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REPORT TO CONGRESS

INTERAGENCY MARINE DEBRIS COORDINATING COMMITTEE REPORT ON MICROFIBER POLLUTION

Developed pursuant to: Section 132 of the Save Our Seas 2.0 Act, 2020 (Public Law 116-224)

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THIS INTERAGENCY MARINE DEBRIS COORDINATING COMMITTEE REPORT IS PROVIDED PURSUANT TO THE SAVE OUR SEAS 2.0 ACT, 2020 (PUBLIC LAW 116-224) AND SECTION 132 OF THE ACT REQUIRES

Not later than 2 years after the date of the enactment of this Act, the Interagency Marine Debris Coordinating Committee shall submit to Congress a report on microfiber pollution that includes—

> *(1) a definition of microfiber;*
> *(2) an assessment of the sources, prevalence, and causes of microfiber pollution;*
> *(3) a recommendation for a standardized methodology to measure and estimate the prevalence of microfiber pollution;*
> *(4) recommendations for reducing microfiber pollution; and*
> *(5) a plan for how federal agencies, in partnership with other stakeholders, can lead on opportunities to reduce microfiber pollution during the 5-year period beginning on such date of enactment.*

THIS REPORT RESPONDS TO THE ACT’S REQUEST.

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solely as a pointer to information on topics related to environmental protection that may be useful to the Federal Government and the public.

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Cover photo courtesy of Sherri A. Mason.

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I. EXECUTIVE SUMMARY

Microfibers have been found almost everywhere, including in surface and sub-surface waters, sea ice, deep-sea and coastal sediments, terrestrial soils, and indoor and outdoor air and dust. The tiny fibers released from clothing, carpets, cigarette butts, and other fiber-based products are one of the most pervasive types of microplastic particles found in many environmental compartments.[1] In response to growing concerns about the prevalence and persistence of microfibers in the environment, as well as their potential ecological and human health impacts, the United States Congress has directed the Interagency Marine Debris Coordinating Committee (IMDCC) to develop a Report on Microfiber Pollution. Under Section 132 of the Save Our Seas 2.0 Act (Public Law (P.L.) 116-224), the Report on Microfiber Pollution must include: 1) a definition of microfiber; 2) an assessment of the sources, prevalence, and causes of microfiber pollution; 3) a recommendation for a standardized methodology to measure and estimate the prevalence of microfiber pollution; 4) recommendations for reducing microfiber pollution; and 5) a plan for how Federal agencies, in partnership with other stakeholders, can lead on opportunities to reduce microfiber pollution during the 5-year period beginning on the date of the Act's enactment.

This report provides an overview of the current state of knowledge on the sources, prevalence, pathways, and impacts of microfiber pollution, as well as an assessment of the emerging solutions to mitigate microfiber pollution. Recommendations are provided that form the basis of a Federal Plan for how Federal agencies in partnership with stakeholders can work to address the problem.

The government, academic, and textile sectors all use different terminology when referring to microfibers; therefore, **Section III** of the report proposes an initial definition of the term "microfiber" to serve as a reference point for all sectors engaged in microfiber research and prevention. The definition is inclusive of both plastic and non-plastic microfibers and encompasses three base criteria: the polymer composition of and chemical additives/treatments added to microfibers and textiles, as well as the size and shape of microfibers. It does not include natural fibers that are not treated. This definition is a starting point for future conversations with a diversity of stakeholders to build consensus around a standard definition.

There are many sources of microfiber pollution including apparel, carpets, upholstery, fishing and boating gear (e.g., ropes, lines, and nets), agrotextiles, and cigarette butts, which often release cellulose acetate fibers when they break down. **Section IV** provides an in-depth overview of these sources, as well as the prevalence, pathways, and impacts of microfiber pollution. Microfibers (including both plastic and non-plastic fibers) are a prominent type of debris found across environmental compartments. They can enter the environment through natural pathways, including rivers, streams, and transport via atmospheric circulation, or through engineered pathways such as wastewater systems, sewage sludge/biosolids, stormwater systems, solid waste management systems (including transfer stations, landfills), and agricultural fields. Though several major sources and pathways for microfiber pollution have been identified, more research

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[1] In this report, the term "environmental compartment" refers to any physical environment, such as air, soil, surface water, and biota.

is needed to quantify microfiber contributions from each of these sources and pathways and understand how to prevent them from polluting aquatic and terrestrial ecosystems.

Though the public health and environmental effects of microfiber pollution are largely unknown, there is evidence from laboratory studies that indicate organisms can experience physical, chemical, and/or biological effects as a result of exposure to microfibers (see Section IV.D Potential Environmental and Human Health Impacts of Microfiber Pollution). Effects may be due to the ingestion of fibers or the interaction between microfibers and organisms (e.g., in gills). Ingestion of microfibers has been observed in a wide range of aquatic and terrestrial species. Exposure to microfibers may expose biota to toxic chemicals that may have been applied to the fibers as additives during textile production or pollutants that the fibers have absorbed from the environment. A detailed accounting of what is known is provided in Section IV.

Section V discusses the various research methods used to measure microfiber prevalence in various environmental compartments and provides recommendations for the development of standardized methods. For research on the occurrence of microfibers in various environmental compartments, efforts and resources should focus on the development of standardized methods for sampling, extraction, and analysis of microplastics in general, while including appropriate and specific guidelines for quantifying and characterizing microfibers (i.e., plastic and non-plastic fibers) as a morphology of microplastics. Furthermore, robust Quality Assurance/Quality Control measures should also be employed to reduce potential contamination in microplastic and microfiber studies.

Efforts by researchers, governments, the private sector, and non-governmental organizations to address microfiber pollution have focused primarily on textiles, and specifically on textile design and laundering. These and other mitigation measures are discussed in **Section VI**, which summarizes the emerging solutions to address microfiber pollution. Current and proposed solutions are focusing on the upstream design of textiles (e.g., designing textiles to have low-shed rates; designing textiles with their end-of-life fate in mind), as well as the production and manufacturing of textiles (e.g., reducing fiber shedding associated with production stages; control measures to reduce microfibers discharged from manufacturing facilities). This section also covers actions consumers can take when interacting with fiber-based materials on a day-to-day basis. In considering these and other solutions and mitigation measures, it will be important to evaluate their effectiveness, their cost-effectiveness, and any barriers or challenges associated with them. The potential effectiveness of these solutions is also dependent on international and cross-sector coordination, cooperation with the private sector, and an informed public making new consumer choices and behavior changes.

Many knowledge gaps and key research needs are discussed throughout the report. **Section VII** summarizes these key research gaps and recommendations based on the information in the previous sections of the report. For instance, the development of standardized methods for field sampling, detection, quantification, and characterization of microfibers in various environmental compartments would help researchers to produce useful data to fully understand the prevalence of microfibers and impact of microfibers on the environment and biota. Furthermore, the relative scale of microfiber contributions from various sources and pathways will help to prioritize solutions. In addition to addressing major research needs, general recommendations to reduce microfiber pollution include supporting efforts to reduce upstream sources, implementing solutions to capture and remove microfibers, and fostering collective action through multi-stakeholder collaborations.

Finally, **Section VIII** provides a Federal Plan to Reduce Microfiber Pollution. The Federal Plan encompasses five main goals, starting with a goal to support additional research to help fill critical data gaps. The next two goals focus on preventing, reducing, and capturing microfibers from both textile and non-textile sources alike. The fourth goal looks at the chemicals associated with microfibers, including dyes and finishes from textiles. The last goal focuses on coordination and knowledge sharing. The 5-year Federal Plan outlines objectives and actions that Federal agencies can address in partnership with other stakeholders. Implementation of the Federal Plan will depend on the participating agencies' budgetary constraints, staff capacities, research needs, and other factors, and the goals, objectives, and actions articulated in the Federal Plan may be subject to change.

II. INTRODUCTION

A. The Problem with Microfibers

Microfiber pollution is an emerging issue of environmental concern due to the growing body of research uncovering the pervasiveness and potential ecological and human health impacts of microfibers in the environment. Though research confirms that humans and a diverse range of aquatic and terrestrial organisms are exposed to microfiber pollution, the impacts of microfiber pollution on environmental and human health are largely unknown and further research is needed (see Section IV.D Potential Environmental and Human Health Impacts of Microfiber Pollution). Microfiber pollution refers to the tiny strands of plastic and non-plastic fibers that are shed during product life cycles and eventually end up polluting the environment. Microfibers have been detected on every continent (61 countries) and in every major ocean and freshwater environment (Athey & Erdle, 2022; Gago et al., 2018; Patil et al., 2021; Suaria et al., 2020), including the remote polar regions (Moore et al., 2020; Ross et al., 2021), deep sea floor (Athey et al., 2020), and pristine mountain catchments (Allen et al., 2019). Scientists have also found microfibers in indoor air (Dris et al., 2015; Gavigan et al., 2020; Kaya et al., 2018), drinking water and other beverages (Koelmans et al., 2019; Kosuth et al., 2018; Liebezeit & Liebezeit, 2014; Mason et al., 2018), and foods for human consumption (AMAP, 2021; Moore et al., 2020; Rochman et al., 2015; Van Cauwenberghe & Janssen, 2014).

Microfibers originate from a variety of sources. Fabrics and textiles (primarily apparel) have been documented as a prominent source of microfiber pollution. Fibrous filters in cigarette butts are also a concern due to the frequency with which these items are littered in the environment and the amount and types of chemicals used to create cigarettes. While these are two known sources of microfiber pollution, there are other sources that have received less attention to date, including fibers shed from other textiles (for example, apparel, carpet, upholstery, bedding), wet wipes, construction materials and geotextiles, fishing and boating gear (for example, ropes and nets), and other materials (Athey & Erdle, 2022; Sutton et al., 2019). While this report discusses what is known about the various sources of microfibers, there is a heavy focus on textiles (specifically apparel) due to information available on this type of microfiber pollution.

In the last 20 years alone, global textile fiber production has almost doubled, reaching about 109 million tons in 2020, and is expected to reach 146 million tons in 2030 assuming business-as-usual conditions (Textile Exchange, 2021). Most fibers produced today are synthetic (plastic), which are the dominant type of fiber being used in a rapidly growing textile sector. In 2020, synthetic fibers accounted for 62% of global fiber production (Textile Exchange, 2021). Polyester is the most commonly used type of synthetic fiber, making up 52% of global fiber production in 2020, followed by polyamide (also known as nylon), which accounted for 5% – both are plastic fibers (Table 1). The textile sector consumed about 14% of total plastic production in 2017, making it the third largest market for plastics after packaging (36%) and building and construction (16%) (Geyer, 2020). Not surprisingly, synthetic textiles are one of the largest sources of microplastics in the environment (Boucher & Friot, 2017).

Researchers have expressed concern about the prevalence and potential environmental and health risks associated with plastic microfibers. However, because all fibers used in apparel and other textiles, regardless of base polymer type,[2] are often treated with chemicals, (e.g., resins, softeners, dyes, and functional finishes like stain resistants or flame retardants), non-plastic fibers (e.g., man-made cellulosics[3] like rayon, treated plant fibers like cotton and linen, and treated animal fibers like wool and silk) are also under study to better understand the influence of mechanical and chemical treatments to the overall degradability and toxicological hazards associated with non-plastic microfibers that shed throughout product life cycles. A more precise definition of the term "microfiber" is discussed in later sections of this report.

Table 1. Overview of Main Textile Types in Production in 2019. This table is adapted from the Organisation for Economic Co-operation and Development's (OECD) report titled "Policies to Reduce Microplastics Pollution in Water" (OECD, 2021) and displays data from the Textile Exchange's "Preferred Fiber & Materials Market Report 2020" (Textile Exchange, 2020).

Fiber Type	Resource Base	Textile Type	% of Total Textile Production
Natural (Non-plastic Treated)	Plant-based	Cotton	23.2%
		Others: hemp, linen, etc.	5.9%
	Animal-based	Wool	1%
		Others: down, silk	<1%
Man-Made Cellulosic Fibers (Non-plastic Manufactured)	Cellulose-based	Viscose (rayon)	5.1%
		Others: acetate, lyocell, modal, cupro	1.3%
Synthetic (Plastic)	Primarily Petroleum-derived	Polyester	52.2%
		Polyamide (nylon)	5%
		Others: acrylics, modacrylics, elastane, etc.	5.7%

Microfibers are a highly complex and diverse suite of contaminants. Research on the subject is particularly challenging due to a lack of standard definitions and research methods, which makes comparisons across studies difficult. Due to growing concerns about the prevalence and persistence of microfibers in the environment, as well as their potential ecological and human health impacts, the United States Congress has directed the Interagency Marine Debris Coordinating Committee (IMDCC) to develop a Report on Microfiber Pollution. Under Section 132 of the Save Our Seas 2.0 Act (P.L. 116-224), the Report on Microfiber Pollution must include: 1) a definition of microfiber; 2) an assessment of the sources, prevalence, and causes of

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[2] Polymer: A substance with a molecular structure of repeating units, of the same or of different types, bonded together. Polymers can be composed of either natural or synthetic substances. Adjective: polymeric.

[3] Man-made cellulosic fibers are "regenerated fibers usually made from the dissolved wood pulp or "cellulose" of trees. Viscose, lyocell, and modal are all kinds of man-made cellulosics" (Textile Exchange, 2023).

microfiber pollution; 3) a recommendation for a standardized methodology to measure and estimate the prevalence of microfiber pollution; 4) recommendations for reducing microfiber pollution; and 5) a plan for how Federal agencies, in partnership with other stakeholders, can lead on opportunities to reduce microfiber pollution during the 5-year period beginning on the date of the Act's enactment.

B. Report Development

The United States Environmental Protection Agency's (EPA) Trash Free Waters program, in partnership with the National Oceanic and Atmospheric Administration's (NOAA) Marine Debris Program, developed this Report on behalf of the IMDCC. The IMDCC reviewed and provided comments on this report in the stages toward its completion and submission.

Materevolve, the contractor working with the EPA Trash Free Waters program and the NOAA Marine Debris Program, formed an Expert Advisory Committee (EAC) composed of individuals from relevant academic, government, and industry sectors to provide individual advice and information throughout the development of this report. The IMDCC was given the opportunity to nominate individuals to the EAC, which included experts from across the United States and Canada. Materevolve selected the members of the EAC and led all communications with the EAC members. The EAC was critical in ensuring that Sections I - VII of this report were informed by the most relevant and recent research across a diversity of academic disciplines. In October of 2021, the IMDCC reviewed and provided comments on Sections I - VII of the report. The initial feedback from the individual EAC members and IMDCC on these sections was used as the basis for developing a 5-Year Federal Plan. The 5-Year Federal Plan was developed and finalized with input from 12 Federal agencies, including representatives from all 12 IMDCC member agencies, over the course of two workshops and an agency questionnaire. The plan is included as Section VIII of this report and sets forth the commitments that the Federal agencies were able to make within the framework of each of their existing legal authorities. Full implementation of the Federal Plan will depend on the availability of sufficient staff and resources.

In addition, this final version of the Report on Microfiber Pollution includes thoughtful feedback received from the public during a 30-day public comment period, which ran from September 15, 2022 to October 17, 2022. Appendix A provides an overview of the public comments received and how these comments were addressed in the report. The public comments can be viewed on the report docket on regulations.gov (www.regulations.gov/docket/NOAA-NOS-2022-0061/comments).

III. DEFINING MICROFIBER

The term “microfiber” is presently used in a wide variety of ways, with no standardization among user groups. The lack of a standard definition creates challenges for those working to understand and address the issue (e.g., researchers, policymakers, industry members). Non-standardization in terminology makes it difficult to compare across sectors and scientific studies.

The establishment of a standard definition of microfiber (or the adoption of a new term such as “fiber fragments”) would help to facilitate research, regulations, and mitigation measures related to microfiber pollution. A standardized definition should be informed by considering the ways in which the term “microfiber” is presently being used, as well as by future research and regulatory needs. This report proposes an initial definition of microfiber to serve as a starting point to build consensus around a standard definition, or set of terminology, that could be adopted by the U.S. Government for research and development of solutions, including potential legislative and regulatory changes.

A. Proposed Definition of Microfiber

For the purposes of this report, the IMDCC uses the following definition of “microfiber”:

> *Microfibers are solid, polymeric, fibrous materials that include plastic and non-plastic fibers less than 5 millimeters in all dimensions.*[4]

Figure 1 provides a simple guide to determine if a particle fits within the definition:

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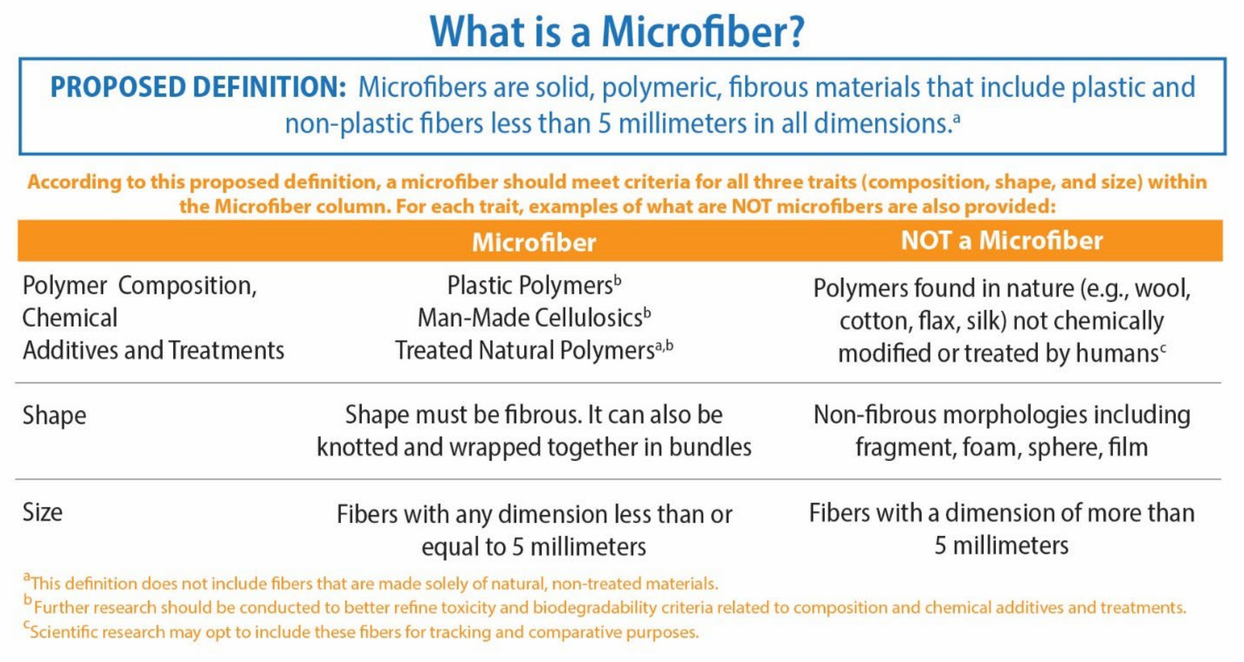
[4] This definition does not include fibers that are made solely of natural, non-treated materials.



What is a Microfiber?

PROPOSED DEFINITION: Microfibers are solid, polymeric, fibrous materials that include plastic and non-plastic fibers less than 5 millimeters in all dimensions.[a]

According to this proposed definition, a microfiber should meet criteria for all three traits (composition, shape, and size) within the Microfiber column. For each trait, examples of what are NOT microfibers are also provided:

	Microfiber	NOT a Microfiber
Polymer Composition, Chemical Additives and Treatments	Plastic Polymers[b] Man-Made Cellulosics[b] Treated Natural Polymers[a,b]	Polymers found in nature (e.g., wool, cotton, flax, silk) not chemically modified or treated by humans[c]
Shape	Shape must be fibrous. It can also be knotted and wrapped together in bundles	Non-fibrous morphologies including fragment, foam, sphere, film
Size	Fibers with any dimension less than or equal to 5 millimeters	Fibers with a dimension of more than 5 millimeters

[a] This definition does not include fibers that are made solely of natural, non-treated materials.

[b] Further research should be conducted to better refine toxicity and biodegradability criteria related to composition and chemical additives and treatments.

[c] Scientific research may opt to include these fibers for tracking and comparative purposes.

Figure 1. Proposed microfiber definition and review of microfiber traits.

This proposed definition is highly inclusive and based on a consideration of the potential toxicological effects of microfibers. The definition should be refined as further research continues to increase our understanding of how the physical and chemical characteristics of microfibers influence their behavior in the environment (e.g., persistence, mobility, bioaccumulation, toxicity).

The IMDCC recognizes that some activities may need a more specific definition of microfibers, including for:

- Conducting research on microfibers and developing standardized test methods for microfiber research;
- Developing and enforcing regulations related to microfiber pollution;
- Developing standards for products to reduce microfiber pollution (e.g., washing machine filters, low-shed clothing); and
- Developing toxicity and biodegradability thresholds for materials and chemical solutions to microfiber pollution.

B. Rationale for Proposed Definition

This definition was developed through a review of existing definitions of microfiber from academic literature, government agencies, and relevant industries (see Appendix B). Input on the definition was also received from individual EAC members and reviewers from the IMDCC (including EPA, NSF, and NOAA), as well as the general public through a public comment period (see Appendix A). The determination of which particles to include in the definition is based on a consideration of the potential adverse impacts of the microfibers in the environment due to their shape, persistence, and toxicity. In the following sections, rationale is provided for the three base criteria that provide the foundation of the proposed definition.

Polymer Composition, Chemical Additives, and Treatments

Based on the current state of knowledge on the prevalence and impacts of microfibers of various origins, this report recommends that a standard definition of "microfibers" include those composed of both plastic and non-plastic polymeric materials, defined as follows:

- **Plastic fibers -**
    - **Manufactured:** This category is the most commonly found in current scientific research and includes plastic fibers (e.g., polyester, polyethylene, polypropylene, nylon, elastane, acrylic), often referred to using the general term "synthetic." Emerging plastic polymers with the potential to be less persistent due to polymer design would also be included in this category.
- **Non-plastic fibers -**
    - **Manufactured:** This category includes man-made cellulosic fibers (e.g., rayon, viscose, lyocell, modal), sometimes referred to as regenerated cellulose, or "semi-synthetic" fibers.
    - **Treated natural:** This category includes both plant (e.g., cotton, flax, linen, hemp) and animal (e.g., wool, cashmere, alpaca, silk) fibers and are naturally occurring polymers.

> **Throughout the remainder of this report, these terms (plastic manufactured, non-plastic manufactured, and non-plastic treated natural fibers; or plastic and non-plastic fibers) will be used instead of the commonly used "synthetic" and "semi-synthetic" terms found in scientific literature. See Appendix B for background information on terminology used by the scientific community, textile industry, and governments.*

Research has demonstrated that microfibers made of plastic have a diverse set of negative potential impacts, as discussed in Section IV.D. However, whether these impacts are due to the polymer composition (plastic, non-plastic), shape (discussed below), or chemicals associated with the fibers, requires further investigation. As such, non-plastic fibers are also included in the proposed definition of microfibers due to their shape and because some research suggests that the application of chemical additives to fibers in the production of fiber-based products may increase their toxicity and persistence in the environment (see Appendix B for further detail). Chemical additives used in the production of textiles can include toxic compounds, such as bisphenols, azo dyes, polyfluorinated alkyl compounds (PFAS), and formaldehyde (Athey & Erdle, 2022; Lacasse & Baumann, 2012; Ladewig et al., 2015). It is important to note that the non-plastic category could include a subset of nontoxic, biodegradable fibers, but further research is needed to refine the criteria and limits for inclusion or exclusion. Fibers that are solely made of natural, non-treated materials are not included in this proposed definition of microfiber because they are thought to more readily degrade in the environment and can also exist in the environment without human interactions (and therefore cannot be controlled with mitigation measures). Both polymer composition and addition of chemical additives and treatments should be considered for further consensus building on the definition.

Shape

The shape of microfibers (fibrous particles regardless of the polymeric composition – i.e., plastic, non-plastic) may also play a significant role in potential impacts to the environment. For this definition, a "microfiber" must have a fibrous shape. This specification excludes other common microplastic particle types, such as spheres, pellets, foam, and fragments. Fiber bundles that include multiple fibers intertwined and knotted are considered microfibers (California State Water Resources Control Board, 2020; Sutton et al., 2019). The inclusion of a specific criterion for dimensions (a length to width aspect ratio of greater than three), like that included in the proposed ECHA definition and discussed in the California State Water Board Definition, was considered. However, this report does not define an aspect ratio requirement, allowing for a more broad and inclusive definition and avoiding inconsistencies with other microplastics definitions.

Size

Due to insufficient research on the relationship between fiber size and toxicological effects, it is not yet possible to define appropriate size criteria (both upper and lower) based on toxicological considerations (ECHA, 2020). Therefore, the upper size limit of 5 mm is based on the existing scientific literature (see Appendix B) and the California State Water Board Definition (California State Water Resources Control Board, 2020). This report does not include a lower size limit in the definition; however, the IMDCC recommends that a future definition of microfiber for specific purposes include a lower size limit that is based on toxicological considerations as well as practical considerations related to the availability of analytical techniques and technologies to separate and detect microfibers.

C. Future Considerations

Further study and cross-sector consensus building will help to refine this definition or the development of new related terminology such as "fiber fragments," particularly in the following areas:

1. **Polymer Composition, Chemical Additives, and Treatments** - Include more specific definitions for subcategories of plastic and/or non-plastic polymers, as well as a list of examples of common chemical additives or treatments that impact persistence and toxicity.
2. **Shape** - Include more specific characterization of fibrous particles, ensuring that other fibrous shapes are better defined (e.g., aspect ratio for individual fibers; fiber bundles) and other particle types are not included (e.g., non-fibrous particles such as tire rubber fragments, film).
3. **Size** - Include lower and upper size limits that are based on toxicological considerations and available sampling protocols and detection techniques.
4. **Biodegradability/Persistence** - As future research enhances the understanding of fiber biodegradability, include defining criteria related to the biodegradation potential of polymers, recognizing that biodegradability varies depending on microfiber characteristics and environmental conditions.

IV. ASSESSMENT OF THE SOURCES, PREVALENCE, CAUSES, AND IMPACTS OF MICROFIBER POLLUTION

Microfiber pollution is a relatively young and rapidly evolving field of research, but the number of studies on this topic has increased dramatically over the last decade. The following sections provide a summary of the state of the knowledge on the sources, causes, prevalence, and impacts of microfiber pollution. Though Section 132 of the Save Our Seas 2.0 Act does not require that this report include an assessment of the impacts of microfiber pollution, this information is an essential part of efforts to determine the most urgent research needs, as well as to develop effective solutions to mitigate the problem.

A. Microfiber Sources

Microfibers in the environment come from a wide range of products made from plastic and non-plastic fibers, including textiles, carpets, wet wipes, cigarette filters, and fishing gear (ropes and nets) (Athey & Erdle, 2022; Avio et al., 2020; Barrows et al., 2017; Belzagui et al., 2021; GESAMP, 2015; Moran et al., 2021; Murray & Cowie, 2011; Napper et al., 2022). However, due to insufficient research, the relative contributions of these and other sources of microfibers in the environment remain unknown. Furthermore, the use, durability, chemical composition, care, and end-of-life for various products differ significantly, and therefore the amounts and mechanisms for release of microfibers vary as well (Table 2). It has been shown that microfiber pollution results when fibrous materials shed or break away from the parent item (e.g., yarn, clothing, other textiles, and non-textiles) and enter the environment at some point during the product life cycle, which includes production, use (including cleaning, laundering, and everyday wear or use), and disposal (Athey & Erdle, 2022).

Apparel and Consumer Textiles

Textiles and apparel as a source of microfiber pollution have received significant attention from researchers (Table 2). High concentrations of microfibers have been documented in washing machine effluent, suggesting that apparel is likely a major contributor of the microfiber pollution observed in wastewater (Gavigan et al., 2020; Hartline et al., 2016; Hernandez et al., 2017; McIlwraith et al., 2019). Based on the findings of 12 studies measuring microfiber shed rates via apparel washing experiments, Geyer et al. (2022) estimated that about 140 grams of microfibers are shed per megagram (about 1.1 tons) of clothing washed.

Gavigan et al. (2020) estimated that between 1950 and 2016, a cumulative 6.17 million tons (5.6 million metric tons) of plastic manufactured microfibers have been shed by apparel and emitted via hand and machine washing globally, with annual microfiber discharge increasing from 134 tons (122 metric tons) in 1950 to about 400,000 tons (360,000 metric tons) in 2016. In a similar study, Belzagui et al. (2020) used a different methodology to estimate global plastic manufactured microfiber discharge from domestic laundry, finding that about 0.28 million tons of microfibers were released per year. Both studies only considered plastic manufactured fibers and fibers shed as a result of washing apparel, not those released into the environment via clothes dryers and normal wear. They also only estimated microfiber release from apparel and excluded other textiles, like carpets, upholstery, and curtains.

Clothes dryers, vented to the outdoors, have also been identified as important sources of microfibers in the environment (Cheng et al., 2016; Kapp & Miller, 2020; Kärkkäinen & Sillanpää, 2021; O'Brien et al., 2020; Pirc et al., 2016). Microfibers are released when users clean out the inbuilt filter (a.k.a. lint filter) and via the exhaust vent that deposits materials outside the home (Cheng et al., 2016; Kapp & Miller, 2020). Clothes dryers, also called tumble dryers, can be manufactured as vented (vents hot exhaust containing microfibers out of the dryer, often directly outdoors) and ventless. Ventless dryers include condenser dryers, which condense hot exhaust into water vapor that accumulates in a collection tank or drainpipe and is eventually discharged as wastewater. While ventless dryers are popular in Europe, nearly all of the 90 million domestic dryers used in the United States are vented dryers, with ventless dryers representing approximately 1% of the market in the United States (Energy Star, 2011).

Laboratory testing of dryers as a source of microfibers to the environment is limited to only a few peer-reviewed studies (Kapp & Miller, 2020; Kärkkäinen & Sillanpää, 2021; O'Brien et al., 2020; Pirc et al., 2016; Tao et al., 2022). Most methods employed by these studies for measuring microfiber output from vented dryers do not measure the exhaust directly, but do measure the amount of microfiber-laden lint collected on internal screens or lint traps. Kapp and Miller (2020) managed to measure microfibers captured by internal screens, as well as those that bypassed the internal screens and are discharged with exhaust by using a mesh bag. They show that the efficiency of internal screens can vary, capturing between 20-60% of outgoing fibers by weight (Kapp & Miller, 2020). Tao et al. (2022) measured microfibers released from dryer exhaust using a high-volume particle air sampler (vacuum pump), estimating that during a 15-minute drying period, over 93,000 polyester fibers and over 72,000 cotton fibers could be released from 1 kg of textiles (Tao et al., 2022). In these studies, variations in the cycle settings and test textiles make comparisons across studies challenging (Kapp & Miller, 2020; O'Brien et al., 2020; Pirc et al., 2016).

Similarly, only a few studies have examined microfiber release from clothing during general use/wear. A study by De Falco et al. (2020) analyzed microfiber release into the air in a small room, where a participant completed a series of movements for 20 minutes. This study compared the release of fibers from four different types of polyester garments (including one cotton/polyester blend), and with varying textile design parameters: fabric structure (woven v. knitted), fiber type and length (continuous filaments v. short staple), yarn twist (high/low), yarn hairiness (high/low). Microfiber release depended on the garment parameters, with a range of 1 ± 1 to 403 ± 65 microfibers per gram of fabric (De Falco et al., 2020). When scaling up the results of microfibers released into the air during general wear/use, amounts released per year are similar to that of fibers released into water from laundering clothing (De Falco et al., 2020).

Carpet

There has been little research on microfiber release from carpeting, but early research suggests that carpets could be an important source of microfibers in indoor dust (Soltani et al., 2021) and wastewater (Alipour et al., 2021). In a study analyzing 32 indoor airborne dust samples from homes in Australia, Soltani et al. (2021) found that microplastic deposition was significantly higher in carpeted homes (on average, 2,339 fibers/m^2/day) than in homes without carpeting (on average, 1,484 fibers/m^2/day). Given the potential for human exposure to microfibers in indoor air, carpets are a source of microfiber pollution that merits further research.

Nonwovens

Nonwovens are a category of textiles that are typically used in many disposable products such as wet wipes, diapers, surgical masks and gowns, and menstrual sanitary products, as well as geotextile[5] products (Kwon et al., 2022). Compared to knit and woven materials used for most apparel, relatively little research has been done on microfiber release from nonwoven materials (Kwon et al., 2022). However, several studies have examined and documented microfiber shedding from specific nonwoven products, including wet wipes (Lee et al., 2021) and menstrual hygiene products (Ó Briain et al., 2020). With the emergence of the COVID-19 pandemic and the increased usage of surgical masks as personal protective equipment, several recent studies have documented microfiber shedding from masks, which are frequently littered (Rathinamoorthy & Balasaraswathi, 2021; Saliu et al., 2021; Shen et al., 2021).

Non-Textile Sources

Several studies have sought to measure microfibers released from non-textile sources, including cigarette filters and aquaculture and fishing equipment. Cigarette filters in particular have been identified as a potentially significant source of microfibers in the environment. A single cigarette filter contains over 12,000 fibers composed of cellulose acetate (a non-plastic manufactured fiber derived from natural materials) with a suite of chemical additives (Pauly et al., 2002). Cigarette filters, also known as cigarette butts, are one of the most common littered items found in urban and coastal shoreline environments across the globe (Ocean Conservancy, 2021; Torkashvand et al., 2020). It is estimated that discarded cigarette filters may release 0.3 million tons of microfibers to the aquatic environment annually (Belzagui et al., 2021). This is comparable to the estimated 0.28 million tons of microfiber emitted from clothes laundering (Belzagui et al., 2020).

Discarded or lost boating and fishing gear is a commonly cited source of marine debris (Andrady, 2011). Monofilament fishing lines, ropes, and netting are some of the most common types of lost or abandoned fishing gear and can be sources of microfiber pollution when they break down (Andrady, 2011; Welden & Cowie, 2017; Wright et al., 2021). Studies have found plastic manufactured fibers, likely originating from fishing lines and ropes, in the gastrointestinal tracts of fish (Baalkhuyur et al., 2020; Saturno et al., 2020) and in seawater samples (Zhang, Li, et al., 2021). However, few studies have directly measured microfiber release from sources related to boating and fishing, though Napper et al. (2022) recently studied the issue. In that study, researchers analyzed the release of rope fragments to the environment from rope hauling activities (i.e., abrasion of rope), which are often performed on fishing boats. They evaluated factors such as rope age, characteristics of the rope (material type, size), and wear surface and

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[5] Geotextiles are polymer fabrics used in construction activities (e.g., building roads, drains, breakwaters). They are also used in land and coastal reclamation projects and used for other civil engineering purposes. Geotextiles create a smooth, flat ground surface and prevent the removal of soil particles from the soil surface. For more information, see www.sciencedirect.com/topics/engineering/geotextile#:~:text=Geotextiles%20are%20those%20fabrics%20used,layers%2C%20reinforcement%2C%20or%20stabilisation.

compared the corresponding release of rope particles from hauling activities. Rope age was found to be a significant factor in the release of rope fragments, with ropes 2 years and older releasing more particles than new and 1-year-old ropes (Napper et al., 2022).

In recent years, tires have been identified as major sources of microplastic pollution. Tires are usually made from a combination of natural and synthetic rubbers and contain a wide range of potentially harmful chemical additives (Kole et al., 2017; Tian et al., 2021). In addition, tires often contain layers of fabric, which adhere to the tire's rubber surface to provide structural integrity (Grammelis et al., 2021). This fabric is a potential source of microfiber pollution, but there is very little available research on the extent to which tires release microfibers during production, use, or end-of-life. Therefore, potential release of microfibers from tires will not be covered in this report. Note that measures to reduce tire particles in the environment have been a subject of recent research, and the U.S. EPA's (2023) report, "Where the Rubber Meets the Road: Opportunities to Address Tire Wear Particles in Waterways", identifies potential reduction and mitigation actions.

Table 2. Microfiber Pollution Sources. This table lists known and likely sources of microfiber pollution, the potential mechanism for microfiber release into the environment, and existing studies on each source. This list only includes microfiber sources that have been identified in existing literature and is not a comprehensive list of all potential sources of microfibers.

Source Type	Potential Mechanism for Release	Literature Reference(s) Available
Textiles (e.g., apparel, bedding, footwear, upholstery)	Consumer washing machines	Athey et al., 2020; Browne et al., 2011; Carney Almroth et al., 2018; Cesa et al., 2020; De Falco, Gentile, et al., 2018; De Falco et al., 2020; Hartline et al., 2016; Kärkkäinen & Sillanpää, 2021; Kelly et al., 2019; Lant et al., 2020; McIlwraith et al., 2019; Napper et al., 2020; Napper & Thompson, 2016; Praveena et al., 2021; Sillanpää & Sainio, 2017; Tiffin et al., 2022; Vassilenko et al., 2019; Yang et al., 2019; Zambrano et al., 2019, 2021
	Consumer drying machines	Kapp & Miller, 2020; Kärkkäinen & Sillanpää, 2021; O'Brien et al., 2020; Pirc et al., 2016
	General consumer use	Cai et al., 2021; De Falco et al., 2020
Textiles (e.g., apparel, bedding, footwear, upholstery)	Manufacturing / production process	The Nature Conservancy and Bain & Company, 2021; Zhou, Zhou, et al., 2020
	Disposal, landfill	Liu, Yang, et al., 2019 (and citations within)
Fiber-based vehicle parts (i.e., tires, brake pads, belts)	Vehicle use, tire wear	Kole et al., 2017; Sutton et al., 2019
Carpet	General use, cleaning,	Alipour et al., 2021; Soltani et al., 2021

Source Type	Potential Mechanism for Release	Literature Reference(s) Available
	landfill degradation	
Personal care products (i.e., “flushable” wet wipes, menstrual products, diapers)	Flushed into wastewater, general use, landfill degradation	Lee et al., 2021; Martínez Silva & Nanny, 2020; Ó Briain et al., 2020
Face masks	General use, landfill degradation	Chen et al., 2021; Fadare & Okoffo, 2020; Saliu et al., 2021; Shruti, Pérez-Guevara, Elizalde-Martínez, et al., 2020; Wang et al., 2021; Wu et al., 2022
Cigarette butts	Litter, degradation	Belzagui et al., 2021; Moran et al., 2021
Agro- and geotextiles	General use, degradation	Bai et al., 2022
Building materials (includes concrete, building wraps, insulation)	General use, degradation	Islam & Bhat, 2019; Shafei et al., 2021
Fishing, shipping, and recreational boating gear (lines, nets, ropes, etc.)	General use, degradation	Baalkhuyur et al., 2020; Napper et al., 2022; Saturno et al., 2020; Zhang, Li, et al., 2021

B. Microfiber Prevalence in Environmental Compartments

Microfibers have been found nearly everywhere, including oceans, rivers, lakes, sea ice, soils, and in drinking water and food. They have been documented on every continent and in every ocean (Athey & Erdle, 2022). Microfibers have even been found in remote environments, like in Arctic snow (Bergmann et al., 2019), on the surface of the Pyrenees Mountains in France (Allen et al., 2019), and in deep-sea sediments (Sanchez-Vidal, 2018). Across environmental compartments, many studies have documented microfibers as the most abundant type of anthropogenic microparticle (Athey & Erdle, 2022; Barrows et al., 2018; Liu, Yang, et al., 2019).

Much of the available information on microfiber prevalence in the environment comes from scientific research that, until recently, focused primarily on microplastics (Belzagui et al., 2020; Sutton et al., 2019). In microplastics studies, microfibers are considered one of several different shape categories of microplastics (along with spheres, fragments, foams, etc.). Many microplastics studies that report the presence of plastic manufactured fibers in field samples do not report the abundance of non-plastic manufactured or non-plastic treated natural fibers found in the same samples (Athey & Erdle, 2022; Barrows et al., 2018). In a review of 465 studies that document the abundance of microfibers in various environmental compartments, Athey and Erdle (2022) found that most research prior to 2017 focused primarily on plastic manufactured microfibers. Following 2017, however, there has been a large increase in the number of studies that include non-plastic (man-made cellulosic and treated natural) fibers. In the following sections, microplastics studies are presented that report only plastic manufactured fibers as well as microfiber studies that report plastic manufactured and non-plastic fibers (manufactured and treated natural fibers).

The following summary of scientific literature also distinguishes between “microparticles” and “microplastics.” As used in the scientific literature summarized here, microparticles are particles smaller than 5 mm that are visually identified as anthropogenic litter of an undetermined polymeric material type (includes all types of microplastics and non-plastic microfibers), whereas microplastics are microparticles that are confirmed to be plastic through Raman or Fourier Transform Infrared (FTIR) spectroscopy (Barrows et al., 2018; Sutton et al., 2019). It is important to take note of this distinction because many microplastics studies do not analyze all microparticles found in environmental samples to determine their composition.

Athey and Erdle (2022) found that most studies on microfibers have been conducted in aquatic ecosystems, with 60% of the reviewed studies investigating the occurrence of microfibers in marine waters, sediments, and biota, and 23% of the studies investigating microfiber occurrence in freshwater environments (Athey & Erdle, 2022). Based on their literature review, they identified several environmental compartments (Figure 2) that are particularly understudied in research on microfibers, including terrestrial environments, groundwater, ice and snow, and indoor air and dust (Athey & Erdle, 2022). The following sections summarize the existing literature on the prevalence of microfibers in various environmental compartments.

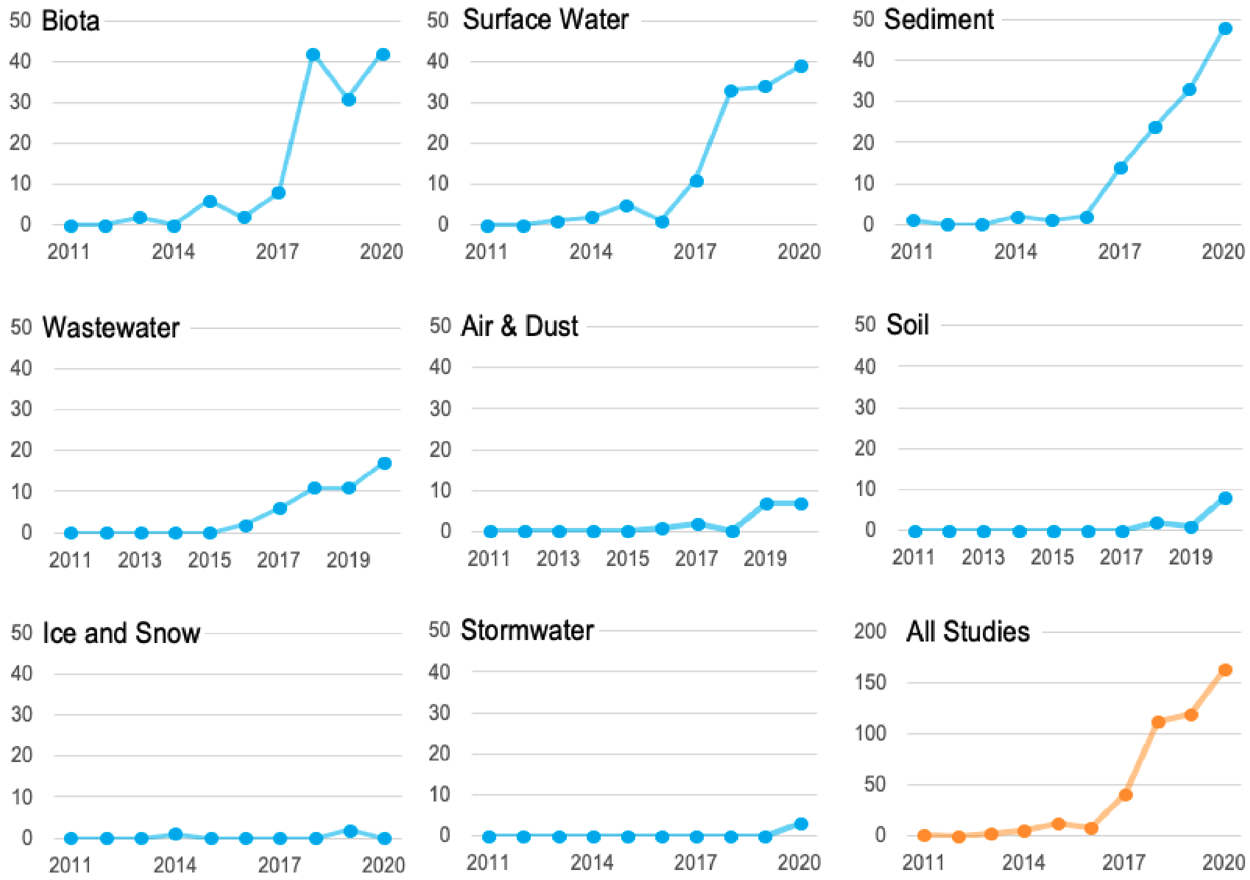

Figure 2. Number of studies published in peer-reviewed journals (y-axis) between 2011 and 2020 (x-axis) that document the abundance of microfibers in various environmental compartments. Data from Athey and Erdle (2022), used with permission from the authors.

Caution is necessary when directly comparing microfiber contamination across studies, because of variations in study objectives, sampling and analysis approaches, and quality control procedures, as well as the use of non-standardized size ranges of microplastic particles and microfibers studied. Variations in research methods for measuring microfiber pollution are discussed further in Section V of this report.

Oceans, Estuaries, Rivers, Lakes, and Other Freshwater Systems

Over the last decade, microplastics have been extensively documented throughout the world's oceans and coastal areas (Andrady, 2011; Dris et al., 2015). A global study found that ocean surface waters consistently contain microfibers, with higher concentrations found in the open ocean and in the polar regions (Barrows et al., 2018). In that study, microfibers made up 91% of the anthropogenic microparticles found in over 1,000 surface water samples collected from every major ocean (Barrows et al., 2018). Microfibers were also found to be the most prevalent type of microparticle present in San Francisco Bay surface waters in a comprehensive microplastics study carried out by the San Francisco Estuary Institute (Sutton et al., 2019; Zhu et al., 2021). Microplastics (including fibers) have been found at all depths in marine environments, from the ocean surface to ocean floor (Choy et al., 2019; Kane et al., 2020).

Studies have also reported microfiber pollution in freshwater lakes, rivers, and tributaries across the United States (Baldwin et al., 2016; Miller et al., 2017; Savitz, 2021; Zhu et al., 2021). For instance, the Hudson River, the output of one of the largest drainage basins in the eastern United States, is estimated to transport over 300 million microfibers to the Atlantic Ocean per day (Miller et al., 2017). In another study, microfibers were the most common microparticle type found within tributary surface waters to the Great Lakes, making up more than 71% of the anthropogenic particles identified (Baldwin et al., 2016). Once the tributaries enter the Great Lakes, data indicate that microfibers sink due to their density (Baldwin et al., 2016; Lenaker et al., 2019, 2021).

To date, most freshwater studies have focused on lakes and rivers, but several studies on microfiber contamination in groundwater have been published in recent years (Bharath et al., 2021; Chia et al., 2021; Huang et al., 2021; Mintenig et al., 2019; Panno et al., 2019; Samandra et al., 2022; Selvam et al., 2021), an environmental compartment that may play an important role in transport of and human exposure to microfiber pollution due to its connection to drinking water resources (Athey & Erdle, 2022; Re, 2019).

Similarly, there are also limited studies on microfiber pollution in ice and snow (Athey & Erdle, 2022). Approximately 75% of Americans in the western United States depend on ice and snow melt for freshwater. Existing research on microfiber pollution in snow has detected microfibers in populated (Kapp & Miller, 2020; Scopetani et al., 2019) and remote areas, including on glaciers and within high-mountain ecosystems (Huntington et al., 2020; Napper et al., 2020; Parolini et al., 2021; Pastorino et al., 2021).

Beaches and Sediments

Based on studies from around the globe, microfibers are also found to be a dominant anthropogenic particle type in marine and freshwater sediment, along with the loose sand, clay, silt, and other soil particles that have settled at the bottom of oceans, rivers, and lakes (Athey & Erdle, 2022; Ballent et al., 2016; Claessens et al., 2011; Haave et al., 2019; Lenaker et al., 2019; Tran Nguyen et al., 2020; Zhang, Liu, et al., 2020). Studies have documented the occurrence of microfibers in remote, deep-sea sediments in the Arctic Ocean, North Atlantic Ocean, Mediterranean Sea, and Indian Ocean (Adams et al., 2021; Bergmann et al., 2017; Reineccius et al., 2020; Woodall et al., 2014).

Similarly, microfibers are a predominant particle type found on sandy beaches in the United States (Whitmire et al., 2017; Yu et al., 2018). A 2017 study funded by the NOAA Marine Debris Program, in partnership with the National Park Service and Clemson University, looked at 35 shorelines around the United States and found microfibers were the most common form of anthropogenic particle in the hundreds of samples collected along shorelines on the Pacific and Atlantic coasts, as well as in Alaska and the Great Lakes (Whitmire et al., 2017). Another study documented similar trends along sandy beaches in the Gulf of Mexico (Yu et al., 2018).

Microfibers can enter beaches and sediments as a result of settling from surface waters, incorporation via tidal and wave action, atmospheric deposition, wastewater effluent outflows that discharge directly to shorelines, the dumping and degradation of solid waste, and landfill leachate (Tran Nguyen et al., 2020).

Air

While the bulk of studies investigating microfiber contamination have focused on aquatic environments, several recent studies have shown that microfibers are also prevalent in indoor and outdoor air (Dris et al., 2016, 2017; Kaya et al., 2018; Patil et al., 2021). Airborne microfibers have been documented in major urban areas, including Paris, London, and Shanghai (Dris et al., 2017; Liu, Wang, et al., 2019; Wright et al., 2020). Documented concentrations of microfibers in outdoor air range from 0.3 to 12 particles/m^3 (Abbasi et al., 2019; Dris et al., 2017; Gaston et al., 2020; Liu, Wang, et al., 2019). These levels are influenced by meteorological conditions (e.g., precipitation and wind conditions), population density, and human activity (Dris et al., 2016; Liu, Wang, et al., 2019; Wright et al., 2020). Furthermore, atmospheric microfibers can be transported from populated, urban areas to less-populated regions, such as remote mountain catchments and even U.S. conservation areas, where they can settle out or be deposited via precipitation (Allen et al., 2019; Brahney et al., 2020).

Studies that compared indoor and outdoor microfiber concentrations found that indoor environments contain higher microfiber concentrations than outdoor air (Athey & Erdle, 2022; Dris et al., 2016; Prata et al., 2020). Concentrations in indoor air range from 1-60 particles/m^3 (Abbasi et al., 2019; Dris et al., 2017). This suggests that more human exposure to airborne microfibers occurs indoors than outdoors (Dris et al., 2016; Gaston et al., 2020). A variety of different types of microfibers have been documented in indoor and outdoor air, with treated natural fibers dominating both indoor and outdoor samples (Dris et al., 2016; Gasperi et al., 2018; Gaston et al., 2020).

Terrestrial Soil

While there is relatively little research on microfibers in soils, recent studies have shown that terrestrial ecosystems may be a significant pathway for microfiber pollution entering aquatic ecosystems (Nizzetto et al., 2016). As with marine and freshwater ecosystems, microfibers are the most common form of anthropogenic particle documented in terrestrial soils (Ambrosini et al., 2019; Chia et al., 2021; Zhou, Wang, et al., 2020). Microfibers can move from the soil surface to waterways via erosion, surface runoff, or wind-driven processes (Kim et al., 2020).

Although most research on the prevalence of microplastics, including microfibers, in soil has focused on surface soils, microplastics have also been shown to infiltrate deeper strata (Guo et al., 2020; Qi et al., 2020). There are multiple possible mechanisms for microplastic transport below the soil surface (Chia et al., 2021; Huang et al., 2021; Kim et al., 2020). These mechanisms include agricultural practices such as tillage (Zhang & Liu, 2018), water infiltration and vertical transport from surface soils to subterranean soils (Huang et al., 2021), and activities of soil-dwelling biota such as earthworms (Cao et al., 2017; Rillig et al., 2017).

Biota

Microfibers have been found in the tissues and digestive tracts of a wide range of fish, invertebrate, mammal, and bird species (McGoran et al., 2017; Mizraji et al., 2017; Moore et al., 2020; Nadal et al., 2016). Many studies characterizing microplastic particles in biota have reported microfibers to be the most frequently ingested form of microplastic particle (McGoran et al., 2017; Mizraji et al., 2017; Moore et al., 2020; Nadal et al., 2016). The types of ingested microfibers vary across studies and include plastic and non-plastic fibers (Carlin et al., 2020; Waddell et al., 2020; Zheng et al., 2020).

Between 2011 and 2020, at least 133 studies documented microfibers in biota, including 58 studies that reported microfibers in various fish species and 49 that reported microfibers in invertebrates (Athey & Erdle, 2022). These studies are summarized in Table 3 below. Microfiber ingestion by and interaction with fish in marine habitats has been widely documented, with studies finding microfibers in the digestive tracts, tissues, and gills of fish species around the world, including the Atlantic Ocean (Dantas et al., 2020; Lusher et al., 2013; Neves et al., 2015), the Pacific Ocean (Hipfner et al., 2018; Jamieson et al., 2019), the Arctic Ocean (Fang et al., 2018), the South China Sea (Koongolla et al., 2020), and the Mediterranean Sea (Bottari et al., 2019; Güven et al., 2017; Savoca et al., 2019).

Invertebrates with a wide a variety of feeding behaviors have also been shown to ingest microfibers in the wild, including mussels (Li et al., 2016; Qu et al., 2018), zooplankton (Desforges et al., 2015; Zheng et al., 2020), shrimp (Devriese et al., 2015; Fernández Severini et al., 2020), blue crabs (Waddell et al., 2020), and lugworms (Van Cauwenberghe et al., 2015). Microfibers have even been found in deep-sea benthic invertebrates collected at a depth of over 1,700 meters (Taylor et al., 2016).

Table 3. Number of studies published between 2011 and 2016 that document the abundance of microfibers in biota. (Data from literature review by Athey and Erdle (2022), used with permission from the authors)

Type of Species	Type of Habitat		
	Marine	Freshwater	Terrestrial
Amphibian	0	1	0
Bird	9	1	1
Fish	48	10	0
Invertebrate	46	3	0
Mammal	9	0	0
Plant	1	0	1
Reptile	3	0	0
Total	116	15	2

Microfiber ingestion has also been reported in marine mammals, including grey seals (Hernandez-Milian et al., 2019) and beluga whales (Moore et al., 2020), as well as in various species of birds (Bessa et al., 2019; Le Guen et al., 2020; Zhu, Li, et al., 2019).

Studies on marine fish and invertebrates are most prevalent in scientific literature (Table 3), but researchers have also studied biota in freshwater and terrestrial habitats (OECD, 2021; Wong et al., 2020). Research on microfiber occurrence in freshwater biota demonstrates widespread ingestion of microfibers by freshwater fish and invertebrates in lakes (Athey et al., 2020; Su et al., 2018) and rivers (Collard et al., 2018; McNeish et al., 2018). There are very few studies on microfiber occurrence in terrestrial biota.

Studies suggest that aquatic organisms may mistake microfibers for food. This can depend on the feeding mechanisms and behaviors of species, as well as the characteristics of the microfibers in aquatic habitats, such as size, color, chemical composition, and shape (Bessa et al., 2019; Galloway et al., 2017; Patil et al., 2021; Savoca et al., 2016). Biota can also be exposed to microplastics through the ingestion of contaminated prey, a phenomenon known as trophic transfer (Athey et al., 2020; Mateos-Cardenas et al., 2019; Moore et al., 2020; Provencher et al., 2019). Recent research suggests that inhalation of microplastics via gills is another potentially significant exposure pathway for some aquatic species (Bour et al., 2020; Su et al., 2019; Watts et al., 2016).

In addition to the studies discussed above, which documented microfiber uptake by biota in their natural habitats, there are many other studies that have observed microplastic ingestion by aquatic organisms under carefully controlled laboratory conditions (Au et al., 2017; Desforges et al., 2015; Foley et al., 2018; Jemec et al., 2016; Ziajahromi et al., 2017).

Drinking Water and Food for Human Consumption

Though there is insufficient data on human exposure and hazards associated with microfibers to perform meaningful human risk assessments for microfibers or microplastics, it is widely accepted that humans are exposed to microplastics via ingestion and inhalation (Cox et al., 2019; Mohamad Nor et al., 2021). Researchers have detected microfibers in a wide range of foods intended for human consumption, including salt (Kosuth et al., 2018; Seth & Shriwastav, 2018), milk (Kutralam-Muniasamy, 2020), commercially packaged seaweed (Li et al., 2020), and various commercial seafoods (Rochman et al., 2015; Santillo et al., 2017; Van Cauwenberghe & Janssen, 2014).

Several studies have detected microfibers in raw and treated drinking water as well as bottled water, though comparing findings across studies is difficult due to non-standardized research methods, including the use of non-standardized methods to morphologically characterize and identify the polymer composition of microplastic particles that are reported. Assessing the occurrence of microfibers in drinking water based on existing research is particularly challenging because many of the existing studies on microplastics in drinking water do not report the shape of the microplastic particles found in samples. Furthermore, some studies reporting microfibers in drinking water have been discounted due to the likelihood of sample contamination as a result of inadequate quality assurance and quality control (QA/QC) measures. One of the most commonly encountered challenges in microplastics research is eliminating and/or controlling for contamination of samples by airborne microfibers (Mintenig et al., 2019). See section V.A.2 for a discussion on QA/QC measures.

In a systematic review of microplastics found in drinking water, Danopoulos et al. (2020) identified six studies that analyzed tap water and six that analyzed bottled water. All studies reported some level of microplastic occurrence. Of the six studies on tap water, five reported fibers in samples (Pivokonsky et al., 2018; Shruti, Pérez-Guevara, & Kutralam-Muniasamy, 2020; Strand et al., 2018;[6] Tong et al., 2020; Zhang, Li, et al., 2020). Mintenig et al. (2019) did not analyze fibers present in samples due to the likelihood that fibers in samples were the result of contamination during sample handling. In the six bottled water studies analyzed, microplastic particles were found in 92-100% of samples analyzed (Danopoulos et al., 2020). Three of these studies reported the occurrence of fibers (Kankanige & Babel, 2020; Mason et al., 2018; Wiesheu et al., 2016), while three did not discuss particle shapes (Oßmann et al., 2018; Schymanski et al., 2018; Zuccarello et al., 2019).

Potential sources of microfibers in drinking water include microfiber pollution in the freshwater source (microfibers may have entered freshwater sources via stormwater, wastewater, sewer overflows, or atmospheric deposition), from treatment and distributions systems, or – in the case of bottled water – from the bottling process and/or the bottle itself (Noventa et al., 2021).

A 2019 report on microplastics in drinking water by the World Health Organization concluded that there is a need for well-designed and quality-controlled investigative studies to better understand the occurrence of microplastics in drinking water and freshwater sources (Marsden et al., 2019). California's State Water Resources Control Board is taking steps to adopt requirements for 4 years of testing and reporting of microplastics (including microfibers) in drinking water, including public disclosure of those results, as is required under California Health and Safety Code section 116376(2). The California State Water Board recently adopted a definition of *microplastics in drinking water*, discussed in Appendix B, as well as standardized methods for extraction and analysis of microplastics in drinking water to be used in subsequent testing (California State Water Resources Control Board, 2020).

C. Microfiber Pollution Causes and Pathways

Despite a growing body of research documenting the prevalence of microfibers in various environmental compartments, little is known about the causes of microfiber shedding and the pathways through which microfibers enter and move between environmental compartments (Gasperi et al., 2018; Gavigan et al., 2020). Microfiber release likely results from abrasion or mechanical or chemical stresses on fabrics/fibers during general use or laundering (De Falco, Gullo, et al., 2018; OECD, 2021), or from weathering in the environment (i.e., cigarette filters, ropes, nets in sunlight). As discussed in the previous section, researchers have carried out numerous studies documenting that washing apparel and other textiles in washing machines releases microfibers to wastewater (Athey et al., 2020; Browne et al., 2011; Carney Almroth et al., 2018; Cesa et al., 2020; De Falco, Gentile et al., 2018; De Falco, Gullo et al., 2018; De Falco et al., 2020; Gavigan et al., 2020). Though less studied, there are studies suggesting microfibers are also shed from apparel and other fiber-based materials during normal use (De Falco et al., 2020), in clothes dryers (Kapp & Miller, 2020), and during the production process (Chan et al., 2021; Xu et al., 2018; Zhou, Zhou, et al., 2020; The Nature Conservancy and Bain & Company, 2021).

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[6] Fibers consisted of "cellulose-like material," which the authors of the study did not consider microplastics.

There are a number of pathways by which microfibers can enter the environment. For the purposes of this report, a pathway refers to the physical environmental compartment or engineered route through which microfibers released from sources enter the natural environment. Natural pathways include rivers, streams, and transport via atmospheric circulation (here referred to as atmospheric transport). Engineered pathways include wastewater systems (including combined sewer overflows and sewage sludge/biosolids) and stormwater systems (Figure 2) (Gavigan et al., 2020; Grbić et al., 2020; Sutton et al., 2019). The reported pathways and sources (see Section IV.A) of microfibers to aquatic environments as noted above are mainly land-based (Gavigan et al., 2020). There is very little data on microfiber generation from aquatic (marine and freshwater) sources, such as fishing, aquaculture, boating and other vessel-based activities, and other recreational activities like swimming, snorkeling, SCUBA diving, etc.

More research is needed to understand the relationships among different pathways, and the contributions of microfibers from each of these pathways. Microfibers from apparel and other land-based sources enter aquatic environments via atmospheric transport and deposition (Barrows et al., 2018; Carr, 2017; Dris et al., 2016), runoff from terrestrial environments (Baldwin et al., 2016), and stormwater and wastewater systems (Browne, 2015; Gago et al., 2018; Mason et al., 2016; Napper & Thompson, 2016). The majority of early studies on microfiber pollution pathways focused on wastewater effluent as a pathway for microfibers shed from fabrics in washing machines (Figure 3) (Athey & Erdle, 2022; Browne, 2015; Browne et al., 2011; McCormick et al., 2014). More recently, research has begun to assess the relative importance of atmospheric transport, stormwater, and sewage sludge as key pathways for microfiber pollution (Gavigan et al., 2020; Sutton et al., 2019). Once microfibers enter aquatic systems, they can be distributed by currents, be ingested by biota, settle into sediments, or re-enter the atmosphere (Allen et al., 2020; Mishra et al., 2019).

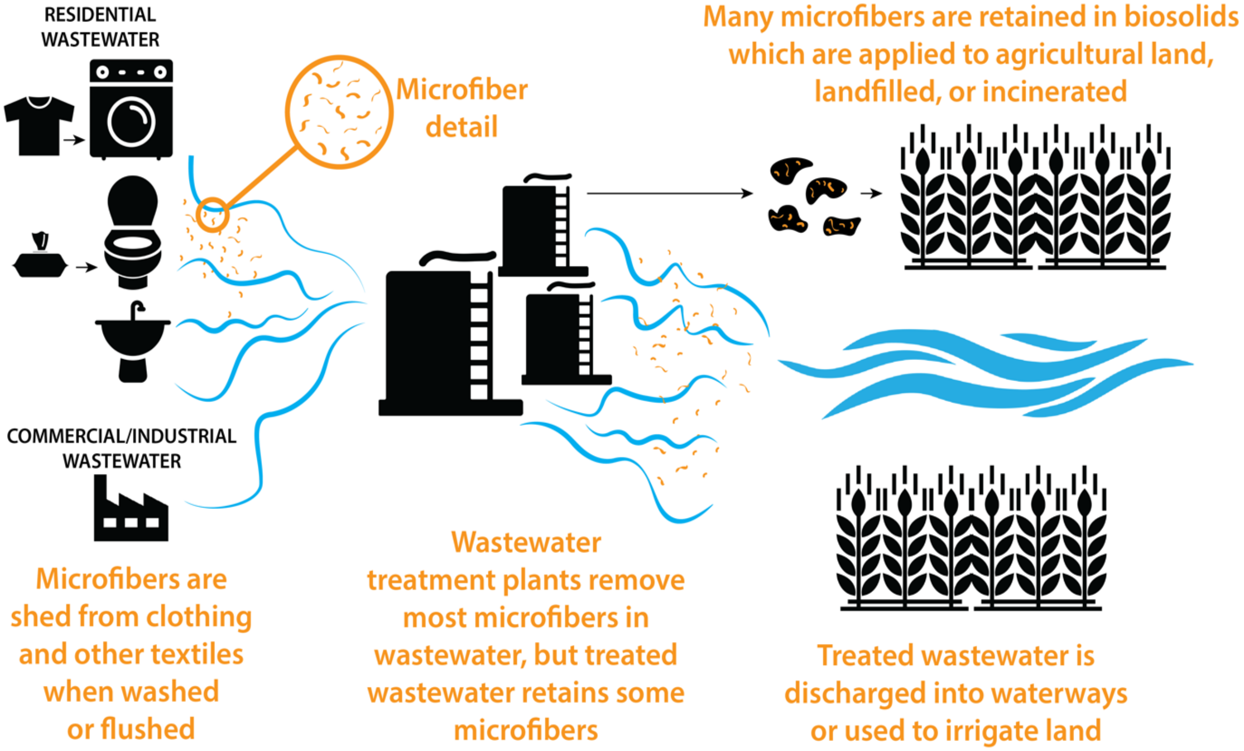

Figure 3. Wastewater as a Pathway for Microfiber Pollution.

Wastewater

Wastewater is a known transport pathway for microplastics, particularly microfibers, (Cowger, Gray, et al., 2020; Gies et al., 2018; Mason et al., 2016; Sun et al., 2019; Zhu et al., 2021) to enter aquatic (Dris et al., 2015; Grbić et al., 2020) and terrestrial (via irrigation and application of biosolids) (Gavigan et al., 2020) environments. Microfibers present in effluent from domestic and commercial washing machines enter the wastewater stream (Browne et al., 2011), which in the United States is often processed through treatment facilities before being released into the aquatic environment (United Nations Statistics Division, 2011; WWAP, 2017). Wastewater from domestic sources (e.g., individual homes), commercial facilities (e.g., laundry facilities, hotels), institutions (e.g., universities, hospitals), and industries (e.g., textile manufacturing) may contain microfibers. Though limited information is available on discharges into wastewater from these various sources under real world conditions, one study estimated that higher concentrations of microfibers are present in wastewater from industrial streams compared to estimated wastewater discharges from domestic streams due to washing conditions (De Falco, Gullo, et al., 2018).

Several studies have identified fibers as the most common type of microplastic particle entering wastewater treatment plants (Gies et al., 2018; Johnson et al., 2020; Kay et al., 2018; Sun et al., 2019; Zhang, Liu, et al., 2020). While global wastewater treatment infrastructure has not been developed specifically to remove microparticles, microplastics, and microfibers, the treatment process often removes most microfibers found in wastewater (Gavigan et al., 2020; Habib et al., 2020). There are several studies documenting the amount of microplastics removed via wastewater treatment (Gavigan et al., 2020; Habib et al., 2020). Estimates for microfiber discharge from treated wastewater vary greatly from region to region and facility to facility due to variations in treatment levels (i.e., preliminary, primary, secondary, and tertiary), integrated filtration technologies, and influent[7] characteristics. However, variations in research methods limit the ability to compare data across studies (Koutnik et al., 2021).

Research has shown that up to 79-98% of microplastics and microfibers are removed by primary treatment, which involves separation and removal of solids (Habib et al., 2020) and 98-99% upon secondary treatment, which involves additional techniques to remove smaller solids, such as an aeration tank where bacteria break down organic matter (Gavigan et al., 2020). The effectiveness of tertiary treatment, normally focused on nutrient removal, varies depending on the technology used. There is no commercially available method to achieve 100% microfiber removal (Habib et al., 2020).

Despite the effectiveness of wastewater treatment processes in removing the majority of microfibers from wastewater, studies have found that substantial volumes of microfibers are discharged into the environment via treated wastewater because of the enormous volumes of wastewater treated each day (OECD, 2021). A 2016 study on microplastic discharges from 17 wastewater treatment plants across the United States found that while the rates of particles found per liter were low (less than 1 particle per liter, ranging from 0.004 to 0.195 particles per liter), the average volume of water processed by these 17 wastewater treatment plants ranged from 2.35 to 382 million liters of water discharged per day (see Tables 2 and 3 from Mason et al. (2016)). Due to the large volumes of water discharged per day, this was equivalent to an average of 4 million microplastic particles, mostly fibers and fragments, released by each facility per day, with discharges ranging from 50,000 to 15 million particles per wastewater treatment plant per day (Mason et al., 2016).

As of 2012, 14,748 publicly owned wastewater treatment plants serve about 76% of the U.S. population. Of the population served by wastewater treatment plants, 54% receive more than secondary treatment, 38% receive secondary treatment, 2% receive less than secondary treatment, and the remaining 6% are served by “non-discharging facilities,” which do not discharge effluent to surface waters, but instead reuse it (U.S. EPA, 2016). Though in the United States and other high-income countries, about 70% of municipal and industrial wastewater is treated, globally, approximately 80% of used water resources are released into the environment without treatment (WWAP, 2017). There is a significant need for further research on the release of microfiber pollution via untreated wastewater.

a) *Sewage Sludge*

Most of the microfibers removed during wastewater treatment are retained in sewage sludge, which is either disposed of via landfilling or incineration, or is recycled for use in energy production or agriculture (Geyer et al., 2022; Mahon et al., 2017). In most countries, including the United States, sewage sludge undergoes physical and chemical treatment to produce a nutrient-rich product referred to as “biosolids.” Biosolids are often used as land amendments for agricultural and non-agricultural lands (Corradini et al., 2019; Weithmann et al., 2018; Zubris & Richards, 2005). Benefits of land application of biosolids include

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[7] Influent water is wastewater entering a wastewater treatment plant.

increased crop yields, improved soil structure, and preservation of limited landfill space. The U.S. EPA (2021a) estimates, based on 2019 data, that of the roughly 4.75 million dry metric tons of biosolids produced by large wastewater treatment plants in the U.S. in 2019, 51% were applied to land (1.4 million dry metric tons applied to agricultural land; 1 million dry metric tons applied to non-agricultural land), 16% were incinerated, 22% were landfilled,[8] and 11% were disposed of by other means (examples include deep well injection and storage).

Even after treatment, biosolids retain microfibers removed from wastewater, making this an important pathway for microfibers found in soil (Corradini et al., 2019; Habib et al., 1998; Mahon et al., 2017; Wang, Liu, et al., 2019; Zubris & Richards, 2005). There is very little research on the impacts of biosolids pretreatment on microfiber retention. One study by Mahon et al. (2017) that examined microplastic abundance and characteristics in sewage sludge after undergoing various forms of treatment (anaerobic digestion, thermal drying, and lime stabilization), suggested that anaerobic digestion processes may reduce microplastic concentrations in biosolids. However, more research is needed in order to assess the potential for microfiber removal via sludge treatment processes.

While direct application of sewage sludge to land is now recognized as a prominent transport pathway for microplastics to the terrestrial environment (Gavigan et al., 2020), and as an eventual source to fresh and marine compartments, few studies have been conducted specifically on microfiber prevalence in sewage sludge or biosolids (Athey & Erdle, 2022). This pathway requires further examination and evaluation of mitigation measures.

b) Combined Sewer Overflows

Combined sewer systems collect stormwater (runoff generated by precipitation events), industrial wastewater, and domestic sewage destined for wastewater treatment all in the same system of pipes. About 750 communities in the United States have combined sewer systems, most of which are located in the Northeast and Great Lakes regions (U.S. EPA, 2004). During heavy precipitation, combined sewer systems are designed to overflow when the capacity of the collection system is exceeded, leading to the release of untreated wastewater and rainwater to the immediate environment (rivers, lakes, and streams). These overflow events, called combined sewer overflows, can be significant sources of chemical and biological pollution to the aquatic environment, including pathogens, nutrients, hydrocarbons, suspended solids, and emerging contaminants such as pharmaceuticals (Munro et al., 2019; Shetty et al., 2019; Tondera et al., 2016; Wu et al., 2021).

The role of combined sewer overflows as pathways for microplastics and microfibers is not well understood, with few studies available on the issue to date (Chen et al., 2020; Dris et al., 2018; Gies et al., 2018). Microfibers could enter combined sewer systems through domestic

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[8] As for the biosolids that are disposed of in landfills, the landfills are meant to be a sink for these microplastics (including microfibers), as well as other solid waste items. However, microplastics can enter the environment or return to wastewater treatment plants in the form of landfill leachate (Kabir et al., 2023). This is discussed further in Section VI.C.

or industrial wastewater or through stormwater. High concentrations of microfibers in combined sewer overflows have been reported in Paris, where researchers found 190-1,046 fibers/L (Dris et al., 2018), and Shanghai, with 130-8,500 particles/L and 43% of the particles being microfibers (Chen et al., 2020).

Stormwater

Unlike combined sewer systems, municipal separate storm sewer systems, which are common in cities across the United States, are designed to collect stormwater from urban areas and discharge it directly into local water bodies without treatment (Figure 4). Municipal separate storm sewer systems convey only stormwater. Researchers have identified municipal stormwater as a potentially significant pathway for microparticles, microplastics, and microfibers, though this pathway is understudied relative to wastewater as a pathway for microparticles, microplastics, and microfibers (Bailey et al., 2021; Dris et al., 2018; Liu, Olesen et al., 2019; Treilles et al., 2021; Zhu et al., 2021).

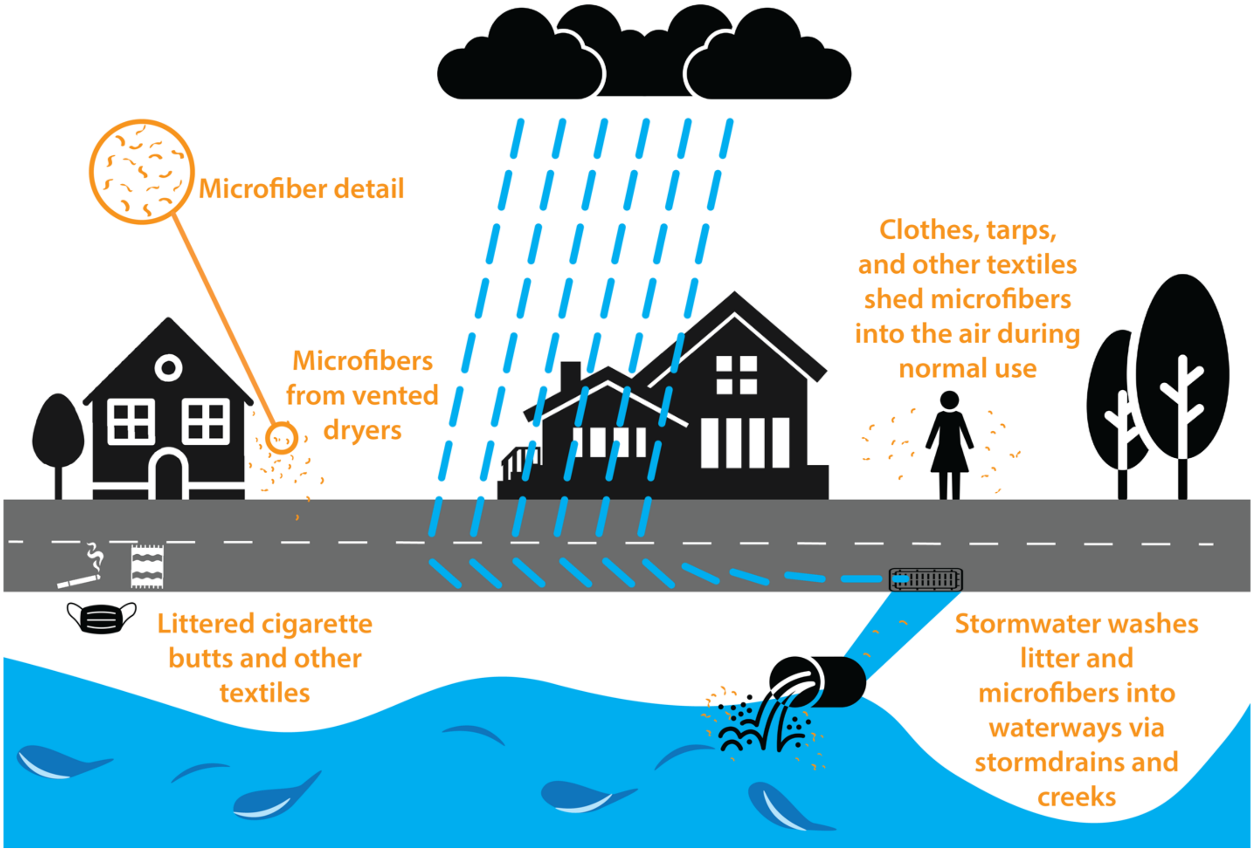

Figure 4. How microfiber pollution enters waterways via stormwater.

Several studies have reported microfibers in urban stormwater runoff, sampled directly from street runoff, a stormwater catchment point, or stormwater retention ponds. These include studies in Tijuana, Mexico (de Jesus Piñon-Colin et al., 2020); the San Francisco Bay area, U.S.A. (Sutton et al., 2019); Paris, France (Dris et al., 2018; Treilles et al., 2021); Denmark (Liu, Olesen et al., 2019); and Toronto, Canada (Grbić et al., 2020; Smyth et al., 2021). Studies that report microplastic concentrations in stormwater show a large variability in results, depending on sample site characteristics, field sampling protocols, and other conditions (Werbowski et al., 2021).

A 2019 study by the San Francisco Estuary Institute (SFEI) found that microplastic concentrations (including all morphologies of microplastics) in stormwater were significantly higher than treated wastewater effluent discharged into San Francisco Bay, though textile-derived microfibers specifically were more abundant in wastewater than in stormwater (Sutton et al., 2019). The microparticles found in San Francisco Bay stormwater consisted primarily of fragments (59%) followed by fibers (39%), whereas the same study found that fibers were the most prevalent type of microparticle found in San Francisco Bay wastewater effluent (55%), surface water (74%), and sediment (69%). The authors suggest that tire wear particles likely account for a large proportion of the fragments identified in stormwater.

Similar findings were reported in a study of microplastics in wastewater effluent, stormwater and agricultural runoff, and surface water in Toronto, Canada (Grbić et al., 2020). While fibers accounted for 90% of the anthropogenic particles found in wastewater treatment plant effluent, fibers made up only 41% of the anthropogenic particles found in stormwater runoff. In this study, tire and road wear particles accounted for 22% of the particles found in stormwater.

In their study of microplastics in stormwater in Tijuana, Mexico, de Jesus Piñon-Colin et al. (2020) observed a direct relationship between precipitation and microplastic load in stormwater runoff. Fibers were the most abundant type of microplastic found in all sample sites, composing 68-87% of microplastics found. The authors hypothesize that the common practice of discharging domestic laundry effluent to the streets in the drainage basin on the sample sites may explain the high percentage of fibers found in stormwater from the sample sites in residential areas.

It is possible that industrial stormwater, i.e., stormwater runoff from textile manufacturing and other industrial facilities, may be a pathway via which microfibers are released into the environment. However, more research would need to be conducted in this area to better understand the significance of this potential pathway.

In urban areas, non-permeable surfaces, such as roads, parking lots, and sidewalks, increase runoff to stormwater systems (Box & Cummins, 2019). Researchers have suggested that rain gardens and bioretention cells have the potential to reduce contaminants and debris in stormwater runoff, with some studies measuring microplastic contamination in influent and effluent of rain gardens and bioretention cells (Gilbreath et al., 2019; Smyth et al., 2021; Werbowski et al., 2021). Smyth et al. (2021) found that bioretention cells are effective in removing microparticles, observing an 84% decrease in the concentration of microparticles in effluent from a bioretention cell. Studies by Gilbreath et al. (2019) and Werbowski et al. (2021) also found that rain gardens were highly effective in removing microparticles from stormwater, reporting average decreases in microparticle concentrations of 91% and 95% respectively. Rain gardens and other types of green infrastructure merit further research as potential mitigation strategies for microplastic and microfiber pollution in stormwater.

Atmospheric Transport

Though research is limited, atmospheric transport has also been identified as a potentially significant pathway for microfibers into various environmental compartments (De Falco et al., 2020; Napper et al., 2023). There are a variety of paths by which microfibers enter the air compartment. Microfibers can become airborne from textiles as a result of abrasion and weathering throughout their life cycle, and from laundering clothing. This includes microfibers formed during textile production (Dris et al., 2016) and normal wear and use of textiles (De Falco et al., 2020), as well as from release from dryer vents (Kapp & Miller, 2020; Tao et al., 2022). Recent research suggests that the direct release of microfibers to air from the wearing of garments is comparable to microfiber release through washing machine effluent (De Falco et al., 2020).

While pathways have been identified for fiber release into the atmosphere, the next steps are to examine and understand the fate and transport of the airborne microfibers once released to air (Cheng et al., 2016; O' Brien et al., 2020; Kapp & Miller, 2020). Such future studies should evaluate how meteorological conditions, such as wind, influence the transport of microfiber-laden air and dust throughout the natural environment (Kapp & Miller, 2020).

Aquatic Activities (fishing, boating, etc.)

Some marine and freshwater activities result in the release of microfibers directly into oceans, rivers, and lakes. These activities include fishing and aquaculture, as well as any vessel-based activity (e.g., shipping, boating, or the use of any vessel that uses ropes, such as for mooring lines). In addition, other aquatic recreational activities (e.g., SCUBA diving, snorkeling, swimming) may also contribute microfibers to the environment. Studies on these potential sources and pathways are scarce.

D. Potential Environmental and Human Health Impacts of Microfiber Pollution

As discussed in the previous sections of this report, microfiber pollution is ubiquitous across a wide range of environmental compartments (Figure 5). Though research confirms that humans and a diverse range of aquatic and terrestrial organisms are exposed to microfiber pollution, the impacts of microfiber pollution on environmental and human health are largely unknown. Physical, biological, and chemical mechanisms can act individually or in combination to produce health effects in an organism (Henry et al., 2019). Impacts may be due to the ingestion of fibers or the interaction between microfibers and organisms (e.g., in gills), in which the presence of the fiber(s) may inflict damage to and/or block the gut of the organism (physical effect). Damage to an organism from microfiber exposure may also weaken the organism's immune system, allowing for viruses or pathogens to affect the organism (biological effect). Exposure to chemical additives in microfibers or sorbed contaminants from the environment may also impact organisms (chemical effect).

The effects of microfiber exposure vary depending on the chemical and physical properties of the microfibers, the dose, and the organism or ecosystem exposed. The potential mechanisms of microfiber toxicity are not well understood. Microfibers are extremely diverse in their size, solubility, polymeric composition, and added or sorbed chemicals. There are many different polymer types and chemical additives used in fiber-based products such as clothing (Darbra et al., 2011). In addition, the degree of microfiber aging or weathering can also influence its physical and chemical interactions with the environment (Binda et al., 2021; Sridharan et al., 2022). These complexities make understanding the risks associated with this contaminant particularly challenging (Coffin et al., 2021). Furthermore, much of the existing research on the subject focuses on microfibers as a type of microplastic. Therefore, the impacts of non-plastic fibers (i.e., treated natural and manufactured fibers), which are often left out of microplastics toxicity studies, are understudied relative to plastic fibers.

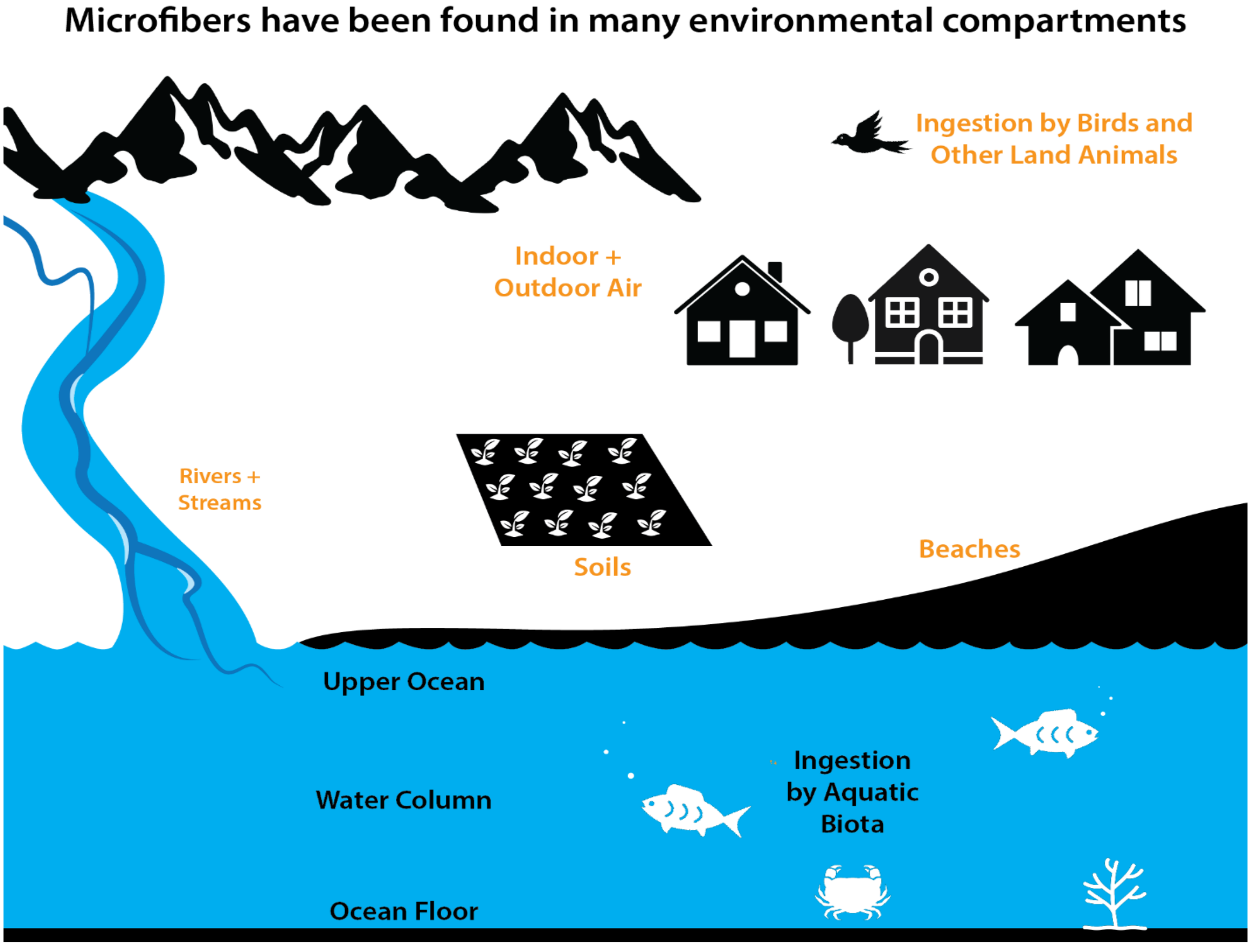

Figure 5. Occurrence of microfiber pollution in various environmental compartments.

The chemical properties of microfibers are incredibly diverse, making risk assessment and mitigation of microfibers difficult (Coffin et al., 2021). Textiles and the microfibers they shed frequently contain intentionally added chemicals (referred to in this report as “chemical additives”) (Lacasse & Baumann, 2012; Wang, Zhang, et al., 2019; Zhu et al., 2020), as well as chemicals that unintentionally accumulate on fibers via sorption from the environment (Saini et al., 2017, 2016). The functions of chemical additives applied at various stages of fiber and textile processing include, but are not limited to, formulating the base polymer, aiding in various textile processing stages (e.g., spinning and yarn oils, binding functional chemistry), providing performance characteristics for the end user (e.g., stain- and water-repellent, waterproof coatings, anti-wrinkle, anti-microbial), and imparting color through dyes or pigments. Most chemicals are applied to textiles during the finishing process, which includes fabric pretreatment, coloring, and functional finishing (Darbra et al., 2011). In most cases, chemical additives are not chemically bound to the polymer matrix and can therefore leach from the material (Bridson et al., 2021). Knowledge of the leachability and toxicity of the many chemical additives associated with microfibers is limited (Sridharan et al., 2022).

Examples of chemical additives applied to textiles (e.g., apparel, agro/geo, footwear, carpeting, upholstery, medical) include per- and poly-fluorinated alkyl substances, also known as PFAS, which are used primarily for water and stain resistance (Schellenberger et al., 2019). As an emerging chemical class of concern due to its environmental persistence, bioaccumulation potential, and toxicity at extremely low exposures, some textile companies are beginning to switch to alternatives (Green Science Policy Institute, 2023). Flame retardants, such as organophosphate esters, are another chemical class of concern that might be applied to a wide range of textile products, including furniture, workwear apparel, and infant clothing (Stapleton et al., 2005; Zhu et al., 2020). Other chemicals of concern that are frequently used in textile production include bisphenols (including bisphenol A) and benzophenones (Xue et al., 2017). The degree to which organisms are exposed to added or sorbed chemicals in microplastics depends on how quickly the chemical leaches out of the microplastic particle and, in the case of ingestion, how long the microplastic particle stays in the organism.

Once in the environment, plastic debris (including microplastics and microfibers) may also provide a substrate for the adsorption of other harmful pollutants from their surrounding environment, including polychlorinated biphenyls, heavy metals, and pesticides (Browne et al., 2011; Teuten et al., 2007). The degree to which plastics sorb contaminants depends on the chemical and physical characteristics of the particles (including age and weathering), as well as the types and amounts of chemical contamination they are exposed to (Rochman, 2015). Few studies have investigated the combined toxicity of microfibers and other environmental stressors (but see the recent article by Seeley et al., 2023). Interactive effects of coincident chemicals (including additives and sorbed chemicals), as well as other environmental stressors, such as elevated temperature and changes in pH (water acidity), merit further investigation.

Overall, research on the impacts of microfiber pollution on aquatic and terrestrial biota, including humans, is extremely limited. The following sections provide examples of the wide range of impacts that have been observed by researchers in various types of biota. However, for many of the impacts reported in these studies, the underlying physical and/or chemical mechanisms that might explain the observed effects are largely unknown.

Impacts on Aquatic Biota

As discussed in the previous section on the prevalence of microfiber pollution, ingestion of microfibers by aquatic organisms is well documented in scientific literature, including studies on fish, marine mammals, shorebirds, invertebrates (e.g., crustaceans, barnacles, corals), and a wide range of other organisms (Avio et al., 2020; Koongolla et al., 2020; Kühn & van Franeker, 2020; Lusher et al., 2017; Moore et al., 2020; Waddell et al., 2020; Zhang, Sun, et al., 2021). Aquatic organisms may mistake microfibers for food (Bessa et al., 2019; Galloway et al., 2017; Patil et al., 2021; Savoca et al., 2016) or may be exposed to microfibers through the ingestion of contaminated prey, a phenomenon known as trophic transfer (Athey et al., 2020; Mateos-Cárdenas et al., 2019; Moore et al., 2020; Provencher et al., 2019). Recent studies suggest that inhalation of microplastics via gills is another potentially significant exposure pathway for aquatic species (Bour et al., 2020; Su et al., 2019; Watts et al., 2016).

A growing body of research examines the impacts of microfiber pollution on aquatic organisms (Kwak et al., 2022). Some studies have found that ingested microfibers pass through the digestive tracts of organisms with few to no observed impacts (Jovanović, 2017; Mateos-Cárdenas et al., 2019; Setyorini et al., 2021). Other studies reported toxic effects, including reduced feeding behavior or metabolism (Cole et al., 2019; Watts et al., 2016; Welden & Cowie, 2016), reduced reproduction (Jemec et al., 2016; Liu et al., 2021), and increased mortality (Jemec et al., 2016). Physical effects of microfiber ingestion that have been observed include tissue inflammation and gut blockage (Au et al., 2017; Foley et al., 2018; Jemec et al., 2016; Ziajahromi et al., 2017). However, in many of the studies that report adverse effects on biota from microfiber exposure, the chemical or physical mechanisms underlying the observed effects are unknown (Horn et al., 2020). Observed effects of microfiber exposure in biota are highly variable, depending on the species affected, the concentration of microfibers to which the organism is exposed, the duration of exposure, and the physical and chemical characteristics of the microfibers (Foley et al., 2018; Hale et al., 2020).

Some laboratory experiments have demonstrated that microplastic exposure can have negative effects on various types of aquatic invertebrates, particularly after long periods of exposure to high concentrations of microfibers (Huang et al., 2021). Ingestion of microfibers has been shown to lead to reduced food consumption in *Carcinus maenas* (crab) (Watts et al., 2015). Another study showed that polypropylene fibers ingested by *Nephrops norvegicus* (lobster) were retained in the animal's chitinous foregut and resulted in decreased growth (Welden & Cowie, 2016). A study by Walkinshaw et al. (2023) evaluated the effects of a treated natural (cotton) fiber and plastic manufactured (polyester) fiber on the growth rate of juvenile mussels in a chronic microfiber exposure study. They found that the growth rate of mussels decreased by 35.6% when exposed to the polyester fiber, and 18.7% when exposed to the cotton fiber. The decreased growth rate due to polyester fibers was significantly different from the control treatment, whereas the decreased growth rate due to the cotton fibers was not significantly different from the control treatment nor the polyester treatment (Walkinshaw et al., 2023). When evaluating the number of fibers found in the mussel tissue, there were almost twice as many cotton fibers as polyester fibers. The researchers hypothesize that either mussels may have a greater capacity to process cellulosic fibers or there may be a difference in cotton fiber morphology compared to the polyester fibers (Walkinshaw et al., 2023).

In addition, several studies have investigated the effects of microfiber exposure on zooplankton and larval fish (Cheng et al., 2021), with observed effects including increased mortality (Jemec et al., 2016), decreased growth (Ziajahromi et al., 2017), decreased respiration rates (Woods et al., 2020), and decreased reproduction (Ziajahromi et al., 2017). In their study on the acute and chronic effects of polyester microfibers on *Ceriodaphnia dubia* (water flea), Ziajahromi et al. (2017) found that water fleas that were submerged in water with high concentrations (about six times higher than reported environmental concentrations) of microfibers did not ingest the fibers, but exposure did lead to deformation of the carapace and antenna of the water flea. Their findings suggest that although many studies have observed impacts associated with ingestion of microfibers by zooplankton, microfibers may also have adverse impacts due to external physical damage.

There are few studies on the impacts of microfiber exposure on fish (Grigorakis et al., 2017; Hu et al., 2020; Jabeen et al., 2018). Grigorakis et al. (2017) found that retention times for microfibers ingested by *Carassius auratus* (goldfish) were relatively low, but a study by Jabeen et al. (2018) found that chronic exposure to microfibers caused inflammation in the liver, intestines, and jaws of goldfish. Another study found that exposure to microfibers resulted in changes to the cells and tissues of the branchial chamber and gills of the Japanese medaka (Hu et al., 2020). A study by Seeley et al. (2023) investigated the effects of co-exposing microplastics with a virus in a salmonid trout species. Microplastics alone did not induce mortality in fish, however, mortality increased when microplastics were co-exposed with the virus (compared to the virus alone). Nylon microfibers co-exposed with the virus were found to induce the highest rates of mortality. Researchers hypothesize that the fibers damaged the fish tissue, allowing the virus to enter and bypass the fish's defenses (Seeley et al., 2023).

Several studies of the effect of microplastics on aquatic biota have suggested that microfibers may be more toxic to some species than other microplastic morphologies (e.g., spheres, fragments). This could be due to differences in retention time, accumulation rate, and physical damages resulting from the particle shape (Jemec et al., 2016; Qiao et al., 2019), but because of differences in experimental setups, it is difficult to compare results between studies. For example, Qiao et al. (2019) found that in zebrafish exposed to microplastic beads, fragments, and fibers, fibers accumulated in the gut more than the other shapes. The accumulation of fibers resulted in toxic effects in the intestines, including reductions in mucus volume in the gut, increased intestinal permeability and inflammation, and alterations to gut microbiota (Qiao et al., 2019). Similarly, multiple studies on microplastic toxicity in *Hyalella azteca* (freshwater amphipods) found that fibers were more toxic than other microplastic shapes, with the ingestion of microfibers resulting in significantly less growth (Au et al., 2017) and increased mortality (Gray & Weinstein, 2017). In a study on *Ceriodaphnia dubia* (water flea), Ziajahromi et al. (2017) found that microplastic fibers posed a greater risk than microplastic beads, with exposure to microfibers resulting in decreased body size and reduced reproductive output. However, in contrast to these studies, multiple studies on *Daphnia magna* (water flea) found that spherical microplastics were more harmful to daphnids than fibers and other shapes (Jaikumar et al., 2019; Schwarzer et al., 2022). The effects of various microplastic morphologies on biota are dependent on a wide range of factors, including the polymer type used and species studied.

Most toxicological studies have been conducted under laboratory conditions, many of which exposed biota to microplastics and microfibers at concentrations considerably higher than the average reported environmental conditions. In some instances, these high concentrations of microplastics may be encountered in heavily polluted areas (Rebelein et al., 2021). Furthermore, existing sampling and analytical methods commonly applied likely underestimate the prevalence of microfiber pollution, and further research on the concentrations of microfiber pollution in various environmental compartments is needed to inform laboratory studies on impacts (Athey & Erdle, 2022).

Impacts on Terrestrial Soil and Biota

Terrestrial species are exposed to microfibers through ingestion and inhalation, though terrestrial ecosystems have received far less attention from scientists studying the impacts of microfibers than aquatic ecosystems (de Souza Machado, Kloas, et al., 2018). Studies have found microplastic particles (including microfibers) in birds, mammals, invertebrates, and insects (Eriksen et al., 2021; Prendergast-Miller et al., 2019). The range of negative health effects of microplastics observed in terrestrial species include altered feeding behaviors, reduced growth, and reduced reproduction (Prendergast-Miller et al., 2019; Selonen et al., 2020; Song et al., 2019).

Few studies have examined the impacts of microfibers on soil biota. One study on snails showed that prolonged exposure to polyethylene terephthalate (PET) microfibers did not cause mortality, but did inhibit food intake and excretion, cause damage to gastrointestinal tissues, and induce oxidative stress in snails (Song et al., 2019). In soil-dwelling earthworms, organisms that are critical for maintaining healthy soils, physiological changes and changes in casting behavior have been observed following exposure to microfibers (Prendergast-Miller et al., 2019). Selonen et al. (2020) studied the effects of polyester fibers in three soil invertebrates, finding that exposure to microfibers had slight effects on isopods (reduced energy) and enchytraeids (reduced reproduction). Their findings suggested some negative effects observed in soil biota may be attributed to physical and chemical changes to the environment resulting from the presence of microfibers, rather than the ingestion of microfibers (Selonen et al., 2020).

Scientists have also begun investigating the possible ways in which microplastics (including microfibers) in soil affect ecosystem functions, including litter decomposition, soil aggregation, and nutrient cycling (Rillig et al., 2019). In a study on the effects of microplastics (including microfibers) on soil, de Souza Machado, Lau, et al. (2018) found that microfibers lead to increased water holding capacity of the soil (polyester fibers), decreased soil bulk density, decreased water stable aggregates, and changes that might affect soil functions and plant growth (polyester and polyacrylic fibers). Similar findings were reported by Liang et al. (2019), who found that microfibers tended to reduce the percentage of water stable aggregates in soil. Further research is needed to understand how microfiber pollution of various types of soil might affect soil chemistry, structure, and function (de Souza Machado et al., 2019; Lozano et al., 2021).

Recent studies have also begun to investigate the interactions between microfibers and plants. Plants are heavily dependent upon the community of biota present in soils, and potential alterations to soil structure due to the presence of microfiber pollution might alter the microbial communities in soil (Rillig et al., 2019). De Souza Machado et al. (2019) found that spring onions exposed to polyester microfibers in soil had significantly higher average root biomass (about 40% increase on average), which the authors hypothesize to be a result of the observed changes to soil structure described above (i.e., changes to soil bulk density, soil aggregation, and water dynamics). Exposure to microfibers also resulted in significant decreases in nitrogen content in leaves. Boots et al. (2019) observed that microfiber pollution in soil led to decreased seed germination in perennial ryegrass but had no effects on shoot height and biomass of the ryegrass. These studies found that the impacts of microplastics and microfibers on plants are highly variable, depending on polymer type, shape, and size (de Souza Machado et al., 2019).

There is research indicating that fibers are the most prevalent shape of microplastics and nanoplastics found in soils. Furthermore, there are studies indicating that plants can uptake microplastics and nanoplastics. However, there is not much data demonstrating the uptake of each of the various forms (including fibers) of microplastics/nanoplastics by terrestrial plants (Zhang et al., 2022).

Impacts on Humans

The potential effects of microfiber pollution on human health is unknown. This presents a major research gap that limits the ability of decision-makers to determine the extent to which regulatory or other interventions are necessary for protecting human health (Noventa et al., 2021). Microfibers can enter the human body through ingestion (via contaminated food and water) and inhalation (Campanale et al., 2020; Catarino et al., 2018; Prata, 2018). Incidental ingestion of microfibers that have settled from indoor air and dust into food and drink or onto food contact surfaces may be another important exposure pathway for microfibers to enter human bodies (Catarino et al., 2018). Existing research suggests that microplastics (including microfibers) have the potential to impact human reproductive, respiratory, digestive, nervous, and urinary systems (Campanale et al., 2020 (and citations within); D'Angelo & Meccariello, 2021; Palacios-Mateo et al., 2021). However, there are presently insufficient research data to draw conclusions about the toxicity of microfibers to humans.

The toxicity of microfibers and other particles ingested by humans is dependent upon a wide variety of physical and chemical properties of the particle, including its size, morphology, polymer composition, and added or sorbed chemicals. There is little research on the fate, transport, and toxicity of microfibers and microplastics that are ingested by humans (Marsden et al., 2019). There is also little known about the degree to which humans are exposed to microfibers through ingestion.

Growing concern about the potential for human ingestion of microplastics via drinking water prompted the World Health Organization to develop an evaluation of the human health risks associated with microplastics in drinking water. In the World Health Organization report on microplastics in drinking water (Marsden et al., 2019), the authors highlight the urgent need for additional research on human exposure to microplastics (including microfibers) in drinking water and the potential related health risks. They conclude that "based on the limited evidence available, chemicals and microbial pathogens associated with microplastics in drinking water pose a low concern for human health" and "no data suggests overt health concerns associated with exposure to microplastic particles through drinking water" (Marsden et al., 2019).

The toxicity of inhaled particles has been the subject of relatively more research than that of ingested particles (Marsden et al., 2019). One study found both non-plastic manufactured (cellulosic fibers) and manufactured plastic microfibers in lung tissue taken from patients with various types of lung cancers, demonstrating that some microfibers may have the capacity to penetrate lung tissues (Pauly et al., 1998). Studies have also found that plastic manufactured microfibers can persist for long periods of time in synthetic lung fluid (Law et al., 1990; SAPEA, 2019). Smaller airborne microfibers have been shown to be more prevalent in the air compartment (Gasperi et al., 2018) and can be more readily inhaled deeper into the respiratory tract (Pauly et al., 1998; Vianello et al., 2019). These findings are consistent with studies on toxicity of asbestos and other elongate mineral particles, which have found that thin fibers tend to accumulate in the lower lung at higher rates than thick fibers (Zarus et al., 2021).

A literature review by Zarus et al. (2021) summarizes existing research on occupational exposure to microplastics and nanoplastics and the associated hazards for workers in the flocking (applying short fibers to a surface for surface texture), fiber manufacturing, and textile manufacturing industries. Studies have found that occupational exposure to high concentrations of polyester and/or nylon microfibers may lead to higher risk of respiratory irritation (SAPEA, 2019). A unique type of interstitial lung disease has occurred in workers in three different nylon flock plants, in which high concentrations of inhalable nylon fibers were found in workplace air samples (Burkhart et al., 1999; Warheit et al., 2001). In a study that used synthetic lung tissue to simulate the impact of polyester and nylon microfibers on the human lung, van Dijk et al. (2021) found that both polyester and nylon microfibers negatively affected the growth and development of human and mice lung organoids, with nylon being the most harmful due to leaching of chemical additives. Already established lung organoids, however, were not affected by microfiber exposure in this study.

In addition to reported respiratory effects associated with inhaling microfibers, occupational studies also reported increased risk of colorectal cancer (De Roos et al., 2005; Vobecky et al., 1984; Zarus et al., 2021) among textile workers. Reports of colorectal cancers and respiratory illnesses among fiber and textile workers suggest that chronic inhalation of microfibers may increase the risk of a variety of illnesses, but concentrations of airborne microfibers in workplace studies are much higher than levels measured in household and outdoor air (Zarus et al., 2021). Further research on human exposure to microfibers as well as uptake and absorption of microfibers is critical to understanding the health risks associated with microfiber pollution.

Though the toxicological hazards associated with microfibers, particularly the impacts to humans, remain largely unknown, their persistence, prevalence in the environment, and the lack of feasible cleanup options are reasons for concern (Brander et al., 2020; Coffin et al., 2021). Citing the irreversible nature of plastic contamination in the environment, the European Commission classified microplastics (which includes microfibers) as a “non-threshold contaminant” (i.e., “any release to the environment and environmental monitoring data regarded as a proxy for an unacceptable risk”) (ECHA, 2020). In addition, the Regional Monitoring Program for the San Francisco Bay, a collaborative effort among regulators, dischargers, and scientists, recently elevated microplastics to “Moderate Concern” status, with scientists recommending the need for investigations that will inform microplastic pollution mitigation efforts (Sedlak et al., 2019). Evidence of exposure and toxicity of microfibers to humans is evolving quickly, and the state of California is moving forward with regulatory efforts concerning microplastics (including microfibers) in drinking water. While more research is needed to fully understand the effects of microfibers, some researchers have recommended a precautionary approach to managing microfibers (Brander et al., 2020; Coffin et al., 2021).

V. RECOMMENDATIONS FOR A STANDARDIZED METHODOLOGY TO MEASURE AND ESTIMATE THE PREVALENCE OF MICROFIBER POLLUTION

Research on the sources, prevalence, causes, and impacts of microplastics, including microfibers, has increased rapidly over the last decade with minimal harmonization between projects, resulting in diverse study designs, sampling and analysis methods, and reporting practices (Athey & Erdle, 2022; Brander et al., 2020; Cowger, Booth, et al., 2020).

Athey and Erdle (2022) reviewed existing microfiber research in an effort to identify research gaps, challenges, and best practices. The review shows a high degree of variation across project design and methods that are used to analyze microfibers in environmental matrices. One of the most significant challenges identified was the lack of a standard definition for "microfiber." Many of the studies stress the need to consider a definition for "microfiber" that includes fibers consisting of treated natural, non-plastic manufactured, and plastic manufactured materials (Athey & Erdle, 2022). With varying definitions, it is difficult to compare results across studies and draw definitive conclusions necessary for informing microfiber pollution control and mitigation measures. In addition, the review highlighted the wide variety of methods used to collect and analyze microfibers, highlighting that field methods are in early stages of development for many environmental compartments, such as air, soil, groundwater, snow, and ice.

Recently, microplastic experts have collaborated to develop guidelines and best practices for microplastics research, many of which are applicable to research on microfibers (Cowger, Booth, et al., 2020; GESAMP, 2019; Lusher et al., 2020; Provencher et al., 2020). These guidelines help to ensure that scientific studies are comparable and reproducible, thus building confidence in results and conclusions (Brander et al., 2020; Cowger, Booth, et al., 2020). However, there is an urgent need to establish standardized (same procedures are used) and harmonized (different procedures may be used as long as results data can be compared) methods for microfiber research in order to ensure robust scientific results, develop environmental quality criteria, and assess the effectiveness of future mitigation strategies (AMAP, 2021; Cowger et al., 2021; Provencher et al., 2020). Since microfiber pollution is found in all environmental compartments and requires a wide range of field, lab, and even remote methods, standardized methods may be difficult to develop in a reasonable timeframe for all compartments. Developing guidance to harmonize research methodologies is therefore an important short-term priority to be pursued in concert with the longer-term priority of developing standardized methods.

The following sections will provide an overview of research methods used by the environmental and textile science communities to study the occurrence of microfiber pollution. Recommendations for establishing a standardized methodology for the growing field of microfiber pollution research are described at the end of this section.

A. Design of Microfiber Studies

The scientific community is encouraging harmonization among studies as new projects are designed. Harmonization allows projects to be designed to be comparable and reproducible and encourages incorporation of standardized methods that include stringent QA/QC measures.

Reporting and Comparability Between Studies

Comparability between scientific studies is essential to form a complete understanding of microfiber pollution and its environmental impact. Issues related to comparability and reproducibility are a challenge for any new field of research and can result when studies report insufficient details relating to methods and results. Detailed information should be provided for the sampling environment (e.g., meteorological conditions, depth, salinity, sediment deposition rates, water flow rates), characteristics of the sample matrix (e.g., water content, porosity, sediment grain size, organic matter content), and reporting terminology (e.g., definitions, units, and metrics). Not only do these details aid in comparability between studies, but they are also necessary for informing microplastic and microfiber modeling studies. These details improve the interpretation and utility of microfiber pollution studies and should be considered during the design phase, as well as the reporting/publishing and review phases (Cowger, Booth, et al., 2020).

The unit of measurement for microfiber release often varies across studies, making comparisons among studies that use different metrics a challenge. Microfiber release is most often quantified by either counting the number of microfibers or measuring the mass released (Tiffin et al., 2022). Counting microfibers is a time-consuming approach and most studies require subsampling, where microfibers are counted on a selected area of the filter containing the entire sample (De Falco, Gullo, et al., 2018; Napper & Thompson, 2016) or within a small portion of the entire sample (Athey et al., 2020; McIlwraith et al., 2019) and extrapolated. As mentioned before, this approach assumes homogeneous distribution of microfibers on the filter and/or within the sample, which may not always be true or possible to obtain. Some studies avoid counting and instead quantify microfibers by weight (Kelly et al., 2019; Pirc et al., 2016). Both methods can be time-consuming. Future research should aim to standardize reporting of results in accordance with harmonized methods (Cowger, Booth, et al., 2020), including both weight and count data, when possible, and should always report the size range of particles identified.

Furthermore, the size range of microfibers analyzed often varies between projects. A standardized definition of microfiber may help relieve some of the issues related to this common problem.

Quality Assurance and Quality Control Measures

Because microfibers are so prevalent in indoor and outdoor spaces, they can contaminate research spaces, during both field sampling and lab analysis (Song et al., 2021; Woodall et al., 2015). Sources of contamination include ambient air and dust, sampling equipment, laboratory supplies (e.g., wipes and towels), researcher clothing (e.g., sampling attire), and personal protective equipment (PPE; e.g., face masks, laboratory coats). While research suggests that ambient microfiber contamination is generally low (Scopetani et al., 2020; Song et al., 2021; Wesch et al., 2017), it is essential that robust QA/QC measures are taken in an effort to reduce potential contamination in microfiber studies (Brander et al., 2020; Cowger, Booth, et al., 2020; Woodall et al., 2015). Brander et al. (2020) suggest several QA/QC measures for various stages of a project, including sample collection as well as laboratory processing, and consider inclusion of blanks, multiple controls, standard reference materials, and matrix spikes to evaluate and control for bias introduced by background levels of microfiber contamination.

Monitoring and minimizing microfiber contamination in research spaces, in the field, and in the laboratory is essential for producing accurate data on microfibers. This includes studies that aim to assess the sources of microfibers to the environment, as well as studies that monitor environmental levels. Adopting and adapting techniques from other fields (e.g., forensic fiber analysis, environmental chemistry) can be useful for developing QA/QC procedures (Rochman et al., 2019; Woodall et al., 2015). Brander et al. (2020) proposed three approaches for reducing microplastic and microfiber contamination. The first approach involves the implementation of good field and lab practices that minimize contamination in the research space. Laboratory processing and testing should be conducted in a space that is cleaned regularly. Microfibers can be present in air, dust, chemical reagents, and water used in laboratory processing, as well as released from the clothing and PPE of research personnel. Reducing the amount of microfiber contamination during laboratory testing could involve minimizing the number of study personnel in the space during testing. While not accessible to all laboratories, air filtration units (e.g., HEPA filters) and clean hoods or benches have been found to significantly decrease microfiber contamination (Wesch et al., 2017). Because normal wear of clothing can shed microfibers to air (De Falco et al., 2020), many research groups have adopted the practice of wearing white 100% cotton lab coats over clothing when working with samples (Avio et al., 2020; Hamilton et al., 2021; Woodall et al., 2015). However, with the increasing interest in studying natural fibers in environmental samples, white 100% cotton lab coat fibers may be hard to distinguish from the sample fibers. For this reason, some researchers have started wearing lab coats and PPE in colors that are not typically documented in the environment (e.g., bright pink, orange, purple). Regardless of what is worn, researchers should maintain careful notes of the color and polymer material type of fabrics worn by study personnel so that they can be compared to sample fibers. Furthermore, researchers should strive to wear the same attire when processing samples and blanks. Care should also be taken to reduce the amount of fibrous materials used around samples (e.g., wipes, paper towels). All materials and surfaces should be cleaned before use (Song et al., 2021). Samples, supplies, and reagents should remain covered throughout processing to avoid microfiber deposition from air.

Another approach to microfiber contamination is monitoring potential sources of contamination (Brander et al., 2020) so that they might be accounted for. Because microfibers are ubiquitous in sampling and research environments, it is important to monitor background levels of contamination in air, chemical, and water sources. Inserting a non-shedding filter to water sources may reduce microfiber contamination (Woodall et al., 2015). Use of procedural blanks, matrix blanks, and field blanks are important for monitoring microfiber contamination during sample collection and processing. Blank samples are samples collected alongside project samples to understand if there are any microfibers entering the samples from another source (e.g., shedding from researchers' clothing, fibers from atmospheric deposition, fibers from a dirty ventilation system). Final values of microfibers can be corrected for background contamination recorded by blanks. Blank correction methods are not standard across studies and should be described in detail in final reporting (Adams et al., 2021; Athey et al., 2020).

Procedural blanks can be used to determine the limit of detection, which here is defined as the lowest concentration at which microfibers can be reliably identified in a sample apart from background contamination. Methods for determining the limits of detection from procedural blanks are not standardized within the microplastics field and remain a challenge given the diversity of particle characteristics (Brander et al., 2020; Primpke et al., 2019; Rochman et al., 2019; Wong & Coffin, 2021).

Other QA/QC practices that are commonly employed in the environmental chemistry field could be applicable to the study of microfibers in the environment. This includes interlaboratory testing, in which multiple, independent research groups test the same method and samples. Following testing, the groups then compare the results in an effort to understand the reproducibility of the method and assess the performance of individual research groups. Only recently has interlaboratory testing been conducted using microplastics, including fibers (Tiffin et al., 2022; Tsangaris et al., 2021; van Mourik et al., 2021). An ongoing interlaboratory project is being carried out by the State of California Water Resources Control Board, California Ocean Protection Council, University of Toronto, Southern California Coastal Water Research Project, and HORIBA Inc. to build best practices for sampling, extraction, and analysis (De Frond et al., 2022).[9] As research on microfiber pollution grows, interlaboratory testing will be important for development and standardization of methods. Standard procedures for conducting interlaboratory testing exist and can be used to facilitate these studies, including ASTM-E691-18 (Heyes, 2018) employed by Tiffin et al. (2022) to assess a method for measuring microfiber release from textile washing.

Another important consideration is replication. Replicate samples should be collected in the same way within the sample site as primary samples. Replication can be used to evaluate sampling precision and environmental variability. The exact number of replicates that are used should be based on the abundance and diversity of microplastics present, as well as variability between samples (Brander et al., 2020).

B. Field Sample Collection

As discussed in Section IV, microfibers are prevalent in many different environmental compartments, ranging from the deep ocean to wastewater to air. For all compartments, the field methods for sampling microfibers are evolving, and for many environmental compartments, there are no standardized methods for collecting samples for measuring microfiber prevalence. The remainder of this section lists trends and research needs identified in recent literature. The end of the section includes a summary table, Table 4, that describes the available methods used to analyze microfibers in different compartments and provides the key considerations, including important research gaps, identified in the research.

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[9] This article is part of a *Chemosphere* Special Issue on "Informing methods for detecting and quantification of microplastics through the lens of a global intercalibration exercise." More information can be found here: www.sciencedirect.com/journal/chemosphere/special-issue/1028DWKF0HR.

Ocean, Estuaries, Rivers, and Lakes

Most of the early studies on microplastic contamination in the surface waters of ocean, estuaries, rivers, and lakes employed a piece of equipment called a manta net, which is a modified neuston net (mesh size typically >300 μm). Neuston and bongo nets have also been used in surface waters and the water column, respectively. Microfibers were collected in the nets during these early microplastics studies, most of which were not focused specifically on microfibers; more recently, studies have shown that using large mesh nets leads to an underestimate of microfiber prevalence due to the narrow diameter of the fibers and their ability to pass through the mesh (Barrows et al., 2017; Hung et al., 2021; Lindeque et al., 2020; Miller et al., 2021). Approximately one third of the studies examining microfibers in surface waters employed the use of coarse mesh nets (>300 μm) and, therefore, underestimated microfiber concentrations due to insufficient capture (Athey & Erdle, 2022).

Bulk water sampling methods have been used to collect and enumerate microfiber concentrations in surface waters and more recently throughout the water column. These include grab samples, either using a container (e.g., sample jars, buckets, or bottles) or water pumps to collect water samples (Brander et al., 2020; GESAMP, 2019; Sedlak et al., 2017; Sutton et al., 2019). Collected water samples are then filtered (via mesh nets, sieves, filter paper) to extract microfibers in the field or lab for further analysis (Brander et al., 2020; GESAMP, 2019; Sedlak et al., 2017; Sutton et al., 2019). The lower limit of detection for bulk water sampling is dependent on the mesh sieve or filter size used (on the vessel or in the lab) to process the water samples.

Sampling techniques are advancing quickly with the aim of improving the accuracy of microfiber capture methods. Recent research suggests that bulk water sampling (grab samples or pump) provides a more representative sampling of microfibers than traditional net-based methods (Hung et al., 2021; Karlsson et al., 2020; Tamminga et al., 2019). Furthermore, research suggests that higher volume samples of water are less affected by spatial heterogeneity of microfibers compared to small volume samples (Felismino et al., 2021; Huntington et al., 2020). The volume of water required to obtain a representative microfiber sample likely varies depending on the sampling environment and ambient microfiber levels. In 2020, ASTM (formerly known as the American Society for Testing and Materials) developed a standard for "Collection of Water Samples with High, Medium, or Low Suspended Solids for Identification and Quantification of Microplastic Particles and Fibers," which suggests collecting 1,500 liters, most easily collected using a pumping system (ASTM D8332-20, 2020).

While there are several studies investigating microfiber concentrations in surface waters, only within the past few years has there been an increase in studies collecting microfibers within the water column. Pump sampling and Niskin bottles may be deployed to collect bulk water samples throughout the water column (Barrows, 2017; GESAMP, 2019; Martin et al., 2018).

Beaches, Sediments, and Soils

Field methods used to determine microfiber concentrations in sediment or soils depend on the sampling environment. For intertidal sediment (e.g., sandy beaches, muddy shorelines), grab samples are typically collected along transects using glass jars or stainless-steel buckets and metal spoons or shovels (Deng et al., 2020; Frias et al., 2018; GESAMP, 2019; Whitmire et al., 2017). Terrestrial soils are also commonly collected using this method (Ambrosini et al., 2019; Amrutha & Warrier, 2020; Piehl et al., 2018; Zhou, Wang, et al., 2020).

Subtidal sediment sampling is more challenging and involves the collection of material that has deposited on the bottom of a water body, including lakes and oceans. Methods vary depending on accessible equipment and environment (e.g., shallow lake versus deep sea) and include box corers, Ekman dredges, Van Veen grab samplers, and even remotely operated vehicles (Adams et al., 2021; Athey et al., 2020; Frias et al., 2018; Whitaker et al., 2019). In these methods, one large grab or core of sediment is collected and brought to the surface, where it is subsampled for microplastic and microfiber analysis.

Air

Studies of microfiber concentrations (and microplastics) in air are relatively rare. There are two main approaches for sampling microfibers in air, including filtering a volume of air or collecting microfibers that settle onto surfaces (Constant et al., 2020; Dris et al., 2017; Zhang, Kang, et al., 2020). Most studies that have sampled microfibers in air have focused on outdoor air (Brander et al., 2020; Dris et al., 2016; Kaya et al., 2018; Prata et al., 2020). Few studies analyze microfiber deposition in indoor air, though sampling techniques may be similar to those used in an outdoor environment (Athey & Erdle, 2022; Dris et al., 2017; Vianello et al., 2019; Zhang, Kang, et al., 2020). An evaluation of methods for detecting other airborne contaminants may be helpful in developing appropriate methodologies for detecting airborne microfibers.

Wastewater, Sludge, and Stormwater

Although microfibers in wastewater effluent have been studied more than stormwater and sewage sludge, there is no standardized method for sampling wastewater (Athey & Erdle, 2022). Access to wastewater facilities and sampling points heavily impacts sampling timing and approach. The existing studies use similar methods to collect and filter effluent water, wastewater that has been treated and will be discharged into the environment (Athey & Erdle, 2022; Habib et al., 2020; Mason et al., 2016; Sedlak et al., 2017). Generally, the accepted sample collection method includes filtering effluent through a series of sieves, with grab and time composite sampling as options (ASTM D8332-20, 2020). The volume of effluent required for an accurate sample varies based on the study design and objectives.

In addition to wastewater effluent, influent waters and overflow wastewater from combined sewer overflow events[10] are important points to measure to accurately estimate microfiber capture and discharge by wastewater treatment plants and understand sources of microfiber pollution. Options for sampling combined sewer facilities include using bulk sampling that is collected by repeated grab sampling or a pump system (Brander et al., 2020). Very few studies have been conducted specifically looking at microfibers in influent waters and combined sewer overflow events.

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[10] Combined sewer overflow events usually occur during larger rain events where wastewater enters the environment untreated (see Conley et al., 2019).

Brander et al. (2020) discussed guidelines for sampling microplastics in wastewater that should be applied to microfiber sampling in effluent and influent wastewater matrices. If the goal is to understand microfiber transport during peak flows, grab samples or flow-paced samples may be strategic. If there is a need to calculate daily microfiber loads, it may make more sense to collect 24-hour composite samples (Brander et al., 2020). The flow rate and duration of sample collection should be documented, allowing loads to be calculated (Brander et al., 2020).

Biosolids (sewage sludge that has been treated for land application, mainly from activated sludge treatment processes) are typically collected as a grab sample using buckets or, if dewatered, shovels (Lares et al., 2018; Xu et al., 2020). Very few studies have been conducted analyzing microfibers in biosolids; however, the recent publication by Geyer et al. (2022) quantified plastic microfiber pollution from biosolids in California, along with other pathways.

The few available studies analyzing microplastics and microfibers in stormwater discharge have identified stormwater as a transport pathway for microfibers (Grbić et al., 2020; de Jesus Piñon-Colin et al., 2020; Liu et al., 2021; Sutton et al., 2019; Zhu et al., 2021). Stormwater systems vary greatly between project areas and should be clearly described to allow for comparisons between project areas.

The methods used to analyze microplastics and microfibers in stormwater vary between studies, with some of the most recognizable differences being the equipment used, volumes collected, and the location and timing of sampling. Treilles et al. (2021) carried out a study in the greater Paris area that suggested that microfiber concentrations do not vary throughout a storm event, which is what is typically seen with macroplastics and other microplastics. Typically, macroplastics and microplastics respond to storm events, where the highest concentrations are seen just before the peak flow of a rain event (Treilles et al., 2021). Sampling storm events can be challenging, logistically and physically, adding to the complexities of field work in the stormwater pathway (Baldwin et al., 2016; Liu, Olesen, et al., 2019; Sutton et al., 2019).

Drinking Water and Food

Most studies use similar field sampling methods to assess microplastics and microfibers in drinking water. A literature review prepared by the World Health Organization identified nine studies looking at microplastics in drinking water, both tap and bottled (Marsden et al., 2019). The most prevalent variation in field methods used were the volume of water filtered for each sample and the QA/QC efforts related to the project (Koelmans et al., 2019). More research should be conducted to inform standard methods for consistency across studies.

The California State Water Board has developed two standardized methods to analyze microplastic concentrations (including microfibers) in drinking water using Raman or infrared spectroscopy (Wong & Coffin, 2021). The methods were mandated by law to be developed by July 1, 2021, and will be tested for 4 years, during which microplastics concentrations will be reported (California State Water Resources Control Board, 2020). The California State Water Board is also developing standardized methods for sediment, fish tissue, and ocean water, in partnership with the Southern California Coastal Water Research Project (Langknecht et al., 2023; Thornton Hampton et al. 2023).

The Save Our Seas 2.0 Act, pursuant to Section 304, mandates that the EPA enter into an agreement with the National Academies to conduct a "Study on Effects of Microplastics in Food Supplies and Sources of Drinking Water." Section 304 specifically states that risks from microfibers in food and drinking water be evaluated, and that "recommendations for standardized monitoring, testing, and other necessary protocols" be included in the study.

Biota

Most microfiber studies on marine, freshwater, and terrestrial biota have focused on measuring ambient levels of microfibers in the tissues of invertebrates and fish that are typically eaten by humans (Dehaut et al., 2016; Rochman et al., 2015). The collection methods for biota vary widely depending on the sampling habitat and target organism, as well as the general research question being investigated. Typically, upon capture, either the entire organism or select tissues are transported to the laboratory and preserved frozen until further analysis (e.g., microfiber enumeration described in Section V.C.2). For example, studies measuring microfiber contamination in macrofauna have generally focused on select organs for examination, primarily the gastrointestinal tract and muscle tissue (Philipp et al., 2022; Rochman et al., 2015), while studies on microfauna and flora typically measure microfiber contamination within the whole organism (Absher et al., 2019; Mahara et al., 2022). As for other environmental matrices, replicate samples or specimens collected at each site are required for robust sampling (Brander et al., 2020). In addition, species' known activities and behaviors (e.g., feeding behavior, nesting sites, migratory patterns) need to be taken into consideration when designing the study and sampling plan (GESAMP, 2019).

Groundwater, Ice, and Snow

Over the last 2 years, microfiber research in groundwater, ice, and snow has been expanding. To date, there are still only a handful of studies on microfibers in groundwater (Bharath et al., 2021; Chia et al., 2021; Huang et al., 2021; Kumar and Sharma, 2021; Mintenig et al., 2019; Panno et al., 2019; Samandra et al., 2022; Selvam et al., 2021), all showing that microfibers are the dominant microplastic type found in groundwater samples. The methods used to sample groundwater vary throughout the studies and it is recognized that standardization is needed in the field (Huang et al., 2021). Most studies access groundwater through groundwater wells or household and public taps, but there is little harmonization between studies on the project design and volumes analyzed (Huang et al., 2021).

The methods for snow and/or ice collection and analysis are similar across all studies. These involve collecting low volumes of snow (1 to 4 liters) in glass or stainless-steel containers using a metal spoon (or drill for ice), then melting the sample at room temperature and filtering out the microfibers. Typically, results are reported as the number of fibers per liter. Because little information has been reported on the physical characteristics of the snow collected (e.g., snow-water equivalent, snow depth, and density), comparisons between studies are difficult (Kinar & Pomeroy, 2015).

Table 4. Summary of methods and key considerations related to microfibers for each environmental compartment.

Compartment	Methods
Surface waters and water column	Manta trawl, neuston and bongo nets
	Bulk sampling (grab samples and pumps)
Beaches, benthic sediment, and soils	Grab samples
	Box corers, Ekman dredge, Van Veen grab sampler, and remotely operated vehicles
Air (outdoor and indoor)	Filtration and surface deposition sampling
Wastewater, sludge, and stormwater	Bulk samples (pump and grab samples) for liquids
	Grab samples for solids
Drinking water and food	Bulk sampling (grab samples, pump, tap filtration)
	Store bought, purchased from local producers, fishermen
Biota (Species sampling (organs, tissue, and/or entire animal))	Collected via net, trap, trawls, hook & line
	Purchased at markets or from fishermen
Groundwater, ice, and snow	Bulk samples (grab samples, tap filtration)
	Stainless steel corer (ice), bulk samples (snow collection with stainless steel spool/ladle)

Key Considerations

- More investigation and further method development are needed in understudied compartments (e.g., air, influent waters (wastewater entering a treatment plant), overflow wastewater from combined sewer overflow events (usually larger rain events), sludge, and stormwater sampling).
- Additional research is needed to develop the most robust standardized methods and guidelines to confidently measure microfibers within individual environmental compartments (especially those understudied compartments). Consideration for sampling volume (especially for bulk sampling) is essential for ensuring accurate representation of ambient microfiber levels in drinking water and other water compartments (e.g., surface water, water column, wastewater, stormwater, groundwater).
- Robust QA/QC practices are essential for confidently measuring microfiber contamination.
- Lack of standardized methods and harmonized reporting makes it difficult for cross-study comparison needed to improve the understanding of microfibers in field settings.

C. Laboratory Methods

To fully understand the characteristics of microfibers found in the environment, a range of laboratory methods is used to determine the composition of microfibers found in the environment. Table 5 lists the most common laboratory techniques used to characterize and enumerate microfibers from field samples and includes key considerations where the research gaps and trends are identified.

In past research on the prevalence and impacts of microfiber pollution, many studies have focused solely on plastic manufactured fibers (i.e., synthetic fibers). The exclusion of non-plastic fibers (e.g., man-made cellulosic fibers and/or treated natural fibers) can be attributed to different factors. For example, many methods used to enumerate and characterize microfibers in environmental samples were designed for the recovery of plastic materials and are not suitable for non-plastic fibers (Athey & Erdle, 2022). Considerations are provided in this section for extracting and characterizing both plastic and non-plastic microfibers.

Techniques for Characterizing Microfibers

There are generally two main ways in which plastic and non-plastic particles (including microplastics and microfibers) found in environmental media are characterized: morphology (i.e., size, shape, color) and chemical composition (i.e., polymer, additives, dyes) (Athey & Erdle, 2022; Zhu, Nguyen, et al., 2019). Characterization of microfiber morphology is typically conducted visually through optical microscopes (magnification), whereas chemical composition is determined using spectroscopy. Spectral analysis is conducted by comparing absorption and emission patterns of an unknown material with known materials. Common spectroscopy techniques include Raman spectroscopy and Fourier-transform infrared (FTIR) spectroscopy (Athey et al., 2020; Zhu, Nguyen, et al., 2019). Approximately 98% of studies that employ spectroscopic techniques for identifying polymer composition of microfibers use FTIR or Raman spectroscopy (Athey & Erdle, 2022). Other methods include pyrolysis-GCMS (gas chromatography/mass spectrometry). However, pyrolysis-GCMS is less common as it requires destruction of the particle to determine polymer composition, as well as mass of the particle analyzed.

FTIR and Raman spectrometers compare spectra (bands of colors produced by separation of the components of refracted light) collected on a sample fiber to a library of reference spectra of known polymers. FTIR spectroscopy works by shining light at the particle and measures the wavelengths of infrared light absorbed. Raman spectroscopy measures the energy that is scattered after the particle is excited by a laser. Because of the technical challenges in analyzing microfibers, (e.g., incorrect library matches between similar materials such as rayon and cotton, low signal intensity of natural fibers, signal interference by chemical additives and dyes), it is recommended that researchers use multiple lines of evidence (i.e., morphology) to support the spectral identification of fibers (Athey & Erdle, 2022; Munno et al., 2020), in addition to shared spectral databases built specifically for the analysis of microplastics (including fibers) (Cowger, Booth, et al., 2020; Cowger et al., 2021). Weathered microfibers should also be considered and included in spectral libraries to better understand, quantify, and characterize environmentally relevant particles.

Zhu, Nguyen, et al. (2019) explain that typical spectroscopic methods are often challenging to use on microfibers due to their small width and because they often contain dyes and/or are polymeric composites. In addition, the high cost and time-consuming nature of spectroscopic techniques has led researchers to explore other methods to distinguish between plastic manufactured particles and those naturally present in the environment (treated natural and non-plastic manufactured particles).

An approach used by Maes et al. (2017) employs fluorescent staining to identify microplastics in marine sediment samples. Fluorescent dyes applied to the samples bind to plastic surfaces, rendering microplastic particles detectable under a microscope. Zhu, Nguyen, et al. (2019) developed a low-cost, multi-step method that uses polymer-dye binding chemistry, density tests, unique surface morphological traits, and fluorescent staining to identify the polymer types of microfibers in environmental samples. However, both methods are limited in their accuracy, affected by weathering and/or biofouling of the particles (Maes et al., 2017; Tamminga et al., 2017; Zhu, Nguyen, et al., 2019). Additional research should assess the applicability of lipophilic staining for rapid detection and quantification of plastic manufactured fibers (Catarino et al., 2018; Devalla et al., 2019; Prata et al., 2020; Stanton et al., 2019). Zhu, Nguyen, et al. (2019) also discuss the need to better understand the dyes that are typically used on textiles, which would make identification in the lab quicker and more reliable.

Another method occasionally used by researchers to identify microplastics is a "hot point test (or hot needle test)," in which researchers touch particles to a hot needle using tweezers. Microplastics can be visually identified based on their response to contact with the hot needle. (Kapp & Yeatman, 2018; Karlsson et al., 2017; Vandermeersch et al., 2015). The hot needle method is a low-cost way to verify manufactured (synthetic) microplastic particles but cannot identify microplastics by polymer type (Kapp & Yeatman, 2018). Overall, more research is needed to develop reliable low-cost methods to characterize microfibers.

Microfiber Enumeration Methods

Methods for enumerating microfibers in environmental media are numerous and diverse, showing a need for developing guidelines to assist future microfiber projects. However, many of the same methods are applied to different environmental compartments (Athey & Erdle, 2022). Based on the environmental media, different levels of processing will be required to isolate and extract microfibers. For instance, air and water samples (with little organic matter) may simply require a filtration step following collection. However, organic-rich matrices (e.g., sediments, tissues, some water samples), may require more extensive approaches to isolate particles. For these organic-rich matrices, two main approaches are used: 1) chemical digestion of organic matter; and 2) density-based separation of microfibers and dense organic materials. Some studies only employ one of these approaches, but many studies perform both depending on the matrix (e.g., seawater and sediments, respectively). In studies with large samples, subsampling can be helpful.

Chemical digestion methods used to separate microfibers from organic-rich matrices vary in the chemicals used, as well as the incubation time and temperature (Athey & Erdle, 2022). One consideration when using these digestants is the degradation of manufactured plastic and non-plastic polymers. Care should be taken when selecting the digestive agent. Furthermore, experiments with matrix spikes should be conducted to evaluate particle recovery rates (Brander et. al., 2020).

Oxidative agents (e.g., hydrogen peroxide) are the most common digestants used in the microfiber literature (Athey & Erdle, 2022). Chemical digestion has been applied to aquatic sediments (Yao et al., 2019; Zheng et al., 2019), biota (Ambrosini et al., 2019; Avio et al., 2020), freshwater (Wilkens et al., 2020; Zhao et al., 2019), wastewater (Gündoğdu et al., 2018), and sewage sludge/biosolids (Gies et al., 2018; Li et al., 2010). Recovery testing using plastic manufactured and treated natural fibers shows that high concentrations of oxidative agents can degrade some polymers (Nuelle et al., 2014; Prata et al., 2020; Treilles et al., 2020). Fibers may be particularly vulnerable due to their extremely narrow width and large surface area to volume ratios.

The second most commonly used digestants are alkalis, such as potassium hydroxide (KOH), sodium hydroxide (NaOH), and Fenton reagent. KOH is most commonly applied to tissues of aquatic biota (Athey & Erdle, 2022). Similar to oxidative agents, KOH has been found to cause degradation of some to plastic manufactured and non-plastic microfibers (Cai, Yang, et al., 2020; Dehaut et al., 2016; Karr et al., 2020; Treilles et al., 2020). Furthermore, treated natural fibers are more degraded with KOH treatment than plastic manufactured fibers (Treilles et al., 2020). KOH has been shown to cause more damage to fibers at higher temperatures (Bråte et al., 2018; Thiele et al., 2019).

Other digestants include enzymes (e.g., cellulase, protease). The impact of these digestants on microfibers in samples is generally unknown, as recovery testing using positive controls that include plastic and non-plastic fibers is rare. More than 18% of studies on microfiber pollution include methods with unknown impacts on microfiber recoveries and, therefore, could underestimate microfiber levels (Athey & Erdle, 2022). Future research should include quality control measures to estimate the method's precision and accuracy (e.g., percent recovery, relative standard deviation).

Table 5. Laboratory Studies to Analyze Microfibers, Common Techniques, and Key Considerations

Studies	Techniques
Techniques for characterizing microfibers	Optical microscope (including fluorescent staining)
	Spectroscopy microscope
	Other (e.g., pyrolysis-GCMS)
Microfiber extraction methods	Filtration, chemical digestion, density-based separation

Key Considerations

- Standardized laboratory methods are needed that describe the steps to characterize microfibers.
- Though costly, spectroscopy or other techniques (e.g., Pyr-GC/MS) are needed to characterize the polymer type of the microfibers.
- More research is needed to develop reliable low-cost, accessible methods to extract, subsample, and characterize microfibers, such as rapid screening tests that don't rely on spectroscopy.
- Method recovery testing is required to accurately estimate microfiber concentrations in environmental samples when chemical processing is used for enumeration (i.e., digestion, density separation).

D. Additional Recommendations for Developing Standardized Methodologies

In addition to the key considerations specific to developing methods for field and laboratory research presented in Tables 4 and 5, the following broad recommendations were developed to help guide efforts to create standardized methodologies for quantifying and characterizing microfibers in various environmental compartments.

Methods for measuring the prevalence of microfiber pollution should be embedded into broader efforts to develop standardized methods for measuring microplastic prevalence, with microfibers included as specific morphology of microplastic.
Many of the past and ongoing studies on the prevalence of microfibers in environmental compartments do not focus solely on microfibers, but instead investigate microplastics more broadly, reporting microfibers as one of several morphological categories of microplastics. Efforts to develop standard research methods should focus on microplastics in general, with the inclusion of standard operating procedures related to the recovery and analysis of microfibers as a subcategory of microplastics. This would ensure that the resulting standardized methods are useful for microplastics researchers, while providing adequate measures to ensure that future research produces the information needed to advance the understanding of the sources and pathways of microfiber pollution. This recommendation has implications for the definition of "microplastics," if it is to include of all types of microfibers, both plastic and non-plastic. California's definition of "microplastics in drinking water" is an example of a definition for microplastics that is inclusive of microfibers as defined in this report (see Section III and Appendix A for an in-depth discussion of this definition).

Leadership and coordination at the national level on methods development is necessary.
As the fields of microfiber and microplastic pollution expand, there is a growing body of published research using various methods for field sampling, isolation, extraction, and characterization of microplastics. Working groups of leading experts and researchers have collaborated to generate best management practices for designing and conducting robust research on microplastics and microfibers (AMAP, 2021; Athey & Erdle, 2022; Brander et al., 2020; Cowger, Booth, et al., 2020; GESAMP, 2019). Leadership at the national level is necessary to review the existing scientific literature, convene the appropriate experts, and build consensus around a set of standard research methods for measuring microfiber prevalence in various environmental compartments. Microfibers, and microplastics in general, are a particularly complex suite of pollutants and a separate set of research methods will be required for each environmental compartment, including surface waters, soil, and air. Therefore, developing standard methods will require substantial investments of time and resources as well as strong collaboration and coordination across a variety of stakeholder groups, including academia, government, and the private sector.

VI. SOLUTIONS FOR REDUCING MICROFIBER POLLUTION

As new research continues to uncover the prevalence and potential risks of microfibers, concerns about this complex pollutant are driving government, private sector, and civil society actors to begin developing and implementing solutions to mitigate the microfiber pollution problem. This section provides an overview of the various solutions that have emerged and the progress to date in these solution areas.

The landscape of emerging solutions to the microfiber pollution problem is dominated by efforts that focus on microfiber pollution from textiles. As explained in Section IV (Assessment of Sources, Prevalence, and Causes of Microfiber Pollution), though textiles, specifically apparel, are one major source of microfiber pollution, scientists have identified many other sources of microfiber pollution, including cigarette butts, fishing and boating gear, and personal care products (e.g., wet wipes). To date, there has been little progress on preventing microfiber pollution from non-textile sources. However, efforts to reduce marine debris in general could have the effect of reducing microfiber pollution from some sources. For example, proper disposal of cigarette butts would help to reduce the amount of cigarette filters polluting the environment, which become sources of microfibers when they break down (Belzagui et al., 2021). Research on the relative contributions of microfiber pollution from all sources would help to ensure that solutions to reduce microfiber pollution are more effectively targeted at the most significant sources.

A. Rethinking Textile Design and End-of-Life Fate

With concerns about and awareness of microfiber pollution increasing, sustainable textile industry leaders are working to develop better materials and textile systems to address this issue. This line of research can include designing textiles with low shedding rates (minimizing the amount of microfibers released during the item’s lifetime) or designing textile products with the end-of-life (disposal) of that product in mind (including nontoxic and biodegradable fibers). The following sections provide more insight into these design considerations. It is also noteworthy to mention the momentum of and interest in these topics, which are stimulating research and development for solutions via microfiber challenges (Conservation X Labs, n.d.), and other innovative efforts by the textile industry, non-profit organizations, and academia, which aim to prevent (or reduce harm from) microfiber shedding.

Designing Low-Shedding Fabrics

One potential way to reduce fiber shedding from textiles is to design and construct textiles that shed fewer fibers. This solution requires a better understanding of how microfiber release is influenced by various textile characteristics, including fiber polymer type, yarn and textile construction (Cai, Mitrano, et al., 2020), dyes and finishes (Zambrano et al., 2021), fabric or garment mechanical or chemical processing, fabric cutting and sewing methods (Cai, Mitrano, et al., 2020; Cai, Yang, et al., 2020), and aging characteristics (Hartline et al., 2016).

A report by the OECD (2021) provides a detailed accounting of potential solutions to mitigate microfibers during the design stages, such as using yarns made of continuous filaments (compared to short staple fibers), promoting twisted and woven yarn and fabric structures instead of knit fabrics, considering different textile finishes, including protective coatings, and avoiding specific mechanical finish practices, among others. The report further compares and contrasts potential benefits of these mitigation measures to the implementation costs and other potential environmental considerations (e.g., use of chemical additives) (OECD, 2021).

Though some potential mitigation measures are starting to emerge, research on these topics is ongoing, and more research is needed to develop effective guidelines for producing low-shedding fabrics. Because the textile industry is complex, with a wide range of entities involved in designing, developing, sourcing, and manufacturing fibers, fabrics, and the variety of textiles that people use, coordination and communication will be essential for the research, development, and implementation of low-shed textile innovations.

Standardized test methods for determining shedding (or fiber release) via laundering, drying, and general wear would be helpful in furthering this research and paving the way for the design and labeling of low-shedding textiles. Over the last 5 years, the textile industry (primarily apparel) has been focused on the development of a testing methodology to measure fiber release in simulated laundering from garments and textiles. In the United States, the American Association of Textiles Colorists and Chemists (AATCC), a textile trade organization known for global textile testing standards development, was an early leader in bringing together a diverse group of brands, testing labs, and textile manufacturers to work on developing a testing methodology. In 2021, AATCC released a Test Method for Fiber Fragment Release During Home Laundering (method AATCC TM212-2021) (Wyman, 2021).

The Microfibre Consortium, a United Kingdom-based non-profit organization that facilitates cross-sector collaboration on the problem of microfiber shedding from textiles, has also developed a standard test method to determine fibers released from fabric during domestic laundering. The test method is a part of The Microfibre Consortium's broader collaborative efforts to generate the necessary knowledge to develop materials with lower shed rates. The Microfibre Consortium (2023) created a "Microfibre Data Portal" to house data on microfiber shedding obtained using its test method, which will allow researchers to share data more easily.

Though there has been significant progress in recent years on developing standardized methods for testing microfiber shedding in domestic laundry machines, there are not yet standardized methods for evaluating fiber release from textiles in dryers or through abrasion or general wear. Research on these pathways will inform upstream and downstream solutions.

Designing Nontoxic and Biodegradable Textiles

With the current material landscape weighted toward plastic manufactured fibers, comprehensively evaluating interactions and impacts that traditional natural fiber (e.g., wool, cotton, linen, hemp, alpaca) and natural dyes (i.e., indigo) have on biota is important and may be an important part of the solution to address this issue. Natural fiber organizations are working with scientific researchers to better understand the impacts of existing dyes and finishes on biodegradability (Closed Loop Partners, 2020). This kind of research will improve the understanding and ability to develop better alternatives or incentivize minimal or nontoxic alternatives. Some non-profit organizations are already leading efforts to develop collaborative strategy-building opportunities between brands, manufacturers and farmers to develop sustainable natural fiber textile systems.

Another approach by the textile industry to address microfiber pollution is the research and development of biodegradable fibers. Manufacturers of man-made cellulosic fibers are working with scientific researchers to better understand the biodegradability of existing cellulosic materials (e.g., cotton, rayon; Zambrano et al., 2020b) and newly developed man-made cellulosic fibers utilizing new processes or feedstocks (e.g., textiles waste, agricultural waste), and the potential for biodegradation, or lack thereof, of synthetic materials in the market (e.g., polyester). Biodegradation refers to the process by which a material is broken down by microbial activity into simpler substances such as carbon dioxide, water, and microbial biomass (Closed Loop Partners, 2020). Other material innovators are developing new manufactured plastic polymers (e.g., polyhydroxyalkanoates (PHA)) and non-plastic polymers (e.g., bioengineered protein), essentially considering the end-of-life pathway or fate of these materials during product design. There is also ongoing research to identify chemical additives that might accelerate the biodegradability of conventional polymers such as polyester, polyethylene, polypropylene, and nylon. Early adopters are already bringing "biodegradable" fiber-based products to market with these claims. However, the lack of aligned definitions related to biodegradability, testing methodology standardization, and understanding of key human and environmental thresholds presents major barriers for the development of biodegradable materials as a solution to microfiber pollution.

B. Reducing Microfiber Pollution During Textile Production and Manufacturing

During textile production and manufacturing stages, microfibers can be released into the air or water (OECD, 2021; The Microfibre Consortium, 2022). Research on mitigation measures to reduce microfiber emissions and discharges during the textile manufacturing process is limited, but several textile companies and environmental organizations are beginning to engage on the issue. According to a recent report from The Nature Conservancy and Bain & Company (2021), developed in collaboration with a range of textile industry stakeholders and scientists, the key changes that need to take place in textile manufacturing to eliminate pre-consumer microfiber pollution include better understanding the relative release of microfibers at each manufacturing step (from fiber to yarn to fabric to garment) and developing microfiber control technologies and best practices.

As part of its Microfibre Roadmap, The Microfibre Consortium has ongoing efforts to facilitate collaboration between textile manufacturing stakeholders, including the industry group Zero Discharge of Hazardous Chemicals (ZDHC), to identify mitigation measures to reduce microfiber pollution during textile manufacturing. The following guidance (The Microfibre Consortium, 2022) focuses on reducing fibers emitted in wastewater from manufacturing facilities by:

- Optimizing existing on-site processes to capture and remove microfibers.
- Implementing advanced filtration technology if current capture and removal technologies are not sufficient (e.g., microfiltration, ultrafiltration, reverse osmosis).
- Managing sludge produced in the wastewater treatment processes so microfibers are not released into the environment.

Pre-washing of fabrics at manufacturing facilities may also be a potential solution to reduce microfiber release (i.e., capturing fibers prior to distribution to retailers and consumers) if the facility has an adequate wastewater treatment system (OECD, 2021). Addressing microfiber release at the manufacturing wastewater stage has benefits, including focusing efforts on one location for fiber collection and control within the facilities, reduced labor needs for operating and maintaining filters to capture fibers, and relatively lower costs for retrofitting existing facilities with filtration equipment (The Microfibre Consortium, 2022). However, not all manufacturing facilities have on-site wastewater treatment systems, in which case the wastewater effluent would be discharged into municipal wastewater treatment plants (The Microfibre Consortium, 2022).

As for capturing microfibers released into the air, Carney Almroth et al. (2018) suggest evaluating in-line vacuum systems. Such an air filtration system could capture fibers released from mechanical finishing stages (e.g., brushing, sanding, raising). Air treatment systems have not yet been developed and would likely be costly (OECD, 2021).

C. Reducing Microfiber Pollution from Washing Machines and Dryers

Because washing machines have been identified as important pathways for microfiber pollution, they have been the focus of many efforts to address the problem. These efforts can be grouped into two main categories: 1) developing best practices for washing clothes in a way that minimizes microfiber shedding; and 2) developing technologies to capture microfibers shed in washing machines and prevent them from entering wastewater streams. Though in recent years dryers have also been identified as significant sources of microfibers in the environment, there has been little progress to date on developing solutions to prevent microfiber pollution from dryers.

Studies have found that changes in the way clothes are washed can result in reduced fiber shedding. For example, Lant et al. (2020) found that using colder and quicker washing cycles reduced microfiber generation per load by 30%. They also found that North American High-Efficiency top-loading washing machines produced significantly lower microfiber release than standard top-loading machines with 69.7% less for polyester fleece and 37.4% less for a polyester t-shirt (Lant et al., 2020). Other studies have sought to understand how a wide range of factors, including water volumes and fabric softener and detergent use, might impact the degree of shedding. In general, studies on microfiber release based on the use of standard detergents, softeners, or enzyme-containing detergents have shown highly variable and inconclusive results. Some research concluded that using liquid or powder detergent resulted in higher microfiber release during washing compared to using no detergent (Carney Almroth et al., 2018; Hernandez et al., 2017; Yang et al., 2019). In contrast, there is also research that shows that detergent use can reduce microfiber release (Cesa et al., 2020), vary (Napper & Thompson, 2016), or show no effect at all (Lant et al., 2020; Pirc et al., 2016).

Developing guidelines for how washing machine users can reduce microfiber shedding could be a low-cost and immediate way to reduce microfiber discharges. However, without additional research and standardized test methodologies for evaluating fiber release from textiles in washing machines, it is difficult to develop reliable guidance that consumers can use.

Another way to prevent microfiber pollution from washing machines is to capture and dispose of the microfibers in the washing machines' effluent. Several external washing machine filters and in-wash fiber capturing products are on the market and have been proven to reduce the amount of microfiber pollution from washing machines, and there is ongoing work to develop new technologies. For example, the Swedish Environmental Protection Agency funded the Zero Microplastics Challenge 2020, an innovation challenge that aimed to stimulate the development of microfiber capture and removal technologies for washing machines (RI.SE, 2020).

The microfiber capturing efficiency of two early consumer products (Cora Ball and Lint LUV-R) were investigated by McIlwraith et al. (2019). They found that the Lint LUV-R, an external washing machine filter that is designed to capture microfibers in washing machine effluent, captured 87% of microfibers in the wash by count. An in-wash microfiber-catching laundry ball called the Cora Ball captured 26% of the microfibers in the wash. Vassilenko et al. (2021) found the efficiency of two external microfiber filters (Lint LUV-R and Filtrol) to vary depending on the porosity of the internal filter (available in sizes of 100-1500 μm) and textile fiber type (nylon versus polyester). The retention was higher for polyester fibers (80-90%) compared to nylon (~40%). Napper et al. (2020) looked at 6 different devices, both in-wash and external filters, and reported a range of 21-78% efficiency for the devices. The most effective device in this study was the Xfiltra external filter (78% efficiency), followed by the Guppyfriend washing bag (54% efficiency). All studies acknowledged the need for further research and collaboration to understand the best intervention points further upstream (discussed further in Section VII). An ongoing study, soon to be released by the San Francisco Department for the Environment, will provide initial feedback from consumers that have implemented several microfiber capture devices and the key hurdles for greater adoption (e.g., cost, ease of installation, efficacy).

Considering that clothes dryers may be an equivalent, if not greater, source of microfibers to the environment compared to washing machine effluent (Pirc et al., 2016), more research is needed to better estimate microfiber emissions from domestic drying. In addition, dryer model and size, air flow, cycle settings, internal screen design, ducting, age, and vent design (Kapp & Miller, 2020), as well as fabric characteristics (O'Brien et al., 2020), may influence the number of microfibers released from domestic dryers. These factors should also be further investigated as they could inform mitigation strategies. While industrial methods (i.e., ISO 6330) offer standardized cycle settings for testing textiles, they do not measure microfibers in outgoing exhaust.

The best option for disposing of fibers collected from laundering textiles is placing the fibers in the trash to be landfilled. Filters, capture devices, or screens should not be rinsed in the sink as this would introduce fibers into wastewater and wastewater treatment plants. Disposing of fibers in the landfill is not a perfect solution, as briefly mentioned in Section IV.C.1.a, because microfibers that are disposed of in a landfill could escape via the landfill leachate. This may form a microplastic / landfill leachate / wastewater treatment plant biosolids loop, though not a completely closed loop, with the potential for some microplastics to escape in the process. From studies published to date, fibers and fragments are the predominate forms of microplastic found in landfill leachate (Kabir et al., 2023). Additional research is needed to understand the release of microfibers from this loop system into the environment, as well as to determine if microfiber disposal in household trash is a key pathway for microfiber introductions into the environment from landfill leachate.

D. Reducing End-of-Life Textile Waste and End-of-Pipe Microfiber Pollution

There are also opportunities to capture microfibers as they make their way through the wastewater system (i.e., capturing particles at the "end of the pipe") before they are released into receiving waters. Treatment options applied in wastewater treatment systems transfer microfibers from the water to the sewage sludge, which can be treated to form biosolids, then be applied to land as a soil enhancement or fertilizer (OECD, 2021). Thus, it is important to consider solutions associated with managing sewage sludge in addition to wastewater. There also may be opportunities to recycle entire garments and other textile products to divert these items from entering landfills or the environment. These topics are discussed in more detail below.

Reducing Microfiber Pollution in Wastewater Treatment Plants

Some of the solutions discussed in Section VI.B (e.g., addressing wastewater from manufacturing facilities) may also be applicable in publicly owned wastewater treatment plants. These solutions include implementing advanced filtration technology if current capture and removal technologies are not sufficient (e.g., ultrafiltration, reverse osmosis) (The Microfibre Consortium, 2022). However, variations in treatment options within primary, secondary, and tertiary treatments at wastewater facilities may also influence the number of microfibers captured (OECD, 2021). In addition to evaluating advantages offered by treatment options and capture efficiencies, cost-benefit analyses (cost of operations and maintenance) and other environmental costs (e.g., energy) (OECD, 2021) may be a driving factor regarding investment and potential implementation of such wastewater treatment options.

Reducing Microfiber Pollution in Sewage Sludge

Sewage sludge produced in wastewater treatment plants may be applied to agriculture lands as fertilizer or incinerated (OECD, 2021). For sewage sludge destined for land application, the sludge may undergo thickening and dewatering processes, as well as stabilization processes (to address risk of odors and pathogens that may result from biodegradation of organic matter). Such processes may result in the melting or shearing of microplastics, but generally do not effectively remove particles (OECD, 2021). Potential solutions to date may include avoiding land application of sludge that contains higher microplastic concentrations (e.g., sludge from primary treatments likely contains more microplastic particles than sludge produced from secondary treatments) (OECD, 2021). Incineration or landfilling may be better options for sludge containing more concentrated microplastics (OECD, 2021).

Reducing Textile Waste by Recycling

Between 2000 and 2018, textile waste as a share of total municipal solid waste in the United States increased from 3.9% to 5.8% (U.S. EPA, 2020a). Of the 17 million tons of textile waste generated in the United States in 2018, about 14.7% was recycled, 66.3% was landfilled, and 18.9% was combusted (U.S. EPA, 2020b).

Presently, closed-loop recycling (i.e., recycling of clothing into new clothes) rates are low. It is estimated that less than 1% of the clothing used in textile manufacturing are recycled into new clothing items at the end of the life of the item (Ellen MacArthur Foundation, 2017). Recycling is also challenging due to the properties of finished garments, such as dyes added to the fabric, garments that are made of blends, or other treatments applied to the fabrics (Ellen MacArthur Foundation, 2017). Because of these challenges, clothing items may be recycled into lower value products, such as insulation materials, wiping cloths, and mattress stuffing. This is called cascaded recycling. Together, closed-loop recycling and cascaded recycling account for only 13% of total material input after clothing use (Ellen MacArthur Foundation, 2017).

Recycling may be a viable solution, given improvements to the current recycling structure of textiles. Textiles that are landfilled represent a monetary loss and loss of material resources that could otherwise be reused (Ellen MacArthur Foundation, 2017). However, there are additional uncertainties that may arise with the recycling of textiles and should be considered: 1) fiber shedding during the recycling process and redesign of fibers into new textiles; and 2) the durability of the new garments made from recycled (aged) textiles, i.e., understanding the fiber shedding rates of virgin polymers compared to recycled polymers (Frost et al., 2020; OECD, 2021 and citations within). Research is needed to assess these uncertainties and the viability of textile recycling as a solution to microfiber pollution. With almost no research in garment or product aging or general wear effects on microfiber release across the vast variety of textiles offered in the market today, more data is needed to inform strategies for the collection and recycling of priority products.

E. Government-Led Initiatives

Some national and state government bodies have begun to take steps to manage and reduce plastic pollution through legislation, planning, and research. For example, the European Union has taken significant steps to reduce plastic pollution broadly, beginning in 2008 with the adoption of the Marine Strategy Framework Directive to ensure that “properties and quantities of marine litter do not cause harm to the coastal and marine environment” (European Union, 2008). Furthermore, in 2015, the European Parliament banned single-use plastic bags and, more recently, single-use plastic items, including wet wipes. More recently, the European Union’s 2018 Strategy for Plastics in a Circular Economy Commission highlighted the need for better information on the release of microfibers from textiles as well as monitoring of microplastics in drinking water.

There are very few international or national policies that specifically address microfiber pollution. France is the first and only country to pass legislation related to microfibers as part of a circular economy law passed in 2020 (LOI n° 2020-105 du 10 février 2020 relative à la lutte contre le gaspillage et à l'économie circulaire (1)), which requires a filter for capturing microfibers in all new washing machines by 2025 (RÉPUBLIQUE FRANÇAISE, 2020). In the United States Congress, a variety of legislation has been introduced to address upstream manufacturing as well as downstream filtration technology to reduce microfiber pollution, indicating ongoing interest in addressing microfiber pollution at the national level.

In the United States, Federal agencies including NOAA, EPA, the United States Geological Survey, the National Science Foundation, and the National Institute of Standards and Technology have conducted or provided funding for research and monitoring on microplastics, with some of these efforts also focusing on microfibers as a type of microplastic particle.

EPA's Trash Free Waters program, which co-led the development of this report on behalf of the IMDCC with NOAA's Marine Debris Program, works to reduce the volume of trash entering U.S. waterways by collaborating with partners to implement solutions that target land-based sources. As part of these efforts, the Trash Free Waters program has developed outreach materials to educate the public about the problem of microfiber pollution as well as macro- and microplastic pollution generally. The program also convened a Microplastics Expert Workshop in 2017 to identify and prioritize the scientific information needed to understand the risks posed by microplastics to human and ecological health. In 2021, EPA released a follow-up report to document the progress that has been made since the 2017 Microplastics Expert Workshop and the current research gaps.

The NOAA Marine Debris Program is the Federal lead on efforts to research, prevent, and reduce the adverse impacts of marine debris. The NOAA Marine Debris Program was originally authorized by Congress in 2006 through the Marine Debris Research, Prevention, and Reduction Act (33 U.S.C. § 1951 et seq.; Marine Debris Act), which was amended in 2012, 2018, and 2020. Under the amended Marine Debris Act, the NOAA Marine Debris Program is mandated to lead national and regional coordination; assess, research, prevent, reduce, and remove marine debris; and address the adverse impacts of marine debris on the economy of the United States, the marine environment, and navigational safety. Marine Debris Program staff are positioned across the country in order to support projects and partnerships with state and local agencies, tribes, non-governmental organizations, academia, and industry. The NOAA Marine Debris Program also facilitates the development of marine debris action plans for states and regions around the country by engaging regional and state partners and other stakeholders to create a strategic framework for addressing the problem of marine debris. A few plans have identified microfibers as a potential threat and knowledge gap (e.g., the California Ocean Litter Prevention Strategy, the Mid-Atlantic Marine Debris Action Plan, and the Long Island Sound Marine Debris Action Plan). In addition, the Program has funded research projects on microplastics, many of which include microfibers.

In the United States, individual states have also taken steps towards better understanding microfiber pollution and related solutions through statewide legislation. As described in Appendix B, California is the first state government to address microfiber pollution in drinking water by developing a definition of microplastics and a standard methodology to determine microplastic levels in drinking water (California Legislative Information, 2018). In addition, California has adopted a Statewide Microplastics Strategy, which was developed by the

California Ocean Protection Council (2022). This strategy includes a comprehensive prioritized research plan to better understand the impacts of microplastics on California's marine environment and identifies policy options to prevent and reduce microplastic pollution. The strategy also includes specific recommendations related to microfiber pollution. California has also seen many additional proposed bills that address microfiber pollution.

The Connecticut Legislature passed Public Act 18-181 in 2018 that established a working group of experts from the apparel, fashion, and scientific communities to develop a consumer awareness and education program on microfiber pollution (State of Connecticut, 2018). In early 2020, the Microfiber Working Group submitted a report to the legislature, titled "Report to the Legislature on the Findings of the Synthetic Microfiber Working Group," that provided recommendations for legislation on education and ways to reduce microfibers in Connecticut's waterways (Connecticut Department of Energy & Environmental Protection, 2020).

It is likely that local, state, and national level efforts to understand and mitigate the effects of microfiber pollution will continue. Additional work to understand what existing laws may be applicable to addressing microfiber pollution, and to understand the potential effectiveness of new policies could help to advance policy approaches to mitigating microfiber pollution.

F. Messaging and Public Education

Studies suggest that the public is more aware of microplastics and plastic pollution in general than microfibers (Herweyers et al., 2020). A study carried out in Belgium to evaluate public awareness about microfibers revealed that just under 40% of people in the study knew about the existence of microfibers and their potential impacts (Herweyers et al., 2020). This is comparable to a U.K. census study that gauged the public's awareness of microfibers and found that 44% of the 2,000 U.K. residents surveyed were unaware of microfibers as a plastic pollution issue (Envirotec, 2018). Educating the public about microfibers will be essential for the solutions outlined above to be effective. For instance, an informed consumer will be important when purchasing new garments and other textiles, especially as low-shed and biodegradable fabrics become more prominent. Public education is also important for encouraging the use of best management practices surrounding laundering habits to reduce microfiber pollution. Education around the use of filters to capture microfibers is also important for the success of such solutions, including the proper disposal of fibers collected from washing machine filters and dryer lint traps (disposing in household trash – not cleaning filters in the sink). This section takes a closer look at educational campaigns and consumer relationships with textiles, particularly clothing.

Reducing Textile Waste by Reusing/Re-wearing and Repairing

Reusing, repairing, and recycling (see Section VI.D.3) textiles can have the positive effects of reducing the amount of textile waste that is landfilled or incinerated and reducing the social and environmental impacts associated with the extraction of raw materials and manufacturing of new products (OECD, 2021). Reusing or re-wearing clothing is an easily implemented solution. This can mean both reusing/wearing clothes multiple times before washing the items, thereby reducing the frequency of laundering clothing, as well as retaining clothing for extended periods of time. Research has evaluated microfiber release with the age of the item when washing textiles. One study found that microfiber release decreased with repeated wash cycles. The study hypothesized the reduction in microfiber release after 5-6 washings could be due to the removal of residual production-related microfibers trapped in textile structure from manufacturing (Cai, Mitrano, et al., 2020). Several additional studies have found similar results, with new garments and fabrics generating the most microfibers in their first few washes (Carney Almroth et al., 2018; Cesa et al., 2020; Lant et al., 2020; Napper & Thompson, 2016; Sillanpää & Sainio, 2017). These studies suggest that repairing an apparel item should be the first option instead of discarding it. If the item cannot be repaired, it may be less impactful to replace items purchased at secondhand or consignment stores rather than buying new items.

However, a different study found that artificially aged textiles release more microfibers than newer ones (Hartline et al., 2016). Future investigations should also look at fiber release during general use, including fibers released after wearing a garment once v. multiple times (prior to washing), as well as general fiber release of the garment over time as they age. All of these considerations point to the need for further investigation by designers and manufacturers regarding garment aging over the lifetime of the item and potential best practices in upstream manufacturing stages to extend the lifetime of fabrics/garments, as well as consumer behaviors that can be practiced to extend a garment's lifetime (OECD, 2021).

Any solutions surrounding reuse/re-wear and repair will require consumer education and behavior change in light of social norms surrounding garment purchasing behaviors.

Education Campaigns to Reduce Microfiber Pollution

Educational campaigns on microfiber pollution and solutions are becoming more common, though due to the significant research gaps that have been discussed in previous sections of this report, public education and outreach efforts are hindered by the lack of possible actions that the public can take to effectively reduce microfiber pollution. The "What's in my Wash" campaign aims to raise public awareness of microfiber pollution from clothes and encourage individuals to take measures to care for their clothes in a way that is likely to minimize microfiber shedding and increase the clothes' lifespan (Hubbub, n.d.). The tips include washing clothes less, using cooler and shorter wash cycles, and air-drying clothes rather than using tumble dryers.

Similarly, the Plastic Soup Foundation created the "Ocean Clean Wash" campaign to educate the public about microfiber pollution from washing clothes (Plastic Soup Foundation, 2016). A video and infographics on the campaign webpage urge consumers to use liquid detergent instead of powder, use fabric softener, wash at lower temperatures, and avoid buying manufactured plastic clothing. A science feature titled "Me, my clothes and the ocean" by Ocean Wise Conservation Association provided a public-friendly summary of research on microfiber shedding as well as tips for how consumers can reduce microfiber pollution from laundry, including installing a microfiber filter in laundry machines, washing clothes in colder temperatures, and washing clothes less (Vassilenko et al., 2019).

Existing educational campaigns related to microfibers focus overwhelmingly on microfibers from apparel, with an emphasis on plastic manufactured fibers. There has also been significant media attention around filtration as an option for the general public to reduce the number of microfibers leaving their homes through their washing machine's effluent. Some educational campaigns have recommended that consumers use natural fiber textiles as an alternative to plastic manufactured fibers, but based on existing research, it is not yet clear that natural fibers (most of which are chemically treated for use in apparel) are a less harmful alternative to plastic manufactured fibers. Therefore, this guidance should be avoided until there is more research available.

G. Cross-Sector Collaboration

Due to the large variety of stakeholders that play a role in the microfiber pollution problem, cross-sector collaboration is critical to the development and implementation of effective solutions. International and national coalitions, workshops, and working groups have started bringing together experts to collaborate on efforts to understand the prevalence, sources, pathways, and impacts of microplastics and microfibers and to develop solutions to the problem. At the international level, the European Union's Science Advice for Policy by European Academics Consortium (SAPEA 2019), European Commission's Group of Chief Scientific Advisors (n.d.), European Union's Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP, 2023), and Organization for Economic Co-operation and Development (OECD, 2021) are some of the leading organizations facilitating coordination on microplastic research and solutions development.

In 2017, University of California, Santa Barbara Bren School of Environmental Science & Management, along with the Ocean Conservancy and Future 500, brought together experts from industry, academia, and environmental organizations to evaluate existing knowledge and solutions on microfibers and develop a Microfiber Roadmap that identified priority actions to address microfiber pollution (Bren et al., 2017).

Another collaborative effort is the Microfiber Partnership, which was formed in 2017 by Ocean Wise Conservation Association (Ocean Wise, 2017). This initiative brings together apparel companies, Canadian government agencies, and researchers to co-design and carry out scientific studies that will inform the development of solutions to microfiber pollution in the areas of textile design, wastewater management, and environmental detection and monitoring.

The California Microfiber Workshop: Science, Innovation and Connection, hosted by the NOAA Marine Debris Program and Materevolve in November 2020, convened a group of textile and white goods[11] industry representatives and environmental scientists to discuss the latest science and solutions related to microfiber pollution (Wood & Box, 2021). Similarly, a recent Microfiber Solutions Workshop, hosted by Ocean Wise Conservation Association, brought together apparel and textile businesses, government agencies, researchers, and NGOs to discuss and strategize ways to improve the understanding of microfiber pollution and make this information more accessible to the public and other stakeholders. Both workshops identified information and data sharing as a critical component in efforts to advance solutions to microfiber pollution (Wood & Box, 2021).

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[11] White goods are large consumer durables such as washing machines, refrigerators, water heaters, etc. Generally, these appliances are used for washing and cleaning, or heating and cooling.

VII. KEY RESEARCH NEEDS AND RECOMMENDATIONS

Based on the assessment of the microfiber pollution problem and its emerging solutions found in the previous sections of this report, this section provides a summary of key research needs and recommendations to guide efforts to address microfiber pollution in the United States. The recommendations are broad and are directed towards all U.S. Government and non-government stakeholders who play a role in addressing any aspect of the microfiber pollution problem. These recommendations and the identified research needs also inform the Federal Plan to Reduce Microfiber Pollution in Section VIII. This report does not constitute future commitments and all Federal actions are subject to the availability of resources.

A. Summary of Major Knowledge Gaps and Key Research Needs

Knowledge Gap 1: Microfiber Prevalence in Environmental Compartments

There is a need for additional research on microfibers in all environmental compartments, particularly those for which there is little existing research, like stormwater, groundwater, soil, and indoor and outdoor air. As discussed in Section V, the development of standardized methods for field sampling, detection, quantification, and characterization of microfibers in various environmental compartments would help researchers to produce useful data that can be compared across studies to dramatically improve the understanding of the pervasiveness of microfiber pollution, as well as its sources, pathways, and fate.

Specific Research Needs Include:
Methods development to quantify and characterize microfibers in drinking water, food, stormwater, surface water, groundwater, ice, snow, indoor and outdoor air, wastewater, sewage sludge, and biota (separate methods are needed for each environmental compartment)
Documentation of microfiber pollution prevalence in various environmental compartments, especially those for which there is little or no existing research (e.g., stormwater, groundwater, soil, and indoor and outdoor air)
Conceptual modeling to understand how microfibers move between environmental compartments (e.g., how airborne microfibers might end up in stormwater)
Comparison of data on microfiber prevalence and characteristics in environmental compartments and pathways to identify the most significant microfiber sources (including land-based and sea-based sources of microfibers), pathways, and sinks

Knowledge Gap 2: Rates and Mechanisms of Microfiber Release from Various Sources

Further research is needed to understand the mechanisms by which microfibers are released at all stages in the life cycles of fiber-based products. There are also significant knowledge gaps surrounding the relative contributions of various known and potential sources of microfibers, including footwear, bedding, carpet, personal care products, tires, cigarettes, and fishing/boating gear. A better understanding of the relative contribution of fibers released from tires is particularly important given the growing number of studies demonstrating the widespread presence of tire particles in the environment and their impacts on aquatic organisms.

Studies on the release of microfibers during the production of textiles and other known sources of microfibers at each manufacturing step (from fiber to yarn to fabric to garment) would aid in the development of mitigation measures to be applied in manufacturing processes. There is also a need to understand the degree to which various types of textiles shed microfibers during general use, when laundered, and in drying machines. More research is needed to understand the relationship between garment age and microfiber shedding. In addition, research on the relationship between microfiber shedding rates and textile characteristics (e.g., virgin or recycled content, yarn twist, construction, dyes, finishes) is necessary for the development of "low-shed" textiles. Research investigating the effects of various washing machine characteristics (e.g., detergent or fabric softener use, wash speed, water temperature, load size) and dryer characteristics (e.g., temperature, speed) would help to develop best practices to reduce microfiber pollution during the laundering and drying processes. Future research on microfiber contributions from dryers should also measure the dryer exhaust directly and consider a variety of dryer models and designs (few have been studied to date). Studies should also measure the fiber concentrations captured on the lint trap (for landfill disposal) and fibers released into ambient indoor air when cleaning the lint trap (a potential source of microfibers in indoor air).

Specific Research Needs Include:
Quantification of microfiber release during the production of textiles and other fiber-based products
Comparison of the relative contributions of various known and suspected sources of microfiber pollution (e.g., footwear, bedding, carpet, personal care products, tires, cigarettes, fishing/boating gear)
Assessment of microfiber shedding during normal use of textiles and the significance of various textile characteristics (e.g., polymer type, fabric construction, chemical additives, yarn twist, fiber length, virgin or recycled materials, age/wear) on shedding rates
Evaluation of microfiber shedding from textiles in washing machines and the impact of various washing machine characteristics on shedding rates
Evaluation of microfiber shedding from textiles in dryers and the impact of various dryer characteristics on shedding rates.
Identification of best practices to reduce microfiber shedding in washing machines and dryers

Knowledge Gap 3: Impacts of Microfiber Pollution

More research is needed to understand the toxicity of plastic and non-plastic microfibers in marine, freshwater, and terrestrial organisms, including humans, as well as their impacts on environmental processes. Research on the toxicity of microfibers is complicated by the high degree of variation in the physical and chemical properties of microfibers, which often contain a combination of chemical additives and can also serve as vectors of transport for toxic chemicals absorbed from the environment. Little is known about the physical, chemical, and biological mechanisms by which microfibers affect biota as well as the concentration levels of microfibers that lead to adverse effects. These knowledge gaps limit researchers' abilities to conduct meaningful risk assessments for microfiber pollution.

Another research gap that limits understanding of the risks associated with microfiber pollution is the degradability of various types of microfibers under different (realistic) environmental conditions as well as the consequences of microfiber degradation. Research should also assess the potential risks associated with new polymers and textiles that are labeled as "biodegradable" or "compostable" and determine if biodegradable and/or compostable textiles are a viable solution. Furthermore, research is needed to harmonize test standards for the assessment of degradable textiles/microfibers in various environmental media.

Specific Research Needs Include:
Documentation of impacts from plastic and non-plastic microfibers on aquatic and terrestrial biota
Identification of specific physical, chemical, and biological hazards associated with microfiber impacts in biota
Documentation of impacts from plastic and non-plastic microfibers on environmental processes
Verification of human exposure to microfibers via inhalation, ingestion, or dermal contact
Documentation of impacts of plastic and non-plastic microfibers on human health
Determination of the relationships between chemical additives in plastic and non-plastic microfibers and toxicity to biota, including humans
Assessment on the degradability of plastic and non-plastic microfibers under various environmental conditions
Evaluation of specific production treatments on non-plastic fibers to identify which treatments will be of concern for biological pathways and degradation, and which will not

Knowledge Gap 4: Effectiveness and Feasibility of Filtration-related Mitigation Measures

Research is needed to assess the effectiveness and feasibility of various technologies that would capture and remove microfibers from known pathways, including laundry machine effluent, stormwater, and air.

Specific Research Needs Include:
Assessment on the efficiency of external and internal laundry machine and dryer filters designed to capture microfibers in laundry machine effluent and potential challenges associated with their use
Evaluation of the efficiency of stormwater controls/practices, including green infrastructure (e.g., bioretention) and treatment technologies, in capturing and removing microfibers in stormwater and the limitations of using these controls/practices for this purpose
Assessment on the efficiency of air filters in capturing and removing microfibers from indoor and outdoor air and barriers to their use
Development of new technologies to capture and remove microfibers from various pathways

B. General Recommendations to Reduce Microfiber Pollution

Address Major Research Needs

As indicated previously, there is a critical need for more research on the sources, pathways, prevalence, and impacts of microfiber pollution as well as its potential solutions. Stakeholders in the United States should consider the following recommendations to address the most significant research gaps related to microfiber pollution. *These recommendations may help address the* *following management questions: What are the major sources of microfiber pollution? How do fibers from these sources enter the environment (i.e., transport pathways)? How can we prevent the release of significant quantities of microfiber pollution from major sources and pathways? What are the impacts of exposure to and interaction with microfibers on the environment, biota, and humans? Where should mitigation measures be focused? How much are microfibers contributing to the total microplastic concentrations?*

- Conduct and support research to close knowledge gaps in the understanding of sources, pathways, and impacts of microfiber pollution and inform the development and implementation of solutions. Research on impacts should include the evaluation of the toxicity of plastic and non-plastic microfibers on the environment and biota to determine if certain types of materials are most harmful and at what concentrations.
- Prioritize the development of fit-for-purpose standard definitions of microplastics, microfibers, and other related terms, in order to help streamline the standardization and/or harmonization of research methods. Ensure that all relevant stakeholder groups, including researchers; Federal, state, local, and international governments; and relevant industries (e.g., textiles, white goods), are meaningfully engaged in this process so that the resulting definitions are as useful as possible to a wide variety of relevant sectors.
- Prioritize the development of standardized research methods necessary for advancing knowledge of the sources, pathways, and impacts of microfiber pollution. Efforts should focus on the development of standardized methods for sampling, extraction, and analysis of microplastics in general, while including appropriate and specific guidelines for quantifying and characterizing microfibers as a morphology of microplastics. Support existing and new efforts by testing standards organizations like AATCC and ASTM to develop and standardize research methods for microfibers and microplastics more broadly.

Support Upstream Efforts to Prevent and Reduce Microfiber Pollution

As discussed in Section VI, there are efforts underway to reduce microfiber pollution upstream (in both senses of the word) through the design of textiles that use less harmful microfibers and/or shed fewer microfibers and textiles engineered to biodegrade. Stakeholders should support and build upon these efforts, while considering the recommendations below. *These recommendations may help address the following management questions: What are the major sources and causes of microfiber pollution from the production and manufacturing of fiber-based products? How do fibers from these sources enter the environment (i.e., transport pathways)? How can we prevent the release of significant quantities of microfiber pollution from upstream sources and pathways? What controls or best management practices could be implemented during production stages and at manufacturing facilities? Where should mitigation measures be focused?*

- Collaborate with the textile community to evaluate microfiber release during the textile design and production stages, and inform solutions and best practices to mitigate microfiber pollution.
- Evaluate textile manufacturing as a source of microfiber pollution and identify specific pathways of release to the environment, including air deposition, solid waste and sludge

disposal, and wastewater discharges. Evaluate whether any of these pathways result in microfiber pollutants in quantities or concentrations in the environment that could violate requirements in existing environmental statutes.
- Evaluate the relationship between textile recycling and microfiber pollution, including microfiber release during the recycling process (at recycling facilities), as well as microfiber shed rates from textiles made from recycled materials.

Implement Solutions to Capture and Remove Microfiber Pollution

Many of the emerging upstream solutions to mitigate microfiber pollution during product design and production will require years of research and development before they can become effective in reducing microfiber release. To address the problem in the shorter term, it is important to focus on downstream solutions to capture and remove microfiber pollution in major known pathways. *The following recommendations may help address the following management questions: How can we prevent the release of significant quantities of microfiber pollution from major sources and pathways? How effective (and cost-effective) are the various capture devices? Does the implementation or installation of a capture device result in other environmental impacts (e.g., higher water and/or electricity use)?*

- Develop, identify, and promote filtration and microfiber capture options for residential, commercial, and industrial washing machines and dryers.
- Provide incentives to retrofit existing washing machines with external filters at the residential homes and commercial and industrial facilities.
- Engage with researchers and the white goods industry (i.e., laundry machine manufacturers) to evaluate opportunities and barriers associated with the use of filters to capture microfibers. Assess filter designs and corresponding effects on the efficiency of machines (operation and maintenance).
- Evaluate the effectiveness and cost-effectiveness of stormwater controls/practices, including treatment technologies and green infrastructure like rain gardens, bioretention, and bioswales to prevent and/or reduce microfiber discharges via stormwater.

Evaluate and Implement Options to Minimize Toxicological Hazards Associated with Microfiber Pollution

As discussed throughout the report, there are concerns with chemical additives added to textiles (and other fiber-based materials) to enhance the performance and/or appearance of the product. There are also concerns associated with claims of biodegradable fibers/textiles, given little research and standardized guidance on this topic to date. The following recommendations focus on developing a better understanding of the hazards associated with microfibers and taking steps to minimize the use of materials and chemicals that are known to be most toxic. *These recommendations may help address the following management questions: What are the potential chemical impacts associated with the production of and subsequent release of textiles/microfibers in the environment? What standard certifications do textiles need to meet to be considered biodegradable (and how will they be similar or different from current compostable standard certifications)? How do we ensure accurate labeling of biodegradable* *and compostable textiles? How should the safe use of chemicals in textile production be regulated?*

- Conduct research and evaluate results regarding the toxicity of chemical additives in textiles. Identify categories of "safe" v. "potentially harmful" chemicals to help incentivize the use of safer materials, including nontoxic additives and dyes, during the design and production stages.
- Work with organizations that develop and certify biodegradable and compostable products to set clear and precise criteria for biodegradability and compostability of plastic and non-plastic fibers and textiles, across a range of environments (e.g., industrial composting facilities, home composting, natural environment). For compostable textiles, criteria should meet globally accepted standard specifications for compostables to ensure full biodegradation by naturally occurring microbes and address concerns related to persistent contaminants.
- Work with textile and environmental science communities to ensure that biodegradable and compostable product claims are accurate and take into account the full life cycle of the product (e.g., textile end product must be tested and evaluated for biodegradability/toxicity, not just the fiber/polymer used to construct it).
- Based on research outcomes discussed above, develop policies that will discourage or reduce the use of textile materials and chemical additives with the capacity to release harmful microfibers, and favor the use of textile materials and treatments that are known or demonstrated to be safe throughout the lifecycle (manufacture, use, and disposal) and biodegradable.

Foster Multi-stakeholder Collaboration

Microfiber pollution is a complex issue. Working to address different aspects of the problem in silos could result in wasted time and counterproductive efforts. Developing and implementing effective solutions requires collaboration across many sectors, including government, academia, the private sector, and the public. In their work to address microfiber pollution, stakeholders should consider the following recommendations to ensure fruitful collaboration:

- Create a microfiber pollution taskforce (or multiple task forces) with a diverse range of relevant stakeholders to coordinate research and solutions development and implementation. This taskforce should also work closely with relevant microplastic task forces and work groups, specifically to share knowledge and encourage collaboration as appropriate.
- Recognize the non-standardized and potentially confusing ways in which different sectors (e.g., textile industry and environmental science community) use the term "microfibers." Acknowledge and prioritize the use of the term "fiber fragments" as a synonym for "microfibers" to facilitate cross-sector communication and further define terminology and criteria needed to prevent and solve for microfiber pollution.
- Promote international cooperation and stay engaged with existing collaborative efforts.
- Encourage public engagement through education and outreach efforts. Implement outreach campaigns to educate the public on microfiber pollution, actions they can take as consumers, and other potential solutions. Work with broad stakeholder groups to design campaigns with consistent and effective messaging.

VIII. FEDERAL PLAN TO REDUCE MICROFIBER POLLUTION

A. Background and Development

The following plan lays out goals, objectives, and actions that Federal agencies should consider as they work with stakeholders to reduce microfiber pollution in the United States, with the understanding that future actions will be subject to the availability of staff and resources.

The plan consists of five main goals for addressing microfiber pollution, each of which is broken down into several objectives. Representatives of participating Federal agencies then identified actions that the U.S. Government could take, within each of these agencies' existing legal authorities, to help achieve the stated objectives in partnership with other stakeholders. Two workshops for Federal agency representatives were held to develop actions and further refine the goals and objectives in the plan.

Agencies that have ongoing or planned activities that contribute to a particular action are identified in the plan as "implementing agencies." Agencies that may be able to contribute to a particular action in the future are listed as providing "potential support." Agencies listed as "implementing agencies" are not responsible for carrying out any particular action in its entirety, but instead are doing work that makes progress toward achieving the action or may do so in the future.

The implementation of any actions for which an "implementing agency" or an agency providing "potential support" has been identified will be contingent on the participating agencies' budgetary constraints, staff capacities, research needs, and other factors. The goals, objectives, and actions articulated in the Federal Plan may also be subject to change based on the rapidly evolving research related to microfibers and microplastics. The following Federal agencies participated in the development of this plan and may be listed as "implementing agencies" or providing "potential support":

- Consumer Product Safety Commission (CPSC)
- Department of Energy (DOE)
- National Institute of Standards and Technology (NIST)
- National Oceanic and Atmospheric Administration (NOAA)
- National Park Service (NPS)
- National Science Foundation (NSF)
- U.S. Department of Justice (DOJ)
- U.S. Department of State (DOS)
- U.S. Environmental Protection Agency (EPA)
- U.S. Fish and Wildlife Service (FWS)
- U.S. Food and Drug Administration (FDA)
- U.S. Geological Survey (USGS)

This plan consists of the following five main goals:

- **Goal 1:** Conduct and support research to address the most critical research needs related to microfiber pollution
- **Goal 2:** Prevent and reduce microfiber pollution from textiles and other sources from entering the natural environment
- **Goal 3:** Capture microfibers in major microfiber pollution pathways
- **Goal 4:** Minimize toxicological hazards associated with microfiber pollution
- **Goal 5:** Coordinate and share microfiber pollution accomplishments, best practices, and science

Those who participated in the development of this plan determined that the objectives and actions included are important for accomplishing the plan's five goals. This is a 5-year plan (2023-2028); however, timelines associated with individual actions are not specified as this may be dependent upon individual agency timelines and availability of resources, as well as the priorities and resources of other stakeholders. In addition, the "implementing agencies" and agencies listed as "potential support" next to actions may have differing timelines to fulfill such actions. It should also be noted that some actions may take more than 5 years to complete given the nature of the action and/or if an action is dependent on other actions in the plan.

This plan is designed to demonstrate the wide range of activities and investments necessary to effectively understand and mitigate microfiber pollution over the next 5 years and beyond. Actions identified in this plan are not commitments, and at present, the participating Federal agencies do not have the funding and resources to complete all of the actions listed in this plan, and some agencies may not have clear authorities or congressional mandates to address microfibers.

In some instances, there are no assigned "implementing agencies." These are denoted with a "TBD." Though these "TBD" actions do not have an assigned agency, the representatives from the 12 agencies that attended the two workshops identified these actions as important actions to advance the larger goal of preventing and mitigating microfiber pollution and opted to keep the actions in the plan. These actions are aspirational and may require additional resources, support from other stakeholders, research, or other inputs in order to bring them to completion. These "TBD" placeholders may be filled by other Federal agencies with future interest in the plan or may also highlight areas where the Federal Government is looking to industry, academia, and other stakeholders to address such actions. This plan helps to illuminate how the work of various Federal agencies and other stakeholders fits into a larger plan to tackle this complex problem and provides a framework through which Federal agencies can understand the progress being made toward achieving the five key goals.

Goal 1: Conduct and support research to address the most critical research needs related to microfiber pollution

The ability to address the problem of microfiber pollution is limited by a significant lack of knowledge regarding the sources, pathways, and impacts of microfiber pollution. This goal focuses on addressing these critical research gaps.

Objectives	Actions	Report Sections to Reference
1.1: Adopt a general definition of the term "microfibers" as well as fit-for-purpose definitions as needed in coordination with relevant domestic and international stakeholders from academic, government, and industry sectors	1. Build consensus among relevant stakeholders for a standard definition of "microfibers" and coordinate with domestic and international stakeholders from academic, government, and industry sectors (Implementing Agencies: EPA; Potential Support: FDA, NIST, NOAA). 2. Ensure that standard definitions for "microfibers" and "microplastics" are aligned (Implementing Agencies: EPA; Potential Support: FDA, NIST, NOAA).	III.A. Proposed Definition of Microfiber III.B. Rationale for Proposed Definition
1.2: Develop/adopt standardized microfiber research methods in coordination with relevant domestic and international stakeholders from academic, government, and industry sectors	1. Work towards the development/adoption of standardized methods for testing microfiber prevalence in various media and environmental compartments (Implementing Agencies: NIST; Potential Support: EPA, FDA, NOAA). 2. Encourage microplastics researchers to report the occurrence of plastic and non-plastic microfibers (Implementing Agencies: EPA, NIST; Potential Support: NOAA). 3. Develop/adopt standardized methods for testing microfiber shed rates from textiles in laundry machines and dryers and during normal use (Implementing Agencies: TBD). 4. Develop/adopt standardized methods for testing microfiber persistence (biodegradability) in various environments and under various conditions, and/or impacts to environmental and human health. Consider chemical release and toxicity during biodegradation (Implementing Agencies: TBD; Potential Support: EPA, NIST). 5. Conduct or support research to develop new, benign materials to augment and/or replace current microfiber technologies (Implementing Agencies: TBD; Potential Support: NSF). 6. Conduct or support research to evaluate existing potentially benign materials to augment and/or replace current microfiber technologies (Implementing Agencies: TBD).	V.B. Field Sample Collection V.C. Laboratory Methods V.D. Additional Recommendations for Developing Standardized Methodologies VII. Key Research Needs and Recommendations

Objectives	Actions	Report Sections to Reference
1.3: Improve knowledge of the sources, pathways, fate, and impacts of various types of microfiber pollution to develop and prioritize mitigation efforts	1. Conduct or support research, conduct literature reviews, and/or engage with expert researchers to improve the understanding of environmental and/or human health impacts of microfiber pollution (Implementing Agencies: TBD; Potential Support: CPSC, NIST, NPS, NOAA, NSF). 2. Conduct or support research to understand the sources, pathways (e.g., atmospheric deposition, wastewater effluent, stormwater runoff), and fate (i.e., abiotic and biotic breakdown) of microfiber pollution to inform future mitigation efforts (Implementing Agencies: TBD; Potential Support: DOE, EPA, NIST, NOAA, NPS, NSF, USGS). 3. Evaluate, support, or conduct research to understand new sources and/or the relative contributions of various sources of microfiber pollution (e.g., apparel, carpeting, upholstery, geotextiles, construction materials, and cigarette butts) as well as the toxicity of microfibers from various sources (Implementing Agencies: TBD; Potential Support: NOAA). 4. Assess the toxicity of microfiber pollution containing various chemical additives commonly used in fiber-based products and assess the toxicity of chemicals that may potentially sorb to microfibers (e.g., heavy metals) (Implementing Agencies: TBD).	IV.A. Microfiber Sources IV.C. Microfiber Pollution Causes and Pathways VI.C. Reducing Microfiber Pollution from Washing Machines and Dryers

Goal 2: Prevent and reduce microfiber pollution from textiles and other sources from entering the natural environment

Microfibers in the environment come from a wide range of products made from plastic manufactured, non-plastic manufactured, and treated natural fibers, including textiles, carpets, wet wipes, cigarette filters, fishing gear, and others. This goal focuses on upstream solutions to microfiber pollution that aim to reduce microfiber shedding from known major sources or reduce the prevalence of microfiber sources themselves.

Objectives	Actions	Report Sections to Reference
2.1: Design textiles that shed fewer microfibers throughout their lifetime	1. Foster collaboration between researchers in academia, government, and the textile industry to improve understanding of the relationship between textile characteristics and fiber shedding and toxicity (Implementing Agencies: NIST; Potential Support: EPA, NSF). 2. Develop, share, and incentivize the application of science-based design guidance to be used by the textile industry to produce low-shed products (Implementing Agencies: TBD; Potential Support: EPA, NIST). 3. Educate consumers on the benefits of low-shed products (Implementing Agencies: TBD).	VI.A. Rethinking Textile Design and End of Life Fate VI.B. Reducing Microfiber Pollution During Textile Production and Manufacturing VII.C. Reducing Microfiber Pollution from Washing Machines and Dryers VI.F. Messaging and Public Education
2.2: Develop and share best practices for textile care that minimize microfiber shedding	1. Review scientific literature and consult with the textile industry to identify consumer care practices to reduce shedding from textiles (Implementing Agencies: TBD; Potential Support: NIST). 2. To aid in the development of best practices for laundry, conduct factorial experiments cross-examining different materials (plastic manufactured, non-plastic manufactured, treated natural polymers) and mixtures of materials, washing machine characteristics, and washing conditions (water temperature, detergents and softeners, load size, etc.) (Implementing Agencies: TBD; Potential Support: NIST). 3. Create communications and outreach campaigns for sharing best practices for textile care aimed at reducing microfiber shedding (Implementing Agencies: TBD).	VI.A. Rethinking Textile Design and End of Life Fate VI.C. Reducing Microfiber Pollution from Washing Machines and Dryers VI.F. Messaging and Public Education

Objectives	Actions	Report Sections to Reference
	4. Provide incentives to households, as well as businesses using commercial and industrial washing machines and dryers, for the implementation of best practices to reduce fiber shedding (Implementing Agencies: TBD). 5. Explore working with producers of washing machines and dryers to find opportunities for incorporating microfiber prevention into the design of household laundry appliances (e.g., a setting on washing machines that optimizes conditions for minimizing microfiber shedding, similar to “eco mode” on washing machines) (Implementing Agencies: TBD; Potential Support: EPA, NIST).	
2.3: Develop and apply best practices for reducing microfiber pollution during fiber and textile production	1. Quantify microfiber pollution from textile manufacturing facilities in the United States (Implementing Agencies: TBD; Potential Support: NIST). 2. Review current regulations under 40 C.F.R. 410 – Textile Mills Effluent Guidelines to evaluate need for revised effluent limits on microfiber discharges and identify any pollution prevention practices for textile manufacturing facilities (Implementing Agencies: TBD; Potential Support: EPA). 3. Review existing research and support new research to develop best practices for reducing microfiber pollution at various stages of fiber and textile production. Incentivize application of best practices among domestic and international suppliers of fiber and textile products consumed in the United States (Implementing Agencies: TBD; Potential Support: EPA, NIST).	VI.B. Reducing Microfiber Pollution During Textile Production and Manufacturing VI.E. Government-Led Initiatives
2.4: Minimize textile waste by implementing reuse programs and other circular economy approaches	1. Evaluate textile reuse as a mechanism for reducing microfiber shedding. Conduct research to understand the relationship between textile age and shed rates (Implementing Agencies: TBD; Potential Support: EPA). 2. Conduct an outreach/education campaign to encourage consumers to take actions to reduce, reuse, or recycle textile waste (Implementing Agencies: EPA; Potential Support: TBD). 3. Evaluate the relationship between textile recycling and microfiber pollution (e.g., microfiber release during recycling process, microfiber shed rates from textiles made from recycled materials) (Implementing Agencies: TBD; Potential Support: NIST, EPA).	VI.A. Rethinking Textile Design and End of Life Fate VI.D. Reducing End of Life Textile Waste and End of Pipe Microfiber Pollution VI.E. Government-Led Initiatives VI.F. Messaging and Public Education
2.5: Reduce and remove microfiber pollution from cigarette butt litter	1. Evaluate or support alternative materials for cigarette butts that may be more biodegradable and less harmful than cellulose acetate and other commonly used fibers used in cigarette butts (Implementing Agencies: TBD).	IV.A. Microfiber Sources VI.F. Messaging and Public Education

Objectives	Actions	Report Sections to Reference
	2. Support efforts at the state and local levels to reduce cigarette butt litter (e.g., street sweeping, public education and outreach) (Implementing Agencies: EPA; Potential Support: NOAA). 3. Conduct national outreach and education campaigns to encourage proper disposal of cigarette butts (Implementing Agencies: TBD; Potential Support: EPA, NPS, NOAA, USFWS).	
2.6: Reduce and remove microfiber pollution from fishing/boating gear	1. Quantify microfiber pollution from fishing/boating gear through literature reviews and/or field or laboratory research (e.g., assess the impact of rope/net/line weathering on microfiber shed rates) (Implementing Agencies: NOAA). 2. Develop and share best practices for caring for and sustainably disposing of boating/fishing gear (Implementing Agencies: NOAA, USFWS). 3. Evaluate innovative plastic manufactured rope designs that are aimed at reducing microplastic shedding (Implementing Agencies: TBD; Potential Support: NIST, NOAA). 4. Capture and remove derelict fishing and boating gear to prevent future microfiber pollution (Implementing Agencies: NIST, NOAA; Potential Support: NPS, USFWS).	IV.A. Microfiber Sources
2.7: Reduce and remove microfiber pollution from personal care products	1. Quantify microfiber pollution from personal care products (including face masks) through literature reviews and/or field or laboratory research (Implementing Agencies: TBD; Potential Support: NIST). 2. Conduct outreach/education campaigns to encourage proper disposal of wet wipes (they should not be flushed down toilets or littered), menstrual sanitary products, PPE, and others (Implementing Agencies: TBD). 3. Address the potentially misleading claims of biodegradability in the marketing of “flushable” wipes (Implementing Agencies: TBD; Potential Support: NIST). 4. Encourage proper disposal of personal care products and PPE (known to break into/shed microfibers) and remove PPE that enters the environment (Implementing Agencies: TBD).	IV.A. Microfiber Sources

Goal 3: Capture microfibers in major microfiber pollution pathways

A microfiber pollution pathway or conveyance refers to the physical environmental compartment or engineered route through which microfibers released from sources enter the natural environment, including natural pathways (rivers, streams, and transport via atmospheric circulation) and engineered pathways (wastewater systems and stormwater systems). This goal focuses on downstream solutions to microfiber pollution that aim to capture and remove microfibers shed from textiles and other sources.

Objectives	Actions	Report Sections to Reference
3.1: Use filters in washing machines to more effectively capture microfibers	1. Engage with researchers and home and commercial laundry machine manufacturers to: 1) Discuss opportunities and concerns associated with the use of filters to capture microfibers, and 2) Evaluate filter designs and corresponding effects on the efficiency of machines (operation and maintenance) (Implementing Agencies: TBD; Potential Support: EPA, NIST). 2. Provide incentives to retrofit existing appliances with after-market filters (consider both household appliances and commercial facilities) (Implementing Agencies: TBD). 3. Explore educating consumers on how to properly use and maintain filters in laundry machines (Implementing Agencies: TBD; Potential Support: EPA).	IV.A. Microfiber Sources IV.C. Microfiber Pollution Causes and Pathways VI.C. Reducing Microfiber Pollution from Washing Machines and Dryers VI.F. Messaging and Public Education
3.2: Work towards reducing microfiber emissions from dryers	1. Support or conduct research to understand microfiber emissions from vented dryers and their alternatives (condenser dryers and air-drying laundry) (Implementing Agencies: TBD). 2. Develop best practices for consumers to minimize microfiber emissions from drying laundry. Conduct factorial experiments cross-examining different materials (plastic manufactured, non-plastic manufactured, treated natural polymers) and mixtures of materials (i.e., a realistic laundry load), drying conditions (temperature, speed, dryer sheets), load size, dryer type, etc. to develop best practices (Implementing Agencies: TBD).	IV.C. Microfiber Pollution Causes and Pathways
3.3: Minimize microfiber pollution via land application of biosolids	1. Investigate current biosolid treatment processes in the United States and explore treatment options to separate microfibers from biosolids (Implementing Agencies: TBD; Potential Support: NIST). 2. Continue to assess how best to evaluate microfibers in biosolids (Clean Water Act (CWA) [40 C.F.R. Part 503]) (Implementing Agencies: TBD; Potential Support: EPA).	IV.C. Microfiber Pollution Causes and Pathways VI.D. Reducing End of Life Textile Waste and End of Pipe Microfiber Pollution

Objectives	Actions	Report Sections to Reference
3.4: Reduce microfibers entering waterways via wastewater effluent and stormwater runoff	1. Conduct or support development, demonstration, and deployment of existing and new practices/controls (e.g., rain gardens, bioswales, etc.) and processes that reduce microfibers in wastewater and stormwater and remove them from surface waters (Implementing Agencies: TBD; Potential Support: EPA, NOAA).	IV.C. Microfiber Pollution Causes and Pathways

Goal 4: Minimize toxicological hazards associated with microfiber pollution

Though research confirms that humans and a diverse range of aquatic and terrestrial organisms are exposed to microfiber pollution, the impacts of microfiber pollution on environmental and human health are largely unknown. This goal focuses on developing a better understanding of the physical, chemical, and biological hazards associated with microfibers (including the chemical additives they may contain, as well as the contaminants they may have absorbed from the environment) and taking steps to minimize the use of materials and chemicals that are known to be most toxic.

Objectives	Actions	Report Sections to Reference
4.1: Minimize use of harmful chemicals in plastic manufactured, non-plastic manufactured, and treated natural textile products	1. Increase data availability and transparency on the chemical additives used in production of fibers, textiles, and non-textile products using fibers (Implementing Agencies: NIST; Potential Support: EPA). 2. Support the use of sustainable alternatives to replace commonly used chemicals in textiles that are known to be toxic (e.g., dyes and other additives) (Implementing Agencies: TBD; Potential Support: DOE, EPA).	IV.D. Potential Environmental and Human Health Impacts of Microfiber Pollution IV.A. Microfiber Sources VI.A. Rethinking Textile Design and End of Life Fate
4.2: Support the development of nontoxic degradable textiles, as informed by a mechanistic understanding of degradation product formation	1. Support standards development through open, consensus Standards Development Organization (SDO) processes for guidelines and specification for pass/fail criteria for degradation of fibers and fiber-based products (Implementing Agencies: TBD; Potential Support: NIST). 2. Conduct or support research to understand the toxicity of degradable fibers (consider chemical additives that might leach from fibers as they degrade) and the design and development of nontoxic degradable materials (Implementing Agencies: TBD). 3. Support efforts to develop degradable polymers to be used in textiles (Implementing Agencies: TBD; Potential Support: DOE).	VI.A. Rethinking Textile Design and End of Life Fate VI.G. Cross-Sector Collaboration

Goal 5: Coordinate and share microfiber pollution accomplishments, best practices, and science

Strategic coordination and communication between government agencies and with other stakeholders, including the textile industry, other relevant industries, and the public will be essential to make this Plan a success. This goal focuses on ways the government can track progress on the Plan and engage with stakeholders to share knowledge and disseminate research findings, best practices, and solutions to reduce microfiber pollution.

Objectives	Actions	Report Sections to Reference
5.1 Create and participate in opportunities for coordination across Federal agencies	1. Host an Interagency Marine Debris Coordinating Committee (IMDCC) meeting on accomplishments and the status of actions at the midpoint of the plan (2-3 years) (Implementing Agencies: NOAA). 2. Articulate IMDCC member actions on microfibers in the IMDCC biennial Report to Congress (Implementing Agencies: NOAA). 3. Coordinate efforts with respect to implementing the 5-year Federal Plan at relevant intergovernmental agency workgroups or workshops (Implementing Agencies: EPA, NOAA). 4. Evaluate development of an online implementation platform to track implementation of the Federal Plan to Reduce Microfiber Pollution over time (Implementing Agencies: EPA, NOAA). 5. Coordinate basic research and development programs focused on materials design, manufacturing, and recovery technologies that support the goals of the Federal Plan, including coordination on common resources for data and models that support improved environmental stewardship along the full textiles value chain (Implementing Agencies: NIST; Potential Support: TBD).	VI.E. Government-Led Initiatives VI.G. Cross-Sector Collaboration
5.2 Create and participate in opportunities to share knowledge	1. Chair or participate in microfiber-focused sessions at conferences and other scientific forums to share scientific knowledge and best practices, as well as approaches, accomplishments, and successes from the Federal Plan to Reduce Microfiber Pollution (Implementing Agencies: EPA, NIST, NOAA). 2. Share messaging, new microfiber knowledge, and best practices with the general public (Implementing Agencies: USFWS; Potential Support: NIST, NOAA, NPS).	VI.E. Government-Led Initiatives VI.F. Messaging and Public Education VI.G. Cross-Sector Collaboration

IX. GLOSSARY

Abrasion. The process of scraping, rubbing, grinding, or wearing away by friction.

Acute. In toxicological experiments, short-term exposure to a substance of concern, usually at a higher dose than chronic exposures.

Anthropogenic. Related to or resulting from the influence of humans or their activities.

ASTM. The international standards organization ASTM International, formerly known as the American Society for Testing and Materials.

Bioaccumulation. The gradual, net accumulation of a contaminant in an organism, from all sources including air, water, and diet.

Biodegradable. "Describes a material that breaks down by microbial activity into carbon dioxide, water vapor and microbial biomass." It is important to note that "Biodegradable does not always mean compostable, but everything that's compostable is inherently biodegradable." (Closed Loop Partners, 2020)

Biodegradation. The process by which organic substances are broken down and decomposed by microorganisms into simpler substances such as carbon dioxide and water.

Biosolids. Solid organic matter recovered from domestic wastewater treatment processes that separate liquids from solids. They are treated sewage sludge that meet the Federal requirements in 40 C.F.R. Part 503 and applicable state requirements.

Biota. Includes flora and fauna of a particular place, time, or habitat.

Characterization. The process of identifying a polymer based on its chemical and physical attributes.

Chemical Additives. Chemicals that enhance functional properties of plastics, such as longevity or resistance to water or fire. Examples include plasticizers, flame retardants, light and heat stabilizers, pigments, and thermal stabilizers.

Chronic. In toxicological experiments, long-term exposure to a substance of concern.

Combined Sewer Systems (CSS). Sewers designed to collect rainwater runoff, domestic sewage, and industrial wastewater in the same pipe. In periods of heavy rainfall or snowmelt, the wastewater volume can exceed capacity and overflow, discharging to nearby streams and rivers.

Combined Sewer Overflows (CSO). Overflows of combined sewer systems that discharge to nearby streams and rivers instead of flowing to a wastewater treatment plant and may contain stormwater, untreated human and industrial waste, toxic materials, and debris.

Compostable. "Describes a material that disintegrates (breaks apart into small enough pieces) and biodegrades under specific conditions, in the specific time-frames needed by composters at their facilities (home or industrial) and does not release any harmful chemicals, toxic components or heavy metals into the environment or soil amendment being created" (Closed Loop Partners, 2020). Note that one key difference between compostable and biodegradable is that compostable materials are breaking down in specific time-frames, where as there is no specified time-frame associated with the term biodegradable. There are certifications for compostable plastics designed to break down in municipal and industrial aerobic composting facilities, for instance, refer to ASTM D5338 and ASTM 6400 for a recognized industrial composting standard (ASTM D5338-15 (2021); ASTM D6400-23 (2023)).

Digestants. A substance that promotes or aids in digestion or decomposition, such as hydrochloric acid, enzymes, or bile salts.

Dimensions. A measurable aspect of an object, such as length, height, or depth.

Effluent Waters. Treated liquid waste discharged from a wastewater treatment plant or untreated waste or sewage discharged directly into receiving waters, such as a river or sea.

Environmental Compartments. The external surroundings and location in which a substance is found (e.g., air, soil, surface water, sediment, groundwater, tissue).

Erosion. Surface processes such as wind and water movement that remove soil, rock, or dissolved materials from one location and transport it to another location.

Extended Producer Responsibility (EPR). A policy approach under which producers are given significant responsibility (physical and/or financial) for the treatment or disposal of post-consumer products.

Extraction. A separation process that removes one component from the underlying matrix.

Fibrous. Containing, consisting of, or resembling fibers; capable of being separated into fibers.

Harmonization. A process to minimize redundant or conflicting standards that may have evolved independently.

Infiltration. The process by which water moves from the ground surface to the soil and groundwater.

Influent Waters. Water flowing into a drain, sewer, or other outlet, that eventually enters a wastewater treatment plant.

Ingestion. The process of consuming food, drink, or another substance by an organism.

Inhalation. The process of breathing in (e.g., in humans, taking breath into the lungs).

Invertebrates. Animal species that do not have a backbone (e.g., insect, coral, mollusk).

Leachate (landfill). Liquid, usually water, that has moved through a solid and extracted soluble or suspended solids (e.g., liquid generated from water moving through a solid waste disposal site and accumulating contaminants).

Limit of Detection. The lowest concentration of an analyte in a sample that can be detected consistently with a stated probability.

Macroplastic. Particles larger than 5 mm that are composed primarily of plastic.

Man-made cellulosic fibers. "Regenerated fibers usually made from the dissolved wood pulp or 'cellulose' of trees. Viscose, lyocell, acetate and modal are all examples of man-made cellulosics" (Textile Exchange, 2023).

Microfiber. A fiber in the micro-scale that is characterized by a thin, fibrous shape.

Microparticles. Particles smaller than 5 mm that are visually identified as anthropogenic litter of an undetermined polymeric material type; includes all microplastics, as well as semi-synthetic and natural microfibers.

Microplastics. Solid synthetic polymers with a size smaller than 5 mm. They are usually found in the environment in shapes such as fragments, fibers, pellets, or beads. They can be found in different sizes, colors, and physico-chemical compositions (OECD, 2021).

Mobility. The ability or capacity to move or be moved freely and easily.

Morphology. The study of the form and structure of an object or organism.

Municipal Separate Storm Sewer System (MS4). In the United States, the EPA defines an MS4 generally as a conveyance or system of conveyances that is owned by a state, city, town, village, or other public entity that discharges to waters of the United States; designed or used to collect or convey stormwater; not a combined sewer; and not part of a sewage treatment plant or publicly owned treatment works.

Nanoplastics. Solid polymeric materials to which chemical additives or other substances may have been added, which are particles with all dimensions in the Nano-size range (1-1000 nm). These particles are a subcategory of microplastics.

Natural Fiber. A long-chain polymeric structure that does not undergo extrusion and is derived primarily from naturally occurring materials (e.g., wool, cotton, and silk).

Nonwoven Materials. A category of textiles in which the fibers are held together by interlocking and bonding by chemical, mechanical, thermal, or solvent treatment. The resulting fabric is often used in disposable products (e.g., wet wipes, diapers, surgical masks).

PFAS. A group of thousands of manufactured chemicals that contain per- and poly-fluoroalkyl substances. PFAS are widely used in industry and consumer products, including plastics, and break down very slowly over time.

Pathway. The physical environmental compartment or engineered route through which microfibers released from sources enter the natural environment.

Persistence. The continued prolonged existence of a substance in the environment.

Polymer. A substance with a molecular structure of repeating units, of the same or of different types, bonded together. Polymers can be composed of either natural or synthetic substances. Adjective: polymeric.

Quality Assurance / Quality Control (QA/QC). The combination of processes used to measure the quality of a product and ensure products meet expectations. Often described as part of quality management during field and laboratory sampling and subsequent analytical procedures.

Reagent. A substance or compound used, due to its chemical or biological activity, to cause a chemical reaction, test if a reaction occurs, or measure a component part.

Replicate. A close or exact copy. Often utilized in field sampling to assess the similarity of two or more samples collected from the same location.

Recovery (testing). The amount of a substance quantified within an environmental sample as compared to the total amount of that substance within the sample.

Runoff. Water and other substances carried within it draining away from the ground surface; subcategories include urban, surface water, and stormwater runoff.

Semi-Synthetic Fiber. A long-chain polymeric structure extruded into a fiber form and chemically processed that is derived primarily from naturally occurring materials such as cellulose. For example, rayon, viscose, and modal. In this report, semi-synthetic fibers are referred to as non-plastic manufactured fibers.

Sorption. The adherence of one substance onto (adsorption) or within (absorption) another substance. Verb: to sorb.

Sludge (Sewage). The solid, semi-solid, or liquid residue that is produced as a by-product during the treatment of domestic wastewater. Sewage sludge includes, but is not limited to, domestic septage; scum or solids removed in primary, secondary, or advanced wastewater treatment processes; and a material derived from sewage sludge. Sewage sludge does not include ash generated during the firing of sewage sludge in a sewage sludge incinerator or grit and screenings generated during preliminary treatment of domestic sewage in a treatment works.

Spectroscopy. Raman and Fourier transform infrared (FTIR) spectroscopy are analytical techniques that provide information about chemical structure, based on the interaction of light or infrared radiation with chemical bonds in a material, and can be used to identify specific polymers.

Standardize. To produce in a consistent manner; to compare or bring into conformity with a standard (e.g., an idea or thing used as a measure, norm, or model).

Stormwater. Storm water runoff, snow melt runoff, and surface runoff and drainage.

Synthetic Fiber. A long-chain polymeric structure extruded into a fiber form and chemically processed that is derived primarily from fossil fuels or feedstocks consisting of recycled content or bio-based materials (e.g., polyester, nylon, and polypropylene). In this report, synthetic fibers are referred to as plastic manufactured fibers.

Terrestrial. Related to the earth (e.g., animals that live predominantly or entirely on land).

Tillage. An agricultural technique that prepares soil for planting and cultivates the soil after planting by mechanical manipulation to eliminate weeds and change the structure.

Toxicity. The degree to which a substance is toxic or poisonous to a particular organism.

Vented Dryer. Clothes dryer models that include a vent to push hot exhaust out of the dryer, often directly outdoors.

Ventless Dryer. Clothes dryer models that do not include a vent, but instead condense hot exhaust into water vapor that accumulates in a tank or drainpipe and is discharged to wastewater.

Wastewater. Water that has been utilized in a number of applications, both residential and industrial, and may include human waste, food scraps, soaps, and chemicals.

Wastewater Treatment Plant. These facilities treat wastewater to remove the suspended solids and ensure the effluent released back to the environment meets certain standards.

Weathering. The process of being worn away by long-term exposure to the environment.

Zooplankton. Organisms that drift in oceans and bodies of freshwater, consisting of small animals and the immature stages of larger animals.

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APPENDIX A: SUMMARY OF PUBLIC COMMENTS AND THE IMDCC'S RESPONSE

Comment Statistics

NOAA received 29 comment letters from the public (comments can be viewed on the report docket on regulations.gov (www.regulations.gov/docket/NOAA-NOS-2022-0061/comments). Commenters included private citizens, non-governmental organizations (NGOs), government agencies (e.g., local and state agencies), industry trade associations (including natural fiber and chemistry councils, home appliance manufacturers, and textile testing standardization groups), polymer and fiber manufacturers, and academia. NOAA also received one comment from one Federal agency: EPA Region 10.

Public comments were received from the following groups: Cashmere and Camel Hair Manufacturers Institute, National Cotton Council, American Wool Council, International Wool Textile Organization, Woolmark Company, Discover Natural Fibres Initiative, Fibershed, 5 Gyres Institute, Ocean Conservancy, Surfrider Foundation, Georgian Bay Forever, San Francisco Estuary Institute, Eastman Chemical Company, American Chemistry Council, Biodegradable Products Institute, Mango Materials, Intrinsic Advanced Materials, American Association of Textile Colorists & Chemists (AATCC), ASTM International, California Product Stewardship Council, The Or Foundation, Maryland Department of Natural Resources, and private citizens.

Support for the Report on Microfiber Pollution

Overall, commenters were supportive of the Report on Microfiber Pollution that includes a Federal plan to prevent and address microfiber pollution. Many highlighted the Report's comprehensive summary of current research, testing, and solutions being used to address microfiber pollution today. Commenters also supported the Report's recommendation for further research on microfiber pollution and further refinement of the definition of microfiber to ensure the appropriate "fit-for-purpose" definitions are developed without unintended consequences (such as the inclusion of nontoxic, biodegradable fiber solutions in monitoring and regulatory policy).

Overview of Public Comments Received

The IMDCC invited comments, feedback, and recommendations on the Report on Microfiber Pollution. These comments can be broken down into two focal areas: 1) comments received on Sections II-VII of the report, and 2) comments received on Section VIII.

Focal Area 1: Comments received on Sections II-VII of the Report

Overall, many commenters focused on different aspects of the Report's proposed definition of "microfiber." Below are the overarching themes and recommendations provided by commenters:

Incorporate Standardized Terminology Related to the Term "Microfiber"

Commenters, including global testing standardization organizations from industry and several non-government organizations, encouraged the IMDCC to consider acknowledging existing textile terminology definitions of “microfiber” and “fiber,” and to adopt the new term “fiber fragment.”

Update “Synthetic,” “Semi-Synthetic,” and “Modified Natural” Categories for Microfiber Definition

Many commenters from a range of stakeholder groups expressed concern about the use of the terms “semi-synthetic” and “modified natural.” They suggested that, while “synthetic” is a term often used to define a subcategory of materials in textiles, “semi-synthetic” and “modified natural” are less common, not used by industry, confusing, and potentially misleading. Some commenters recommended the use of existing terminology like “manufactured” or “artificial” to represent any fiber that has been extruded by a human process, and the use of “treated” to refer to any chemical or mechanical treatment (most often with chemical additives) that has changed the properties of a base fiber. In the case of natural fibers, instead of using the term “modified natural,” which could imply a chemical modification of the structure, commenters recommended the term “treated”instead.

Consider the Unintended Consequences for the Inclusion of Natural Fibers in the Microfiber Definition

The largest number of commenters represented organizations that develop or promote the use of natural fiber systems and expressed concern for the inclusion of natural fibers in the Report’s proposed definition. The primary concern of these commenters was that including modified natural fibers could have unintended consequences and that the development of natural fiber products and systems (including the historical, cultural, and ecological skills associated with these systems) is critical to solve the microfiber pollution problem.

Align with Current Definitions of Microplastics

i) Assign a Lower Limit for Microfibers: Multiple commenters recommended a lower limit for microfibers be identified. However, there was lack of concensus regarding if the lower limit should be based on toxicological considerations, technical feasibility (i.e., current detection limits for microfibers based on analytical equipment), or based on nomenclature (i.e., microfibers vs. nanofibers). Commenters were encouraged that the lower limit for microfibers may be revisited in future definition discussions.

ii) Remove 3:1 Aspect Ratio: Many commenters expressed confusion over the sizing criteria for microfibers used in the Report and recommended better alignment with the sizing definition of microplastics.

Include Biodegradability and Toxicity Criteria for “Microfiber” Definition

Many commenters highlighted the importance of developing biodegradability and toxicity criteria for the microfiber definition. Rather than highlighting the carbon origin/source (e.g. fossil fuels or plant-based) or manufacturing process, many commenters suggested that the definition be refined to better represent the performance of fibers in the environment as related to biodegradability or toxicity. Commenters recommended that the definition of microfibers be consistent with the European Chemicals Agency (ECHA) definition of microplastics that exempts biodegradable materials. Commenters also highlighted the availability of expertise in environmental biodegradation including global standard specifications for compostability and biodegradability that can be leveraged for further development of the microfiber definition and solutions.

Include More Focus on Healthy, Nontoxic Natural Fiber Products and Systems as a Solution to Microfiber Pollution

Commenters expressed concern that the current economic and regulatory frameworks favor synthetic textiles, which makes it difficult for natural fiber textiles to compete. These commenters highlighted the importance of Federal Government research and action to invest in and incentivize the development of healthy, nontoxic natural fiber products as a way to address microfiber pollution.

Emphasize Source Reduction of Harmful Materials Instead of Reducing Shedding

Commenters recommended reduced use of textile materials with the capacity to release harmful microfibers, in favor of textile materials that are known or demonstrated to be safe, nontoxic and biodegradable. Commenters stated that the key issue is not shedding, but instead reducing known harmful microfibers (often referring to microplastic fibers) and toxic chemical additives.

Refine Microfiber Sources and the Categories of Products They Are Derived From

Multiple commenters from various stakeholder groups asked for clarity about various source categories in the Report and identified additional categories of potential sources of microfiber pollution (e.g., tires).

Other Recommendations

One commenter recommended research to focus on specific management questions highlighted in the Report. Another commenter stressed the importance of extended producer responsibility as a mechanism for addressing microfiber pollution. Another commenter recommended the Report include environmental justice considerations and the impact of microfiber pollution on low-income communities.

Focal Area 2: Comments received on Section VIII of the Report

A few commenters identified the proposed actions in the the Federal Plan that they felt were most important and would have the greatest impact. A sample of these themes include:

- Adopting a general definition of the term microfibers as well as “fit-for-purpose” definitions
- Improving knowledge of the sources, pathways, fate, and impacts of various types of microfiber pollution
- Minimizing textile waste by implementing reuse programs and other circular economy approaches
- Reducing and removing microfiber pollution from cigarette butt litter
- Supporting the development of nontoxic degradable textiles
- Creating and participating in opportunities to share knowledge

Several commenters suggested changes to the existing actions and also suggested additional actions. A sample of these themes include:

- More funding and research on source reduction of harmful microfiber materials
- Development of policies and regulations that will discourage or reduce the production and use of textile materials with harmful microfibers
- Development of regulations that use extended producer responsibility models and policies
- Incentives for the garment and textile industry that reduce the amount of new textile products
- Support for the development of degradable textiles
- Inclusion of other stakeholders in opportunities for coordination across Federal agencies

In addition to comments received on the specific actions in the Federal Plan, the General Services Administration (GSA) was identified as a potential implementing agency or an agency to provide potential support to ensure that the buying power of the Federal Government is taken into consideration for all the objectives in the plan (e.g., installation of microfiber filtration units in government-owned clothes washing machines, purchasing low-shed textile designs to address existing government textile needs). There were also recommendations to engage with organizations and stakeholders outside of the regulatory community to leverage expertise and resources to develop these critical methods and materials.

Furthermore, some commenters noted that the Federal Plan section lacks details on implementation and accountability. There were also comments encouraging stakeholder involvement throughout the development and implementation of the plan.

How IMDCC Addressed the Comments

Based on the public comments, the IMDCC refined the definition and terminology related to microfiber in Section III of this Report, "Defining Microfiber." These refinements included removing aspects of the proposed definition that were causing confusion (e.g., aspect ratio) and simplifying the categories of microfibers (originally referred to as synthetic, semi-synthetic, and modified natural). As a result, this section now emphasizes the need for further cross-sector engagement to develop "fit-for-purpose" definitions related to microfiber and includes more information on existing microfiber definitions. In addition, the proposed definition and microfiber traits were added to Figure 1 in Section III to provide more clarity about the intention and key elements of the proposed definition. The proposed definition was refined to be a starting point for cross sector engagement and further development.

To address the significant comments received in support of healthy, nontoxic natural fiber systems and prevalent concerns about the unintended consequences of including non-plastic fibers in the proposed definition of microfibers, the IMDCC made several targeted revisions to the Report. The Report now includes language to ensure that the definition is updated as biodegradability and toxicity data become available, and highlights the evidence already available on the impacts of plastic microfibers.

In general, the IMDCC addressed comments not related to the definition in Section VI "Solutions for Reducing Microfiber Pollution" and Section VII "Key Research Needs and Recommendations." Nevertheless, revisions to address comments mentioned often or those needed for clarity were incorporated throughout other sections. In Section VI, a new Section VI.B "Reducing Microfiber Pollution During Textile Production and Manufacturing" was added to address multiple comments. In Section VII, additional recommendations and key research needs suggested by commenters were added where applicable. Some comments received on the Federal Plan included actions that were outside the scope of the Federal Plan and others were aligned with current actions. One new action (*1.2.6, Conduct or support research to evaluate existing potentially benign materials to augment and/or replace current microfiber technologies*) was added to address comments received related to existing biodegradable and potentially benign materials. In general, the Federal Plan was not changed substantially in response to comments.

APPENDIX B: BACKGROUND INFORMATION ON DEFINITION

This appendix provides background information on the existing microfiber definitions and related terms, as well as additional information on rationale for inclusion of plastic and non-plastic fibers in the definition of "microfiber" proposed in Section III and additional information on related subcategories of plastic and non-plastic fibers.

Existing Definitions of Microfiber and Related Terms

The definition of "microfiber" proposed in Section III is based on definitions used by the ocean science community (including scientific literature and non-governmental organizations), governmental/intergovernmental agencies, and the textile industry.

Microfibers in Scientific Literature

Many scientific studies use the term "microfiber" to refer to a particular morphological category of microplastics (Belzagui et al., 2019; Hernandez et al., 2017; Rochman et al., 2019) that are commonly described as "fibrous" or "threadlike." Microplastics generally refer to plastic particles that are less than 5 mm in size, including particles of various morphologies, from fragments to spheres to fibers (Burns & Boxall, 2018; Rochman et al., 2019; Thompson et al., 2009). However, there is no universally accepted definition of microplastics. Furthermore, most of the available definitions for "microplastics" (e.g., those used by national and international regulatory agencies) include specific criteria for particle dimensions, but not for material composition (California State Water Resources Control Board, 2020). Because microfibers are often defined as a shape category of microplastics, the lack of clarity regarding which specific substances constitute a microplastic particle further complicates efforts to build consensus around a standard definition of microfiber, particularly the criteria for material or chemical composition. Definitions also tend to vary in the criteria for other microfiber properties, including size, dimensions, origin, and source, among others. The following table (Table B.1) provides examples of microfiber definitions that have been used in scientific literature over the last 5 years and demonstrates the ways in which existing definitions vary in their criteria for microfiber properties. This variation makes it difficult to compare scientific findings across studies.

Table B.1. Definitions of "microfiber" from scientific literature

Term	Definition	References
Microfiber	Thin or fibrous particles (sometimes also referred to as microfibers); may come from textiles as well as fishing gear and cigarette filters. This definition includes natural and synthetic fibers.	Sutton et al., 2019; Zhu et al., 2021
	Microfibers are any natural or artificial fibrous materials of threadlike structure with a diameter less than 50 μm, length ranging from 1 μm to 5 mm, and length to diameter ratio greater than 100.	Liu, Yang, et al., 2019
	Microfiber refers to the synthetic, artificial, and natural fibers (< 5 mm) released from fabrics during laundering.	Zambrano et al., 2019
	Microfibers are threadlike particles with a length between 100 μm and 5 mm and a width of approximately 1.5 orders of magnitude shorter (than the length).	Barrows et al., 2018
Plastic microfibers	Flexible, with equal thickness and ends that are clear cut, not frayed or tapered.	Gago et al., 2018; Ross et al., 2021
Fibers	Flexible, with equal thickness throughout and ends that are clear cut, pointed or fraying. Typically, they are tensile and resistant to breakage.	Rochman et al., 2019

Governmental/Intergovernmental Agency Definitions for Microfiber

No U.S. Federal agency has adopted an official definition of the term "microfiber," though a few Federal agencies have used the term in reports on microplastics and communications materials. For example, EPA's *Trash Free Waters Report on Priority Microplastics Research Needs* (U.S. EPA, 2021b) defines "microfiber" as "a synthetic fiber in the micro-scale that is characterized by a thin, fibrous shape." The NOAA Marine Debris Program refers to plastic microfibers as "synthetic materials, such as polyester or nylon. Through general wear or washing or drying, these tiny fibers break off and shed from the larger items" (NOAA, 2023).

The California State Water Board is the first regulatory agency in the world to adopt a specific definition of microplastics, in the context of drinking water regulation. It is also one of the few existing definitions of microplastics that provides specific criteria for substance (chemical composition). The California State Water Board definition for microplastics is described in Table B.2. Microfiber particles would be a subtype of microplastics within this definition.

California's definition is deliberately broad and highly inclusive due to the limited knowledge and significant data gaps related to human exposure and health hazards of plastic particles. A staff report on the definition from the California State Water Board explains, "To prioritize the protection of public health in light of the significant scientific uncertainties, 'Microplastics in

Drinking Water' should be defined broadly, and with as few exclusions as possible, to ensure that policies, regulations, and standardized methodologies based on the definition capture a wide diversity of plastic particle types" (California State Water Resources Control Board, 2020).

The California State Water Board based its definition on a regulatory definition of microplastics proposed by the European Chemicals Agency (ECHA) in 2019 that is also described in Table B.2. There are two key differences between the two definitions: 1) ECHA's criteria for microplastics makes an exemption for "biodegradable polymers," while California's definition does not make this exemption due to the uncertainties surrounding the human health effects of biodegradable polymers; and 2) the ECHA definition specifies dimensions and size criteria specifically for "fibres," stating that microplastics must be larger than 1 nm and smaller than 5 mm in all dimensions or "for fibres, (have) a length of 3 nm ≤ x ≤ 15 mm and length to diameter ratio of > 3." California's definition of microplastics does not include a distinct upper size limit for fibers and instead sets 5 mm as the upper size limit for all microplastics, regardless of morphology.

Table B.2. Relevant Definitions of "microfiber" from government agencies

Term	Definition	References
Microplastics in drinking water	Solid polymeric materials to which chemical additives or other substances may have been added, which are particles which have at least three dimensions that are greater than 1nm and less than 5,000 micrometers (µm) (5 mm). Polymers that are derived in nature that have not been chemically modified (other than by hydrolysis) are excluded. Note included with definition: Evidence concerning the toxicity and exposure of humans to microplastics is nascent and rapidly evolving, and the proposed definition of "Microplastics in Drinking Water" is subject to change in response to new information. The definition may also change in response to advances in analytical techniques and/or the standardization of analytical methods.	California State Water Resources Control Board, 2020
Synthetic Polymer Microparticles (with a description of fibres)	A material consisting of solid polymer-containing particles, to which additives or other substances may have been added, and where ≥ 1% wet weight (w/w) of particles have (i) all dimensions 1* nm ≤ x ≤ 5 mm, or (ii), for fibres, a length of 3* nm ≤ x ≤ 15 mm and length to diameter ratio of >3. Polymers that occur in nature that have not been chemically modified (other than by hydrolysis) are excluded, as are polymers that are (bio)degradable. **These lower limits were increased in ECHA (2022) from 1 nm to 100 nm, and 3 nm to 300 nm, based on*	ECHA, 2019; ECHA, 2022

Term	Definition	References
	comments to ensure enforceability.	
Microfiber	A synthetic fiber in the micro-scale that is characterized by a thin, fibrous shape.	U.S. EPA, 2021b
Plastic Microfibers	[A] type of secondary microplastics…made of synthetic materials, such as polyester or nylon. Through general wear or washing or drying, these tiny fibers break off and shed from the larger items. *Note: This is not a formal definition, but rather how plastic microfibers are referred to in communications around this type of debris.*	NOAA, 2023

Microfibers in the Textile Industry

Since the 1950s, the textile industry and other related sectors have used the term "microfiber" to refer to a specific type of product – a "fiber (or filament strand) with a linear density of less than 1 denier" (see Table B.3) below for existing standardized terms used globally by the textile industry today). These "microfibers" are ultra-fine man-made fibers that are produced deliberately for use in apparel, footwear, carpet, bedding, personal care, and other products (Textile Exchange, 2020). Because of the widespread use of the term "microfiber" to refer to an existing product rather than the environmental contaminant described in previous sections of this report, independent of the issue of microfiber pollution, many textile industry professionals have adopted the term "fiber fragment" to refer to the contaminant fibers that are shed from textiles during product life cycles (see the standard definition for "fiber fragment" adopted by the American Association of Textile Colorists and Chemists (AATCC) and the International Organization for Standardization (ISO) below in Table B.3). This shared definition was developed in collaboration with The Microfibre Consortium and textile industry representatives as part of the *Cross Industry Fibre Fragmentation Roadmap*,[12] which lays out a collaborative global strategy to reduce the environmental impacts of fiber fragmentation from textiles. The roadmap includes fiber fragments of any material type (The Microfibre Consortium, 2021).

Table B.3. Important terminology to consider related to "microfiber" from textile literature

Term	Definition	References
Fiber (Fibre)	A general term for any one of the various types of matter that form the basic elements of a textile and that is characterized by having a length of at least 100 times its diameter.	ASTM D123-19, 2019 AATCC TM20A, AATCC M11
	A generic term for any one of the various types of matter that form the basic elements of a textile, and which are generally characterized by flexibility, fineness, and a high	ISO 4484-1(en)

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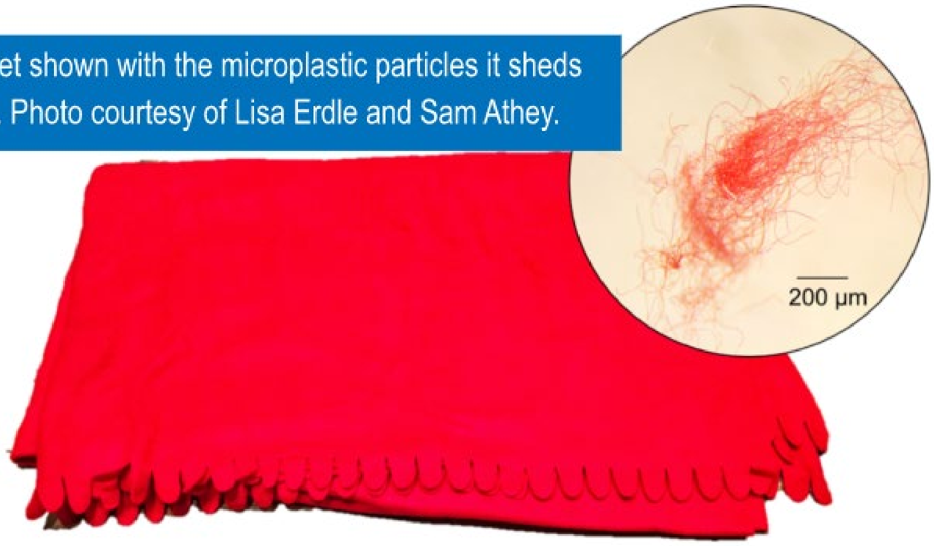
[12] Roadmap can be accessed at: www.microfibreconsortium.com/roadmap

Term	Definition	References
	ratio of length to thickness In textiles, a generic term for any one of the various types of matter that form the basic elements of a textile and which are generally characterized by flexibility, fineness and high ratio of length to thickness	
Natural Fibers	Fibers are identified as having a cellulosic, protein, or mineral base. *Note: This category is harvested from plants, mammals, or other living creatures and is further defined by fiber type in ASTM D7641-21 (2021).*	ASTM D7641-21, 2021
Manufactured Fibers	Fibers identified as having either an organic or inorganic base. A class name for various genera of filament, tow, or staple produced from fiber forming substance which may be (1) polymers synthesized from a chemical compound; (2) modified or transformed natural polymers; or (3) glass. *Note: Synthetic and man-made cellulosic fibers would fall under the category of "manufactured fibers."*	ASTM D7641-21, 2021
Microfiber (Microfibre)	A fiber with linear density less than 1 denier or 1 dtex A filament strand having linear density of approximately 1.0 denier per filament, or less *Note: Only manufactured fibers (also referred to as "synthetic" and "semi-synthetic" fibers) can be identified as microfibers according to the textile industry because the manufacturing process requires that a liquefied solution passes through a spinneret – allowing the cross-sectional measurement to meet the less than 1.0 denier per filament definition. Natural fibers (with the exception of silk) would not demonstrate a denier per filament less than 1.0.*	AATCC TM 212, AATCC M11, ISO 4484-1(en) ASTM D123-19, 2019
Linear Density	For fiber and yarn, mass per unit length	ASTM D123-19, 2019
Denier	The unit of linear density, equal to the mass in grams of 9000 meters of fiber, yarn, or other textile strand that is used in direct numbering system	ASTM D123-19, 2019
Denier per	The mass of a single continuous strand	ASTM D123-19, 2019

Term	Definition	References
filament (dpf)	*Note: Calculated by taking the manufactured yarn sizing (in denier) divided by the total number of filaments.*	
Fiber (Fibre) Fragment	A short piece (typically <5 x 10^-3 m long) of textile fiber, broken away (or separated) from a textile construction. *NOTE: Fiber fragments are of concern as environmental pollutants; they are often referred to as "microfibers" due to their small size*	AATCC TM212 (Wyman, 2021), AATCC M11
	A short piece (typically < 5 × 10^{-3} m long) of textile fibre, broken from the main textile construction *Note: Fibre fragments are of particular concern as aquatic pollutants; they are often incorrectly referred to as "microfibers."*	ISO 4484-1(en)



A fleece blanket shown with the microplastic particles it sheds when washed. Photo courtesy of Lisa Erdle and Sam Athey.

Rationale for Inclusion of Plastic and Non-Plastic Fibers in the Proposed Definition of "Microfiber"

The definition of "microfiber" proposed in Section III includes plastic and non-plastic fibers but does not include fibers that are solely made of natural, non-treated materials. In past research on the prevalence and impacts of microfiber pollution, many environmental studies have focused solely on plastic manufactured fibers. However, recently a growing number of studies have included man-made cellulosic fibers and treated natural fibers in their analysis of microfiber pollution. Figure B.1 below shows the number of studies documenting the abundance of microfibers in various environmental compartments, with studies that reported exclusively synthetic fibers in blue and studies that reported synthetic fibers in addition to non-plastic in orange.

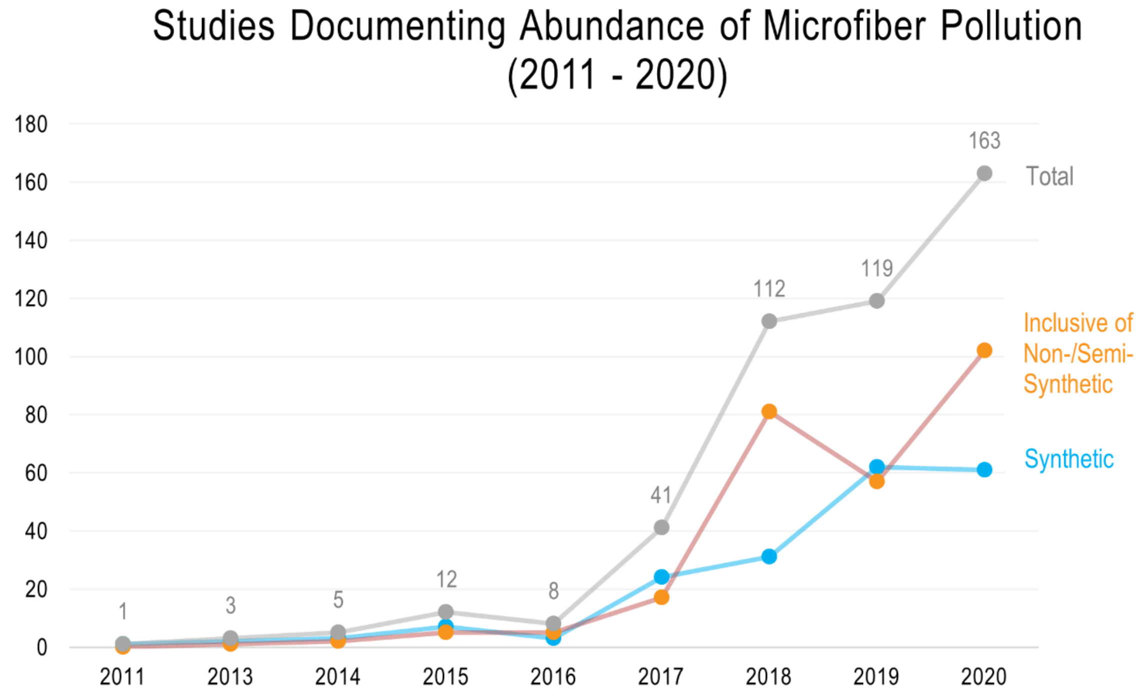


Figure B.1. Studies published in peer-reviewed journals between 2011 and 2020 that document the abundance of microfibers. Graph shows the number of studies that report only plastic manufactured (synthetic) microfibers (blue) and studies that report plastic manufactured microfibers in addition to non-plastic microfibers (manufactured (semi-synthetic) or treated natural microfibers) (orange). Data provided by Athey and Erdle (2022), used with permission from the authors.

The exclusion of non-plastic fibers (e.g., man-made cellulosic fibers and/or treated natural fibers) can be attributed to a variety of factors. First, some studies have shown that man-made cellulosic fibers and treated natural fibers tend to biodegrade more quickly in the environment than synthetic fibers (Puls et al., 2011; Zambrano et al., 2020a), and therefore it has been assumed that non-synthetic fibers are less harmful in the environment than their synthetic counterparts. This assumption is evident in calls for research from funding organizations that prioritize projects focused on synthetic, plastic particles. Furthermore, many of the research methods used to enumerate and characterize microfibers in environmental samples were designed for the recovery of plastic manufactured materials and are not suitable for non-plastic fibers (Athey & Erdle, 2022). As a result, there is significantly more research on the prevalence, fate, and impacts of plastic manufactured microfibers than that of non-plastic microfibers.

Microfibers of all types (e.g., plastic and non-plastic) have been documented across the globe (Athey & Erdle, 2022), and monitoring and detection research suggests that some non-plastic fibers are sufficiently persistent to undergo long-range transport and accumulate in remote environments (Athey et al., 2020; Turner, 2019). While some recent studies suggest that chemical processing of fibers, including dyes and chemical treatments, may make microfibers more resistant to degradation in the environment, it is important to note that research on this is inconclusive (Belzagui et al., 2021; Park et al., 2004; Sait et al., 2021; Sørensen et al., 2020; Zambrano et al., 2020a, 2021). Furthermore, previous studies suggest that non-plastic materials may have a greater capacity to sorb and subsequently disperse chemical additives and hazardous contaminants in the environment when compared to plastic synthetics (Ladewig et al., 2015; Saini et al., 2016). In addition, non-plastic fibers have also been found in a wide range of environmental compartments (Stanton et al., 2019; Suaria et al., 2020) and to have been ingested by aquatic organisms (Cesa et al., 2017; Miller et al., 2017; Remy et al., 2015; Setälä et al., 2014). While little is known about the fates and impacts of various types of non-plastic fibers (Cesa et al., 2017; Zambrano et al., 2020a) as defined by this Report, and some researchers have raised concerns about the potential risks associated with non-plastic fibers (Athey & Erdle, 2022; Ladewig et al., 2015; Stone et al., 2020), it should not distract from the larger body of research showing the prevalence and impacts of microplastic fibers.

More Information Related to Sub-categorizations

Below is additional information on the plastic and non-plastic sub-categorization used in the proposed definition:

Plastic fibers

- *Manufactured:* Today, these fibers are most commonly derived from fossil fuels and sometimes from feedstocks consisting of recycled content (e.g., plastic polyethylene terephthalate (PET) bottles, textile waste) or bio-based materials (e.g., sugarcane, castor oil). The material inputs for this category undergo a process called "polymerization" to create long-chain polymeric structures that are commonly known as "plastics." The polymer is then extruded into fiber form. About 60% of textiles being produced today are made from plastic manufactured (synthetic) fibers (Athey & Erdle, 2022; Cesa et al., 2017), and plastic manufactured fibers account for about 14% of global plastics production (Geyer, 2020). Plastic manufactured fibers make up a majority of fibers sold and used in textile production annually (see Table 1), and research suggests that plastic microfibers are toxic and persistent (see Section IV.D).

Non-plastic fibers

- *Manufactured:* Today, man-made cellulosic fibers are derived from naturally occurring feedstocks like wood pulp consisting of long-chain polymeric structures, such as cellulose, or, less commonly, textile waste feedstocks (e.g., from reclaimed rayon or cotton textile waste). To develop these non-plastic manufactured fibers, the material inputs are chemically processed and formed into fibers via extrusion, similar to synthetic fibers (Athey & Erdle, 2022). Because of the anthropogenic manner in which these fibers are formed and their persistence in the environment, they have been classified as "plastics" by some scientists (Peng et al., 2020; Qu et al., 2018), as well as some policymakers (California State Water Resources Control Board, 2020).
- *Treated natural:* This category does not undergo a human-derived extrusion process to create a fiber and are not considered plastics; however, like all fibers used in textiles, natural fiber textiles are treated through mechanical or chemical processing to alter material properties such as color, appearance, and functional properties (Athey & Erdle, 2022; Lacasse & Baumann, 2012).

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