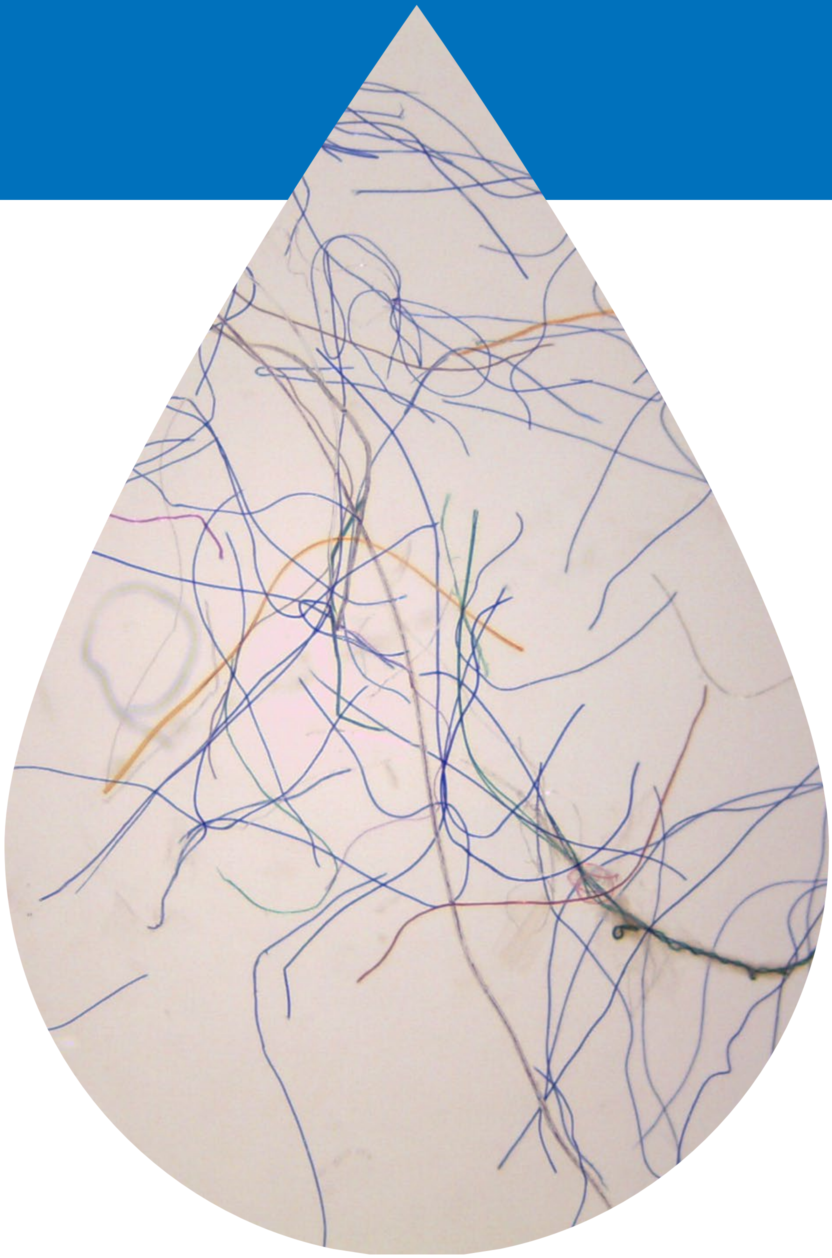

Report on Microfiber Pollution

2022 REPORT TO CONGRESS: DRAFT FOR PUBLIC COMMENT

Report Provided on Behalf of the Interagency Marine Debris Coordinating Committee

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Cover photo courtesy of Sherri A. Mason.

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Executive Summary

Microfibers – synthetic, semi-synthetic, and modified natural fibers – have been found almost everywhere that scientists look, 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] 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 mandated that the Interagency Marine Debris Coordinating Committee (IMDCC) develop a Report on Microfiber Pollution. Under Section 132 of the Save Our Seas 2.0 Act, 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. The United States Environmental Protection Agency's (EPA) Trash Free Waters Program and the National Oceanic and Atmospheric Administration's (NOAA) Marine Debris Program, on behalf of the IMDCC, drafted this report to meet the mandates of Section 132 of the Save Our Seas 2.0 Act.

The Problem with Microfibers

Currently, the majority (about 60%) of fabric produced globally is made with synthetic materials (e.g. nylon, polyester). Researchers have expressed concern about the prevalence and potential environmental and health risks associated with synthetic microfibers as well as semi-synthetic (e.g. rayon) and chemically modified natural microfibers (e.g. cotton, wool). All fibers used in apparel and other textiles, including synthetic, semi-synthetic, and natural materials, are often treated with chemicals, including resins, softeners, dyes, and flame retardants, which may influence the degradability and toxicological hazards associated with microfibers that shed throughout product life cycles. The government, academic, and textile sectors all use different terminology when referring to microfibers, and thus a key goal of this report is providing a definition to serve as a reference point for all sectors engaged in microfiber research and prevention.

Microfibers are a highly complex and diverse type of contaminant and research on the subject is particularly challenging due to a lack of standard definitions and research methods, which make

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

comparisons across studies difficult. Though the public health and environmental impacts of microfiber pollution are largely unknown, there is evidence that organisms might experience physical, chemical, and/or biological impacts as a result of exposure to microfibers (see Section 3.4 Potential Environmental and Human Health Impacts of Microfiber Pollution). Initial studies have found that the ingestion of microfibers by small aquatic organisms can have adverse health effects under laboratory settings. Ingestion of microfibers has been observed in a wide range of aquatic and terrestrial species. In addition to potential physical hazards, 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.

Though several major sources and pathways for microfiber pollution have been identified, more research is needed to quantify microfiber contributions from each of these sources and pathways and how to prevent them from polluting aquatic and terrestrial ecosystems. Many studies have demonstrated that domestic washing machines produce microfibers, though their contribution relative to other sources is unknown. Laundry effluent carries microfibers to wastewater treatment plants (WWTP), which vary in their ability to remove microfibers, but tend to remove the vast majority of the microfibers in wastewater. The microfibers that are not removed during the treatment process are released into the environment. Microfibers that are captured during wastewater treatment may be retained in biosolids, which are often applied to terrestrial environments as soil amendments. Studies have also found that microfibers are released into the air via dryers and regular wear of textiles. Other sources of microfiber pollution include 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.

Efforts by researchers, governments, the private sector, and non-governmental organizations to address microfiber pollution have focused primarily on designing textiles to shed fewer microfibers, using technologies to capture microfibers shed in washing machines and prevent them from entering the wastewater stream, and developing best practices for washing clothes in a way that minimizes microfiber shedding (e.g., water temperature, spin speed, water volume). The success of these and other emerging solutions is highly dependent upon further research to better understand the sources, pathways, fate, and impact of microfibers in the environment. Each 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.

Organization of This Report

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 and a strategic plan for how federal agencies can work to address the problem. Section 2 of the report proposes an initial definition of the term "microfiber." Section 3 is an assessment of the sources, prevalence, pathways and impacts of microfiber pollution. Section 4 discusses the various research methods used to measure microfiber prevalence in various environmental compartments and provides recommendations for the development of standardized methods. Section 5 is a summary of the emerging solutions to address microfiber pollution, and Section 6 summarizes the key research gaps and recommendations based on the information in the previous sections of the report. Finally, Section 7 contains a Federal Plan to Reduce Microfiber Pollution. This is a public review draft, which will be revised as needed in response to the comments received during this public review period before its submission to Congress.

1. Introduction

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. Microfiber pollution refers to the tiny strands of synthetic, semi-synthetic, or non-synthetic fibers that are shed during product life cycles and eventually end up polluting the environment. Microfibers originate from a variety of sources, including textiles (for example, apparel, carpet, upholstery, bedding), wet wipes, cigarette filters, fishing and boating gear (for example, ropes and nets), and other materials (Sutton et al., 2019; Athey and Erdle, 2021). A more precise definition of the term "microfiber" is discussed in later sections of this report.

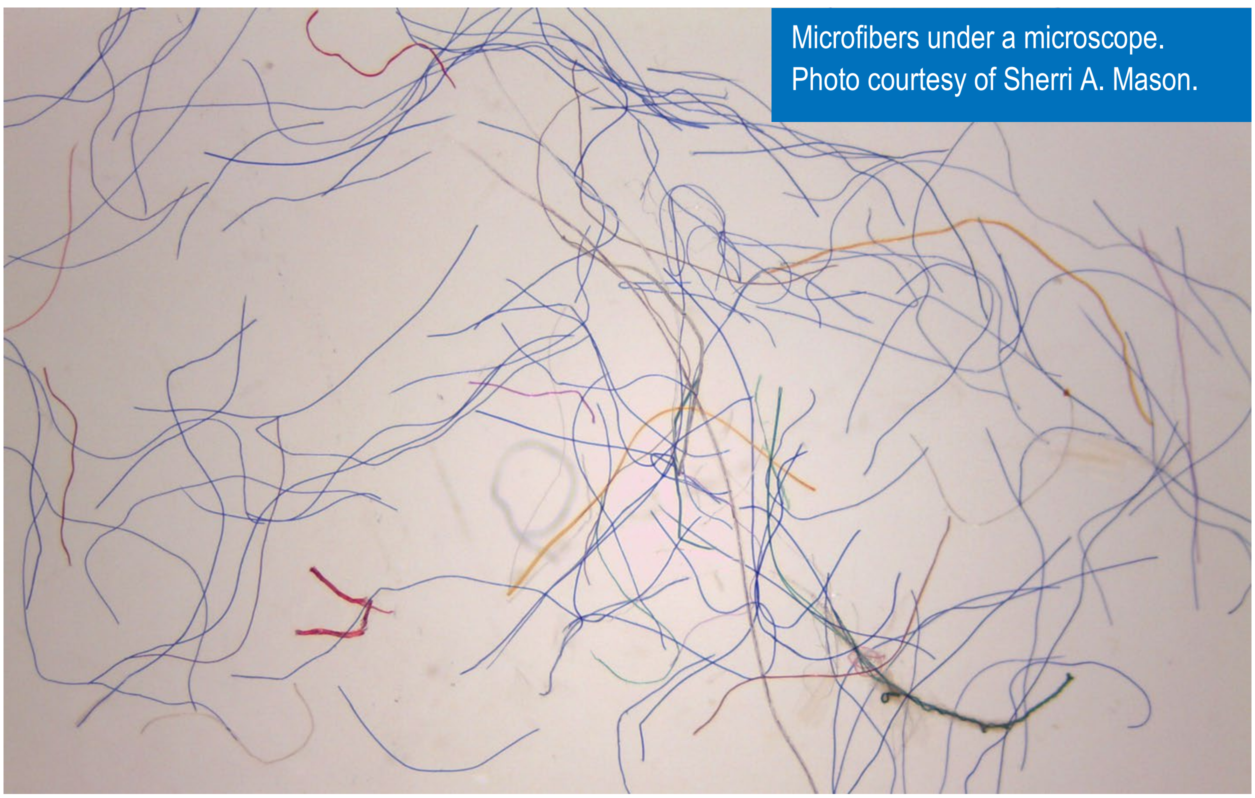
Anthropogenic microfibers derived from natural, semi-synthetic, and synthetic sources have been detected on every continent (61 countries) and in every major ocean and freshwater environment (Athey & Erdle, 2021; Gago et al., 2018; Patil et al., 2021; Suaria et al., 2020), including the remote polar regions (Ross et al., 2021; Moore et al., 2020), 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; Kaya et al., 2018; Gavigan et al., 2020), drinking water and other beverages (Koelmans et al., 2019; Kosuth et al., 2018; Liebezeit and Liebezeit, 2014; Mason et al., 2018), and foods for human consumption (AMAP, 2021; Moore et al., 2020; Rochman et al., 2015; Van Cauwenberghe, L., & Janssen, C. R., 2014).

In the last 20 years alone, global fiber production, both synthetic and natural, has more than doubled, reaching about 122 million tons (about 111 million metric tons) in 2019, and is expected to reach 161 million tons (146 million metric tons) in 2030 assuming business as usual conditions (Textile Exchange, 2020). Most fibers produced today are synthetic and sustain a rapidly growing textile sector. In 2019, synthetic fibers accounted for 63% of global fiber production (Textile Exchange, 2020). Synthetic fibers are a type of plastic. Polyester is the most commonly used type of synthetic fiber, making up 52% of global fiber production in 2019, followed by polyamide, which accounted for 5%. 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). Synthetic textiles are therefore one of the largest sources of microplastics in the environment (Boucher and Friot, 2017).

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 mandated that the Interagency Marine Debris Coordinating Committee (IMDCC) develop a Report on Microfiber Pollution. Under Section 132 of the Save Our Seas 2.0 Act, 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. 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, has developed this Report on behalf of IMDCC.

EPA Trash Free Waters and NOAA Marine Debris Program selected an Expert Advisory Committee (EAC) composed of representatives from relevant academic, government, and industry sectors to provide 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. The EAC was critical in ensuring that Sections 1 - 6 of this report were informed by the most relevant and recent research across a diversity of academic disciplines. IMDCC reviewed and provided comments on a draft of Sections 1 - 6 of this report. These comments have been addressed in this draft of the report, which was used as the basis for developing a Five-Year Federal Plan in collaboration with representatives from many Federal agencies. The plan is included as Section 7 of this report.



Microfibers under a microscope. Photo courtesy of Sherri A. Mason.

2. Defining Microfiber

The term "microfiber" is currently 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). Inconsistency in terminology makes it difficult to compare across sectors and scientific studies, and establishment of a standard definition of microfiber would help to facilitate research, regulations, and mitigation measures related to microfiber pollution. A standardized definition should be informed by a complete understanding of the ways in which the term "microfiber" is currently being used, as well as of future research and regulatory needs. This report summarizes existing definitions from the environmental science, textile industry, and government sectors, and explains the issues that complicate efforts to define the term "microfiber." Finally, we propose an initial definition of microfiber that can serve as a starting point for building consensus around a standard definition that could be adopted by the U.S. Government.

2.1 Existing Definitions of Microfiber

To develop a proposed definition of "microfiber," the authors of this report worked with the EAC to review existing definitions for microfiber that have been used in scientific literature, as well as in communications materials from government agencies, non-governmental organizations (NGOs), and private sector organizations. One of the most significant inconsistencies in existing uses of the term microfiber is around the question of which types of materials – synthetic (sometimes referred to as "plastic"), semi-synthetic (sometimes referred to as "regenerated" or "artificial"), or natural – are included in the definition and are therefore, the focus of research and pollution prevention efforts. These three terms that are used to describe the chemical composition of microfibers are described in more detail below:

- **Synthetic fibers** (e.g., polyester, polyethylene, polypropylene, nylon, polyurethane) are derived primarily from fossil fuels and sometimes from feedstocks consisting of recycled content (i.e., plastic polyethylene terephthalate (PET) bottles, textile waste) or bio-based materials (i.e., sugarcane, castor oil, etc.). The raw materials for synthetic fibers 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 synthetic fibers (Cesa et al., 2017; Athey & Erdle, 2021), and synthetic fibers account for about 14% of global plastics production (Gavigan, 2020).
- **Semi-synthetic fibers** (e.g., rayon, viscose, lyocell, modal) are derived from naturally occurring materials consisting of long-chain polymeric structures, such as cellulose. Despite being derived from natural materials, semi-synthetic fibers are chemically processed and formed into fibers via extrusion, similar to synthetic fibers (Athey & Erdle,

2021). Because of the anthropogenic manner in which these fibers are formed and their persistence in the environment, they have been classified as "plastics" by environmental researchers (Peng et al., 2020; Qu et al., 2018), as well as policymakers (CA State Water Board, 2020).

- **Natural fibers** (e.g., cotton, wool, hemp) are naturally occurring fibers, derived from plant- and animal-based polymers, that do not undergo an extrusion process as they already exist in fiber form. These include wool, cotton, and silk. Natural fibers are not considered plastics; however, like all microfibers used in textiles, they are often incorporated with synthetic dyes, chemical finishes, and other chemical additives that enhance functional properties such as resistance to water or flame (Athey & Erdle, 2021; Lacasse & Baumann, 2004). In this report, natural fibers to which chemical additives or other chemical substances have been added are referred to as "modified natural fibers."

Table 1 below provides an overview of the main types of fibers that were used to make textiles globally in 2019. This table is adapted from OECD's 2021 report titled "Policies to Reduce Microplastics Pollution in Water" and displays data from the Textile Exchange's "Preferred Fiber & Materials Market Report 2020."

Table 1. Overview of Main Textile Types in Production (Source: Textile Exchange (2020) in OECD, 2021)

Fiber type	Resource base	Textile type	% of total textile production
Natural	Plant-based	Cotton	23.2%
		Others: hemp, linen, etc.	5.9%
	Animal-based	Wool	1%
		Others: down, silk	<1%
Semi-synthetic	Cellulose-based	Viscose (rayon)	5.1%
		Others: Acetate, Lyocell, Modal, Cupro	1.3%
Synthetic	Petroleum-derived mostly	Polyester	52.2%
		Polyamide (nylon)	5%
		Others: acrylics, modacrylics, elastane, etc.	5.7%

2.1.1 Microfibers in Scientific Literature

Many scientific studies use the term "microfiber" to refer to a particular morphological category of microplastics (Belzagui et al., 2019; De Falco, 2019; Hernandez et al., 2017) that are commonly described as "fibrous" or "threadlike." Microplastics generally refers 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 currently no universally accepted definition of microplastics. Further, 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 (CA State Water Resources Control Board, 2020). Because microfibers are often defined as a shape category of microplastics, the lack of clarity on which specific substances constitute a microplastic particle further complicates efforts to build consensus around a standard definition of microfiber, particularly the criteria for chemical composition.

In past research on the prevalence and impacts of microfiber pollution, many environmental studies have focused solely on synthetic fibers. The exclusion of semi-synthetic and/or natural fibers can be attributed to a variety of factors. First, some semi-synthetic and natural fibers tend to biodegrade more quickly in the environment than synthetic fibers (Puls et al., 2011; Zambrano et al., 2020), 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 particles. Furthermore, many of the research methods used to enumerate and characterize microfibers in environmental samples were designed for the recovery of synthetic materials and are not suitable for semi-synthetic or natural fibers (Athey & Erdle, 2021). As a result, there is significantly more research on the prevalence, fate, and impacts of synthetic microfibers than that of semi-synthetic and/or natural microfibers.

However, little is known about the fates and impacts of various types of semi-synthetic and chemically modified natural fibers (Cesa et al., 2017; Zambrano et al., 2020), and some researchers have raised concerns about the potential risks associated with non-synthetic fibers (Athey & Erdle, 2021; Ladewig et al., 2015; Stone et al., 2020). Microfibers of all types (i.e., natural, semi-synthetic, and synthetic) have been documented across the globe (Athey & Erdle, 2021), and monitoring and detection research suggests that chemically modified and semi-synthetic natural 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 modification of fibers, including dyes and chemical treatments, may make microfibers more resistant to degradation in the environment, research on this is currently inconclusive (Belzagui et al., 2021; Park et al., 2004; Sait et al., 2021; Sørensen et al., 2020; Zambrano et al., 2020, 2021). Furthermore, previous studies suggest that modified natural and semi-synthetic materials may have a greater capacity to sorb and subsequently disperse chemical additives and hazardous contaminants in the environment when compared to synthetics (Ladewig et al., 2015; Saini et al., 2016). Both semi-synthetic and modified natural fibers have been found in a wide range of environmental compartments (Stanton et al., 2019; Suaria et al., 2020) and have been found to be ingested by aquatic organisms (Cesa et al., 2017; Miller et al., 2017; Remy et al., 2015; Setälä et al., 2014).

Due in part to concerns about the potential impacts of semi-synthetic and modified natural fibers, a growing number of studies have included semi-synthetic and/or modified natural fibers in their analysis of microfiber pollution. Figure 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 semi-synthetic and/or natural fibers in orange.

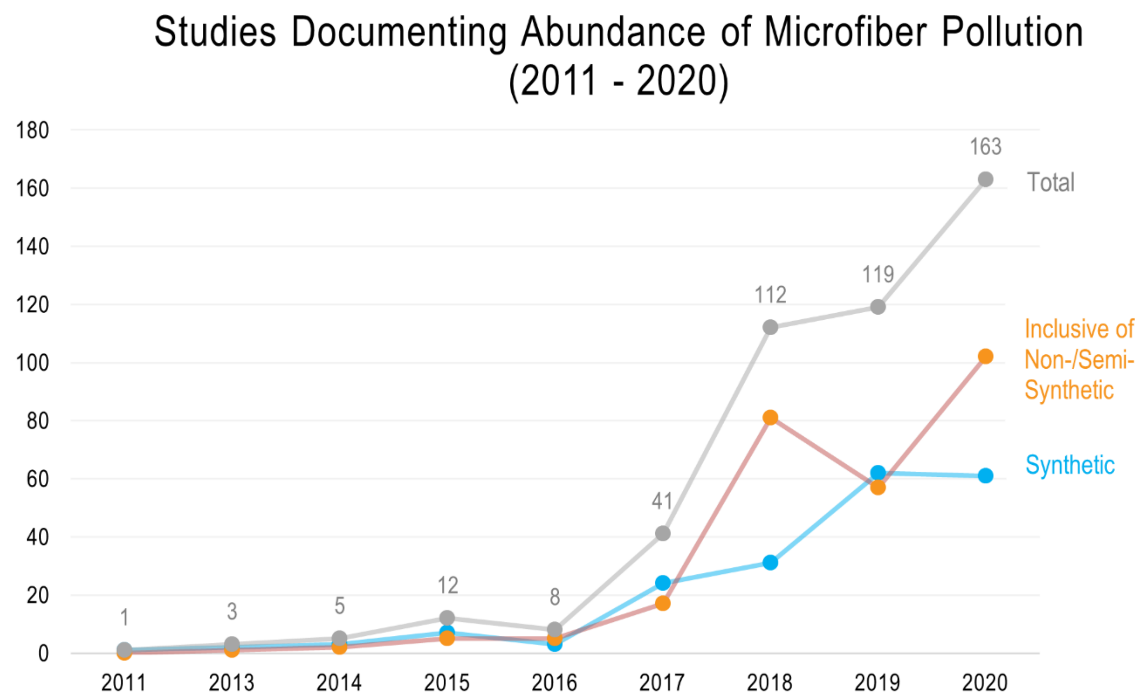


Figure 1. Studies published in peer-reviewed journals between 2011 and 2020 that document the abundance of microfibers. Graph shows the number of studies that report only synthetic microfibers (blue) and studies that report synthetic microfibers in addition to natural and/or semi-synthetic microfibers (orange). Data provided by Athey and Erdle (2021).

In addition to inconsistencies in criteria for material composition of microfibers, definitions also tend to vary in the criteria for other microfiber properties, including size dimensions, origin, and source, among others. The following table provides examples of microfiber definitions that have been used in frequently cited scientific literature over the last five years and demonstrates the ways in which existing definitions vary in their criteria for microfiber properties. This inconsistency makes it difficult to compare scientific findings across studies.

Table 2. Definitions of "microfiber" from scientific literature

Term	Definition	References
Microfiber	Thin or fibrous particle (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 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). *Note: The study in which this definition was used considered synthetic, semi-synthetic, and non-synthetic microfibers.*	Barrows et al., 2018
Plastic microfibers	Flexible, with equal thickness and ends that are clear cut, not frayed or tapered. *Note: This definition is used to distinguish synthetic polymer microfibers from naturally present cellulose fibers during analysis.*	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

2.1.2 Governmental / Intergovernmental Agency Definitions for Microfiber

No U.S. Federal Agency has adopted an official definition of the term "microfiber," though EPA and NOAA have used the term within the context of reports on microplastics as well as communications materials. For example, EPA's *Trash Free Waters Report on Priority Microplastics Research Needs* (EPA, 2021) defines "microfiber" as "a synthetic fiber in the micro-scale that is characterized by a thin, fibrous shape." A NOAA Marine Debris Program webpage summarizing research on microplastics on U.S. National Park beaches defines "microfibers" as "…consist[ing] of synthetic or processed fibers, such as those released from clothing when it's washed or shed from ropes or nets in the ocean. Microfibers may be composed of plastic polymers or naturally occurring fibers (such as cotton)."[2]

The California State Water Resources Control Board (California State Water Board) has taken steps towards defining microfibers within their broader definition for "microplastics in drinking water." The California State Water Board is the first regulatory agency in the world to adopt a specific definition of "microplastics in drinking water." It is also one of the few existing definitions of microplastics that provides specific criteria for substance (chemical composition). The California State Water Board defines "microplastics in drinking water" as:

> *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). Polymers that are derived in nature that have not been chemically modified (other than by hydrolysis) are excluded.*

California's definition of microplastics includes synthetic, chemically modified natural, and semi-synthetic fibers that are greater than 1nm and less than 5,000 micrometers (µm) in size.

The California State Water Board developed this definition to be used in regulatory efforts concerning microplastics in drinking water. The definition was referenced by EPA in its 2021 *Trash Free Waters Report on Priority Microplastics Research Needs* (EPA, 2021). Due to the limited knowledge and significant data gaps related to human exposure and health hazards of plastic particles, California's definition is broad and highly inclusive. 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, the '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 the definition on a regulatory definition of microplastics proposed by the European Chemicals Agency (ECHA) in 2019, though there are two key differences between the two definitions. First, though ECHA's criteria for microplastics specifically excludes "biodegradable polymers," California's definition does not make this exclusion due to the uncertainties surrounding the human health effects of biodegradable polymers. Second, 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 $\leq x \leq$ 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. However, a staff report supplementing California's microplastics definition explains that "A distinctive dimensions criterion for fibers may be included in a future definition of 'Microplastics in Drinking Water' if available standardized methodology, human health

[2] https://marinedebris.noaa.gov/research/quantification-microplastics-and-microfibers-us-national-park-beaches

toxicological information, and occurrence data suggest that such a distinction is necessary" (Coffin, 2020).

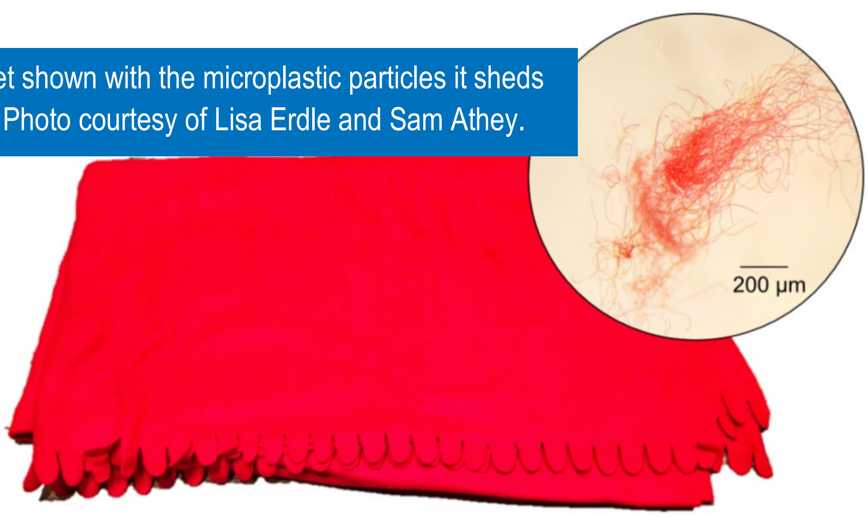
The definition of microfiber proposed in this report is based on California's definition of microplastics in drinking water as well as ECHA's proposed definition of microplastics.

2.1.3 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 – ultra-fine synthetic 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, some textile industry professionals have adopted the term "fiber fragments" to refer to the contaminant fibers that are shed from textiles during product life cycles. The Microfibre Consortium (TMC) is currently working with textile industry representatives to develop a shared definition of "fiber fragment" as part of the *Cross Industry Fibre Fragmentation Roadmap*,[3] 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, including natural, semi-synthetic, and synthetic (The Microfibre Consortium, 2021).

Although we do not recommend adopting the term "fiber fragments" as a replacement for "microfibers," it is important to recognize the inconsistent and potentially confusing ways in which different sectors (e.g., textile industry and environmental science community) use the term "microfibers." Therefore, we recommend acknowledging the term "fiber fragments" as a synonym for "microfibers" to facilitate cross-sector communication.

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



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

2.2 Proposed Definition of Microfiber

For the purposes of this report, the IMDCC proposes the following definition of 'microfiber'. Microfibers are solid,[4] polymeric,[5] fibrous materials:

- to which chemical additives or other substances may have been added, and
- which have at least two dimensions that are less than or equal to 5 mm, length to width and length to height aspect ratios of greater than 3, and a length of less than or equal to 15 mm.

Fibers that are derived in nature that have not been chemically modified (other than by hydrolysis) are excluded.

The purpose of this proposed definition is twofold: first, the definition outlines the scope of this report on microfibers, which includes a "5-year plan for how Federal agencies, in partnership with other stakeholders, can lead on opportunities to reduce microfiber pollution." Second, this definition can serve as a starting point for building consensus around a standard definition that could be adopted by the U.S. Government. The approach used to develop this proposed definition of "microfiber" was driven by the overarching goal of protecting human and ecological health. This approach has resulted in a proposed definition that is highly inclusive. As future research continues to illuminate our understanding of microfibers in the environment (e.g., persistence, mobility, bioaccumulation, toxicity), as it relates to their physical and chemical characteristics, the proposed definition should be refined.

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[4] The following definition is adopted from the California State Water Resources Control Board (2020) definition of microplastics: "Solid" means a substance or mixture which does not meet the definitions of liquid or gas. "Liquid" means a substance or mixture which (i) at 50 degrees Celsius (˚C) has a vapor pressure less than or equal to 300 kPa; (ii) is not completely gaseous at 20 ˚C and at a standard pressure of 101.3 kPa; and (iii) which has a melting point or initial melting point of 20 ˚C or less at a standard pressure of 101.3 kPa. "Gas" means a substance which (i) at 50 ˚C has a vapor pressure greater than 300 kPa (absolute); or (ii) is completely gaseous at 20 ˚C at a standard pressure of 101.3 kPa.

[5] The following definition is adopted from the California State Water Resources Control Board (2020) definition of microplastics: "Polymeric material" means either (i) a particle of any composition with a continuous polymer surface coating of any thickness, or (ii) a particle of any composition with a polymer content of greater than or equal to 1% by mass. "Particle" means a minute piece of matter with defined physical boundaries; a defined physical boundary is an interface. "Polymer" means a substance consisting of molecules characterized by the sequence of one or more types of monomer units. Such molecules must be distributed over a range of molecular weights wherein differences in the molecular weight are primarily attributable to differences in the number of monomer units. A polymer comprises the following: (a) a simple weight majority of molecules containing at least three monomer units which are covalently bound to at least one other monomer unit or other reactant; (b) less than a simple weight majority of molecules of the same molecular weight. "Monomer unit" means the reacted form of a monomer substance in a polymer. "Monomer" means a substance which is capable of forming covalent bonds with a sequence of additional like or unlike molecules under the conditions of the relevant polymer-forming reaction used for the particular process.

We recognize the need for additional criteria in a definition of microfibers that might be used for specific purposes, including but not limited to:

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

This proposed definition may not be sufficiently specific to serve the above listed purposes. Additional coordination and research efforts may be necessary in order to develop fit-for-purpose definitions to supplement the broad definition proposed in this report.

2.3 Rationale for Proposed Definition

This definition was developed through a review of existing definitions of microfiber from government agencies, academic literature, and relevant industries. The authors of this report also received input on the definition from the EAC, as well as reviewers from the IMDCC (including EPA, NSF, and NOAA). The proposed definition is based on the California State Water Board definition of fibers as a particular morphology (particles with a length to diameter ratio of > 3) of "microplastics in drinking water." The one major difference between California's definition and the definition proposed here is in the size criterion for microfibers. Although under California's definition of microplastics, a fiber has a length of no longer than 5 mm, this proposed definition specifies that microfibers can be no longer than 15 mm in length, which follows the dimension and size criteria for "fibres" specified in ECHA's proposed definition of microplastics. Furthermore, unlike the definitions for microplastic from the California State Water Board and ECHA, which set a lower size limit for microplastics of 1 nm in all dimensions, this proposed definition of microfiber does not set a lower size limit.

The rationale for specific criteria under this proposed definition, including the material composition, shape and dimensions, and size, are discussed in the following sections. Based on this rationale, Figure 2 illustrates the key criteria for distinguishing what is and is not a microfiber given the proposed definition above.

2.3.1 Material Composition

The authors of this report, after a review of relevant scientific literature and discussions with stakeholders from academia, government, and the private sector, recommend that a standard definition of "microfibers" include those composed of synthetic, semi-synthetic, and modified natural materials. The proposed defining criteria for chemical composition are modeled after California's substance criteria for microplastics in drinking water, which is based on ECHA's substance criteria for its proposed definition of microplastics, both of which define "polymeric material" as:

> *Either (i) a particle of any composition with a continuous polymer surface coating of any thickness, or (ii) a particle of any composition with a polymer content of greater than or equal to 1% by mass.*
>
> *"Particle" means a minute piece of matter with defined physical boundaries; a defined physical boundary is an interface.*
>
> *"Polymer" means a substance consisting of molecules characterized by the sequence of one or more types of monomer units. Such molecules must be distributed over a range of molecular weights wherein differences in the molecular weight are primarily attributable to differences in the number of monomer units. A polymer comprises the following: (a) a simple weight majority of molecules containing at least three monomer units which are covalently bound to at least one other monomer unit or other reactant; (b) less than a simple weight majority of molecules of the same molecular weight. "Monomer unit" means the reacted form of a monomer substance in a polymer. "Monomer" means a substance which is capable of forming covalent bonds with a sequence of additional like or unlike molecules under the conditions of the relevant polymer-forming reaction used for the particular process.*

Like the ECHA and California State Water Board definitions, the definition of microfibers proposed here specifically excludes "polymers that are derived in nature that have not been chemically modified (other than by hydrolysis)." Examples of natural fibers that have not been chemically modified might include untreated animal hair or wool. Although there is currently limited research on the relationship between the origin of a fiber and its toxicity in the environment, the California State Water Board's staff report explains that the exclusion of unmodified natural polymers is consistent with nearly all academic and regulatory definitions of "microplastics."

Chemically modified natural fibers, as well as semi-synthetic fibers (e.g., rayon), are included in the proposed definition of microfibers because research suggests that the application of chemical additives to natural fibers in the production of fiber-based products may increase their toxicity and persistence in the environment (Athey & Erdle, 2021; Hartmann et al., 2019; Ladewig et al., 2015; Stone et al., 2020). Chemical additives used in the production of textiles include toxic compounds, such as bisphenols, azo dyes, polyfluorinated alkyl compounds (PFAS), and formaldehyde (Athey & Erdle, 2021; Ladewig et al., 2015; Lacasse & Baumann, 2004). Although research on the toxicity of modified natural fibers is limited, early research suggested that leachates and the fibers themselves pose a risk to aquatic organisms (Carney-Almroth et al., 2021; Kim et al., 2021; Mateos-Cárdenas et al., 2021).

Based on the current state of knowledge on the prevalence and impacts of microfibers of various origins, which will be discussed in greater detail in the following sections, the authors of this report recommend that the standard definition of "microfibers" and future microfiber pollution research and mitigation efforts should be inclusive of fibers consisting of synthetic, semi-synthetic, and modified natural materials. However, the criteria for material composition should be updated as needed based on rapidly evolving research on the effects of microfiber type and toxicity.

2.3.2 Shape and Dimensions

This proposed definition also includes defining criteria for particle size and dimensions. The specifications for microfiber dimensions – a length to width aspect ratio of greater than three – is consistent with the morphology of fibers specified within the California State Water Board and ECHA definitions of microplastics.

In academic research on microfibers, there is a high degree of variation in how microfibers are described in terms of dimensions (Table 2). A recommended definition of microfibers proposed by Liu et al. (2019) specified that microfibers have a length to diameter ratio greater than 100, and a study by Barrows et al. (2018) defined microfibers as "a threadlike particle with a length between 100 µm and 5 mm and a width of approximately 1.5 orders of magnitude shorter." Many studies, however, do not specify dimensions for microfibers at all, and instead use qualitative descriptors of fiber shape to distinguish them from other particle morphologies. For example, Moran et al. (2021), in their study of microplastics in urban runoff, characterized fibers as having "a long, narrow thread-like shape, significantly longer in one dimension than in the other two dimensions."

To maintain consistency with shape and dimensions criteria for fibers within existing regulatory definitions of microplastic, we recommend using both a specific criterion for dimensions (a length to width aspect ratio of greater than three) as well as a description of material shape as "fibrous." This specification for shape excludes other particle types, such as spheres, pellets, and fragments.

2.3.3 Size

The upper size limits in the proposed definition of microfiber are based on ECHA's definition of microplastic, which specifies that microplastic fibers have "a length of 3 nm ≤ x ≤ 15 mm and length to diameter ratio of > 3." The proposed definition of microfibers includes fibers that have at least two dimensions that are less than 5 mm and one dimension that is less than 15 mm. The upper size limit of 5 mm for two dimensions is the widely accepted upper size limit for microplastics across academic and regulatory definitions (CA State Water Board, 2020; ECHA, 2020). Due to insufficient research on the relationship between fiber size and toxicological effects, it is not yet possible to define appropriate size criteria based on toxicological considerations (ECHA, 2020).

It is important to note that fibers with a length between 5 and 15 mm would be microfibers under this proposed definition but would not be considered microplastics according to California's definition of microplastics in drinking water. Therefore, research methods for microplastics using California's definition could only be used to recover microfibers with a length of less than 5 mm.

Both ECHA and California State Water Board include a lower size limit in their definitions of microplastics (3 nm in all dimensions and 1 nm in all dimensions, respectively). Hale et al. (2020) explain that the majority of published research on microplastics has focused on materials larger than 100 µm because of methodological constraints, rather than considerations of the impact of particle size on microplastic toxicity. Further, the underestimation of microfiber prevalence in environmental compartments impedes our ability to understand the sources, pathways, impacts of microfiber pollution.

Therefore, the proposed definition of microfiber in this report does not include a lower size limit. However, we recommend that a future definition of microfiber for the purpose of conducting research related to microfiber pollution 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.

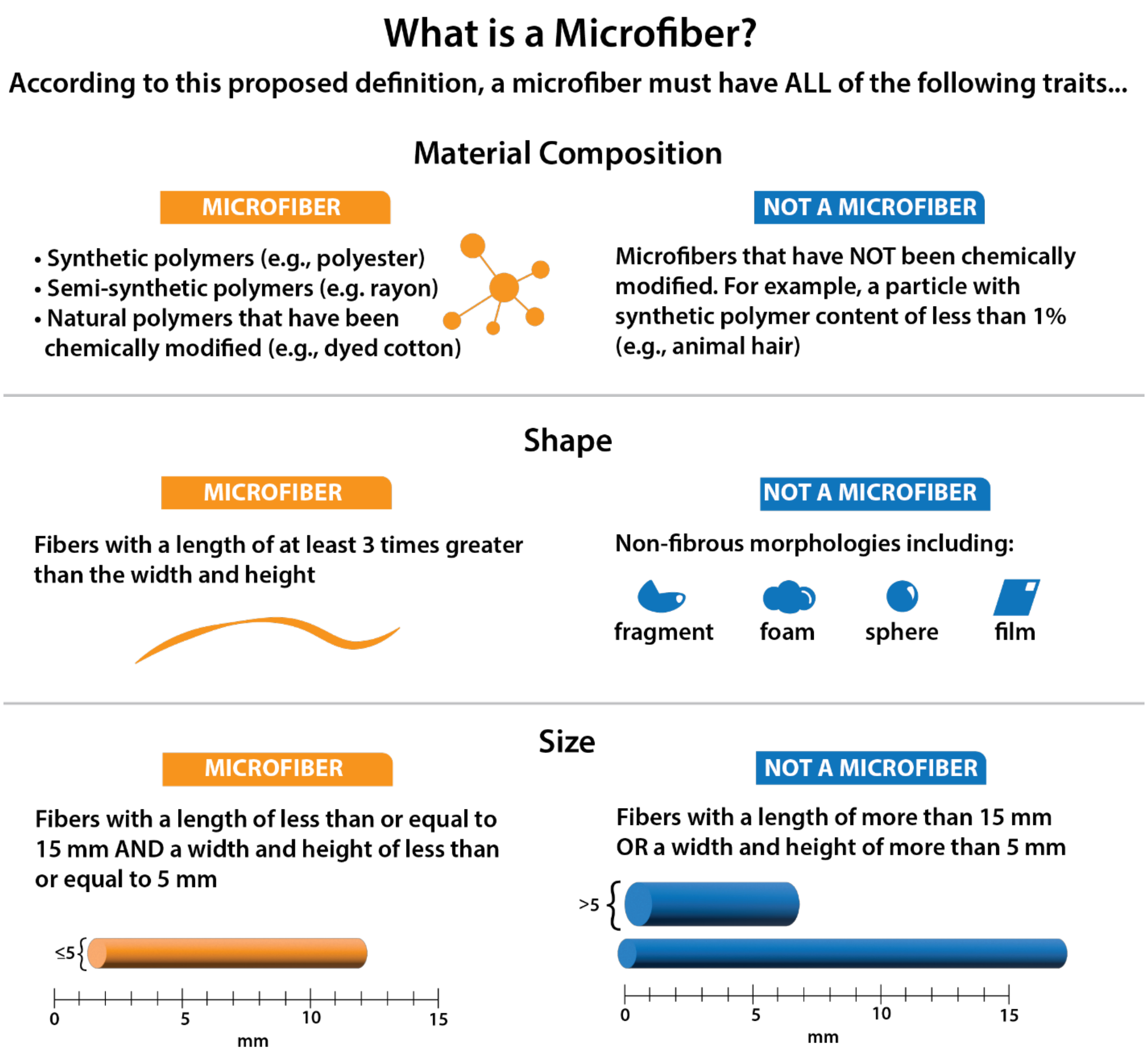

Figure 2. Proposed Microfiber Definition

2.4 Future Considerations

Further study and cross-sector consensus building could help to refine this definition, particularly in the following areas:

1. **Chemical Composition** - Include definitions for subcategories of chemically modified natural, semi-synthetic, and synthetic polymers, as well as a list of examples of common chemical additives.
2. **Shape/Dimensions** - Include more specific characterization of fibrous particles, ensuring other particle types are not included (i.e., non-fibrous particles such as tire rubber fragments).
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 our understanding of fiber biodegradability, explore the possibility of including defining criteria related to the biodegradation potential of polymers, recognizing that biodegradability varies depending on microfiber characteristics and environmental conditions.

According to Coffin et al. (2021), a definition that is aimed at protecting human and ecological health should be highly inclusive to prevent regrettable exclusions and include the hazard traits identified by the California Department of Toxic Substances Control, which defines the following hazard traits related to particles and fibers (22 CCR § 69405.7. Particle Size or Fiber Dimension 2011, 7):

1. The particle dimensions or fiber dimension hazard trait is defined as the existence of a chemical substance in the form of small particles or fibers or the propensity to form into such small-sized particles or fibers with use or environmental release.
2. Evidence for the particle dimensions or fiber dimension hazard trait includes but is not limited to: measures of particle dimensions less than or equal to 10 micrometers in mass median aerodynamic diameter for inhalation exposure, or less than 10 micrometers in any dimension for dermal or ingestion exposure, or fibers with a 3:1 aspect ratio and a width less than or equal to 3 micrometers.

In addition to the above particle-based hazard characteristics, chemical behavior in the environment (e.g., persistence, mobility, bioaccumulation, or toxicity, alone or in combination) is also considered a relevant hazard trait by many regulatory jurisdictions (e.g., California Department of Toxic Substances Control, EPA, ECHA). For example, the California Department of Toxic Substances Control recognizes chemicals classified by the European Union as Substances of Very High Concern as hazardous for the purposes of the Safer Consumer Products Regulations (Cal. Code Regs., title 22, § 69502.2, subd. (a)), which includes substances which are persistent, bioaccumulative, and toxic (PBT), or very persistent and very bioaccumulative (vPvB). The ECHA determined that a PBT/vPvB assessment is not practicable for assessing particulate materials such as microplastics. Although microfibers readily meet the criteria for very persistent (vP) substances in Annex XIII of REACH[6] (ECHA, 2020), the degree to which trophic transfer and bioaccumulation of microfibers occur in the wild at higher trophic levels is largely unknown and more research on this subject is needed (Nelms et al., 2018).

Another important consideration beyond hazard characteristics pertaining to chemical behavior in the environment, a health-informed definition may also consider (eco)toxicological risk assessments based on the derivation of an effects threshold and quantitative risk characterization. Due to uncertainties with respect to microplastics exposure and hazards, the ECHA concluded that "conventional threshold-based risk assessments cannot currently be carried out for microplastics with sufficient reliability…" (ECHA, 2020). Recognizing toxicological uncertainties as well as the irreversible nature of environmental microplastics contamination, the ECHA concluded that human and ecological exceedances of risk "may be considered in terms of when, rather than if" and recommends microplastics be treated as "non-threshold substances" for the purposes of risk assessment – with any released to the environment assumed to result in risk (ECHA, 2020).

[6] REACH is a regulation adopted in 2017 by the European Union to protect human health and the environment from the risks posed by chemicals. It stands for Registration, Evaluation, Authorisation and Restriction of Chemicals. For more information: https://echa.europa.eu/regulations/reach/understanding-reach

3. Assessment of the Sources, Prevalence, and Causes 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, the authors believe that 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.

3.1 Microfiber Sources

Microfibers in the environment come from a wide range of products made from synthetic, semi-synthetic, and modified natural fibers, including textiles, carpets, wet wipes, cigarette filters, and fishing gear (ropes and nets) (Athey & Erdle, 2021; Avio et al., 2020; Barrows et al., 2017; Belzagui et al., 2021; GESAMP, 2015; Murray & Cowie, 2011; Moran et al., 2021). However, due to insufficient research, the relative contributions of these and other sources of microfibers in the environment remain unknown. Microfiber pollution results when fibrous materials shed or break away from the parent item (e.g., yarn, clothing, other textiles, etc.), and escape into the environment at some point during the product life cycle, which includes production, use (including washing, drying, and everyday wear), and disposal (Athey & Erdle, 2021).

3.1.1 Apparel

Apparel is the source of microfiber pollution that has received the most attention from researchers. High concentrations of microfibers have been documented in washing machine effluent, suggesting that because it is regularly washed, apparel is likely a major contributor of the microfiber pollution in wastewater (Gavigan et al., 2020; Hartline et al., 2016; Hernandez et al., 2017; McIlwraith et al., 2019). Based on the findings of twelve 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 7.17 million tons (6.5 million metric tons) of synthetic microfibers have been shed by apparel and emitted via hand and machine washing globally, with annual microfiber emissions 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 synthetic microfiber emissions from domestic laundry, finding that about 0.28 million tons of microfibers were released per year. Both studies only considered synthetic 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.

3.1.2 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.

3.1.3 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 feminine sanitary products, as well as geotextile products (Kwon et al., 2021). 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., 2021). However, several studies have examined microfiber shedding from specific nonwoven products, including wet wipes (Lee et al., 2021) and feminine hygiene products (Ó Briain et al., 2020b). 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 and Balasaraswathi, 2021; Saliu et al., 2021; Shen et al., 2021).

3.1.4 Non-Textile Sources

There are several studies that 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 to the environment. A single cigarette filter contains over 12,000 fibers composed of cellulose acetate (a semi-synthetic fiber derived from natural materials) with a suite of chemical additives (Pauly et al., 2002). Cigarette filters, also known as cigarette butts, are the most common littered item found in 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).

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). Additionally, 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.

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; Weldon & Cowie, 2017; Wright et al., 2021). Studies have found synthetic 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 et al., 2021). However, few studies have directly measured microplastics and microfiber emissions from sources related to boating and fishing.

Use, durability, chemical composition, care, and end-of-life for various fiber-based products differ significantly and, therefore, mechanisms for release of microfibers vary as well. The table below lists known and likely sources of microfiber pollution, the potential mechanism for microfiber release, 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.

Table 3. Microfiber Pollution Sources

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 et al., 2018, 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., 2021; 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

Source Type	Potential Mechanism for Release	Literature Reference(s) Available
Textiles (e.g., apparel, bedding, footwear, upholstery)	Manufacturing / production process	The Nature Conservancy & Bain & Company, 2021; Zhou, H. et al., 2020;
	Disposal, landfill	Liu, J. et al., 2019
Fiber-based vehicle parts (i.e., tires, brake pads, belts, etc.)	Vehicle use, tire wear	Kole et al., 2017; Sutton et al., 2019
Carpet	General use, cleaning, landfill degradation	Alipour et al., 2021; Soltani et al., 2021
Personal care products (i.e., “flushable” wet wipes, feminine products, diapers, etc.)	Flushed into wastewater, general use, landfill degradation	Lee et al., 2021; Martínez Silva & Nanny, 2020; Ó Briain et al., 2020b
Facemasks	General use, landfill degradation	Chen et al., 2021; Fadare & Okoffo, 2020; Saliu et al., 2021; Shruti 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 geo-textiles	General use, degradation	Bai et al., 2021
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 et al., 2021

3.2 Microfiber Prevalence in Environmental Compartments

Microfibers have been found nearly everywhere that scientists look, 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, 2021). Microfibers have even been found in pristine 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, 2021; Barrows et al., 2018; Liu et al., 2019).

As discussed in Section 2, 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 synthetic fibers in field samples do not report the abundance of semi-synthetic or modified natural fibers found in the same samples (Athey & Erdle, 2021; Barrows et al., 2018). In a review of 465 studies that document the abundance of microfibers in various environmental compartments, Athey and Erdle (2021) found that most research prior to 2017 has focused primarily on synthetic microfibers. Following 2017, however, there has been a large increase in the number of studies that include semi-synthetic and modified natural fibers. In the following sections, we will reference microplastics studies that report only synthetic fibers as well as microfiber studies that report synthetic, semi-synthetic, and modified natural fibers.

In the following summary of scientific literature, we also distinguish 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 material type (includes all types of microplastics and semi-synthetic and natural 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 (2021) 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, 2021). Based on their literature review, the authors identified several environmental compartments that are particularly understudied in research on microfibers, including terrestrial environments, groundwater, ice and snow, and indoor air and dust (Athey & Erdle, 2021). The following sections summarize the existing literature on the prevalence of microfibers in various environmental compartments.

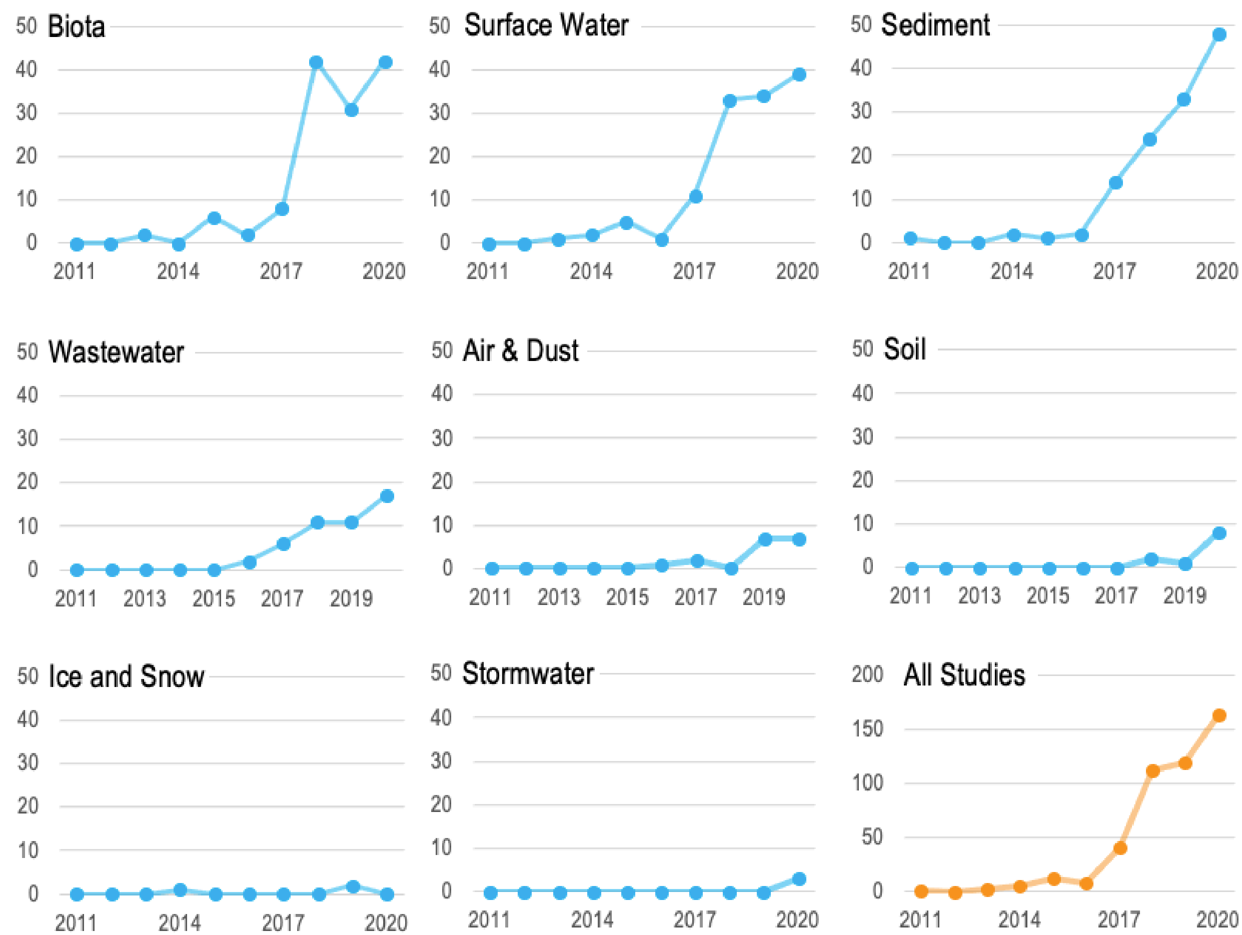

Figure 3. Number of studies published in peer-reviewed journals (y-axis) between 2011 and 2020 (x-axis) that document the abundance of microfibers in various environmental compartments. Data from Athey and Erdle (2021)

Caution is necessary when directly comparing microfiber contamination across studies, due to the use of different study objectives, sampling and analysis approaches, and quality control procedures, as well as inconsistencies in the size ranges of microplastic particles and microfibers studied. Variations in research methods for measuring microfiber pollution are discussed further in Section 4 of this report.

3.2.1 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 this 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 U.S. (Baldwin et al., 2016a; 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 U.S., 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 these tributaries enter the Great Lakes, data indicate that those microfibers sink due to their density (Baldwin et al., 2016b; 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; Selvam et al., 2021; Samandra et al., 2022), 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, 2021; Re, 2019).

Similarly, there are also limited studies on microfiber pollution in ice and snow, despite the fact that approximately 75% of Americans in the Western U.S. depend on ice and snow melt for freshwater (Athey & Erdle, 2021). 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).

3.2.2 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: the loose sand, clay, silt, and other soil particles that eventually settle at the bottom of oceans, rivers, and lakes (Athey & Erdle, 2021; Ballent et al., 2016; Claessens et al., 2011; Haave et al., 2019; Lenaker et al., 2019; Nguyen et al., 2020; Zhang 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 (Yu et al., 2018; Whitmire & Toline, 2017). A 2017 NOAA Marine Debris Program funded study (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 the shorelines on the Pacific and Atlantic coasts, as well as Alaska and the Great Lakes (Whitmire & Toline, 2017). Another study documented similar trends along sandy beaches in the Gulf of Mexico (Yu et al., 2018).

There are a number of pathways by which microfibers can enter beaches and sediments, including 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 (Nguyen et al., 2020).

3.2.3 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, K. 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, K. et al., 2019). These levels are influenced by meteorological conditions (e.g., precipitation and wind conditions), population density, and human activity (Liu et al., 2019; Dris et al., 2016; Wright et al., 2020). Further, 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 levels detected in outdoor air (Athey & Erdle, 2021; Dris et al., 2016; Prata et al., 2020). Concentrations in indoor air range from 0.4 to 59.4 particles/m^3 (Dris et al., 2017; Lui et al., 2019; Abbasi et al., 2019). 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 modified natural fibers dominating both indoor and outdoor samples (Dris et al., 2016; Gasperi et al., 2018; Gaston et al., 2020).

3.2.4 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; Grbić et al., 2020; Zhou et al., 2020;). Microfibers can move from the soil surface to waterways via erosion, surface runoff, or wind-driven processes (Kim et al., 2021).

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, where they may contaminate groundwater supplies (Chia et al., 2021; Kim et al., 2021; Huang et al., 2021). These mechanisms include agricultural practices such as tillage (Zhang & Liu, 2018), water infiltration and vertical transport from surface soils to subterranean soils and groundwater (Huang et al., 2021), and activities of soil-dwelling biota such as earthworms (Cao et al., 2017; Rillig et al., 2017).

3.2.5 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 synthetic, semi-synthetic, and modified natural microfibers (Waddell et al., 2020; Carlin et al., 2020; Zheng et al., 2020).

Studies on marine fish and invertebrates are most prevalent in scientific literature, but researchers have also studied biota in freshwater and terrestrial habitats (OECD, 2021; Wong 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, 2021). These studies are summarized in Table 4 below. In addition to these studies, 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 (Desforges et al., 2015).

Table 4. Number of studies published between 2011 and 2016 that document the abundance of microfibers in biota. (Data from literature review by Athey & Erdle (2021))

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 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; Kühn 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; 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 2,000 meters (Taylor et al., 2016). Many more studies have observed the ingestion of microfibers by invertebrates in laboratory experiments (Au et al., 2017; Foley et al., 2018; Jemec et al., 2016; Ziajahromi et al., 2017).

Research on microfiber occurrence in freshwater biota, though less prevalent than studies on marine 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).

Studies suggest that depending on the feeding mechanisms and behaviors of species, as well as the characteristics of microfibers in aquatic habitats, such as size, color, chemical composition, and shape, aquatic organisms may mistake microfibers for food (Patil et al., 2021; Galloway et al., 2017, Savoca et al., 2016; Bessa et al., 2019). Biota can also be exposed to microplastics through the ingestion of contaminated prey, a phenomenon known as trophic transfer (Athey et al., 2020; Provencher et al., 2019; Mateos-Cardenas et al., 2019; Moore et al., 2020). 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).

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 et al., 2019). There are very few studies on microfiber occurrence in terrestrial biota.

3.2.6 Drinking Water and Food for Human Consumption

Though there is currently 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 inconsistent research methods, including inconsistencies in the size of microplastic particles analyzed and 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 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).

In a systematic review of microplastic contamination of 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 contamination. Of the six studies on tap water, five reported fibers in samples (Pivokonsky et al., 2018; Shruti et al., 2018; Strand et al., 2018;[7] Tong et al., 2020; Zhang et al., 2020). Mintenig et al. (2019) did not analyze fibers present in samples due to

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

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).

Studies that examined microplastic particles smaller than 100 µm in length have found that drinking water samples tend to contain a higher amount of small microplastic particles (smaller than 100 µm in length) than large particles (larger than 100 µm) (Marsden et al., 2019).

A 2019 report on microplastics in drinking water by the World Health Organization (WHO) 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 four years of testing and reporting of microplastics (including microfibers under 5 mm in length) 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 above in Section 2 of this report, 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).

3.3 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). 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 3) (Gavigan et al., 2020; Grbić et al., 2020; Sutton et al., 2019). For microfiber sources, refer back to Section 3.1. The reported pathways and sources 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) activities, such as fishing, aquaculture, boating and other vessel-based activities, and these pathways should be further researched.

As discussed in the previous section, researchers have found that washing apparel and other textiles in washing machines tends to produce large amounts of microfibers, which are released in wastewater from washing machines (Gavigan et al., 2020; Athey et al., 2020; Browne et al., 2011; Carney Almroth et al., 2018; Cesa et al., 2020; De Falco et al., 2018, 2020). Several studies have demonstrated that 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., 2021b; Xu et al., 2018; Zhou et al., 2020; The Nature Conservancy & Bain & Company, 2021).

Microfibers shed from apparel and other land-based sources and enter aquatic environments via atmospheric transport and deposition (Barrows et al., 2018; Carr, 2017; Dris et al., 2016), run-off from terrestrial environments (Baldwin et al., 2016), and stormwater and wastewater systems (Browne et al., 2010; Napper & Thompson, 2016; Mason et al., 2016; Gago et al., 2018). 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 4) (Athey & Erdle, 2021; Browne, 2015; Browne et al., 2011; McCormick et al., 2014). More recently, research has begun to highlight 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, ingested by biota, settle into sediments, or re-enter the atmosphere (Allen et al., 2020; Mishra et al., 2019).

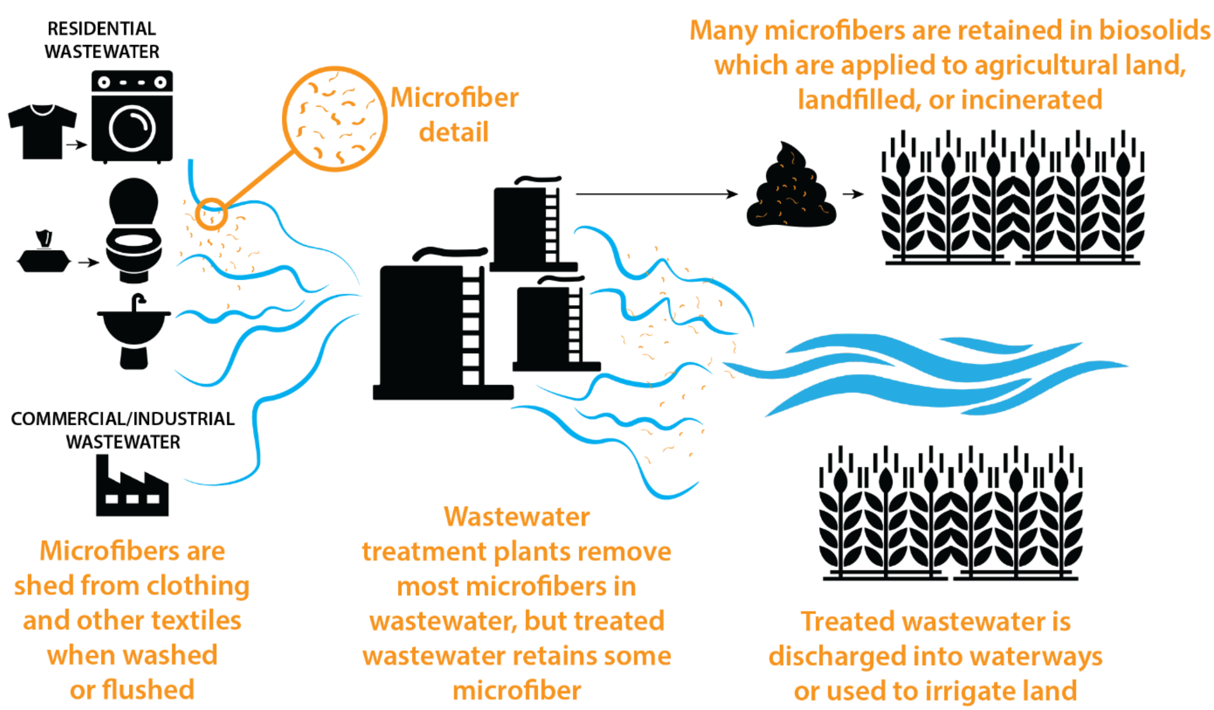

Figure 4. Wastewater as a Pathway for Microfiber Pollution

3.3.1 Microfibers in Wastewater

Wastewater is an important transport pathway for microplastics, particularly microfibers, (Cowger 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, which in the U.S. is usually processed through treatment facilities before being released into the aquatic environment.

Several studies have identified fibers as the most common type of microplastic particle entering wastewater treatment plants (WWTPs) (Gies et al., 2018; Johnson et al., 2020; Kay et al., 2018; Sun et al., 2019; Zhang et al., 2020). While global WWTP infrastructure has not been developed specifically to remove 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 (Habib et al., 2020; Gavigan et al., 2020). Estimates for microfiber emissions 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 characteristics. However, variations in research methods limit our 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 currently 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 WWTPs across the U.S. found that an average of 4 million microplastic particles, mostly fibers and fragments, were released by each facility per day, with discharges ranging from 50,000 to 15 million particles per WWTP per day (Mason et al., 2016).

As of 2012, 14,748 publicly owned WWTPs serve about 76% of the U.S. population. Of the population served by WWTPs, 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 U.S. 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 (Connor, 2017). There is a significant need for further research on the emissions of microfiber pollution via untreated wastewater.

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 (Gies, 2018; Mahon et al., 2017). In most countries, including the U.S., 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 increased crop yields, improved soil structure, and preservation of limited landfill space. U.S. EPA (2019) estimates that of the roughly 4.75 million dry metric tons (dmt) of biosolids produced by large WWTPs in the U.S. in 2019, 51% were applied to land (1.4 million dmt applied to agricultural land; 1 million dmt applied to non-agricultural land), 16% were incinerated, 22% were landfilled, 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., 1998a; Mahon et al., 2016; Wang 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. (2016) 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, 2021). This pathway requires further examination and evaluation of mitigation measures.

Combined Sewer Overflows

Combined Sewer Systems (CSS) 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 U.S. have combined sewer systems, most of which are located in the Northeast and Great Lakes regions (U.S. EPA, 2004). During heavy precipitation, CSS 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 (CSOs), 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 CSOs as pathways for microplastics and microfibers is not well understood, with few studies available on the issue to date (Chen et al., 2021; Dris et al., 2019; Gies et al., 2018). Microfibers could enter CSS through domestic or industrial wastewater or through stormwater. High concentrations of microfibers in CSOs have been reported in Paris, where researchers found between 192,000–241,000 microplastic particles per m^3, with approximately 84% of the particles being microfibers (Dris et al., 2019) and Shanghai, with between 110,000–9,700,000 particles per m^3, with 55% of the particles being microfibers (Chen et al., 2020).

3.3.2 Stormwater

Unlike CSS, municipal separate storm sewer systems (MS4s), which are common in cities across the U.S., are designed to collect stormwater from urban areas and discharge it directly into local water bodies without treatment (Figure 5). MS4s convey stormwater separately from commercial and domestic wastewater, which is conveyed by a different system of pipes referred to as sanitary sewers.

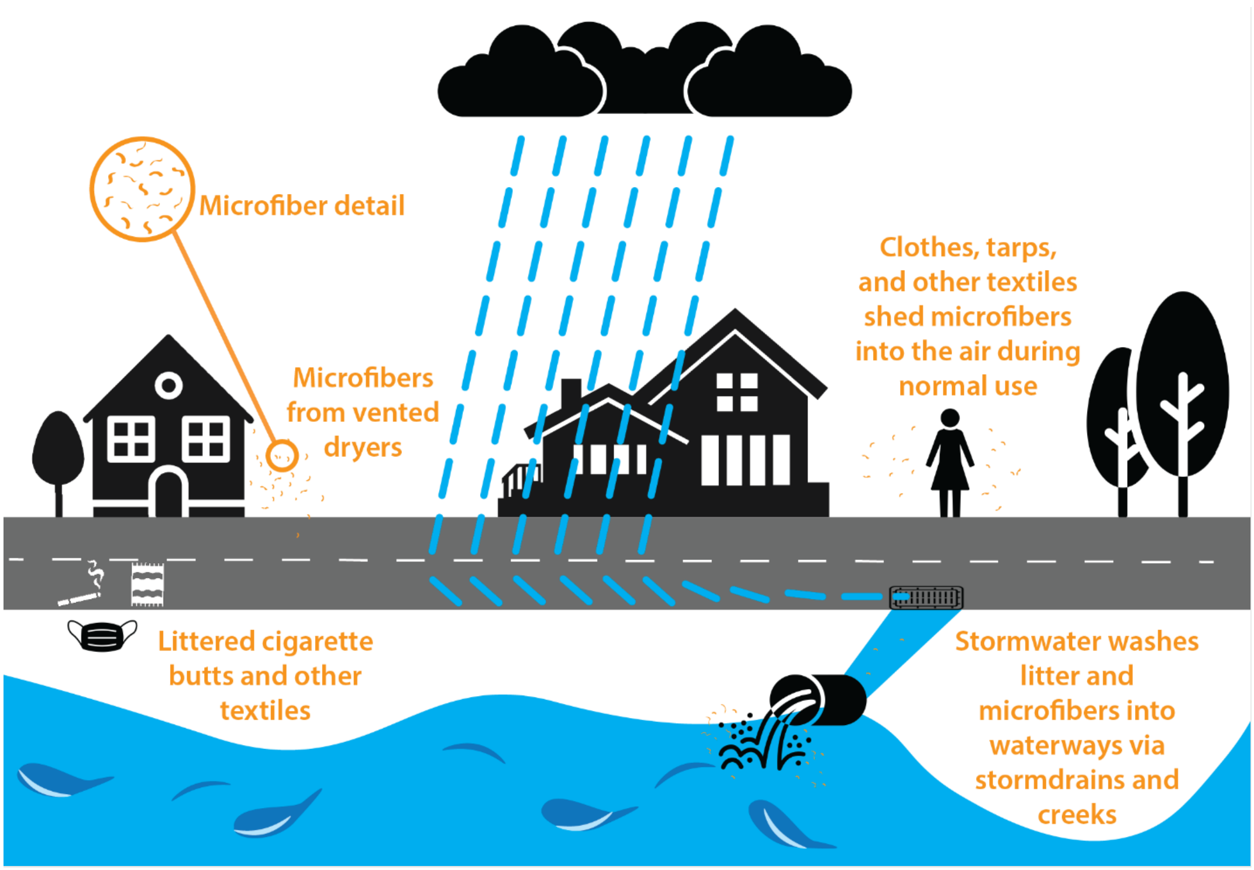

Figure 5. How microfiber pollution enters waterways via stormwater

Researchers have identified municipal stormwater as a potentially significant pathway for microplastics and microfibers, though this pathway is understudied relative to wastewater as a pathway for microplastics and microfibers (Bailey et al., 2021; Dris et al., 2018; Liu et al., 2019; Zhu et al., 2021). Several studies have reported microfibers in urban stormwater runoff, sampled directly from street runoff or at a stormwater catchment point. 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), Denmark (Liu 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, surface water, and sediment. 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 WWTP 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, comprising 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.

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 the concentration of contaminants and debris in stormwater runoff (Gilbreath et al., 2019; Werbowski et al., 2021). There are several studies that measure microplastics contamination in influent and effluent of rain gardens and bioretention cells (Smyth et al., 2021; Gilbreath et al., 2019; 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.

3.3.3 Atmospheric Transport

Though research is limited, atmospheric transport has been identified as an important pathway for microfibers into all environmental compartments (Gasperi et al., 2017; De Falco et al., 2020). 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. This includes during textile production (Dris et al., 2016), as well as normal wear and use (De Falco et al., 2020). 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).

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 condenses 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 U.S. are vented dryers, with ventless dryers representing approximately 1% of the market in the U.S. (Energy Star, 2011).

Laboratory testing of dryers as a source of microfibers to the environment is currently limited to only a few peer-reviewed studies (Pirc et al., 2016; O'Brien et al., 2020; Kapp & Miller, 2020; Kärkkäinen & Sillanpää, 2021; 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).

Future studies should measure the dryer exhaust directly (as in Tao et al. (2022)) and consider a variety of dryer models and designs. 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). Further, while ventless and vented dryers may vary in microfiber emissions, most studies to date employ vented dryers. In these studies, variations in the cycle settings and test textiles make comparisons across studies challenging (O'Brien et al., 2020; Kapp & Miller, 2020; Pirc et al., 2016).

More research is needed to better understand atmospheric transport pathways, including the fate of the airborne microfibers once released to air (O' Brien et al., 2020; Kapp and Miller, 2020; Cheng et al., 2016). Additionally, research is needed to understand how meteorological conditions, such as wind, influence the transport of microfiber-laden air and dust throughout the natural environment (Kapp & Miller, 2020).

3.3.4 Aquatic Activities (fishing, boating, etc.)

Some marine and freshwater activities result in emissions of microfibers directly into oceans, rivers, and lakes. These activities include fishing and aquaculture as well as any vessel-based activity (e.g., shipping, recreational boating, or the use of any vessel that uses ropes such as for mooring lines). Studies on these potential sources and pathways are lacking.

3.4 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 6). 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).

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 – synthetic, semi-synthetic, and modified natural – are extremely diverse in their size, solubility, material composition, and sorbed chemicals. There are many different polymer types and chemical additives used in fiber-based products such as clothing (Darbra, 2011; Rochman, 2015). Additionally, 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-synthetic fibers (i.e., natural and semi-synthetic fibers), which are often left out of microplastics toxicity studies, are understudied relative to synthetic fibers.

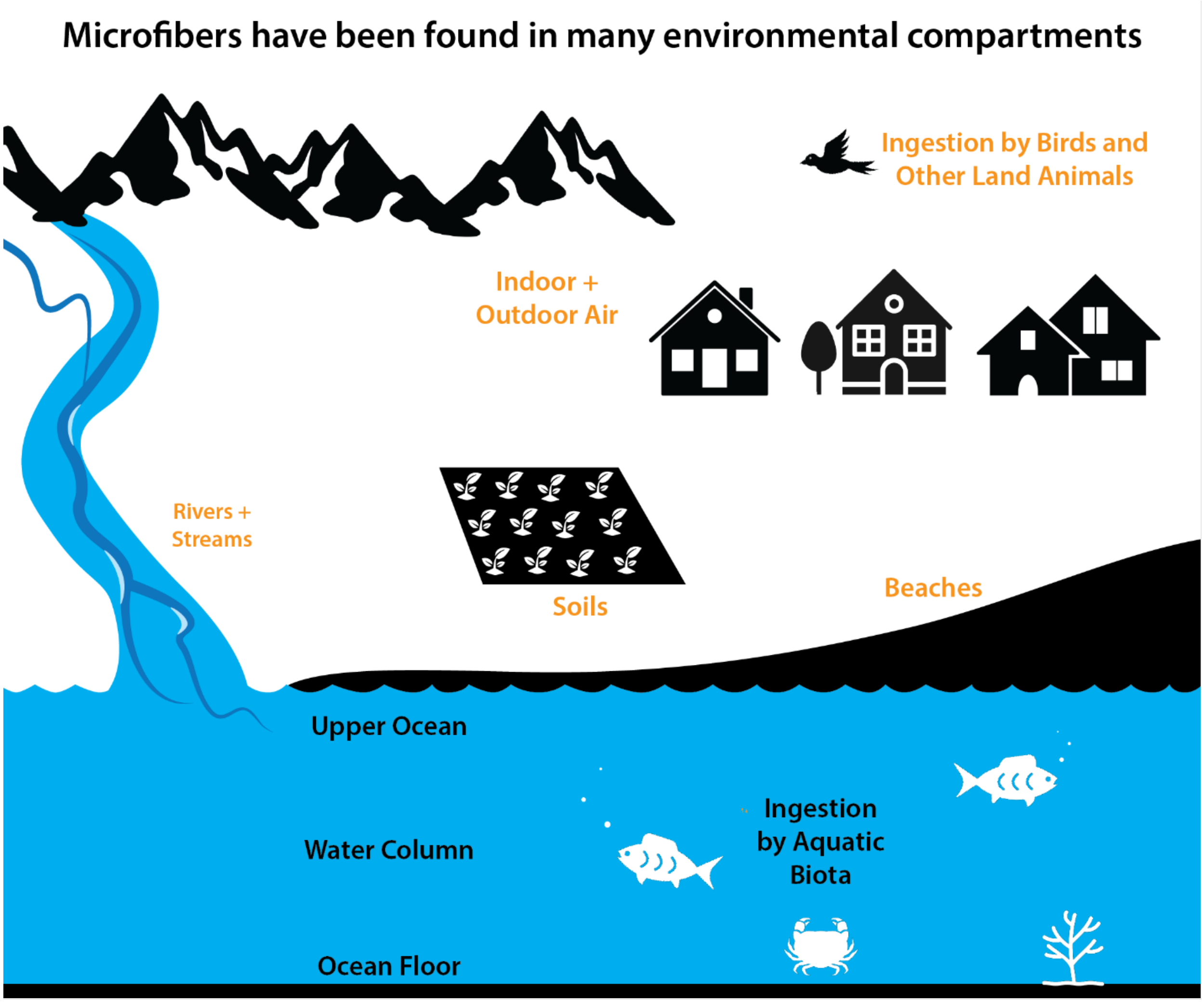

Figure 6. Occurrence of microfiber pollution in various environmental compartments

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") (Zhu et al., 2020; Wang et al., 2019; Lacasse & Bauman, 2012), 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 (i.e., spinning and yarn oils, binding functional chemistry, etc.), providing performance characteristics for the end user (i.e., stain- and water- repellent, waterproof coatings, anti-wrinkle, anti-microbial, etc.), 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, 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 natural, semi-synthetic, and synthetic textiles (i.e., apparel, agro/geo, footwear, carpeting, upholstery, medical, etc.) 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 (PFAS Free Products Page, 2019). 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, 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 microfibers sorb contaminant depends on the chemical and physical characteristics of the microfibers (including age and weathering) as well as the types and amounts of chemical contamination that the microfiber is exposed to (Rochman et al., 2014). Few studies have investigated the combined toxicity of microfibers and other pollutants. Interactive effects of coincident chemicals (including additives and sorbed chemicals), as well as other environmental stressors, such as elevated temperature and 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 impacts are largely unknown.

3.4.1 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, 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, T. 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 little 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 type of 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 (Murray et al., 2011).

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 waterflea (*Ceriodaphnia dubia*), Ziajahromi et al. (2017) found that waterfleas 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 waterflea. 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 goldfish (*Carassius auratus*) 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).

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 due to 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 and Weinstein, 2017). In a study on freshwater zooplankton (*Ceriodaphnia dubia*), 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* (freshwater zooplankton crustacean) 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. However, 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, 2021). There are also several studies that have observed impacts in marine biota exposed to environmentally relevant concentrations of microfibers.

3.4.2 Impacts on Terrestrial Soil and Biota

Terrestrial species are also 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 et al., 2017). 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 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, Machado et al. (2018) found that microfibers lead to increased water holding capacity of the soil, decreased soil bulk density, and decreased water stable aggregates, changes that might affect soil functions and plant growth. 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 (Lozano et al., 2021; de Souza Machado et al., 2019).

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). 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 (Machado et al., 2019).

3.4.3 Impacts on Humans

The potential impact of microfiber pollution on human health is currently 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; Prata, 2018; Catarino et al., 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; D'Angelo & Meccariello, 2021; Palacios-Mateo et al., 2021). However, there is currently insufficient research 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, material 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 (WHO) to develop an evaluation of the human health risks associated with microplastics in drinking water. In the WHO 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 cellulosic and synthetic 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 synthetic 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 micro- 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 microplastics 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). Additionally, 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, a precautionary approach to managing microfibers is recommended (Brander et al., 2020; Coffin et al., 2021).

4. Recommendations for a Standardized Methodology to Measure and Estimate the Prevalence of Microfiber Pollution

Most research focusing 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, 2021; Brander et al., 2020; Cowger, Booth, et al., 2020).

Athey and Erdle (2021) 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 the fibers consisting of natural, semi-synthetic, and synthetic materials (Athey & Erdle, 2021). With varying definitions, it is difficult to compare results across studies and draw definitive conclusions necessary for informing microfiber pollution control and mitigation measures. Additionally, 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 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 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 (Cowger et al., 2021; Provencher et al., 2020; AMAP, 2021). Since microfiber pollution is found in all environmental compartments and requires a wide range of field and lab 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.

4.1 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 incorporating standardized methods that include stringent quality assurance and quality control (QA/QC) measures.

4.1.1 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 (i.e., meteorological conditions, depth, salinity, sediment deposition rates, water flow rates), characteristics of the sample matrix (i.e., water content, porosity, sediment grain size, organic matter content), and reporting terminology (i.e., 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 et al., 2020).

The unit of measurement for microfiber release often varies across studies, making comparisons among studies that utilize 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., 2021). Counting microfibers is a time-consuming approach and most studies require sub-sampling, where microfibers are counted on a selected area of the filter containing the entire sample (De Falco et al., 2018; Napper & Thompson, 2016) or within a small aliquot 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.

4.1.2 Quality Assurance and Quality Control Measures

Because microfibers are so prevalent in indoor and outdoor spaces, they can contaminate research spaces, both during 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 (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 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 (Woodall et al., 2015; Rochman et al., 2019). 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 personal protective equipment (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 filter) 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 material type of fabrics worn by study personnel so that they can be compared to sample fibers. Further, 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. 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).

Another element for quantifying microfiber contamination is to collect procedural blanks to determine the limit of detection. Blank samples are samples collected alongside project samples to understand if there are any microfibers entering the samples from another source. Further investigation may find that microfibers are coming from another source, such as shedding from researchers' clothing or from a dirty ventilation system, etc. In this field of study, the limit of detection (LOD) is defined as the lowest concentration at which microfibers can be reliably identified in a sample apart from background contamination. Methods for determining LODs from procedural blanks are not standardized within the microplastics field and remain a challenge given the diversity of particle characteristics (Wong and Coffin, 2021; Brander et al., 2020; Primpke et al., 2019; Rochman et al., 2019).

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., 2021; 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, the 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.[8] 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. (2021) 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).

[8] https://www.sccwrp.org/about/research-areas/additional-research-areas/trash-pollution/measuring-microplastics-workshop/

4.2 Field Sample Collection

As discussed in Section 3, 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 specific 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 5, 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.

4.2.1 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; E. Miller et al., 2021). Approximately one third of microfiber studies in surface waters employed the use of coarse mesh nets (>300 µm) and, therefore, underestimated microfiber concentrations due to insufficient capture (Athey & Erdle, 2021).

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, where sample jars are filled and later analyzed at the lab, and filtration samples, where a designated amount of surface water is passed through a filter that is sent to a 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). Further, 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 have we seen an increase in the collection of 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).

4.2.2 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; Y. Zhou 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.

4.2.3 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 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, 2021; Dris et al., 2017; Vianello et al., 2019b; Zhang et al., 2020). An evaluation of methods for detecting other airborne contaminants may be helpful in developing appropriate methodologies for detecting airborne microfibers.

4.2.4 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, 2021). 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, 2021; 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 D8333-20, 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 (e.g., wastewater entering a wastewater treatment plant) and overflow wastewater from combined sewer overflow events (e.g., usually larger rain events where wastewater enters the environment untreated) (Conley et al., 2019) are important points to measure to accurately estimate microfiber capture and emissions 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.

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) 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 synthetic microfiber emissions 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; Liu et al., 2021; de Jesus Piñon-Colin et al., 2020; 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. In San Francisco Bay, a recent study showed that microplastics concentrations in the stormwater pathway were 140 times greater than the microplastics concentration entering the Bay from treated wastewater (Zhu et al., 2021).

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, microplastics and macroplastics 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 et al., 2019, Sutton et al., 2020).

4.2.5 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 (World Health Organization, 2019). The most prevalent inconsistencies in field methods used were the volume of water filtered for each sample and the quality assurance and quality control (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 drinking water methods to analyze microplastic concentrations (including microfibers) using Raman or infrared spectroscopy (Wong & Coffin, 2021). The method is mandated by law to be developed by July 1, 2021, and will be tested for four years, while also reporting microplastics concentrations during the testing phase (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.[9]

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. The Section 304 Report to Congress is due in December 2022.

4.2.6 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 4.3.2). Typically, studies measuring microfiber contamination in macrofauna have focused on select organs for examination, primarily the gastrointestinal tract and muscle tissue (Rochman et al., 2015; Philipp et al., 2022), while studies on microfauna and -flora typically measure microfiber contamination within the whole organism (Monteiro Absher et al., 2018; Mahara et al., 2022). As for other environmental matrices, replicate samples or

[9] https://www.sccwrp.org/about/research-areas/additional-research-areas/trash-pollution/measuring-microplastics-workshop/

specimens collected at each site are required for robust sampling (Brander et al., 2020). Additionally, 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).

4.2.7 Groundwater, Ice, and Snow

Over the last two 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 (Kumar and Sharma, 2020; Chia et al., 2021; Huang et al., 2021; Bharath et al., 2021; Selvam et al., 2021; Samandra et al., 2022; Mintenig et al., 2019; Panno et al., 2019), 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 L) 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 is difficult but critical to better understanding snow as a transport medium for microfibers (Kinar & Pomeroy, 2015).

Table 5. Summary of methods and key considerations related to microfibers for each environmental compartment

Compartment	Methods
Ocean, estuaries, rivers, and lakes	Manta trawl, neuston and bongo nets
	Bulk sampling (grab samples and pumps)
Beaches, sediment, and soils	Grab samples
	Box corers, Ekman dredge, Van Veen grab sampler, and remotely operated vehicles
Air	Filtration and surface deposition sampling
	Outdoor and indoor sampling
Wastewater, sludge, and stormwater	Bulk samples (filtration and grab samples) for liquids
	Grab samples for solids
Drinking water and food	Bulk sampling (filtration)
Biota	Species sampling (organs, tissue, and entire animal)
Groundwater, ice, and snow	Bulk samples (filtration and grab samples)

Key Considerations

- More investigation and further method development are needed in understudied compartments (e.g., air).
- Additional research is needed to develop the most robust standardized methods and guidelines to confidently measure microfibers within individual environmental compartments.
- 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 our understanding of microfibers in field settings.
- Influent waters (wastewater entering a wastewater treatment plant), overflow wastewater from combined sewer overflow events (usually larger rain events), sludge, and stormwater sampling are understudied compared to wastewater effluent, and need standardized field methods.
- Consideration for sampling volume is essential for ensuring accurate representation of ambient microfiber levels in drinking water and other pathways.
- Standardized methods for drinking water should consult other projects, such as those created for microplastic monitoring by the California State Water Resources Control Board.
- Efforts required by Save Our Seas 2.0 Act, Section 304, should be consulted.

4.3 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 6 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. As discussed earlier in this section, there are multiple working groups focused on microplastics, and it may be beneficial to organize a working group focused on microfiber research.

4.3.1 Techniques for Characterizing Anthropogenic Microfibers

Microfibers under a microscope. Photo courtesy of Sherri A. Mason.

There are generally two main ways in which anthropogenic 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) (Zhu et al., 2019; Athey & Erdle, 2021). 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 et al., 2019). Approximately 98% of studies that employ spectroscopic techniques for identifying polymer composition of microfibers use FTIR or Raman spectroscopy (Athey & Erdle, 2021). Other methods include pyrolysis-GCMS (gas chromatography/mass spectrometry). However, pyrolysis-GCMS is less common as it requires destruction of the particle to determine material 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 material is excited by a laser. Because of the technical challenges in analyzing microfibers, (i.e., 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., surface morphology) to support the spectral identification of fibers (Athey & Erdle, 2021; Munno et al., 2020), in addition to shared spectral databases built specifically for the analysis of microplastics (including fibers) (Cowger et al., 2020; Cowger et al., 2021).

Zhu 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. Additionally, the high cost and time-consuming nature of spectroscopic techniques has led researchers to explore other methods to distinguish between synthetic particles and those naturally present in the environment. 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 synthetic microplastic particles detectable under a microscope. Zhu 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 (Center for Earth System Research and Sustainability (CEN), 2017; Maes et al., 2017; Zhu et al., 2019). More research is needed to assess the applicability of lipophilic staining for rapid detection and quantification of synthetic fibers (Catarino et al., 2018; Devalla et al., 2019; Prata et al., 2020; Stanton et al., 2019). Zhu 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. Synthetic microplastics can be visually identified based on their response to contact with the hot needle. (Kapp et al., 2018; Karlsson et al., 2017; Vandermeersch et al., 2015). The hot needle method is a low-cost way to verify synthetic microplastic particles but cannot identify microplastics by polymer type (Kapp et al., 2017). Overall, more research is needed to develop reliable low-cost methods to characterize microfibers.

4.3.2 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, 2021). 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 some cases 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 length and temperature (Athey & Erdle, 2021). Oxidative agents (e.g., hydrogen peroxide) are the most common digestants used in the microfiber literature (Athey & Erdle et al., 2021). Chemical digestion has been applied to aquatic sediments (Yao et al., 2019; Zheng, Y. 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). These digestants should be used with caution as recovery testing using synthetic and 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, which allow dye to penetrate more readily.

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, 2021). Similar to oxidative agents, KOH has been found to cause degradation of some anthropogenic microfibers (Cai, Yang, et al., 2020; Dehaut et al., 2016; Treilles et al., 2020; Karr et al., 2020). Furthermore, natural fibers are more degraded with KOH treatment than synthetic 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 synthetic and non-synthetic fibers is rare. More than 18% of studies on microfiber pollution include methods with unknown impacts on microfiber recoveries and, therefore, could underestimate anthropogenic microfiber levels (Athey & Erdle, 2021). Future research should include quality control measures to estimate the method's precision and accuracy (e.g., percent recovery, relative standard deviation).

Table 6. Laboratory Studies to Analyze Microfibers, Techniques, and Key Considerations

Studies	Techniques
Techniques for characterizing microfibers	Optical microscope
	Spectroscopy microscope
	Other
Microfiber enumeration methods	Filtration, subsampling, chemical digestion, density-based separation

Key Considerations

- Standardized laboratory methods are needed that describe the steps to characterize microfibers.
- Though costly, spectroscopy is often needed to understand polymer type of microfibers.
- More research is needed to develop reliable low-cost, accessible methods to enumerate, 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).

4.4 Additional Recommendations for Developing Standardized Methodologies

In addition to the key considerations specific to developing methods for field and laboratory research presented in Tables 5 and 6, the authors of this report and the EAC developed the following broad recommendations 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. National-level efforts to develop standard research methods should focus on microplastics in general, with the inclusion of specific 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 our understanding of the sources and pathways of microfiber pollution. This recommendation has implications for the definition of "microplastics." In order to ensure that standard methods for researching microplastics include all types of microfibers as defined in this report, the methods would need to utilize a standard definition of "microplastics" that is inclusive of modified natural, semi-synthetic, and synthetic materials. California's definition of "microplastics in drinking water" is an example of a definition for microplastics that is inclusive of microfibers (only those under 5 mm in length) as defined in this report (see Section 2 for a 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 utilizing various methods for field sampling, isolation, extraction, and characterization of microplastics. Researchers have routinely highlighted the need for standardized or harmonized sampling and analysis protocols. Working groups of leading experts and researchers have also collaborated to generate best management practices for designing and conducting robust research on microplastics and microfibers (AMAP, 2021; Athey & Erdle, 2021; Brander et al., 2020; Cowger 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.

5. 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. The section that follows is 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 3 (Assessment of Sources, Prevalence, and Causes of Microfiber Pollution), though textiles 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-specific pollution emissions from non-textile sources. However, efforts to reduce marine debris in general could have the effect of reducing microfiber pollution from some source. For example, proper disposal of cigarette butts would help to reduce the amount of cigarette butts polluting the environment, which become sources of microfibers when they break down (Belzagui et al., 2021). More 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.

5.1 Rethinking Textile Design, Production, and Disposal

5.1.1 Designing Low-Shedding Fabrics

One potential way to reduce fiber shedding from textiles is to design and construct textiles that shed fewer or no 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). Though research on these topics is ongoing, significantly more research is needed to develop effective guidelines for producing low-shedding fabrics. Furthermore, 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 we use. This complexity makes research and development for low-shed textile innovation particularly challenging.

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. This research is also needed to inform the design of downstream mitigation strategies related to laundering practices and technology, which will be discussed in a later section. 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. Additional research on these pathways is needed to inform upstream and downstream solutions.

Over the last five years, the textile industry (mostly apparel) has been focused on the development of a testing methodology to measure fiber release in simulated laundering from garments and textiles. In the U.S., 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 (AATCC TM212-2021).[10]

The Microfibre Consortium (TMC), a UK-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 TMC's broader collaborative efforts to generate the necessary knowledge to develop materials with lower shed rates. TMC created a "Microfibre Data Portal" to house data on microfiber shedding obtained using the TMC test method, which will allow researchers to share data more easily.[11]

Some researchers in the textile industry are working to develop more biodegradable fibers, which might be a less harmful alternative to non-biodegradable synthetic fibers. 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.

Conservation X Labs is a company that is working to stimulate research and development for solutions to the microfiber pollution problem through the Microfiber Innovation Challenge,[12] which awards $650,000 to upstream innovations that prevent microfiber shedding. The innovation challenge finalists include sustainable fibers derived from alternative materials like seaweed and citrus, as well as technologies to enhance the surface of fibers within a fabric to prevent microfiber shedding.

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[10] https://aatcc.org/tm212/

[11] https://www.microfibreconsortium.com/tools

[12] https://www.microfiberinnovation.org/

5.1.2 Reducing Microfiber Pollution During Textile Production

Research on mitigation measures to reduce microfiber emissions during the textile manufacturing process is extremely 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 & Co (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 emissions include better understanding the relative emissions 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, TMC 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. TMC aims to release manufacturing guidance resources in 2022.[13]

5.1.3 Reducing Textile Waste by Reusing and Recycling

Textile waste in the U.S. is outpacing the growth of every other major category of waste. Between 2000 and 2018, textile waste as a share of total municipal solid waste in the U.S. increased from 3.9% to 5.8% (US EPA, 2020). Of the 17 million tons of textile waste generated in the U.S. in 2018, about 14.7% was recycled, 66.3% was landfilled, and 18.9% was combusted (US EPA, 2020).

Reusing and recycling 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. However, more research is needed to assess the viability of textile reuse and recycling as solutions to microfiber pollution. Specifically, there is a need for research on the relationship between fiber release and garment age. Though one study found that artificially aged textiles release more microfibers than newer ones (Hartline et al., 2016), several studies have shown that new garments and fabrics generate 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 & Sainnio, 2017). One study hypothesized that the observed reduction in microfiber release after 5-6 washings could be due to the depletion of production-inherited microfibers trapped within the textile structure (Cai et al., 2020a). This points to the need for further investigation by designers and manufacturers on best practices upstream in manufacturing. 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 reuse of priority products.

[13] https://static1.squarespace.com/static/5aaba1998f513028aeec604c/t/614c3c6638f8535da9393e4e/1632386153639/V5-Microfibre-2030-Commitment-Launch-Report.pdf

Similarly, though the textile industry is making progress on mechanical and recycling systems for natural, semi-synthetic, and synthetic textiles, there is insufficient research on the relationship between recycled fiber content and microfiber release from textiles (Frost et al., 2020) to assess the possible effectiveness of this solution.

5.2 Reducing Emissions 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.

Several studies have found that changes to the way clothes are washed can result in reduced fiber shedding. For example, Lant et al. (2020) found that utilizing 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). Another study found that microfiber release decreased with repeated wash cycles. The study hypothesized the reduction could be due to the removal of residual production-related microfibers trapped in textile structure from manufacturing (Cai, Mitrano, 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 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). Other studies showed 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 emissions. 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 emissions from washing machines is to capture and dispose of the microfibers in washing machines' effluent. Several after-market washing machine filters and in-wash filter capturing products are currently 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. The Swedish Environmental Protection Agency funded the Zero Microplastics Challenge 2020,[14] an innovation challenge that aimed to stimulate the development of microfiber capture and removal technologies for washing machines.

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. A 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) (Vassilenko et al., 2021). The retention was higher for polyester fibers (80–90%) compared to nylon (~40%). Napper et al. (2020) looked at 6 different devices, both in-drum and external filters, and reported a range of 21%–78% efficiency for the devices (Napper et al., 2020). 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 (to be discussed later). 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. Additionally, dryer model and size, air flow, cycle settings, internal screen design, ducting, and vent design may all influence the amount 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.

5.3 Government-Led Initiatives

Some national and state government bodies have begun to take steps to manage and reduce microfiber pollution through legislation, planning, and research. The European Union has taken significant steps to reduce plastic pollution broadly, beginning in 2015 when the European Parliament banned single-use plastic bags and, more recently, single-use plastic items, like utensils, straws, coffee stirrers, wet wipes, and expanded polystyrene take out containers. More recently, the European Union's 2018 Strategy for Plastics in a Circular Economy Commission

[14] https://www.ri.se/en/what-we-do/projects/zero-microplastics-challenge-2020

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.[15]

In the United States, federal agencies including the National Oceanic and Atmospheric Administration (NOAA), EPA, United States Geological Survey (USGS), and National Institute of Standards and Technology (NIST) 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. However, federal funding for future research to address the specific knowledge gaps related to microfiber pollution is crucial for the development of solutions to the microfiber pollution problem.

EPA's Trash Free Waters program, which co-led the development of this report, works to reduce the volume of trash entering US 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 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 program is mandated to lead national and regional coordination, and to assess, research, prevent, reduce, and remove marine debris, and to address the adverse impacts of marine debris on the economy of the United Sates, the marine environment, and navigational safety. These mandates and authorities are the foundation for the six pillars of the Program: prevention, removal, research, monitoring and detection, response, and coordination. Marine Debris Program staff is positioned across the country in order to support projects and partnerships with state and local agencies, tribes, non-governmental organizations, academia, and industry. The 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

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[15] https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000041553759/

marine debris. A few plans have identified microfibers as a potential threat and knowledge gap (e.g., California's Ocean Litter Prevention Strategy, the Mid-Atlantic Marine Debris Action Plan, and the Long Island Sound Marine Debris Action Plan). Additionally, the Program has funded research projects on microplastics, many of which include microfibers.

In the U.S., California and Connecticut have taken steps towards better understanding microfiber pollution and related solutions through statewide legislation. 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.[16] Additionally, California has adopted a Statewide Microplastics Strategy, which was developed by the California Ocean Protection Council.[17] 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 multiple proposed bills that address microfiber pollution, including two recent bills: Assembly Bill 622[18] that required filtration on new washing machines, and Assembly Bill 802[19] that mandated the California Regional Water Control Board to identify the best available control technology for filtering microfibers from an industrial, institutional, or commercial laundry facility. Although neither bill was passed into law, similar legislation may be introduced in future sessions of the California State Legislature.

The Connecticut legislature passed Public Act 18-181[20] 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. 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).

5.4 Messaging & 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

[16] https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB1422

[17] https://www.opc.ca.gov/webmaster/ftp/pdf/agenda_items/20220223/Item_6_Exhibit_A_Statewide_Microplastics_Strategy.pdf

[18] https://leginfo.legislature.ca.gov/faces/billStatusClient.xhtml?bill_id=202120220AB622

[19] https://leginfo.legislature.ca.gov/faces/billStatusClient.xhtml?bill_id=202120220AB802

[20] https://www.cga.ct.gov/2018/act/pa/pdf/2018PA-00181-R00HB-05360-PA.pdf

existence of microfibers and their potential impacts (Herweyers et al., 2020). This is comparable to a UK census study that gauged the public's awareness of microfibers and found that 44% of the 2,000 UK residents surveyed were unaware of microfibers as a plastic pollution issue.[21]

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 microfibers pollution. The Ellen Macarthur Foundation created the "What's in my Wash" campaign,[22] which aims to raise public awareness of the microfiber pollution from clothes and encourages individuals to take measures to care for their clothes in a way that is likely to minimize microfiber shedding and increase the clothes' lifespan. 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[23] to educate the public about microfiber pollution from washing clothes. 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 synthetic 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 synthetic 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 synthetics, but based on existing research, it is not yet clear that natural fibers (most of which are chemically modified for use in apparel) are a less harmful alternative to synthetics. Therefore, this guidance should be avoided until there is more research available.

5.5 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

[21] https://envirotecmagazine.com/2018/06/06/research-reveals-limited-public-awareness-of-clothing-microfibres-in-human-food-chain/

[22] https://www.whatsinmywash.org.uk/the-microfiber-issue

[23] https://www.oceancleanwash.org/

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[24] (SAPEA), European Commission's Group of Chief Scientific Advisors,[25] European Union's Group of Experts on the Scientific Aspects of Marine Environmental Protection[26] (GESAMP), and Organization for Economic Co-operation and Development[27] (OECD) 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 (Bren), 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 2016 by Ocean Wise Conservation Association. 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 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 our 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).

[24] https://www.sapea.info/wp-content/uploads/report.pdf

[25] https://ec.europa.eu/info/sites/default/files/research_and_innovation/groups/sam/ec_rtd_sam-mnp-opinion_042019.pdf

[26] http://www.gesamp.org/

[27] https://www.oecd.org/water/oecdworkshoponmicroplasticsfromsynthetictextilesintheenvironmentknowledgemitigationandpolicy.htm

6. 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, the authors, in collaboration with the EAC, have developed the following summary of key research needs and recommendations to guide efforts to address microfiber pollution in the U.S. 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. The EPA and NOAA drew from these recommendations and the identified research needs to inform the development of the Federal Plan to Reduce Microfiber Pollution in the following section of this report.

6.1 Major Knowledge Gaps and Key Research Needs

6.1.1 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 at length in Section 4, 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 our 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 as needed for each environmental compartment)
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

6.1.2 Knowledge Gap 2: Impacts of microfiber pollution

More research is needed to understand the toxicity of 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 our understanding of the risks associated with microfiber pollution is the degradability of various types of microfibers under different 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."

Specific Research Needs Include:
Impacts of modified natural, semi-synthetic, and synthetic microfibers on aquatic and terrestrial biota
Specific physical, chemical, and biological hazards associated with microfiber impacts in biota
Impacts of modified natural, semi-synthetic, and synthetic microfibers on environmental processes
Human exposure to microfibers via inhalation, ingestion, or dermal contact
Impacts of modified natural, semi-synthetic, and synthetic microfibers on human health
Relationship between chemical additives in microfibers and toxicity to biota, including humans
Degradability of modified natural, semi-synthetic, and synthetic microfibers under various environmental conditions

6.1.3 Knowledge Gap 3: 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.

Studies on emissions 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. Additionally, research on the relationship between microfiber shedding rates and textile characteristics (e.g., virgin or recycled content, yarn twist, construction, dyes, finishes, etc.) 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, etc.) and dryer characteristics (e.g., temperature, speed, etc.) would help to develop best practices to reduce microfiber emissions during the laundering and drying processes.

Specific Research Needs Include:
Microfiber emissions during the production of textiles and other fiber-based products
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, etc.)
Microfiber shedding during normal use of textiles and the significance of various textile characteristics (e.g., material type, chemical additives, yarn twist, virgin or recycled materials, age/wear, etc.) on shedding rates
Microfiber shedding from textiles in washing machines and the impact of various washing machine characteristics on shedding rates
Microfiber shedding from textiles in dryers and the impact of various dryer characteristics on shedding rates
Best practices to reduce microfiber shedding in washing machines and dryers

6.1.4 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:
Efficiency of external and internal laundry machine filters designed to capture microfibers in laundry machine effluent and potential challenges associated with their use
Efficiency of green infrastructure (e.g., bioretention) in capturing and removing microfibers in stormwater and the limitations of using green infrastructure for this purpose
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

6.2 General Recommendations to Reduce Microfiber Pollution

1. Address major research needs

As indicated previously, there is a critical need for more research on the sources, pathways, and impacts of microfiber pollution as well as its potential solutions. Government and non-government stakeholders in the U.S. should consider the following recommendations to address the most significant research gaps related to microfiber pollution.

- Conduct, support, and fund research to close knowledge gaps in sources, pathways, and impacts of microfiber pollution to inform the development and implementation of solutions.
- Prioritize the development of fit-for-purpose standard definitions of microplastics, microfibers, and other related terms, which would lay the foundation for the development of standard 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 our knowledge of the sources, pathways, and impacts of microfiber pollution. For research on the occurrence of microfibers in various environmental compartments, consider focusing efforts and resources 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 U.S. testing standards organizations like AATCC and ASTM to develop and standardize research methods for microfibers and microplastics more broadly.

2. Support efforts to reduce microfiber pollution at the source

As discussed in the previous section, there are efforts underway to reduce microfiber pollution at the source through the design of textiles that shed fewer or less harmful microfibers. U.S. Government and non-government stakeholders should support and build upon these efforts, while considering the following recommendations:

- Support research on the toxicity of modified natural, semi-synthetic, and synthetic microfibers to determine which types of materials are most harmful and, therefore, which materials should be prioritized for low-shedding design efforts. Work with the textile community to understand microfiber release at different stages in product life cycles. Support development of best practices to reduce microfiber shedding at various life cycle stages. Conduct research to better understand the degree to which textiles made from recycled materials shed microfibers.

- Support research on the toxicity of chemical additives in textiles and other sources of microfiber pollution. Create subcategories of chemicals to aid in research and regulatory efforts (if needed).
- Set clear and precise criteria for biodegradability or compostability with regards to modified natural, semi-synthetic, and synthetic fibers and textiles. When possible, use realistic environmental conditions for testing. Determine if biodegradable and/or compostable textiles are a viable solution; harmonize test standards for assessment in various environmental media. Work with textile and environmental science communities to ensure that 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).

3. 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 emissions. 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.

- Explore filtration devices on washing machines and their potential for preventing microfibers from entering wastewater. Identify and test filtration options for residential, commercial, and industrial washing machines.
- Conduct research to better understand microfiber emissions from dryers and potential mitigation measures.
- Assess the potential for green infrastructure (rain gardens and bioretention) to reduce microfiber emissions via stormwater.

4. Foster multi-stakeholder collaboration

Microfiber pollution is a crosscutting and 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 to this urgent problem 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 taskforces) with a diverse range of relevant stakeholders to coordinate research and solutions development and implementation.
- Promote international cooperation. Stay engaged with existing collaborative efforts, including those led by The Microfibre Consortium, UNEP, and Ocean Wise.

- Engage with government officials at the local, state, and national levels to conduct an analysis of the applicability of existing local, state, and national policies to address microfiber pollution (e.g., the Clean Water Act, Safe Drinking Water Act, etc.). Assess the potential effectiveness of new policies that might help to reduce the risks associated with microfiber pollution, such as Extended Producer Responsibility programs, new standards for textiles and other sources of microfiber pollution, or regulations targeting major pathways of microfiber pollution.
- 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.

7. Federal Plan to Reduce Microfiber Pollution

7.1 Background & Development

The following plan lays out goals, objectives, and actions that will guide federal agencies as they work with stakeholders to reduce microfiber pollution in the United States. EPA's Trash Free Waters Program and NOAA's Marine Debris Program co-led the development of this plan in collaboration with 12 federal agencies.

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 to help achieve the stated objectives. A two-part workshop for federal agency representatives was 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 committed to doing work that makes progress toward achieving the action.

The implementation of any actions for which an "implementing agency" or an agency providing "potential support" has been identified may be affected by 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 & 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, fund, 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 five-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. Additionally, 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 five years to complete given the nature of the action and/or if an action is dependent on other actions in the plan.

At present, the participating federal agencies do not have the resources and/or authorities to complete all of the actions listed in this plan. 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 felt that these actions were important pieces to 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 fulfilled 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 is designed to demonstrate the wide range of activities and investments necessary to effectively understand and mitigate microfiber pollution over the next five years (and beyond). It 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, fund, and support research to address the most critical research needs related to microfiber pollution

Our 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).	2.1 Existing Definitions of Microfiber 2.2 Proposed Definition of Microfiber 2.3 Rationale for Proposed Definition
1.2: Develop/adopt standardized microfibers 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 synthetic, semi-synthetic, and chemically modified natural 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 fund research to develop new, benign materials to augment	4.2 Field Sample Collection 4.3 Laboratory Methods 4.4 Additional Recommendations for Developing Standardized Methodologies 6.0 Key Research Needs and Recommendations

Objectives	Actions	Report Sections to Reference
	and/or replace current microfiber technologies (Implementing Agencies: TBD; Potential Support: NSF).	
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 fund 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, etc.), 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).	3.1 Microfiber Sources 3.3 Microfiber Pollution Causes and Pathways 5.2 Reducing Emissions 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 synthetic, semi-synthetic, and modified 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).	5.1 Rethinking Textile Design, Production, and Disposal 5.2 Reducing Emissions from Washing Machines and Dryers 5.4 Messaging & Public Education
2.2: Develop and share best practices for textile care that minimize microfiber shedding	1. Review scientific literature and consult with 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 (synthetic, semi-synthetic, chemically modified 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). 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).	5.1 Rethinking Textile Design, Production, and Disposal 5.2 Reducing Emissions from Washing Machines and Dryers 5.4 Messaging & Public Education

Objectives	Actions	Report Sections to Reference
	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 emissions from textile manufacturing facilities in the U.S. (Implementing Agencies: TBD; Potential Support: NIST). 2. Review current regulations under 40 CFR 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 emissions 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 U.S. (Implementing Agencies: TBD; Potential Support: EPA, NIST).	5.1 Rethinking Textile Design, Production, and Disposal 5.3 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). 2. Conduct an outreach/education campaign to encourage consumers to take actions to reduce textile waste (Implementing Agencies: TBD; Potential Support: NPS). 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).	5.1 Rethinking Textile Design, Production, and Disposal 5.3 Government-Led Initiatives
2.5: Reduce and remove microfiber pollution from cigarette butt litter	1. Evaluate, fund, 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).	3.1 Microfiber Sources 5.4 Messaging & 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 synthetic 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: USFWS).	3.1 Microfiber Sources
2.7: Reduce and remove microfiber pollution from personal care products	1. Quantify microfiber pollution from personal care products (including facemasks) 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), feminine 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).	3.1 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).	3.1 Microfiber Sources 3.3 Microfiber Pollution Causes and Pathways 5.2 Reducing Emissions from Washing Machines and Dryers
3.2: Work towards reducing microfiber emissions from dryers	1. Support and fund 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 (synthetic, semi-synthetic, chemically modified 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).	3.3 Microfiber Pollution Causes and Pathways

Objectives	Actions	Report Sections to Reference
3.3: Minimize microfiber pollution via land application of biosolids	1. Investigate current biosolid treatment processes in the U.S. and explore treatment options to separate microfibers from biosolids (Implementing Agencies: TBD; Potential Support: NIST). 2. The literature on microplastics will be reviewed as part of the next two-year biosolid review cycle; microfibers will be included in the biennial report if they are identified as a pollutant in biosolids (Clean Water Act (CWA) [40 CFR Part 503]) (Implementing Agencies: TBD).	3.3 Microfiber Pollution Causes and Pathways
3.4: Reduce microfibers entering waterways via wastewater effluent and stormwater runoff	1. Fund 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).	3.3 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 currently 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 synthetic, semi-synthetic, and non-synthetic 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).	3.4 Potential Environmental and Human Health Impacts of Microfiber Pollution 3.1 Microfiber Sources
4.2: Support the development of non-toxic degradable textiles, as informed by a mechanistic understanding of degradation product formation	1. 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 non-toxic degradable materials (Implementing Agencies: TBD). 2. 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). 3. Incorporate guidance for the textile industry on how to make “biodegradation” claims to consumers into Federal Trade Commission “Green Guides” (Implementing Agencies: TBD). 4. Support efforts to develop degradable polymers to be used in textiles (Implementing Agencies: TBD; Potential Support: DOE).	5.1 Rethinking Textile Design, Production, and Disposal 5.5 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).	5.3 Government-Led Initiatives 5.5 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).	5.3 Government-Led Initiatives 5.4 Messaging & Public Education 5.5 Cross-Sector Collaboration

8. 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.

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 CFR 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 storm water, untreated human and industrial waste, toxic materials, and debris.

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.

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 material type; includes all microplastics, as well as semi-synthetic and natural microfibers.

Microplastics. Solid polymeric materials (microparticles) to which chemical additives or other substances may have been added, which are particles with at least three dimensions that are greater than 1 nm and less than 5,000 micrometers (µm) (CA State Water Resources Control Board 2020).

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 Systems (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 U.S.; 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 (1-100 nm).

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 many similar units bonded together (e.g., synthetic organic materials used as plastics and resins). 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 storm water 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.

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).

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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