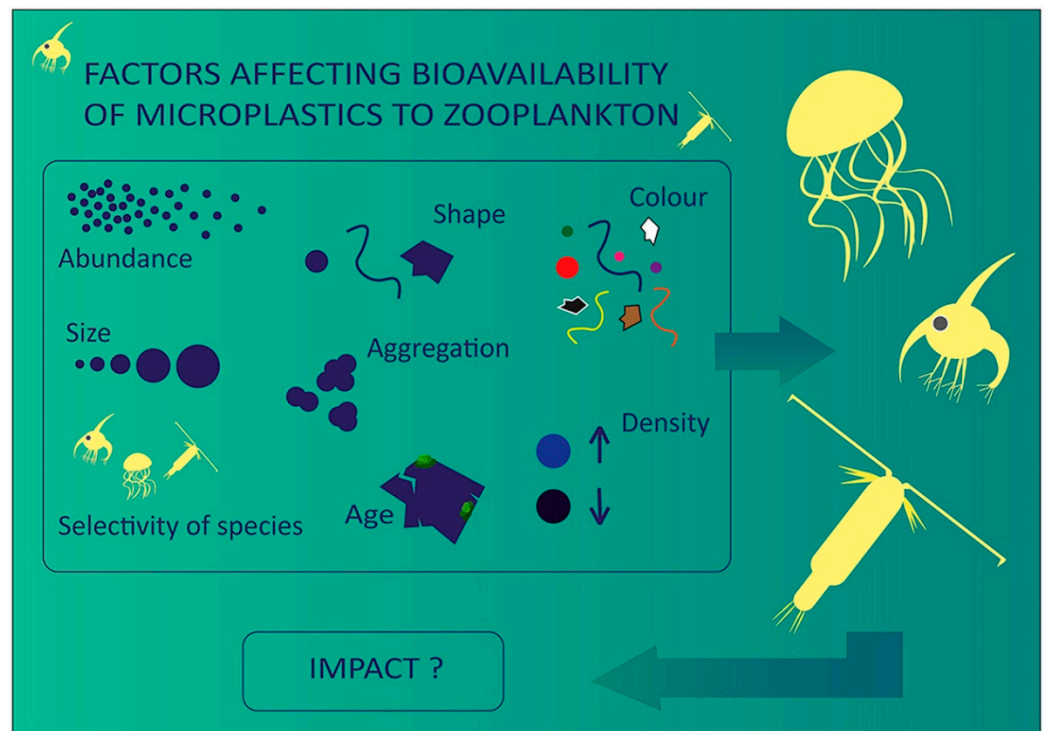
## 2. Measuring Environmental Concentrations

Many studies try to estimate the numbers of microplastic (MP) particles in a body of water. Results are consistent: microplastics are found everywhere they are sought,

including deep-sea trenches [1,2]. However, studies cannot be compared quantitatively because there are no standard methods for collecting and counting MPs. Some studies collect them with nets, which seriously undercount the types of particles in the water since small ones and long thin ones (microfibers, MFs) tend to go through the pores of the nets. Researchers who examine filtered whole water samples (“grab samples”) obtain very different results and find that microfibers are the most common type. Rocha-Santos and Duarte [3] evaluated various sampling methods and concluded that collections in nets find MFs to be much less abundant than in whole water collections. Green et al. [4] reported that manta, bongo and plankton nets can underestimate MFs by three to four orders of magnitude compared to grab (whole water) methods. A meta-analysis found average composition in water was 52% fibers, 29% fragments, with other shapes (beads/sphere, films, foams) comprising only a small proportion [5]. Carr [6] found that over 80% of the MPs in the ocean were fibers and Constant et al. [7] indicated that MFs were the dominant form of MP found on beaches. Once collected, some researchers count the particles under a microscope, while others use Raman or other types of spectroscopy, which is more accurate. Another difficulty in comparing studies is that some report the number of particles per liter, while others report micrograms per liter. Most of the MFs originate from textiles, from our clothing, which sheds them. Some polymers tend to float, while others tend to sink; therefore, collecting samples from surface waters does not provide a representative sample. MFs from clothing, the most abundant MP in the water (e.g., polyester and acrylic), tend to sink rather than float [8]; all MPs found in deep-sea organisms have been fibers. Since MPs differ in chemical composition, size, shape, color, density and effects on biota, they should be regarded as a suite of contaminants and samples should be characterized that way [9]. Furthermore, the nature and degree of their impacts on biota vary depending on these various characteristics.

### 3. Ingestion and Egestion

Ingestion of MPs has been reported in many marine mammals—birds, fishes, macroinvertebrates and plankton—but the rates of ingestion and egestion vary according to the shape of the MP. Botterell et al. [10] reviewed the literature on bioavailability and effects of MPs on zooplankton and found that ingestion had been seen in 39 zooplankton species, most of which were studied in the laboratory. They emphasized the importance of physical differences (size, shape, type, age and abundance) of microplastics in determining their ingestion (Figure 1). Most MPs found in animals’ guts are fibers and fragments [11]; only a small proportion are beads or spheres. MFs could be most numerous because ingestion reflects the environment composition and/or because fibers may not be egested as rapidly as other particles. A recent paper discussed the presence of tangled balls of fibers in the gut of the Norway lobster, *Nephrops norvegicus*, as an indicator of MF pollution [12]. An important issue is to what degree the ingested MPs can penetrate the intestinal wall and get into other body tissues. In general, smaller particles are more likely to be able to do this than larger MPs [13]. There are numerous laboratory studies on ingestion but few on egestion, particularly at concentrations resembling environmental concentrations. Smooth spheres would seem to be more likely to pass through the gut easily, while sharp-edged fragments may be more likely to damage tissues and MFs may be more likely to get tangled and block the digestive system temporarily. Field-collected crustaceans *Nephrops norvegicus* retained plastics in their guts for over two weeks [14]. The rate of egestion depends on the size, shape, etc., of the MP, as well as the length and complexity of the animal’s digestive tract. Another shrimp species, *Palaemon varians*, has different ways of eliminating different shapes of MPs. Saborowski et al. [15] found that while microplastic beads passed through the digestive system and ended up in the shrimp’s feces, the microfibers were generally regurgitated.






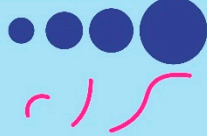
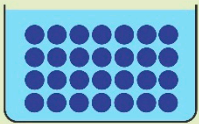
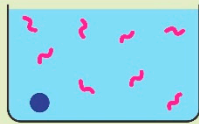
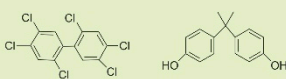
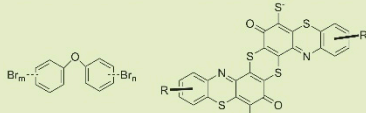
**Figure 1.** Microplastics are a suite of contaminants. Figure from Botterell et al. 2019 [10]. Open Access.

#### 4. Effects

Many experimental studies expose organisms to microspheres or beads, which can be easily purchased at specified sizes and polymers. Far fewer use MFs, which are the most prevalent in the environment. Many studies, furthermore, use concentrations that are much higher than any concentration measured in the environment and expose organisms for short periods of time (hours, days) rather than long term, as would happen in the environment. Therefore, it is difficult to come to conclusions about the effects of MPs, since there is such a mismatch between what is used in experimental studies and what occurs in the environment [16] (Figure 2).

A few studies have used MFs at environmental levels and long exposure periods. One exceptional study, Horn et al. [17], exposed mole crabs (*Emerita analoga*) to levels of MFs found at the site of collection of the crabs and exposed them through three reproductive cycles. They found that crabs ingested the MFs and exhibited deleterious effects on survival, reproduction and embryo development.

When effects of MFs are compared with spheres, MFs tend to be more damaging. The amphipod *Hyaella azteca* egested fibers more slowly than microspheres, but eventually, both showed complete egestion [18]. MFs had greater toxicity than microbeads, possibly because of slower gut passage. Blarer and Burkhart-Holm [19] compared effects of fibers and spheres on feeding rate, assimilation efficiency and wet weight of another amphipod, *Gammarus fossarum*. While both types of MPs were ingested and egested, only the fibers impaired the health of the animals. Mendrik et al. [20] found that MP fibers, but not spheres, reduced photosynthesis of algal symbionts of *Acropora* sp. corals, with a 41% decrease in photochemical efficiency after 12 days.

|               | Experimental Studies  | Environmental Samples  |
|---------------|---|--|
| Shape         |    |   |
| Size          |    |   |
| Concentration |    |   |
| Exposure Time | hours    days   | months    years  |
| Chemicals     |  |  |

**Figure 2.** Mismatch between environmental microplastics used in experimental studies and those in environmental samples. From Weis and Palmquist 2021 [16]. Open Access.

### 5. Associated Chemicals

MPs include toxic chemicals that are part of the plastic (e.g., additives, such as bisphenol a and phthalates). In the marine environment they attract pollutant chemicals (e.g., metals, polychlorinated biphenyls—PCBs, polycyclic aromatic hydrocarbons—PAHs) that attach to them. Thus, MPs can be considered a vector for transferring toxic chemicals into biota. Their high surface/volume ratio allows contaminants to adsorb readily onto them, but the polymer type determines the degree of adsorption [21–23]. Many of these additive chemicals can be toxic, carcinogenic, mutagenic or endocrine disruptors.

Some of the chemical additives can leach out from MPs. The leachate from raw resin pellets (“nurdles”) used in the manufacture of plastic products altered behaviors of periwinkle snails, but the snails responded differently to virgin vs. beached (weathered) pellets. It is likely that the virgin plastic leached out additives, while the older weathered MPs leached out adsorbed environmental chemicals, such as persistent organic pollutants, PAHs and metals. While “virgin” MPs did not affect embryos of the medaka fish (*Oryzias latipes*) [24], MPs coated with B[a]P (benzo [a] pyrene) induced high embryo mortality. Since the MPs attract contaminants, they may transfer these toxic chemicals to animals. Wardrop et al. [25] reported that ingested microbeads can transfer adsorbed PBDEs (polybrominated diphenyl ethers) to rainbow fish (*Melanotaenia fluviatilis*). Lower brominated congeners had high assimilation rates while higher brominated congeners did not transfer, suggesting they may be too tightly adsorbed onto the plastic or unable to be assimilated. Beckingham and Ghosh [26] demonstrated uptake of PCBs from microplastic into benthic worms, but PCB uptake from sediments was much greater than from MPs. Juveniles of the fish *Sparus aurata* were exposed to virgin vs. weathered MPs [27]. Results indicated there was some cellular stress from virgin MPs, but greater stress from weathered MPs. The degree of toxicity would, of course, depend on the nature of the chemicals and microbes adsorbed. The toxicity of leachates from beached MPs vs. virgin industrial MPs to sea

urchin embryos (*Paracentrotus lividus*) was investigated by Rendall-Bhatti et al. [28]. The weathered beached MPs, which contained PAHs and PCBs, produced severe, consistent and specific developmental abnormalities in embryos and larvae, while embryos exposed to virgin MP leachates without environmental contaminants developed normally. Differences in responses can be due to how tightly a particular chemical is bound to the plastic vs. available to biota. This will depend on the polymer, the chemical and the surrounding environment. After being ingested, the “environment” is the gut of the animal and its chemistry, length and complexity would be important factors in determining the degree and rate of desorption of chemicals from the plastic into the animal. Another characteristic of weathered MPs is that they probably also have microbes attached, which could make them more attractive and palatable to animals that consume them and stimulate them to consume more [29].

MFs from textiles, unlike other types of MPs, have unique dyes and include other special chemicals, such as surface treatments, anti-microbials and brominated flame retardants, that are used in the production of textiles and that have been shown to be highly toxic [30–32]. Chemical additives have been detected in aqueous leachates of both virgin and aged (photodegraded) MFs [33]. These have been greatly understudied, despite the knowledge that many of them are highly toxic.

To summarize, most of the microplastics found in the marine environment and elsewhere are microfibers from clothing, although most of the studies on effects to date have been on microbeads, which comprise a small percentage of the microplastics in the environment and very few studies have examined the potential impacts of the unique set of chemicals that are used in textiles. There is a great need to standardize collecting and measuring methods for MPs. Future research should focus more on uptake, egestion, transfer and effects of MFs and their associated chemicals and less on microbeads. Research is also needed on the role of at respiration as a route of uptake, as there are very few studies on this. To make the greatest headway in trying to solve the problems of MPs in the environment, we should focus primarily on MFs and reducing their inputs. The following sections discuss various ways in which inputs of MFs from textiles can be reduced.

## 6. Potential Solutions

There is currently no common strategy on reducing MFs released from textiles. This is not surprising since MF pollution from textiles is still quite a new topic in science. Initial work in 2011 correlated the presence of MFs on shorelines across the globe with the washing of synthetic clothes [34]. Only in 2016, researchers investigated factors that influence their release from textiles [35]. Factors investigated include: textile characteristics, washing parameters, e.g., detergent, temperature and type of washing machine. Recently, studies on how and why they are released during washing have been multiplied, providing more data and interesting results. However, the main issue in trying to compare these different studies is that there is no common methodology to assess the release of MFs during textile washing. Some efforts in this sense have started [36–38], but until now, no common standardization has been established. Nevertheless, some common findings can provide guidelines on where to focus interventions to mitigate MF pollution.

It is clear that the parameters involved in MF pollution are varied and interlinked. At present, the easiest solution that has been considered is the addition of filters to washing machines. However, MFs are not released only to water through washing of textiles, but also to the air. In fact, the wear and tear of textiles cause abrasion forces that cause the release of MFs to the air [39]. Recently, they have been found in human lungs [40], showing that the release of MFs to air is as concerning as to water. Therefore, this kind of pollution should be addressed in a more comprehensive way, addressing the different routes of emission to the environment. The whole cycle of a textile product should be considered. This could be an opportunity to implement new types of Life Cycle Assessment that include all the different ways a textile can cause pollution. This section will consider solutions that

can be implemented at different levels of textile life: manufacturing, use and end of life. Moreover, solutions for wastewater treatment plants will also be briefly discussed.

## 7. Textile Manufacturing

From a textile design and manufacturing point of view, there are two aspects to be considered: chemical composition and textile characteristics. Regarding the first aspect, the current textile market is dominated by synthetic fibers [41]. Research studies do not provide consistent data on the influence of the type of synthetic fiber (e.g., polyester, acrylic, polyamide, etc.) on the release. However, they do show that not only synthetic fibers are released, but also natural ones. Some studies report that natural textiles can release more MFs than synthetic ones during washing [39,42,43]. Naturally, the usual reaction to this finding is that there is no reason for concern about natural fibers in the environment since they are biodegradable [44]. In theory, this could be true, but in reality, many studies have found natural fibers in the environment [45–47]. Textile auxiliaries, dyes and finishes could potentially alter the biodegradation of natural fibers in the environment [48]. Therefore, substituting synthetic fibers with natural ones is not the solution, also considering the poor sustainability associated with their production [49].

An interesting initiative to discover and support potential solutions is the Microfiber Innovation Challenge run by Conservation X Labs [50]. The challenge recently awarded USD 525,000 to five innovations with potential to prevent or reduce MF pollution. These winners were selected among submissions from 19 countries, by a panel from the clothing industry, materials scientists, conservationists and investors. Mango Materials, based in San Francisco, USA, developed a manufacturing technology that obtains biodegradable biopolyester fibers (polyhydroxyalkanoates, PHAs) from waste biogas (methane). They use a fermentation technology that involves feeding waste-methane gas to non-genetically modified bacteria, which produces a powder that, among other applications, can be melt-spun to create fibers for textiles. When they reach their end of life, such textiles can be converted back to methane via anaerobic digestion [51]. Another USA-based company, Tandem Repeat Technologies, successfully developed a new fiber, called Squitex, by using synthetic biology. They isolated genes found in proteins from the suckers of squid that are able to synthesize self-healing fibers and then, by industrial biofermentation, they obtained materials in different forms that are 100% biodegradable and recyclable [52]. A different approach was developed by two American companies, Natural Fiber Welding and Werewool. The first patented a technology to manipulate the hydrogen bonds in natural fibers (e.g., cotton, hemp, wool) and could obtain performances comparable to synthetic fibers [53]. The second company, Werewool, designs fibers at the DNA level to reach tailored characteristics, such as color, elasticity or moisture management [54]. Finally, the last winners of this competition, the English companies PANGAIA x MTIX Microfiber Mitigation, are joining forces to develop a nano-level treatment based on a laser surface enhancement technology, which could strengthen fabric surfaces to prevent the release of microfibers [55].

In addition to these potential new solutions, other actions involve the design and manufacturing of textiles. Several projects have tried to investigate how different textile parameters can influence the release of fibers during washing. Even though these projects differ in methods, some common outcomes can be summarized. It is encouraging that similar findings come from different experimental procedures. First of all, the length of the fibers constituting textile yarns was investigated and studies agree that yarns made of continuous filaments are to be preferred to those made of short staple fibers, since the latter can be released more easily due to their shorter dimensions [39,42,56–58]. Similarly, compact textile structures reduce shedding [39,42,57–60]. Textile characteristics that contribute to reaching a compact structure are: high twist, high density of the yarn, low hairiness, woven structures, knitted structures with a high gauge, etc. Fleece should be avoided, since its fuzzy texture facilitates the release of MFs [57,61–65]. Another step in the manufacturing is the cutting and sewing processes used to manufacture garments. Processes, such as laser

or heat sealing, can mitigate the release of MFs and are to be preferred to the conventional ones (such as using scissors or sewing with thread) [63,64,66]. These are all indications that an appropriate eco-design of textile products could reduce shedding.

Other innovative solutions involve the application of protective coatings on textile surfaces to prevent shedding of MFs. De Falco et al. used pectin, a natural polysaccharide obtained from agricultural and food waste, to create a homogeneous coating on polyamide 6.6 fabrics [67]. The treatment was similar to the padding processes already used in textile finishing and was able to reduce by almost 90% the number of MFs released during simulated washing experiments. Another natural polymer was used by Kang et al. for pre-treatment of polyester, polyamide and acrylic fabrics [68]. Chitosan, obtained from deacetylation of chitin, a polysaccharide found in Crustaceans, fungi and insects, was grafted onto three fabrics, with different rates of success. Washing tests showed that the treatment reduced shedding by 95%, 49% and 48% from polyester, acrylic and polyamide, respectively. Other treatments that have been developed were based on two types of biodegradable polymers: polylactic acid (PLA) and polybutylene succinate adipate (PBSA) [69]. Both polymers were deposited on polyamide 6.6 fabrics using an electrofluidodynamic method that created a continuous nanometric polymeric layer on the textile without altering the main properties of the fabric.

Another aspect to consider is the production and release of MFs during the process of textile manufacturing. Some studies have investigated the presence of MFs during yarn production [70] and in the wastewater coming from textile manufacturing plants [71,72]. Therefore, measures to prevent emission of MFs should be implemented in the textile industry facilities, including ad hoc treatments of the water and also of the air.

After production is completed, an additional measure that could be implemented is labelling of the garment for its possible "MF emission". Eco-labelling solutions are already being discussed for development of a more sustainable textile industry [73]. A recent report tried to explore the possibility of labelling for MF emissions, but could not assess its impact, due to the complex interactions with consumer behavior [74].

More research is still necessary to implement textile manufacturing solutions. Certified standard tests to assess the quantity of MFs released need to be approved. This could help consolidating the data on which textile features are to be preferred to shed less and further garment labelling. In addition, more research is also needed to develop fibers and textiles that can release less, both to water during washing and to air during wearing. The development and use of biodegradable fibers should also be further studied. There is currently much discussion on the definition and testing of biodegradability in the environment [75], so the actual biodegradability of such materials in the real environment should be assessed carefully.

## 8. Textile Use

Most of the information on effects of washing parameters on the release of MFs comes from research performed in the last six years. Again, all these studies apply different methodologies, but common findings can be seen. Therefore, comparing the results of the studies available to date, the following mitigation measures could be applied at the washing phase of textile products:

- Washing using liquid detergent and softener, avoiding powder detergents [56,76–78];
- Choosing less stressing washing programs (i.e., lower temperature, time and spin speed) that use less water [56,77–81];
- Washing full loads but avoiding overfilling that could have a negative effect on the effectiveness of the cleaning and could lead to malfunctioning of the machine [82,83].

Some devices have been developed to be used during washing to reduce MF emissions. They can be divided into three categories: capturing devices, external filters, washing machines with internal filters. The first category includes two products that have been on the market for some years. The Cora ball is inspired by the coral structure and is a ball with stalks that can capture entanglements of fibers [84]. The Guppyfriend washing bag is



polyamide 6.6 bag that can contain the clothes to be washed and protect them during the process, capturing the MFs released [85]. Among the different external filters developed are the LUV-R filter from the company Environmental Enhancements (Dartmouth, NS, Canada) [86], made of a stainless-steel mesh. The Slovenian company PlanetCare Ltd. also developed a cartridge-based filter [87]. The Filtrol is a reusable mesh filter produced by Wexco Environmental to be externally installed in washing machines [88]. These companies state different efficiencies of their devices in retaining MFs and some independent academic studies have tested some of them. Mc McIlwraith et al. found a 5% reduction by weight in MFs released by using the Cora ball and 80% when using an LUV-R filter [89]. Napper et al. observed increasing reduction by weight efficiency for the following devices: PlanetCare filter (25%), LUV-R filter (29%), Cora Ball (31%) and Guppyfriend bag (54%) [90]. Different prototypes of the PlanetCare Filter were also tested by De Falco et al. [91], who found an improved efficiency of 64% of MFs released. Moving to the last category of devices, Xeros Technology Group (UK) patented the XFiltra, a built-in filter for washing machines [92]. It was found to have 78% efficiency in reducing the weight of microfibers released, by Napper et al. [90]. The company partnered with Hanning Elektro-Werke to sell and install their product on washing machines. Samsung is partnering with Patagonia in designing a new washing machine to minimize the release of MFs [93].

France will be the first country to introduce mandatory filters on washing machines for trapping MFs, starting in January 2025 [94]. Other countries that are considering similar legislation are the USA (California), Australia and the UK [95,96]. The potential mitigation of applying MF filters to washing machines was demonstrated by Erdle et al. [97]. They installed Filtrol filters in 97 households in a small town in California and analyzed the final effluents from the wastewater treatment plant (WWTP). There was a significant reduction in the microfibers in the effluent due to the installed filters.

As for textile manufacturing, also for textile use solutions, there is still the need to develop standard tests both to assess the parameters that influence MF shedding and the effectiveness of devices in trapping them during washing. There is also room for policy interventions to regulate the disposal of the MFs collected by such devices, in order to avoid their ending up in the environment by mismanagement.

## 9. Textile End of Life

The textile industry is responsible for the production of over 92 million tons of textile waste per year, much of which ends up in landfills or is burnt [49]. No clear information is yet available on how the end of life of textiles actually contributes to the global release of MFs. However, mitigation measures can be applied to the disposal of textile waste in landfills or by incineration. Pre-consumer and post-consumer textile waste could be reduced by substituting the current concepts behind textile use (dictated by fashion, massive and continuous production of new clothes, characteristics that attract the consumer for attire reasons, etc.), with more sustainability-driven concepts, such as design of garments whose production has less waste of materials, garments of better quality with an improved lifetime and “slow” fashion instead of “fast fashion”. Awareness campaigns focused on consumers should also help to change the perception of fashion, guiding consumers towards a more responsible and sustainable purchase and use of garments. Moreover, practices, such as second-hand markets or textile rentals, could also be improved and spread. There are a few current recycling practices for textiles/garments, such as: conversions to cleaning and wiping rags; fiber recovery (textile structures and yarns are disintegrated to recover fibers to be combined again into new yarns); fiber re-spinning (the polymer constituting the fibers is melted or dissolved and spun again into new filaments); feedstock recycling (the polymer is broken down to its original monomers). Fiber grinding (fibers are ground to be used in other applications, such as construction) should be avoided since the grinding process could intrinsically produce many microfibers [98]. The reduction in pre-consumer and post-consumer textile waste requires greater efforts and a longer timeframe since it requires radical changes in fashion design and consumer mentality. Reuse and recycling of

textiles should be handled carefully since, currently, there is no information on MF release during the lifetime of a garment (i.e., garments can become old and damaged and start releasing more MFs) and on MF release by recycled garments. Therefore, more research is needed to collect data on the release of textiles at their end of life and on the effect of recycling practices on the release of MFs from recycled textiles.

## 10. Wastewater Treatment Plants

Wastewater treatment plants (WWTPs) are the major pathways for the release of all kinds of MPs to aquatic environments [99]. Most of these are MFs from laundry effluent. These plants are not specifically designed to retain MFs from wastewater and have different removal efficiency according to the type of processes used [100].

WWTPs may have different types of treatment stages. Primary treatment is a separation process by which the wastewater passes through sets of screens that separate solids from liquids. If fine-mesh screens are used, some larger MPs could be removed from the liquid into the solid phase (sludge), but many will go through, especially long thin microfibers. Following this is grit removal, flotation and primary settlement, which would separate microplastics with different densities. At this stage, additional MFs could be adsorbed and aggregated into the sludge [101,102]. Removal of a large percent of MFs (over 90%) can take place during this stage [103,104].

Secondary treatment is an activated sludge process, an aerobic biological process in which communities of microorganisms degrade organic pollutants in the sludge. MPs can adhere to the extracellular materials secreted by the microorganisms and will be removed with the generated sludge [101]. Some treatment plants have tertiary treatments, such as coagulation and filtration, ultrafiltration or membrane bioreactors, that can entrap some of the remaining MPs. Those MPs with a density greater than water will mostly be retained in the sludge during primary and secondary treatments, while tertiary treatments can reduce less dense floating particles from the final water effluent [105]. Li et al. investigated removal efficiency of ferric chloride and polyaluminum chloride (PACl) [106]. The removal efficiency of the MFs varied from 86% to 96% depending on the fiber size with the smaller-size microfibers showing a lower removal efficiency. Surfactant in detergent in laundry wastewater reduced the removal efficiency considerably. Edo et al. [107] reported that MPs with sizes between 25 and 104  $\mu\text{m}$  were predominant in the effluents of primary and secondary treatments, which is consistent with the notion that smaller and fiber-shaped MPs are more likely to be found in the effluent [108]. Despite the high removal efficiency, a very large number of MPs is released into the environment, most of which are MFs and these wastewater treatment facilities can be considered hotspots for release of these contaminants to aquatic ecosystems.

It is important to realize that the MP particles removed from the effluent during sewage treatment can nevertheless reach the environment in the sludge, depending on what is done with it. It is possible to compost the sludge in order to reduce microplastic contamination. MPs in the sludge can be degraded during composting in two ways: (i) inoculating the initial sludge with microbial plastic decomposers to remove microplastic from the sludge and (ii) development of high-temperature composting processes [109]. These are not yet in general use, however.

It is of particular concern when the sludge is applied to soil, especially when used as a fertilizer in agricultural soils [110–112]. The amount of MFs retained in the sludge of treatment plants is estimated at about 0.20 million tons per year [104]. It has been estimated that the yearly amount of MPs entering agricultural lands from sludge might be between 63,000 and 430,000 tons in Europe alone [105]. A recently developed promising strategy for reducing MP concentrations in sludge is a hyperthermophilic composting technology (HTC), which was demonstrated to reduce 45% of the microplastics after 45 days of treatment [113]. However, it will take many years for this technology to be in widespread use and until then, the continued release of huge amounts of MPs to the soil is a serious concern for terrestrial biota and food grown in the soil.

The implementation of new technologies to retain MFs (and MPs in general) in WWTPs still represents a challenge considering that each country has its own regulations and systems for water treatment and, therefore, more research and policy efforts are needed.

## 11. Conclusions

In recent years, it has become clear that the most abundant type of microplastics found in water and sediments are MFs, which come primarily from synthetic textiles that shed them during their entire life cycle. They are released during many phases of the life cycle of textiles: during manufacturing, everyday activities (e.g., washing, drying, wearing) and final disposal. Those shed during wearing and drying are released to the air but can later enter the water during precipitation. The major source to aquatic systems is via washing machines, in which huge numbers of them are released in every wash. We have discussed ways in which the shedding can be reduced at each stage of the life cycle of a textile. During manufacture, the length of the fiber and the compaction (tightness) of the textile structure can reduce shedding, as can protective coatings and new materials that are being developed. Mitigation actions introduced at the manufacturing stage of textile life cycle have the potential to reduce the shedding of MFs to the air during wearing and general use. Focusing on washing machines, the washing parameters (temperature, washing time, volume of water and mechanical action) and type of detergents used can greatly affect shedding rate. This information should be publicized to consumers as good practices to reduce this source of pollution. There are items that have been developed to be placed in the washing machines that can trap some of the shed MFs and filters that can be attached to the machine that are far more effective. Some of the filters can be retrofitted onto existing washing machines, while others are meant to be built into new machines. However, it is important also to focus on a correct disposal of the fibers trapped by these capturing devices. Washing machine wastewater then goes to sewage treatment plants, which are very efficient and can be made even more efficient in removing most of them from the wastewater. However, attention must be paid to the fate of the sewage sludge where the vast majority of them end up and which can merely move the pollution from the water to the soil. A combined and synergic mitigation approach involving the whole textile life cycle could be a more effective way to deal with these worrisome pollutants.

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