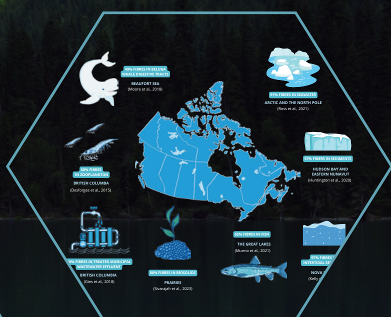
Tackling microfibre pollution through science, policy, and innovation

A framework for Canadian leadership



OCEAN DIAGNOSTICS

RAINCOAST CONSERVATION FOUNDATION

Anna M. Posacka, Peter S. Ross. 2024. Tackling microfibre pollution through science, policy, and innovation: A framework for Canadian leadership. https://doi.org/10.70766/47.9973

Tackling microfibre pollution through science, policy, and innovation

A framework for Canadian leadership

2024 November 12

Citation

Anna M. Posacka, Peter S. Ross. 2024. Tackling microfibre pollution through science, policy, and innovation: A framework for Canadian leadership. https://doi.org/10.70766/47.9973

Affiliations

Anna M. Posacka, Strategic Advisor, Ocean Diagnostics
Victoria BC Canada
www.oceandiagnostics.com

Peter S. Ross, Senior Scientist, Raincoast Conservation Foundation
Sidney BC Canada, W̱SÁNEĆ Territory
www.raincoast.org

This project was undertaken in partnership with
Ce projet a été réalisé en partenariat avec

Environment and Climate Change Canada
Environnement et Changement climatique Canada

About Ocean Diagnostics

Ocean Diagnostics is a Canadian environmental impact company tackling microplastic pollution and biodiversity loss through innovative technologies, cutting-edge laboratory analysis services, community science and education.

www.oceandiagnostics.com

About Raincoast Conservation Foundation

Raincoast is a team of conservationists and scientists empowered by our research to protect the lands, waters, and wildlife of coastal British Columbia.

www.raincoast.org

This comprehensive report, alongside a summary report, was made possible through the financial support of Environment and Climate Change Canada.

Acknowledgements

We would like to thank Marie Noël, Liliane Stewart, Sean Yang, Iselle Flores, Sherwin Arnott, Alex Harris and Ashleigh Erwin for contributing to this report. This project was made possible through the financial support of Environment and Climate Change Canada (ECCC). We would also like to thank Anne Clarisse Ndjou'ou, Vanessa Evans, Joel Chung and Eric Corneau at ECCC for their valuable project input.

We are grateful for the expert reviews and inputs from the following:

Farida Bishay, Metro Vancouver
Kelly Drennan, Fashion Takes Action
Lisa Erdle, 5Gyres
Douglas Gilliand, EU Joint Research Centre
Joel Mertens, Cascale
Rhiannon Moore, City of Victoria
Catrin Norris, Flora & Fauna
Chelsea Rochman, University of Toronto
Jesse Vermaire, Carleton University

Ocean Diagnostics acknowledges with respect the Lekwungen peoples on whose traditional territory our office stands, and the Songhees, Esquimalt and WSÁNEĆ peoples whose historical relationships with the land continue to this day.

Contents

Figures

Tables

Abbreviations and acronyms

ASTM American Society for Testing and Materials

AATCC American Association of Textile Chemists and Colorists

EPA Environmental Protection Agency

EPR Extended Producer Responsibility

EU European Union

ECCC Environment and Climate Change Canada

NOAA National Oceanic and Atmospheric Administration

ISO International Standards Organization

WWTP Wastewater Treatment Plant

Executive summary

Microfibre pollution has emerged as a global conservation and public health concern, prompting a wave of research related to its source, transport, fate and effects, as well as mitigation strategies. This report provides support for the Government of Canada in decision-making on microfibres, by summarizing important elements of the topic from the scientific literature, stakeholder consultations and cross-sector activities. The goal herein is to characterize the primary sources, discharge mechanisms and environmental fate of microfibre pollution in Canada, review available methodologies and definitions, list candidate solution strategies for Canadian application, and review global advances in policy and industry.

Many sources and types of microfibres exist, but current evidence suggests that environmental microfibre contamination originates largely from the textile sector, with releases arising during manufacturing, trade and laundry processes. Two broad categories of textiles in this sector are relevant to the characterisation of sources, applications and processes that result in microfibre pollution in Canada, namely conventional (clothing) and technical textiles. We focus herein on conventional textiles, as a significant, but not exclusive, source of microfibres to the Canadian environment. Additional types of products that contribute microfibres to the environment are those used in the fishing, civil engineering, medical, personal care and construction sectors, and consumer products such as cigarettes. The underlying polymers used in these products can be both synthetic and natural, with both being the focus of this report.

Our awareness of microfibre pollution grew out of the broader research on microplastics. This research demonstrates that microfibres, often the dominant type of microplastics, are pervasive in the environment, wildlife and drinking water. In Canada, microfibres account for approximately 80 per cent of the microplastic particles reported across water, soil, biota, air, and wastewater samples. While Canadian researchers will continue to benefit from new approaches to the sampling, detection and identification of microfibres and microplastics in the environment, having comparable data among studies and monitoring programs is crucial. Agreed-upon Quality Assurance/Quality Control (QA/QC) protocols are needed by producers, researchers, natural resource managers, consultants and regulators. This report assesses progress in the important, but at times challenging developments in the standardization and harmonization of microfibre methods, and provides guidance for stakeholders on best scientific and technical practices and the latest measurement methods.

Microfibre pollution arising from textiles is a multifaceted environmental challenge that cannot be effectively mitigated through technical solutions alone. Meaningful and lasting reductions in microfibre pollution will require a holistic approach that recognizes the interconnected role of the textile value chain and the ways in which microfibres contaminate the environment. Such a system prioritizes waste reduction and waste management at all stages.

Achieving a demonstrable reduction in microfibre pollution in the environment necessitates a re-evaluation and transformation of how textiles are designed, produced, used, and disposed of, ensuring sustainability is embedded at every stage. While domestic circumstances in Canada offer the most immediate regulatory and policy solution opportunities, a dual approach that helps to also capture the international supply chain is critical to the success of efforts to curtail microfibre pollution in the Canadian environment.

Microfibre pollution is but one - albeit important - environmental impact associated with the textile sector. We therefore touch herein on additional impacts that may be considered so as to maximize sustainability aims and the protection of human health. A systems change approach will allow Canada to achieve wider environmental goals around the textile sector, such as reducing plastic and microfibre pollution, conserving water and energy resources, reducing the release of potentially harmful dyes and additives, reducing greenhouse gas emissions, and ultimately minimizing the overall ecological footprint of our clothing choices.

Key findings

1. **Microfibres are widespread global contaminants that threaten the health of Canadians and the environment.** The scientific evidence is clear: there is a significant release of microfibres into the Canadian environment. Concerns about microfibres include their environmental persistence, complex interactions in the environment, and potential to harm human and environmental health. In Canada, microfibres account for approximately 80% of microplastic particles detected across water, soil, biota, air, and wastewater samples. Canada can serve as an international leader for microfibre pollution science, by enabling advanced research on the release, fate and effects of microfibres, and emphasizing comparable sampling methods, analytical processing, and data processing protocols.

2. **Microfibre releases remain largely uncontrolled and unregulated.** Limited regulatory and policy actions today reflect the very recent discovery of microplastics and microfibres as notable environmental and public health concerns, and virtual lack of effective monitoring initiatives. This is in part due to gaps in standardized methodologies, emerging understanding of exposure and effects, and challenges in conducting human and ecological risk assessments for these novel contaminants. However, significant advances internationally have resulted in suitable methods and tools needed to quantify and characterise the releases and environmental concentrations of microfibres. Furthermore, some jurisdictions have started to formulate or implement strategies and regulations aimed

at reducing microfibre releases. Canada should develop a national approach that acquires insights from domestic and international experiences, and initiate a multi-sector / multi-agency approach that is meaningful and trackable.

3. **Microfibres are generated across the lifecycle of textile materials used for clothing**. Estimates from scientific and grey literature suggest that global apparel manufacturing contributes 0.12 million tonnes of microfibres, while domestic and commercial laundry between 0.018-0.53 million tonnes of microfibres to the environment each year. Significant amounts of microfibres are thought to be released from electrical drying and everyday clothing wear, but data availability is limited. Our analysis reveals significant microfibre pollution contributions to the Canadian environment through:

    - **Homes**: Canadian households generate approximately **1,920 tonnes** of microfibres annually.
    - **Wastewater**: **264 tonnes** of microfibres pass through wastewater treatment facilities and enter water bodies, with an additional **35 tonnes** entering waterways as untreated wastewater.
    - **Biosolids: 1,621 tonnes** of microfibres accumulate in biosolids every year in Canada. The land application of these biosolids in agriculture and land reclamation practices spreads an estimated **795 tonnes** of microfibres onto Canadian soils each year.
    - **Commercial laundry:** Preliminary estimates suggest that commercial laundry operations could be releasing up to **1,099 tonnes** of microfibres annually.
    - **Textile manufacturing**: there is insufficient data to evaluate microfibre releases from textile manufacturing processes in Canada, underscoring the need for further research.

By 2030, the laundering of textiles is projected to contribute **6,558 tonnes of** microfibres to the Canadian environment, marking a critical timeline for Canada's ambitious zero plastic waste objectives. This is equivalent to over 44 million T-shirts.

A microfibre pollution reduction blueprint for Canada

1. **Innovation in textile design and production techniques can reduce microfibre releases by industry and by consumers both in Canada and internationally**. Standards or guidelines for environmentally-friendly textile design and manufacturing represent one of the key ways to achieve reductions in microfibre releases from Canadian sources. Since the majority of textile products sold in Canada are imported, Canadian fashion brands and retailers have an important role to play in driving innovation in practices and processes needed to protect the Canadian environment from microfibre contamination. This report consolidates the latest technical solutions and strategic approaches that have the potential to transform textile industry practices, and reduce its contribution to microfibre pollution.

2. **Widespread washing machine filtration could result in a dramatic reduction (up to 90%) in microfibre discharges from domestic and commercial wastewater effluent in Canada**. Evidence from scientific studies of aftermarket devices underscores the effectiveness of this measure. Recent policy and regulatory initiatives introduce mandatory filtration in new washing machines to reduce microfibre pollution. Promotion of best practices for product care and further innovation by appliance manufacturers to minimize microfibre releases during laundry can offer additional benefits towards mitigating the issue.

3. **Electrical drying of clothing represents a relatively recent concern, with research pointing to significant releases of microfibres into the air**. The majority of Canadian households utilize electrical drying for laundry, underscoring the need for targeted solutions, such as improved lint capture and consumer education.

4. **The accumulation of microfibres in biosolids, with the subsequent release into terrestrial ecosystems through land application, underscores the potential for significant and widespread distribution of microfibres in agricultural, forestry and land reclamation areas.** Reductions in liquid waste microfibre content through source control practices (as above), and new approaches to biosolids processing should be explored.

5. **A national textile circularity and sustainable fashion strategy, with an emphasis on reducing overproduction and combating microfibre pollution, should be a top priority for Canada. Such a strategy would position Canada alongside a growing cadre of nations actively developing or implementing circular textile initiatives.** Enhancing the

utilization and durability of our clothing and lowering the demand for new products indirectly contributes to microfibre pollution mitigation.

6. **Increasing awareness amongst industry players and the public.** There continues to be a lack of fulsome awareness of what microfibres are, where they come from, and what we can do about them across Canadian sectors. Clear, concise and widely available information on the topic would enable solution-oriented actions at all levels in Canada and contribute to the 'team approach' required to fix the microfibre problem.

7. **Advancing knowledge through research and collaborative initiatives will enhance data availability, build consensus and contribute to decision-making across the board**. Leadership through Ottawa will not only aid in a better understanding of the stakes, but would also position Canada as the leader in the global effort to combat microfibre pollution.

Chapter 1: Introduction

The widespread recognition of microplastics and microfibres was in part triggered by the study by Thompson et al. (2004), "Lost at Sea: Where is All the Plastic?". In this study, the analysis of coastal sediments and archived plankton samples from the 1960s unravelled a troubling finding: tiny pieces of plastic are an intricate part of the fabric of our environment. Among the diversity of shapes and colors identified, fibrous plastic particles, measuring approximately 20 microns in width, were most frequent. Early reports from Canada revealed widespread distribution of microplastics - dominated by microfibres - in the NE Pacific Ocean (Desforges et al., 2014), with further documentation of microfibres in the Great Lakes (Cox et al., 2021, Erickssen et al., 2013, Grbic et al., 2020) and across the Canadian Arctic (Ross et al., 2021).

The scientific community has since produced a significant body of work on microplastic pollution in all aspects of the global environment. Despite methodological challenges, one finding by microplastic researchers emerges clearly – microfibres have become the most prevalent form of microplastic pollution across different environments, from oceans and drinking water to soil and even within human bodies (Kutralam-Muniasamy et al. 2020, Athey and Erdle, 2021).

Investigations into their origins have traced a path from our homes and the clothes we wash, to treatment plants and subsequently rivers and oceans. Microfibres can be lost from clothing during washing, resulting in the release of millions of these microscopic particles from just one garment. Their small size represents a challenge to a water treatment, often leading to releases of microfibres into various water bodies. The understanding of the microfibre pollution problem has evolved in recent years to recognize releases from different types of textile products at every stage of their lifecycle, including production, everyday use, treated biosolid utilization and in some cases textile disposal. Other important sources of microfibres are fishing equipment, cigarette filters, and face masks.

The public health and environmental risks associated with microfibres, while not fully understood, are attracting increased concern. The potential for harm from microfibres is tied to the resilience of the polymers used in their production, which can be both synthetic and natural in their origin, and the ease with which these microfibres can be ingested accidentally, and the potentially toxic dyes and additives they can contain. Current studies on the effects of microfibres report a variety of outcomes, including mortality (water flea, *Daphnia magna*, Kim et al. 2021), intestinal damage (goldfish, *Carassius auratus*, Jabeen et al. 2018, terrestrial snails Song et al. 2019), diminished energy reserves or feeding rates (zooplankton species, Au et al., 2015; Cole et al., 2019; Jemec et al., 2016), and potential multigenerational toxicity (roundworm, *Caenorhabditis elegans*, Li et al. 2021).

These concerns have recently extended to human exposure, which can occur through the air of indoor environments or the consumption of contaminated water and food (Kosuth et al. 2018, Vianello et al. 2019). Although research into the effects on human health is in its early stages, a recent study, for example, found that nylon microfibres could impair the development of human lung organoids, which was linked to the release of chemicals from microfibres (Song et al., 2023). These preliminary insights signal a critical need for more research to fully understand the implications of microfibre pollution on human health and environment. They also emphasize the importance of adopting precautionary measures to minimize environmental and human exposure to these complex contaminants.

Objectives

In recent years, scientific research and cross-sector initiatives have identified a variety of technical solutions to reduce microfibre emissions from textiles, particularly clothing. Some jurisdictions have begun to formulate or adopt strategies to curb microfibre pollution, such as the inclusion of filtration systems in new washing machines or standards for textile design.

Our objective herein is to create a framework that addresses microfibre pollution in Canada by synthesizing the latest scientific findings, identifying existing gaps and potential opportunities in microfibre research and data, and examining a wide range of solutions and advancements made by various international stakeholders. This report provides an analysis and recommendations for the Government of Canada's consideration, focusing on solutions with the greatest potential for a national reduction in microfibre pollution.

This report focuses on both synthetic and natural microfibres from textiles. We conducted a comprehensive review of scientific and grey literature, as well as consultations with experts relevant to the report themes. Recent key documents offering solutions to microfibre pollution were an important resource in this project, and we draw on the experiences of the US Environmental Protection Agency (EPA), National Oceanic and Atmospheric Administration (NOAA), the National Institute of Standards and Technology (NIST), the Organization for Economic Co-operation and Development (OECD), and the European Union's Circular Textile Strategy.

Our examination of sources, pathways, and the fate of microfibres particularly focused on scientific studies from Canada. Our aim was to collate and assess the breadth of publications available on the topic in Canada, identify potential trends, and document research gaps where international studies were used to provide a more complete picture of microfibre pollution.

Report scope

Our report covers the following key topics.

What are microfibres? (Chapter 2): How are microfibres defined by different stakeholders, and can we establish a unifying terminology that supports Canadian science, innovation, and policy?

Sources, releases, and fate of microfibres (Chapter 3): What do we know about the sources, emissions, and fate of microfibres in Canada and around the world? How large are the releases of microfibres from different sectors and through different pathways?

Advances in scientific methods and measurement technologies (Chapter 4): What progress has been made to standardize methodologies, and what methods are most suitable for microfibres?

Solutions (Chapter 5): Which interventions - in Canada or internationally - have strong potential to reduce microfibre pollution at any point along the life cycle of textiles, and how can policy enhance their implementation?

Canada's role and opportunities (Chapter 6): What solutions hold the greatest promise for Canada in tackling microfibre pollution?

Chapter 2: What are microfibres?

Microfibres have been found in waters throughout the world and are being ingested by biota and humans. Textiles appear to explain much of the microfibre contamination of air, water and soils. The absence of a standardized definition for microfibres in Canada represents a barrier to monitoring and regulatory measures.

Box 1: A proposed definition of microfibres to guide Canadian science, innovation and policy

Microfibres in the environment refer to solid, fibrous strands of anthropogenic origin, with a length that is significantly greater than the width (ratio of >3), and a length of <15 mm. They are composed of synthetic polymers (e.g. polyester, nylon, and acrylic), or chemically-modified natural or semi-natural polymers (e.g. cotton, cellulose acetate, wool).

This definition is technically consistent with the US NOAA/EPA[1] and EU Water Directive microplastics methodology[2] definitions.

The caveat: Published scientific data derived to document microfibers may or may not fully capture all microfibers as per this definition due to difference in methods employed in a given study. Documenting detailed sampling, processing and instrumental methods applied is strongly recommended so as to enable comparisons across studies.

[1] *Interagency Marine Debris Coordinating Committee (IMDCC). (2024). Report on Microfiber Pollution. 149 pp..*

[2] *European Commission. (2024, March 11). Commission Delegated Decision supplementing Directive (EU) 2020/2184 of the European Parliament and of the Council by laying down a methodology to measure microplastics in water intended for human consumption.*

Microfibres are small, often microscopic, fragments of fibres shed from textiles and other fibre-based products during their production and use. These fibres can be both natural, such as cotton or wool, and synthetic, like polyester or nylon. The global production of fibres has significantly increased in recent decades, with an estimated 112 million tonnes produced in 2022 and 147 million tonnes projected by 2030 (Textile Exchange, 2023). This escalating production not only reflects the growing demand for textile products, but also suggests that if microfibre loss to the environment is not checked, people and wildlife will be increasingly exposed to potentially harmful levels of these emerging pollutants.

Microfibre definitions vary across sectors and national jurisdictions, reflecting the emerging awareness and understanding of microfibre pollution as a significant environmental issue. Having a standardized definition in Canada will enhance efforts to compare data and research findings, and improve alignment across scientific, monitoring and regulatory efforts. As part of this report, we propose a unified definition of microfibres that can guide research efforts, innovation, policy, and interventions across Canada, and ensure comparability for international comparisons.

Establishing a common definition for microfibres in Canada requires considering the current and future needs of research, regulation, and practical application. This means identifying a definition that addresses the unique characteristics of microfibres, such as their size, composition, and sources, while also being sufficiently inclusive to accommodate definitions used by other jurisdictions and evolving scientific understanding. As noted in the latest version of the Canada Plastics Science Agenda (CaPSA, 2022), "harmonizing/standardizing the detection, monitoring and characterization of the sources, pathways, concentrations, and fate of plastics in the environment" represents a priority for Canada's science to advance actions to combat plastic pollution.

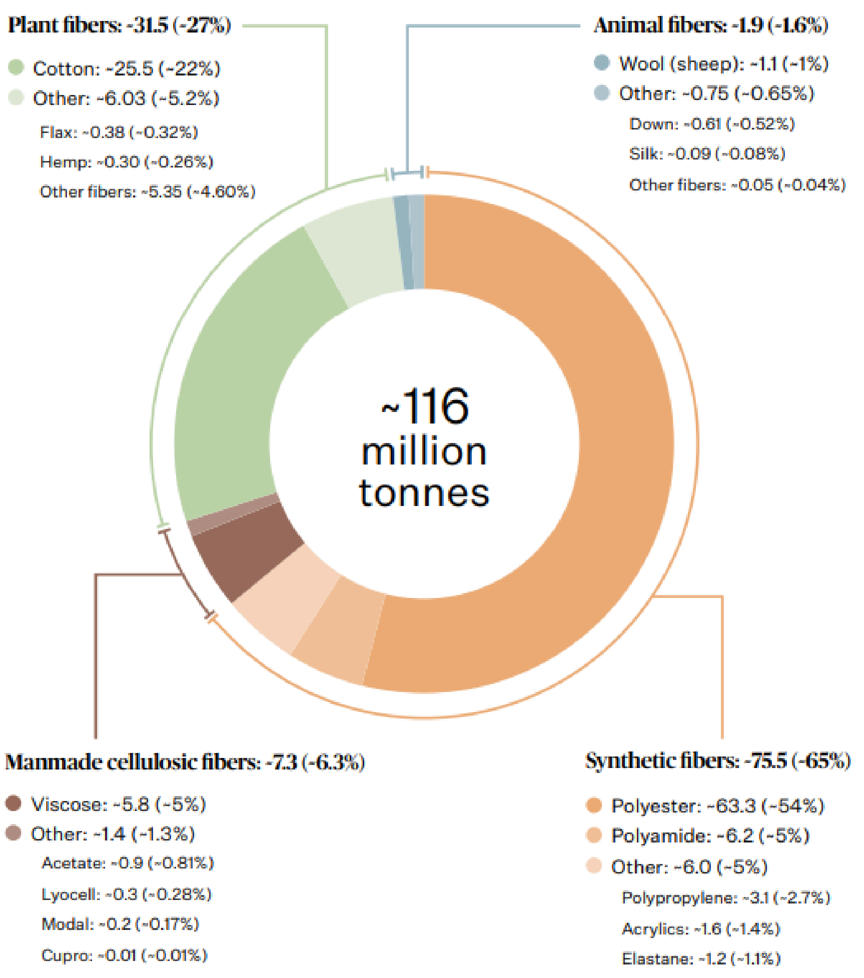
2.1 Microfibre characteristics

Microfibres from textiles. Textile products are made with diverse fibre polymer types, depending on product needs and their application. These can be distinguished into synthetic (plastic) (e.g. polyester), semi-synthetic (e.g. rayon) and natural fibres (e.g. cotton) (**Table 1**). Synthetic fibres currently dominate the global fibre market share, with polyester alone representing around 65% of all fibres used (**Figure 1**). Semi-synthetic and natural fibres undergo chemical processing for textile use and are increasingly observed in the environment (Athey and Erdle, 2022). In the textile industry, "microfibre" is a term defined as synthetic fibres with a linear density of less than 1 denier (*commercial microfibres*, TMC, 2023). These ultra-fine fibres are typically spun into yarns and threads to manufacture textiles. In the environment, the term "microfibre" refers to those fibre fragments from all sources that are detected through scientific observation. Evidence suggests that the majority of these fibres are shed from textiles, through processes such as laundry, and released into the environment (*environmental microfibres*). Their environmental persistence, has led to their inclusion in some microfibre definitions and research efforts (**Table 2-4**). Unlike the standardized definition in the textile industry, environmental microfibres lack consistent technical parameters regarding their size or material composition, posing challenges for measurement and comparison.

Vassilenko et al. (2021) examined microfibre shedding from a variety of textile products during laundry, covering synthetic, semi-synthetic and natural materials (**Figure 2A**). The study revealed that although the length of microfibres released varied considerably (from 43 to 1,603 μm), their width varied little and was on average 12.4 ± 4.5 μm. The large variability in microfibre lengths is also characteristic of environmental samples (**Figure 2B**), although environmental literature data displays a much broader length diameter range, in some cases exceeding 5 mm, which is a common upper size threshold for microplastics. A key challenge in scientific studies is distinguishing between human-made microfibre types and naturally occurring microfibres found in the environment. Physical and polymer chemistry attributes of microfibres, such as the presence of dyes and additives, have been successfully applied to distinguish between these two types of microfibres found in today's environment.

Figure 1. Global fibre production rates

Global fibre production rates showing the proportions of different polymer categories used in the market. Polyester is the dominant synthetic fibre, while cotton dominates the natural fibre polymer category. Source: Textile Exchange, Preferred fibre and Materials Market Report, 2023.

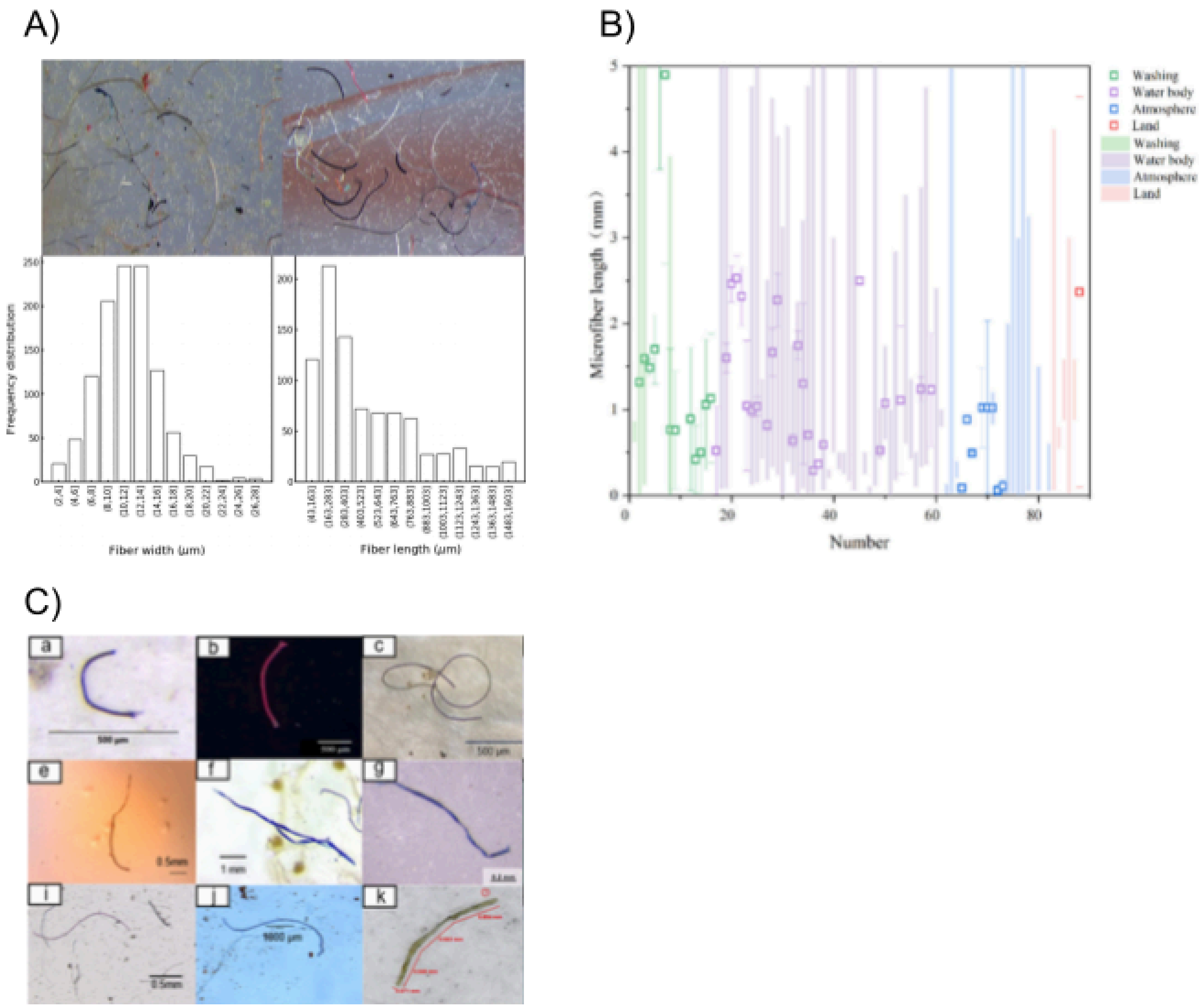


Source: Textile Exchange based on data from CIRFS, FAO, ICAC, IVC, IWTO, Maia Research, and its own modelling.

Note: This chart includes recycled fibers. Other animal fibers included here are alpaca, angora, camel, cashmere, guanaco, llama, mohair, vicuna, and yak. Other plant fibers included here are jute, coir, sisal, abaca, ramie, kenaf, kapok, and agave.

Figure 2. Microfibre diameters in laundry effluent and environmental samples

Microscopy images and size frequency distribution of microfibres in washing machine effluent illustrate the narrow width dimensions and variable lengths of microfibres released during typical domestic laundry of clothing (A, Source: Vassilenko et al. 2021). Environmental samples similarly display wide length variability but with a greater range compared to those in a controlled laundry study (B, Source: Li et al. 2023). Different types of microfibres detected in various environmental samples (C, Source: Li et al. 2023).



Other products

Other products that are constructed with microfibres include fishing gear, ropes, geotextiles, face masks and cigarette filters. However, the characteristics and prevalence of these items as sources of microfibres is poorly characterized.

Fishing gear, including ropes, lines, and nets are constructed of strands consisting of yarns, which in turn consist of several monofilaments (McKenna et al., 2004). Monofilaments are single-strand fibres and are generally thicker and more visible than microfibres (**Figure 3**). The average diameter of monofilaments from lost and abandoned fishing gear in a UK study was 420 ± 20 μm (Wright et al. 2021), which is more than 30 times greater than the typical widths of microfibres released from fabrics during laundry. In published research, monofilaments and pieces of rope are often classified as "fibres", which can lead to confusion when discussing the subject of microfibres (**Table 2-4**).

Figure 3. Characteristics of ropes and fishing gear

Images showing rope (A, B), fishing line (C) and mono- and multi-filaments. Source: Wright et al. 2021

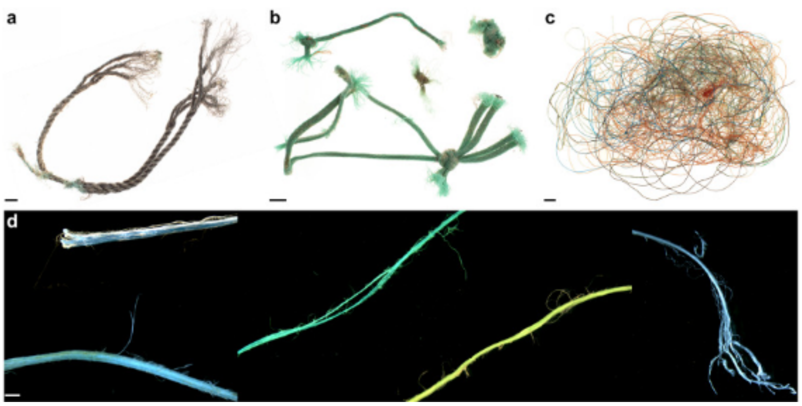


Table 1. Microfibres can originate from products made with synthetic or natural and semi-synthetic fibres, with polymer uses varying by application

Categorization adapted from: Athey & Erdle 2022.

Category	Polymer	Density (g cm^{-3})	Application
Synthetic	Polyester	1.3-1.63	Clothing
	Polyamide	1.06-1.16	Clothing, teabags
	Polyethylene	0.88-0.96	Fishing nets, ropes
	Polypropylene	0.84-0.91	Fishing ropes, medical non-woven devices
	Acrylic	1.14-1.15	Clothing, carpets
Natural or semi-synthetic	Cotton	1.3-1.63	Clothing
	Rayon, viscose, lyocell	1.53	Clothing
	Cellulose acetate	0.88-0.96	Cigarette filters
	Silk	0.84-0.91	Clothing
	Wool	1.14-1.15	Clothing

2.2 Stakeholder definitions

Typically, microfibres are studied as part of wider scientific assessments of environmental microplastics, rather than as a distinct contaminant category. A common definition of microplastics and microfibres is still subject to discussion, due to the evolving nature of this field, the multiple product chemistries, and the divergent products and applications that generate them (WHO, 2021, EPA/NOAA, 2022).

Microplastics are defined as plastic particles less than 5 mm in diameter, with this definition offering a practical means of distinguishing them from larger plastic litter items in the environment (WHO, 2021). Striking the balance between inclusivity and specificity in defining microplastics represents a complex challenge for effective risk assessment and management of microplastics. The challenge lies in reconciling the need for inclusivity to avoid "regrettable omissions" (California State Water Resources Control Board, 2020), with the requirement for specificity essential for regulatory enforceability (Mitrano et al. 2020).

Incorporating microfibres into the broader definition of microplastics has presented a number of challenges. The field methods in microplastic research are rarely optimized for capturing microfibres (Athey & Erdle, 2021), while a lack of lab-based microfibre-specific metrics and standards for analysis has created a risk of misidentification or underrepresentation. With the seeming domination of microfibres among microplastic categories, existing methods are likely underestimating the true abundance of microfibres in the environment. The lack of interlaboratory studies focused exclusively on microfibres renders it difficult to evaluate the scope of this challenge. This underscores the need for more specialized attention to research and regulation.

The definitions used to describe microfibres and microplastics in different sectors around the world are summarized in **Table 2-4**. Of note is that the term "microfibre" now commonly used in environmental research originally stems from the textile industry, where it refers to extremely fine fibres with a linear density less than 1 denier (ISO 4481-1, International Standards Organization, 2023). This term has been adopted by researchers due to the significance of textile materials as a source of these particles.

However the term recently adopted by industry is "fibre fragment" to facilitate the distinction from the term used in textile production (ISO 4481-1, International Standards Organization, 2023, Textile Microfibre Consortium (n.d.), **Table 3**). In their "Report on Microfibre Pollution", the US National Oceanic and Atmospheric Administration (NOAA) and Environmental Protection Agency (EPA) conducted a detailed review of the many definitions that have been used not only in the scientific literature but also in various communication materials from government, non-governmental organizations, and industries (IMDCC, 2024). They recommended acknowledging the term "fibre fragments" as a synonym for "microfibres" to facilitate cross-sector communication (IMDCC, 2024). For the purpose of this report, the term "microfibre" will exclusively refer to environmental microfibres, consistent with the manner by which they have been detected and described by scientists studying the environment.

Candidate microfibre definitions vary from general ones to those that specify the sizes and polymer content of microfibres, reflecting the differences in their applications and evolving nature of the problem. For instance, a 2019 definition developed by European Chemicals Agency (ECHA, 2019) that would support the restriction of microplastics in EU products under Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), set limits on the length ranges of microfibres of 3 nm to 15 mm with a length to diameter ratio of >3. This definition has been recently revised to exclude the lower size limit: "fibre-like particles under 15 mm in length and with a length to diameter ratio greater than 3". This definition is part of a recently approved Commission Regulation (EU) 2023/2055 of 25 September 2023, published in the Official Journal of the European Union. Excluded from the definition and regulation are degradable polymers, which diverges with a recently proposed definition by EPA and NOAA for the US Congress (NOAA & EPA, 2023) and that of the California State Water Board Drinking Water regulation that are inclusive of natural, semi-synthetic and synthetic microfibres.

On March 11, 2024, the European Commission adopted a methodology to measure microplastics and microfibres in drinking water (EC, 2024). Microfibres are defined as "microplastic fibres" that are objects whose length is equal to or less than 15 mm and whose length to width ratio is > 3, without specifying polymers. The Commission however prioritizes synthetic polymers for measurements, with chemically modified or natural polymers as optional.

Table 2. A synthesis of regulatory definitions proposed or adopted relevant to microfibres

Organization	Definition	Source
European Commission	Microplastic - a small discreet object that is solid, insoluble in water and is partially or wholly composed of synthetic polymers or chemically modified natural polymers. Microplastic fibre - a microplastic object whose length is equal to or less than 15 mm and whose length to width ratio is greater than 3. This definition was published under the methodology limited to particles with a dimension between 20 μm and 5 mm.	Annex C(2024) 1459 final of Directive (EU) 2020/2184 of the European Parliament and of the Council by laying down a methodology to measure microplastics in water intended for human consumption published on March 11, 2024.
European Food Safety Authority (EFSA)	Microplastics - Heterogeneous mixture of differently shaped materials referred to as fragments, fibres, spheroids, granules, pellets, flakes, or beads, in the range of 100 nm–5 mm.	European Food Safety Authority EFSA (2016).
European Chemicals Agency (ECHA) – European Commission	Microplastics - Consisting of solid polymer-containing particles, to which additives or other substances may have been added, and where ≥ 1% w/w of particles have (i) all dimensions 1 nm ≤ x ≤ 5 mm, or (ii), for fibres, a length of 3 nm ≤ x ≤ 15 mm and length to diameter ratio of >3 (ECHA, 2019); revised to "fibre-like particles under 15 mm in length and with a length to diameter ratio greater than 3 (European Commission, 2023). The following polymers are excluded from this designation: a) polymers that are a result of a polymerization process that has taken place in nature, b) polymers that are degradable, c) polymers that have solubility greater than 2 g/L, and, d) polymers that do not contain carbon atoms in their chemical structure.	Annex XVII of Regulation (EC) No.1907/2006 'Registration, Evaluation, Authorization and Restriction of Chemicals'.

US California State Water Board	Microplastics- solid polymeric material to which chemical additives or other substances may have been added, which are particles, which have at least three dimensions that are greater than 1 nm 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.	State Water Resources Control Board Resolution No 2020-0021. "Adoption of definition of "Microplastics in Drinking Water"
US National Oceanic and Atmospheric Administration (NOAA) and Environmental Protection Agency (EPA) Trash Free Waters Program	Microfibres - solid, polymeric, fibrous materials to which chemical additives or other substances 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 ratio of greater than 3, and a length of less than or equal to 15 mm. fibres that are derived in nature that have not been chemically modified (other than by hydrolysis) are excluded.	Interagency Marine Debris Coordinating Committee (IMDCC). (2024). Report on Microfiber Pollution.
European Commission's Marine Strategy Framework Directive (MSDF)	Microlitter – a subcategory of marine litter with a length of its maximum dimension below 5 mm. Definition of marine litter follows that of UNEP (2021): "any persistent, manufactured or processed solid material discarded, disposed of or abandoned in marine and coastal environment (note this would be synonymous with microplastics). Filaments – slender thread-like microliter particles, including fibres and threads.	MSDF Technical Group on Marine Litter (2023)
Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP)	Microfibres - long fibrous material with a length substantially longer than its width and fibres with the longest dimension < 5 mm.	GESAMP (2016). Sources, fate and effects of microplastics in the environment: part two of a global assessment.
Arctic Monitoring Assessment Programme (AMAP)	AMAP established an Expert Group on microplastics and litter in 2019, which aims to develop guidelines for monitoring microplastics and litter across the Arctic ecosystem. While the first version of the guidelines does not provide specific definitions, they cover "macro-sized litter as well as microplastics (< 5 mm), essentially including smaller size ranges (>1 µm). Shapes include fibres, films, foams, beads, etc."	AMAP, (2021). AMAP Litter and Microplastics Monitoring Guidelines. Version 1.0.

Table 3. A synthesis of industry definitions proposed or adopted relevant to microfibres

Organization	Definition	Source
International Standards Organization (ISO)	Microplastics: Solid plastic particles insoluble in water with any dimension between 1 mm and 5 mm (large microplastics) and 1 µm and 1,000 µm (microplastic). Fibre – is a generic term in the textile sector for one of the various types of matter that form the basic elements of a textile and which are generally characterized by flexibility, fineness and a high ratio of length to thickness. Fibre fragment - a short piece (typically < $5x\ 10^{-3}$ m long), broken from the main textile construction. Microfibre: a fibre with linear density less than 1 denier.	International Standards Organization (ISO) 2020. ISO/TR21960:2020 on Plastics – Environmental Aspects – State of Knowledge and Methodologies ISO/DIS 4484-1. Textiles and textile products – Microplastics from textile sources - Part 1: Determination of material loss from fabrics during washing.
ASTM International	Microplastics - any solid, synthetic organic polymeric material to which chemical additives or other substances may have been added, which are particles largest dimension, and fibres no longer than 15 mm in length with an aspect ratio of at least 30:1 and < 500 µm in its smallest dimensions.	ASTM D8332-20. Standard Practice for Collection of Water Samples with High, Medium, or Low Suspended Solids for Identification and Quantification of Microplastic Particles and fibres. Published 2020
American Association of Textile Chemists and Colorists	Fibre fragment - A short piece of textile fibre, broken from the main textile construction or through its subsequent breakage in the natural environment	AATCC TM212-2021. Test Method for fibre Fragment Release During Home Laundering.

Table 4. Examples of microfibre definitions used in scientific research

Definition	**Source**
Microfibre – natural or artificial materials of threadlike structure with a diameter of less than 50 μm, length ranging from 1-5 μm, and a length-to-diameter ratio greater than 100.	Liu et al. 2019
Fibre - 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
Microfibre - are threadlike particles with a length between 100 μm and 5 mm and a width of approximately 1.5 orders of magnitude shorter (than the length).	Barrows et al. 2018
Synthetic fibre - the particle contains no visible cellular structures; has a constant width and even coloration; has flat and not tapered ends; and the fibre curls, crimps, or bends in three dimensions.	Ross et al. 2021

2.3 How should we define microfibres in Canada?

A consistent definition is key to maximize comparability among studies and enable meaningful and defensible policies, practices and procedures to combat microfibre pollution in Canada. Such a definition must balance the need for comparable data, the opportunity for innovation in research, and the need to protect the health of Canadians and the Canadian environment.

A proposed definition of microfibres to guide Canadian science, innovation and policy is presented in **Box 1** (page 13). This definition aligns with recent definitions, notably the IMDCC, the California State Water Board and European Commission, which are inclusive of synthetic, natural and semi-synthetic fibre chemistries. It is important to note that while natural microfibres are included in this definition, current field or lab methods may not be adequately equipped to quantify them.

This definition aims to recognize the broad categories and general characteristics of microfibres and serve as a foundational framework for research and regulation. We recommend that studies clearly define the scope of their method's identification and quantification of microfibres (i.e. sizes, microfibre categories) to facilitate innovation and comparability.

Chapter 3: Sources, pathways and fate of microfibres in the environment

Microfibres enter the Canadian environment from numerous sources and sectors, but textile design, manufacture, trade and laundry are thought to explain the widespread distribution and persistence of microfibres in water, biota and humans.

3.0 Key messages

- **Microfibres come from many sources, but textiles dominate.** Microfibres are generated during production and use of products in a variety of sectors, including textile, automobile, agriculture, and healthcare. Most research in Canada and internationally has concentrated on microfibres linked to clothing.
- **The textile sector is a heavy user of plastic polymers.** The textile sector ranks as one of the leading producers of plastic products globally, with 60% of synthetic fibres used for clothing.
- **Microfibres are lost to the environment at several steps in the life cycle of textiles.** Microfibres enter the environment during textile product manufacturing, laundering, wear and use, wastewater and stormwater discharge and biosolid (treated sewage sludge) application.
- **Microfibres dominate microplastic composition in the environment.** Canadian research indicates that microfibres account for approximately 80% of total microplastics detected in various environmental samples. Polyester is the most frequently detected synthetic microfibre type, reflecting its global production dominance, combined with its vulnerability to loss from certain textile products. However, human-made natural fibres are increasingly being detected in the environment. While they are expected to be less persistent than their synthetic counterparts, their detection in remote environments and biota points to potential environmental persistence.
- **There is a need for additional research in Canada to address knowledge gaps.** There is a need to enhance the quality and comparability of scientific and monitoring data in Canada to better understand the pollution trends and impacts of microfibres.

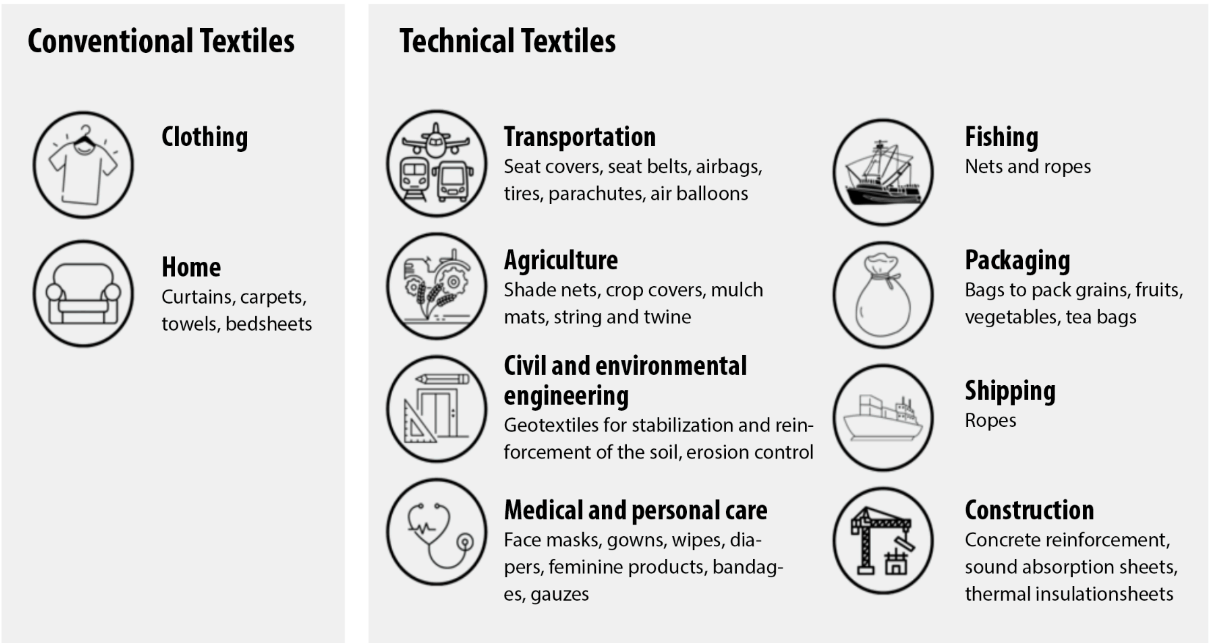
3.1 Where does microfibre pollution come from?

Global microfibre pollution stems from the extensive production and use of textiles and other fibre-based products. Textiles are predominantly manufactured for end-use as clothing, but also have applications in households (e.g. towels, bedsheets, curtains, carpets, mattresses), transportation, construction, fishing and aquaculture, and healthcare sectors (Fashion Takes Action, 2021). In addition, textiles are also used in the manufacture of shoes, soft toys, and belts (Nynne Nørup et al., 2018). Despite the diversity of product applications, the textile industry is primarily driven by fashion, with 60% of the world's fibre production used for clothing (Niinimäki et al., 2020).

Given the multifaceted nature of the textile applications, this chapter introduces two distinct categories that form the basis of analysis of microfibre sources - conventional and technical textiles - guided by the classification from Fashion Takes Action (**Figure 4**, Fashion Takes Action, 2021). We also include cigarette butts, which are a separate but important category of products that significantly contribute to microfibre pollution.

Figure 4. The major categories of textiles and sectors that release microfibres to the environment.

Textiles can be divided into two major categories: conventional textiles encompassing clothing and household items and technical textiles which have uses in a wide range of sectors. Graphic created based on textile categorization of Fashion Takes Action (2021).



3.1.1 Technical textiles

Technical textiles are characterized by strength, flame resistance and chemical resistance (Ahmad et al., 2020), and play an important role in a range of sectors. The Textile Institute defines technical textiles as "*textile materials and products manufactured primarily for their technical performance and functional properties rather than their aesthetic or decorative characteristics*" (The Textile Institute, n.d.). While conventional textiles dominate the market with a market value of approximately 700 billion USD, the technical textile sector, valued at 200 billion USD, is rapidly growing. This growth is driven by the demand for specialized functionalities in safety, healthcare, construction, automotive, and industrial applications (Ahmad et al., 2020).

 | DOI: 10.70766/47.9973

Civil and engineering textiles

Civil and engineering textiles, also known as geotextiles, are a group of materials used commonly in coastal reclamation. When exposed to sunlight and harsh environmental conditions they can degrade, leading to an unintended release of microfibres to the environment. A recent study conducted in Yancheng, China examined the contribution of geotextiles to microfibre pollution in coastal reclamation areas (Bai et al. 2022). The study found that many geotextiles in the coastal area studied were made from polyethylene terephthalate (PET). Laboratory experiments demonstrated that UV exposure accelerates the breakdown of PET geotextiles, resulting in the release of microfibres of various sizes. The study estimated that these processes could be responsible for a release of 0.24 to 0.79 million tonnes of microfibres into coastal reclamation areas worldwide. While research in this area is still emerging, this sheds light on a potentially significant yet unexplored source of microfibre pollution.

Fishing, shipping and aquaculture gear

Fishing, shipping and aquaculture gear consist of various synthetic polymers, including nylon, polyethylene and polypropylene (Nelms et al., 2021), and are considered significant sources of plastic waste in the ocean (Wright et al. 2021). The UN Food and Agriculture Organization (FAO) estimates that abandoned, lost and discarded fishing gear (ALDFG) represents approximately 10% of marine debris by volume.

In Canada, the contributions of fishing and aquaculture sectors to marine pollution are not well documented. However, an effort in Nova Scotia retrieved 29,298 kg of ALDFG between 2020-2021 (McIntyre et al. 2023), highlighting the maritime sector's impact on litter and debris in coastal Canada. Wright et al. 2021 studied potential microplastic release from fishing gear in the United Kingdom. They estimated that the disintegration of ALDFG could generate $1,277 \pm 431$ microplastic pieces m^{-1}, with fishing rope (44%) and net (49%) as the largest emitters. Although specific data on microfibre releases from fishing gear is lacking, the evidence suggests that it can be a significant contributor to global microfibre pollution.

Agriculture

In the agricultural sector, the use of textile materials such as nets, shade cloths, ground covers, and protective fleece is extensive. These materials are predominantly made from synthetic fibres like polyethylene, polypropylene, and nylon, providing durability, pest protection, weed control, and microclimate maintenance for crops. To the best of our knowledge, no research has been conducted on microfibre losses during the use of these materials.

Medical and Personal Protective Equipment

The healthcare system represents a potentially significant source of textile microfibres because of the heavy use of both reusable and disposable textiles in various items, including uniforms, bedding, gowns, towels, and Personal Protective Equipment (PPE). In the Canadian health care system, many of these items are treated as non-hazardous general solid waste and ultimately end up in landfills. This also applies to masks for the public (Government of Canada, 2020). Microfibre release can occur during the usage, cleaning and/or disposal of PPE.

The COVID pandemic led to a dramatic increase in discarded or improperly disposed masks. The widespread use of masks, which are typically made with non-woven polypropylene fibres, was estimated to introduce a considerable amount of microfibres into the environment. When these masks are not disposed of correctly, they can break down, releasing microfibres into both terrestrial and aquatic ecosystems (**Box 2**).

Box 2: Personal Protective Equipment use, disposal, and mismanagement during COVID-19 pandemic and resulting microfibre pollution.

During the COVID-19 pandemic, there was a significant increase in the use of Personal Protective Equipment (PPE), including disposable face masks.

Disposable face masks are made of three layers of synthetic polymer fabric, mainly polypropylene.

Limited information is available for Canada:

- Since the beginning of the COVID-19 pandemic, there has been an increase in discarded masks, gloves and wipes entering Annacis Island WWTP in Metro Vancouver (Rasmussen 2020).
- Health Canada estimated that 63,000 tons of PPE entered landfills between June 2020 and June 2021 (Government of Canada, 2020).

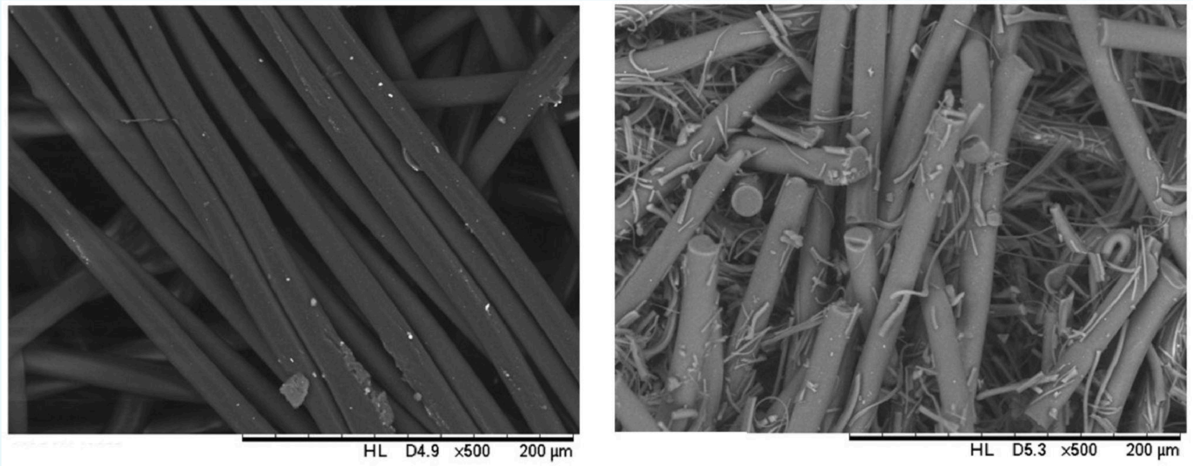
Case Study: Environmental presence of PPE in Toronto (Ammendolia et al., 2021):

- A survey of residential areas, grocery store parking lots, recreational trails and hospital districts was conducted in 2020.
- Disposable gloves were the most reported items (44%) followed by face masks (31%) and disposable wipes (25%).
- The greatest amounts of PPE were found at the grocery store parking lots (n=584) followed by the hospital district (n=256), residential area (n=194) and recreational trail (n=143).

Global estimates of microfibre releases from face masks:

- 14,032 – 177,602 microfibres released from masks during usage (Rathynamoorthy et al., 2022).
- 1,370 trillion microfibres entered the coastal marine environment from masks (Sun et al., 2021).

Scanning electron microscopy image of a single use face mask showing microfibres (Source: Saliu et al., 2021).



Construction

Textiles and fibres are used in construction for a variety of purposes, including concrete reinforcement, safety coatings, indoor and outdoor furniture and decoration, and noise and thermal insulation (Prasittisopin et al. 2023, Gao et al. 2023). The most common polymers used are polypropylene, polyethylene and polyvinyl chloride (Prasittisopin et al. 2023). Research on microfibre releases from construction sources has not been conducted to our best knowledge.

Cigarettes

Each year 6 trillion cigarettes are consumed around the world, of which 75% are estimated to be improperly discarded. The filters, also known as the cigarette butts, can comprise up to 15,000 cellulose acetate microfibres (Novotny et al., 2009). Their disintegration in the environment has been estimated to contribute 0.3 million tonnes of microfibres annually (Belzagui et al., 2021). Cigarettes contain over 7,000 toxic chemicals (Health Canada (n.d.) and some of these are readily leached into aquatic habitats (Roder Green et al., 2014; Akhbarizadeh et al., 2021). Exposure to these chemicals has been shown to lead to toxicity and even mortality in species of bacteria and crustaceans (Micevska et al., 2006), invertebrates (Green et al., 2020), and fish (Slaughter et al., 2011). In 2022, 164,995 cigarette butts were collected from shorelines across Canada by volunteers, making them the most frequently found litter item on the Great Canadian Shoreline Cleanup 'Dirty Dozen' list (Ocean Wise, 2022).

3.1.2 Conventional textiles

Conventional textiles encompass materials used for clothing and household items, with the former being the primary focus in scientific research and this report.

Manufacturing

Microfibres can be released at various stages of textile production, including fibre engineering, manufacturing, cutting, sewing, dyeing, printing, finishing, and pre-washing. Each of these processes can contribute to fibre breakage and their subsequent release into the air of manufacturing facilities or into waste effluents (Zhou et al.2020; Xu et al. 2018; Chan et al. 2021). Manufacturers use their own in-plant effluent treatment and/or a common effluent treatment plant to capture microfibres in trade effluents depending on location and local regulations (Zhou et al., 2020; The Nature Conservancy, 2021).

Despite the high microfibre capture efficiency of industrial treatment, of up to 85% (Zhou et al., 2020), substantial emissions from manufacturing sites can still occur due to the large volumes of microfibres generated during textile production. For example, one study reported up to 538 microfibres per litre of industrial effluent, leading to an estimated release of 430 billion microfibres per day (Zhou et al., 2020). Moreover, it has been estimated that garment manufacturing could contribute 0.12 million tonnes of microfibres to the global environment annually (The Nature Conservancy, 2021). While further research is needed to better inform on the scale of emissions from manufacturing, preventative action and innovative solutions, particularly in regions with high production levels, are urgently needed to mitigate against this major source of microfibres worldwide.

Domestic textile laundry, use and electric drying

At the household level microfibres are primarily released during textile laundering, use, and electric drying. When textiles are washed, a combination of mechanical and chemical stresses within the laundry environment causes the detachment of microfibres from the yarns that make up the textile. This process is commonly known as “microfibre shedding”. Research suggests that laundering a single garment can release anywhere between 120 and 730,000 microfibres in a domestic wash cycle (Bruce et al., 2016, Roos et al., 2017, Henry et al., 2019, Vassilenko et al., 2021).

The rate of microfibre release during the laundry process is influenced by several factors, including the age of fabrics washed (Hartline et al., 2016), wash water temperature (Zambrano et al., 2019, Yang et al., 2019), type of detergent (Cesa et al., 2020), wash speed (Cotton et al., 2020), textile construction (Hernandez et al., 2017, De Falco et al., 2019, Carney Amroth et al., 2018, Vassileno et al., 2021, Zambrano et al., 2019) and chemical finishing (Zambrano et al., 2021).

A study focused on British Columbia's Metro Vancouver area, found that 46% of surveyed households use top-loading machines (Bartsen, 2021), which have been reported to generate seven times more microfibres during laundry of textiles than front-loading machines (Hartline et al., 2016). The study also revealed that household size, number of children, and gender are important predictors of microfibre releases. Weekly loads of laundry varied from 1 to 4.5 with the highest frequencies by professionals and large families (Bartsen et al., 2021). The rise of fast fashion and lower-quality garments is likely contributing to an escalation of microfibre pollution, as it has been suggested that less durable textiles may be prone to shedding more microfibres during washing (Vassilenko et al., 2021).

Due to their small size, microfibres emitted from homes can bypass wastewater treatment plant processes and consequently enter the aquatic environment (Vassilenko et al. 2021, Gies et al. 2018, de Falco et al., 2019). Given that the average Canadian household completes 218 loads of laundry annually (NRC, 2023), substantial amounts of microfibres are likely to reach wastewater treatment facilities across Canada. A recent study estimated that the average household in Canada and the U.S.A. produces up to 135 g of plastic microfibres annually - equivalent to 5.33×10^6 microfibres. All households combined add an estimated 0.022 million tonnes of microfibres (or 85×10^{15} microfibres) to wastewater treatment plants each year, with 878 tonnes (or 3.5×10^{15} microfibres) eventually reaching rivers, lakes and the ocean post-treatment (Vassilenko et al., 2021). On a global scale, microfibre release from home laundry is estimated to range from 0.018 to 0.53 million tonnes annually (Boucher & Friot, 2017, Belzagui et al., 2019, UNEP, 2018, The Nature Conservancy, 2021).

Wearing of clothing represents a significant, albeit insufficiently explored, source of environmental microfibre pollution. One estimate indicates that an individual could release up to a billion of microfibres (1.03×10^9) per year by wearing polyester garments (De Falco et al., 2020). Some research indicates that the extent of microfibre release from wearing clothing can be influenced by the wearer's activity level (Licina et al., 2019).

Use of electric dryers also contributes to microfibre emissions, with some research suggesting that dryers can discharge up to 3.5 times more microfibres per laundry load than washing machines (Pirc et al., 2016). Kapp and Miller (2020) reported that a single fleece blanket could release between 404 and 1,160 microfibres within a 30 feet radius of the dryer vent. This issue is particularly significant in countries with widespread use of electric dryers, such as France, where 38% of households utilized them in 2011, the U.S.A. with 80.3% in 2015 (Kapp and Miller, 2020), and Canada, with 81% in 2008 (Statistics Canada, 2009). Although electric dryers are typically equipped with a lint trap, microfibres can either bypass these filters or be released into the air during trap maintenance. Once airborne, microfibres can settle in nearby environments or be transported over long distances to both terrestrial and aquatic ecosystems (Kapp and Miller, 2020). Recent estimates suggest that emissions from dryers in Canada could range between 90 to 120 million microfibres per year (Tao et al., 2021).

The factors influencing these emissions vary across different types of fabric, with specific factors varying across materials. For example, a study by Tao et al. (2022) found that polyester microfibre release increased with the mass of the clothing processed, a trend not observed for cotton textiles.

Commercial laundry

Commercial laundry operations likely play a significant role in microfibre pollution due to the scale and intensity of the washing processes involved. Unlike domestic laundry, commercial laundry services cater to a wide range of sectors including hospitality, healthcare, and retail, processing large volumes of textiles daily. This high-throughput washing is likely to contribute a substantial quantity of microfibres into wastewater.

However, during the writing of this report only one preliminary study, conducted by the Swedish Environmental Protection Agency, examined the role of such facilities in microfibre pollution (Brodin et al. 2018). This study selected six facilities, categorizing them by their primary business sectors, namely hotels, hospitals, and workwear services. It found that microfibre releases into commercial laundry effluent varied significantly, ranging from 500 to 367,000 microfibres per litre of effluent, with the estimated rate of emissions being between 2,559 and 913,750 micrograms per kilogram of item washed (Brodin et al., 2018).

In Canada, commercial laundry facilities are generally required to treat their wastewater before discharging it, either to municipal sewage systems or directly into the environment, depending on their location and the specific regulations that apply. However, the lack of data regarding microfibre concentrations in treated effluents from these commercial laundries constrains a fulsome characterization of their current role in microfibre pollution.

3.2 How do microfibres enter the environment?

Microfibres enter the environment with untreated and treated wastewater effluents, sludge and agricultural runoff, urban stormwater and atmospheric deposition.

3.2.1 Wastewater treatment plant effluent

Public facilities

Although conventional wastewater treatment plants are not specifically designed to remove microfibres and microplastics from wastewater, they can capture up to 99% of these particles (Sun et al., 2019, Gies et al. 2018). Despite this high efficiency, a significant amount of microfibres are released into the environment with treated effluents over long timescales due to the large volumes of wastewater processed by these facilities. The release and fate of microfibres are influenced by local factors such as population density, treatment technology, and environmental conditions (Vermaire et al., 2017, Gies et al., 2018, Sun et al., 2019, Bujaczek et al., 2021, Kye et al., 2023).

Only a handful of studies have been conducted on microfibres and their releases in Canada. Research conducted in Saskatoon reported an annual release of 115.6 million microfibres to the South Saskatchewan River from a single treatment plant (Prajapati et al., 2021). A study on a secondary treatment facility in Vancouver, B.C., reported much higher estimates of 19 billion microfibres, primarily consisting of polyester and modified cellulose (Gies et al., 2018). In contrast, microfibres in WWTP effluent emitted into Lake Ontario were mostly composed of indigo / indigo carmine and cellulose (87%), followed by polyester and polyurethane (Grbíc et al., 2020).

Studying microfibre concentrations around WWTPs can provide important insights into their dispersal and impact. Research conducted on the Ottawa River found significantly higher microplastic concentrations downstream (1.99 microplastics m^{-3}) compared to upstream of a local WWTP (0.71 microplastics m^{-3}), with microfibres accounting for over 73% of these particles (Vermaire et al. 2017). In other studies, including those based in the St. Lawrence and Saskatchewan Rivers (Bujaczek et al., 2021, Crew et al., 2020), microplastic abundances in waters surrounding WWTPs did not vary significantly. These findings suggest that environmental factors, such as rapid water flow and effective effluent dispersal, may dilute microplastic concentrations (Crew et al., 2020). Higher microfibre concentrations upstream (5.2 ± 1.4 microfibres m^{-3}) compared to downstream (2.1 ± 0.3 microfibres m^{-3}) of a WWTP were also reported in research (Campbell et al., 2017). Collectively, these studies highlight the variability in microfibre distribution around WWTP discharges and point to the unique conditions that may influence the transport and accumulation of microfibres in the receiving waters.

Industrial treatment

Globally, the treatment of industrial waste, including from textile manufacturing, varies widely by jurisdiction. It can involve utilizing public facilities or dedicated systems within textile facilities. In some cases textile industries discharge untreated wastewater into water bodies without any treatment (Siddique et al., 2017). Due to the high-volume production and processing, textile industry effluents are expected to be abundant in microfibres. However, literature on microfibre emissions from this sector and microfibre removal efficiencies of industrial treatment facilities is limited.

Studies investigating microfibre emissions and removal efficiencies in industrial treatment plants were conducted in Sweden (Brodin et al., 2018), China (Zhou et al., 2020; Chan et al., 2021), and Turkey (Akyildiz et al., 2022). These studies focused on wet processing, a typical stage in conventional manufacturing of clothing. The quantities of microfibres emitted by textile facilities are influenced by the type of textile material, the total amount of material processed (Chan et al., 2023), and the level of treatment. For example, a study of untreated effluents from a mill processing polyester, viscose, polyamide, and cotton, found microfibre levels up to 1,450 microfibres L^{-1} (Brodin et al., 2018). In another location, treated effluent samples from a textile manufacturing facility equipped with a primary treatment showed significantly lower microfibre concentrations, between 15 to 120 L^{-1} across various polymer types (Akyildiz et al., 2022). Secondary and tertiary treatments have the potential to further reduce microfibre concentrations, with levels of 0.5 to 90 L^{-1} in treated textile effluents reported (Zhou et al., 2020; Chan et al., 2021). This emerging research underscores the critical role of effluent treatment in minimizing microfibre pollution from the textile manufacturing sector.

In Canada, most of the wet processing mills discharge to municipal wastewater collection systems where effluents receive various degrees of treatment (Environment Canada, 2005). A small percentage (approximately 2%) do not receive any treatment (Environment Canada, 2005). There exists a distinct lack of studies on microfibre releases from textile mills in Canada. The Canadian manufacturing sector is comparatively small and its effluents are subject to treatment, suggesting that household laundry releases may play a larger role in microfibre pollution compared to manufacturing releases in Canada.

3.2.2 Sludge, biosolids and agricultural runoff

Treatment of wastewater involves settling and sedimentation of solids, which ultimately accumulate in the sludge. In this process significant quantities of microfibres are removed from the wastewater (Carr et al., 2016, Gies et al., 2018, Talvitie et al., 2017). However, these microfibres are then transferred to biosolids (treated sludge) which are commonly applied to agricultural farmlands, forestry lands, and mining reclamation sites. It is estimated that 50% of treated sludge is applied to agricultural lands in Europe and North America (Nizetto et al., 2016). This application represents a significant pathway for microfibres to terrestrial systems (Nizzetto et al., 2016, Ng et al., 2018, Crossman et al., 2020). In the U.S.A., soil samples taken from fields treated with sludge exhibited higher levels of microfibres compared to untreated fields. Furthermore, farming practices or organisms present in the soil can re-distribute these microfibres, potentially promoting their spread throughout the soil environment (Zubris and Richards, 2005).

Few studies quantified microplastic levels in sludge or biosolids from Canadian WWTPs. The proportion of microfibres in these matrices relative to other microplastics was reported to vary from 40-70% (Gies et al. 2018, Crossman et al. 2020). In Ontario, the concentration ranged from 8 to 15 microplastics g^{-1} in biosolids (Crossman et al., 2020), whereas sludge from a major Vancouver WWTP in Vancouver contained between 4 and 15 microplastics g^{-1} (Gies et al., 2018). In contrast, biosolid samples from another WWTP in Ontario contain over 500 microplastics g^{-1} (Lavoy & Crossman, 2021).

Recently, Sivarajah et al. (2023) sampled biosolids from 22 WWTPs across Canada and two commercial fertilizer producers. They found between 228 and 1,353 particles g^{-1} dry weight with 85% on average being microfibres (a range of 196 to 1,163 microfibres g^{-1}). No significant differences in microplastic profiles were found between different types of WWTP treatment, although there was some evidence that the amount of raw sewage processed by the facilities affects the abundances of microplastics, and therefore likely microfibres, in sludge (Sivarajah et al., 2023). In Canada, it is estimated that 388,700-500,000 tonnes of biosolids are produced every year, with 43-60% being applied to agriculture, potentially adding 1,518 – 8,770 tonnes of microplastics to these systems every year (CH2MHill Canada, Mohajerani and Karabatak, 2021; Milojevic and Cydzik-Kwiatkowska, 2021). Subsequent mobilization of microplastics within the soil after biosolid application may be influenced by parameters such as soil density, accumulation within organic matter and movement by soil biota (Rillig et al., 2017).

The movement and spread of microfibres in the environment are influenced by various factors. Rainfall and irrigation can facilitate their transfer from the soil surface into waterways through runoff. This not only distributes microfibres across different terrestrial habitats, but can also introduce them into water bodies, where they can be carried into broader water systems. Additionally, soil erosion, a common phenomenon in agricultural lands, can further disperse microfibres. As soil particles are washed away or carried off by the wind, microfibres are similarly likely to spread throughout the environment. The mobilization of microfibres and other microplastics from soils after biosolid application is influenced by soil density, with denser soils characterized by greater particle losses from surface runoff (Crossman et al., 2020). These conditions pose a challenge for the containment and management of microfibres during and after the land application of biosolids.

3.2.3 Urban stormwater

Stormwater acts as a conveyor of pollutants from urban landscapes to rivers, lakes, and oceans. In recent years, researchers have increasingly turned their attention to microplastics and microfibres in stormwater. In the Baltic Sea, for instance, stormwater runoff was estimated to be responsible for 62% of microplastics (Schernewski et al. 2021). Several factors have the potential to influence these particles in urban stormwater, including land use and impervious surface area within catchments (Chen et al., 2020, Österlund et al., 2023). Direct measurements of microfibres in stormwater are limited, but microfibres are often identified as a major component of microplastics or other anthropogenic particles.

Ross et al. (2023) investigated microplastics in stormwater from 15 sites in the City of Calgary (AB), where stormwater and sewage are transported within separate pipe networks, during dry and wet conditions. Microfibres accounted for nearly half of microplastics in samples (47.7 ± 33.0%) and comprised cotton (34.8%), polyester (23.3%) and unknown anthropogenic fibres (10.1%). Microplastic abundances, including microfibres, were higher in samples collected during rainfall (33.5 ± 26.1 microplastics L^{-1}) compared to those collected during baseflow (19.1 ± 15.2 microplastics L^{-1}). There was a positive relationship between microplastics sampled and the number of dry days before sampling occurred highlighting the build-up of microplastics on impervious surfaces over time (Ross et al., 2023).

Microfibres accounted for 79% of microplastics in stormwater runoff on average, or 147 ± 137 microfibres L^{-1}, in the Kortright Center for Conservation in the Greater Toronto Area (Smyth et al. 2021). The study's catchment area consisted mainly of parking lots, and it was suggested that air deposition was primarily responsible for introducing microfibres into the stormwater. Additionally, rainfall and the duration before the rainfall were associated with elevated microparticle levels, suggesting that local weather conditions can intensify microfibre pollution.

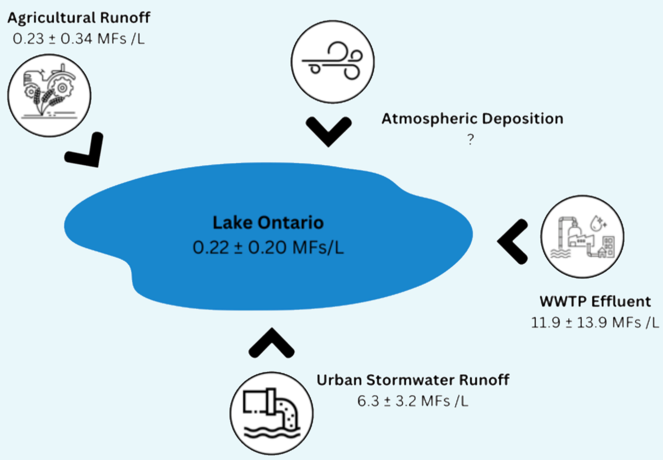
Grbíc et al. (2020) investigated the prevalence and inputs of microplastics into Lake Ontario in the Greater Toronto Area, including via stormwater, agricultural runoff and wastewater. In the lake, microfibres accounted for 41% of microplastics (6.3 ± 3.2 microfibres L^{-1}) and consisted of diverse polymers, likely reflecting a range of pollution sources surrounding Lake Ontario. Microfibres constituted a significant proportion of microplastics found in stormwater and wastewater, while agricultural runoff had the lowest abundances of these particles. Wastewater samples contained almost twice the amount of microfibres compared to stormwater on average, highlighting the influence of home laundry practices on Lake Ontario's microplastic challenge.

Case Study: Examining sources of microfibres into Lake Ontario, Greater Toronto Area (Gbríc et al., 2020)

The Greater Toronto Area, the largest Canadian urban area with 6.5 million residents (City of Toronto, 2023), is located along the shores of Lake Ontario.

104 sub-watersheds drain into Lake Ontario (38,472 km^2).

The study investigated microplastics and other anthropogenic particles from Lake Ontario surface waters and source waters, including stormwater runoff, agricultural runoff, and treated wastewater effluent.



Stormwater and treated wastewater had higher microplastic abundances compared to agricultural run-off. Microfibres were highest in wastewater. Microparticle abundances in Ontario Lake were affected by proximity to urban areas.

3.2.4 Atmospheric transport and deposition

Air currents can distribute atmospheric particles over short time scales of hours and days (Stohl, 2006). Therefore, atmospheric transport can facilitate the rapid dispersal of microfibres across land and water environments. Once airborne, these particles can travel vast distances and eventually settle in the environment by either wet or dry deposition. Hydrolysis, UV degradation, accumulation of organic films, and aggregation with other particles are all processes that act on atmospheric particles (Gewert et al., 2015) and are likely influencing microfibres. It was suggested that microfibres are more likely to travel longer distances than other microplastics because of their small diameters and elongated shape (Allen et al., 2019, Zhang et al., 2020).

In a sparsely populated residential area on the shore of the Eastern Red Sea, the mean atmospheric deposition rate was estimated at 70 microfibres m^{-2} per day, with origins from approximately 25 m away (Martynova et al., 2024). Surprisingly, the majority of microfibres were found to be of natural origin (e.g. cellulose) and only 10% constituted of synthetic polymers (mainly polyester). A recent analysis of scientific literature indicated that cellulosic microfibres are more frequently reported for atmospheric samples than their synthetic counterparts (24 studies, Finneghan et al., 2022). However, due to challenges with methodological comparability, further research is needed to better understand the relative importance of different microfibre types in the atmosphere.

In Canada, data on microfibres and microplastics in the atmosphere is limited, with only three studies available on this topic to date (Welsh et al., 2022; Hamilton et al., 2021; Postma, 2022). Atmospheric deposition was estimated at 10 ± 9 microfibres m^{-2} day^{-1} near Whitehorse in the Yukon (Postma, 2022). Microplastic pollution around a seabird colony in the remote Qikiqtani Region of Nunavut was measured via the collection of air, surface water, sediment, and Northern Fulmar guano samples (Hamilton et al., 2021). Atmospheric deposition samples collected at this Arctic site showed a mean value of 2433 ± 1235 particles m^{-2} day^{-1}, 81% of which were identified as microfibres. Using Raman and FTIR spectroscopy, Hamilton et al. (2021) found that the most common materials collected in atmospheric deposition samples were cellulose (45%), unknown material (24%), and polypropylene (10%) (Hamilton et al., 2021).

Across four study sites in the Muskoka-Haliburton area, a remote location in south-central Ontario, anthropogenic particle deposition rates ranged from 32-73 particles m^{-2} day^{-1}, with an average of 57 particles m^{-2} day^{-1} (20,704 particles m^{-2} $year^{-1}$), of which 89% were microfibres (Welsh et al., 2022). The most commonly identified polymers among the plastic microfibres were polyethylene terephthalate (25%), followed by polyamide, polypropylene, and styrene isoprene copolymers (13% each) (Welsh et al., 2022).

3.2.5 Maritime commerce and operations

The extent of microplastic and microfibre pollution stemming from maritime activities—including shipping, aquaculture, and fisheries—is not fully understood. The origins of microplastics in this sector are varied, involving not only operational waste but also materials inherent to maritime operations, such as plastic pellets, ship paint, marine coatings, and particulates found in sewage and graywater (Peng et al., 2022).

Cruise ships are characterized by their large passenger capacities and extensive amenities. These 'floating cities' produce significant volumes of greywater from laundry, showers, and kitchen activities. Despite the paucity of studies on microplastic levels in graywater across different ship types (Peng et al., 2020), preliminary research reported concentrations ranging from 2,000 to 50,000 microplastics L^{-1} in effluents from cruise ships (Mikkola, 2020). Moreover, recent analysis highlighted that shipping activities in the Canadian Arctic could be releasing between 3.8 to 84.5 billion plastic microfibres annually (Jones-Williams et al., 2021).

3.3 Microfibres in the Canadian environment

Studies suggest that microfibres may be more mobile than other types of microplastics (Cable et al., 2017, Khatmullina and Isachenko, 2017, Wright et al., 2021, Athey et al., 2022), which likely explains their presence in diverse matrices, from seawater, air, sea ice, glaciers, and deep sea sediments (Fang et al., 2018, Huntington et al., 2020, Adams et al., 2021, Carlsson et al., 2021, Ambrosini et al., 2019, Obbart et al., 2014, D'Angelo et al., 2023).

Several studies have quantified microfibres in the Canadian environment. The Arctic has emerged as a particularly sensitive environment for the accumulation of microfibres, with uncertain implications for the health of Arctic food webs and Indigenous Peoples (AMAP, 2017, Ross et al. 2021). In addition to transporting through oceanic currents, riverine discharges, migratory seabirds and other biota (Amélineau et al., 2016; Provencher et al., 2018), modeling of atmospheric transport of microplastics revealed high transport rates of microplastics to the Arctic from southern locations (Evangeliou et al., 2020) and the Arctic Monitoring and Assessment Programme (AMAP) has added marine plastics and microplastics to the list of Chemicals of Emerging Arctic Concern (AMAP, 2017).

3.3.1 Sediment

Sediment represents a well-documented sink for microplastics in both marine and freshwater environments (Kane and Clare, 2019, Courtene-Jones et al., 2020, Boucher et al., 2016, Kim et al., 2023). For instance, Reineccius et al. (2020) estimated that 9,800 tonnes of microfibres settle through the water column and into the bottom sediments in the North Atlantic Subtropical Gyre annually. Microfibres represent between 30-90% of microplastic composition in Canadian sediment samples, with abundances ranging from 0 to 2 microfibres g^{-1} of dry sediment (**Figure 5, Table 5**).

Studies in the Great Lakes Area suggested microfibre deposition and distribution in sediment are influenced not only by proximity to urban areas but also riverine transport, local currents and resuspension and redistribution of sediments (Kumar et al., 2021, Tibbetts et al., 2018, He et al., 2021, Grbić et al., 2020, Belontz et al., 2022). In a study of Lake Ontario, nearshore sediments exhibited a higher proportion of microfibres relative to other types of microplastics compared to the tributary area (Ballent et al., 2016). It was suggested that microfibres may be more prone to long-distance transport and suspension mechanisms compared to fragment microplastics (Ballent et al., 2016). In sediments of St. Lawrence River proportions of microfibres were substantially lower (27%, Crew et al. 2020) compared to Ottawa River (>95%, Vermaire et al. 2017), with differences in sediment organic, mineral content and river morphology suggested as contributing factors (Crew et al. 2020). On the west coast of Canada, microplastic studies in marine sediments reveal localized hotspots of microfibres, such as in Victoria Harbour and Prince Rupert Harbour, likely influenced by a combination of local sources and oceanographic conditions (Noël et al., 2022).

In a recent study of sediment collected along a 2,200 km transect from the Greater Toronto Area to Hudson Bay and the Canadian Arctic including Lake Ontario and Lake Superior, microfibres accounted for 83 to 96 % of the total microplastics (Athey, 2022). Samples collected at southern locations, closer to urban areas contained more microfibres (2.44 ± 0.87 microfibres g^{-1} of sediment) compared to those collected in the Arctic (0.54 ± 0.47 microfibres g^{-1} of sediment). Another study reported between 0.4 and 3.2 microfibres g^{-1} of sediment in samples from across the Arctic Archipelago (Adams et al. 2021). Microfibres accounted for 82% of all microplastics and were predominantly composed of anthropogenic cellulose polymers (Adams et al., 2021).

Figure 5. Microfibres dominate microplastic composition in Canadian sediment samples

Shown are microfibre proportions, as a percentage (%) of total microplastics, from seventeen peer-reviewed studies focusing on marine and freshwater ecosystems. Study information and data underlying the figures are consolidated in **Table 5**.

Table 5. Comparative overview of studies on microplastic and microfibres in Canadian marine and freshwater sediments

Retrieved from seventeen peer-reviewed scientific publications. *Microfibre levels were explicitly reported in the paper; **Microfibre levels were not reported; n-number of studies; n/a-not available.

Location	n	Year	Reported microplastic abundance (count g^{-1} sediment dry weight)	Proportion of microfibres (%)	Calculated or reported microfibre abundance (count g^{-1} sediment dry weight)	Dominant polymer types		Laboratory method		Reference
						Synthetic	Natural (cotton) or semi-synthetic (e.g. rayon)	Digestion and/or extraction	Characterization and quantification	
Arctic										
Arctic Archipelago	21	2018 - 2019	0.54 ± 0.47	89%	0.48 ± 0.42	Polyester (21%)	Modified cellulose (37%)	$CaCl_2$ (calcium chloride) density separation	Light microscopy and Raman spectroscopy	Athey 2022
Hudson Bay to Canadian Arctic Archipelago	20	2017	2	57%	1.14	Polyethylene terephthalate (47.8%)	Modified cellulose (52.2%)	Sodium polytungstate density separation	Light microscopy and FTIR spectroscopy	Huntington et al., 2020

Canadian Arctic Archipelago	14	2014 - 2017	0.6 - 4.7	82%	0.4 - 3.2*	Synthetic polymers (11%)	Modified cellulose (51%)	$CaCl_2$ (calcium chloride) density separation	Light microscopy and Raman spectroscopy	Adams et al., 2021
Great Lakes										
Sudbury	10	2018-2019	0.89 ± 0.64	91%	0.81 ± 0.58	Polyacrylonitrile (7.4%)	Modified cellulose (47%)	$CaCl_2$ (calcium chloride) density separation	Light microscopy and Raman spectroscopy	Athey 2022
Lake Ontario	11		0.65 ± 0.55	89%	0.58 ± 0.49	Polyester (16%)	Modified cellulose (39%)			
Lake Superior	4		0.16 ± 0.14	96%	0.15 ± 0.13	Polyester (19%)	Modified cellulose (48%)			
Hudson Bay	16		0.16 ± 0.11	83%	0.13 ± 0.09	Polyester (22%)	Modified cellulose (43%)			
Greater Toronto Area	5		2.8 ± 1.0	87%	2.44 ± 0.87	Polyester (23%)	Modified cellulose (25%)			
Lake Huron	76	2017	0.059-335	50%	0.03-165	Synthetic (23%)	Anthropogenic natural (72%)	Sodium polytungstate density separation	Light microscopy and FTIR spectroscopy	Belontz et al. 2022

Lake Ontario	33	2012-2015	0.76	n/a	n/a	Polyethylene (31%)	n/a	Sodium polytungstate density separation	Raman and X-ray fluorescence spectroscopy	Ballent et al., 2016
Lake Erie	29	2014-2015	0 - 0.39 (Nearshore) 0.01 - 0.46 (Tributaries) 0.05 - 0.15 (Beach)	64% (Nearshore) 37% (Tributaries) 63% (Beach)	0 - 0.25 (Nearshore) 0.003 - 0.17 (Tributaries) 0.03 - 0.09 (Beach)	Polyethylene (61%)	n/a	Sodium polytungstate density separation	Light microscopy, Fourier Transform Raman spectroscopy and dispersive Raman spectroscopy	Dean et al., 2018
Lake Erie	12	2014	0.43 - particles > 335 µm 0.61 - particles between 125 355 µm	59%	0.25 for particles larger than 0.355 mm; 0.34 for particles 0.125 - 0.355 mm	Polypropylene (14%)	Modified cellulose (23%)	$ZnCl_2$ density separation (zinc chloride, d=1.6 g mL^{-1}), wet peroxide oxidation of floating debris and calcite digestion using hydrochloric acid (4.5%)	Light microscopy and FTIR spectroscopy	Lenaker et al., 2020

Eastern Canada										
St Lawrence River	25	2017	0.83 ± 0.15	27%	0.22 ± 0.08	n/a	n/a	Canola oil extraction	Fluorescent microscopy	Crew et al., 2020
St Lawrence River	33	2010 - 2013	13,759 ± 13,685**	n/a**	n/a	n/a	n/a	n/a	Light microscopy	Castañeda et al., 2014
Ottawa River	10	2015	0.22	> 95%	0.21	n/a	n/a	Sodium hexametaphos phate density separation	Light microscopy	Vermaire et al., 2017
Thames River, Ontario	34	2016	0.006 - 2.4	60%	0.111	Polyethylene terephthalate (20%)	Modified cellulose (67%)	Sodium polytungstate density separation	Light microscopy and FTIR spectroscopy	Corcoran et al., 2019
Western Canada										
Cowichan-Koksila Estuary	14	2020	0.0 – 0.019	n/a	0.0068*	n/a	n/a	"Loss-on-ignitio n" method for organic removal, NaCl density separation	Light microscopy and FTIR spectroscopy	Alava et al., 2022

Lambert Channel and Baynes Sound (intertidal)	16	n/a	n/a	n/a	0.1 - 0.3*	n/a	n/a	NaCl density separation	Light microscopy and hot needle test	Kazmiruk et al., 2018
Coastal British Columbia (intertidal)	16	2016	0.020 ± 0.023	99.20%	0.019 ± 0.021	n/a	Modified cellulose (100%)	KOH digestion	Light microscopy and FTIR spectroscopy	Covernton et al., 2019
Vancouver Island (east coast)	8	2015	0.060 ± 0.063	91%	0.055 ± 0.057	n/a	n/a	KOH digestion	Light microscopy	Collicut et al., 2019
Coastal British Columbia	36	2015 - 2018	0.032 ± 0.005	61.10%	0.019 ± 0.003	Polyester (54%)	n/a	Hydrogen peroxide and ferrous sulfate digestion, canola oil extraction	Light microscopy and FTIR spectroscopy	Noël et al., 2022

3.3.2 Freshwater

Canadian freshwater ecosystems, including rivers and lakes, are invaluable resources providing essential drinking water and sustaining a rich biodiversity including icon species such as salmon. While rivers often function as channels for transporting micro-debris away from urban areas to the oceans (Gasperi et al., 2014;, Lechner et al., 2015, Rech et al., 2014) they can also act as reservoirs that retain and accumulate pollution, including microplastics (Woodward et al., 2021). Proximity to wastewater treatment plants, water body size, water turbulence, vessel traffic and geomorphological characteristics all influence the abundance of microplastics, including microfibres, within rivers and their sinking and accumulation in bottom sediments (Mani et al., 2015, Fischer et al., 2016).

In Canada, the majority of microplastic studies have focused on the Great Lakes and the St. Lawrence River systems (**Figure 6, Table 6**). In one study, average microfibre abundances in the waters of Lake Huron, Lake Superior and Lake Michigan were 0.119 ± 0.04 microfibres mL^{-1} (Whitaker et al., 2019). Hendrickson et al. (2018) found that Lake Superior had higher levels of microfibres compared to Lake Michigan, likely due to varying degrees of urbanization. Cox et al. (2021) collected 187 water samples across Lake Superior, finding that 67% of microplastics were microfibres, predominantly made of polyethylene polymer. They noted variations in microplastic abundances across different parts of the lake, indicating that circulation patterns might influence their distribution. It was estimated that up to 2.5 billion plastic particles, or 1.7 billion microfibres, are present across the entire surface of Lake Superior (67%, Cox et al., 2021).

Studies on the Saskatchewan River reported microfibre concentration in the range of 17.8 to 48.7 microfibres m^{-3} (Kumayon et al., 2023, Bujaczek et al., 2017). In eight lakes sampled in British Columbia, Klasios and Tseng (2023) found an average of 0.607 ± 0.153 microplastics L^{-1}, of which 76% were microfibres (0.46 - 0.12 microfibres L^{-1}) that were dominated by polyester (78%). The levels across B.C. lakes did not vary significantly, with authors attributing microplastic contamination to recreational activities and atmospheric deposition (Klasios and Tseng, 2023).

Figure 6. Microfibres dominate microplastic composition in Canadian rivers and lakes

Shown below are microfibre proportions, as a percentage (%) of total microplastics, from fourteen peer-reviewed studies focusing on freshwater ecosystems. Study information and data underlying the figures are consolidated in **Table 6**.

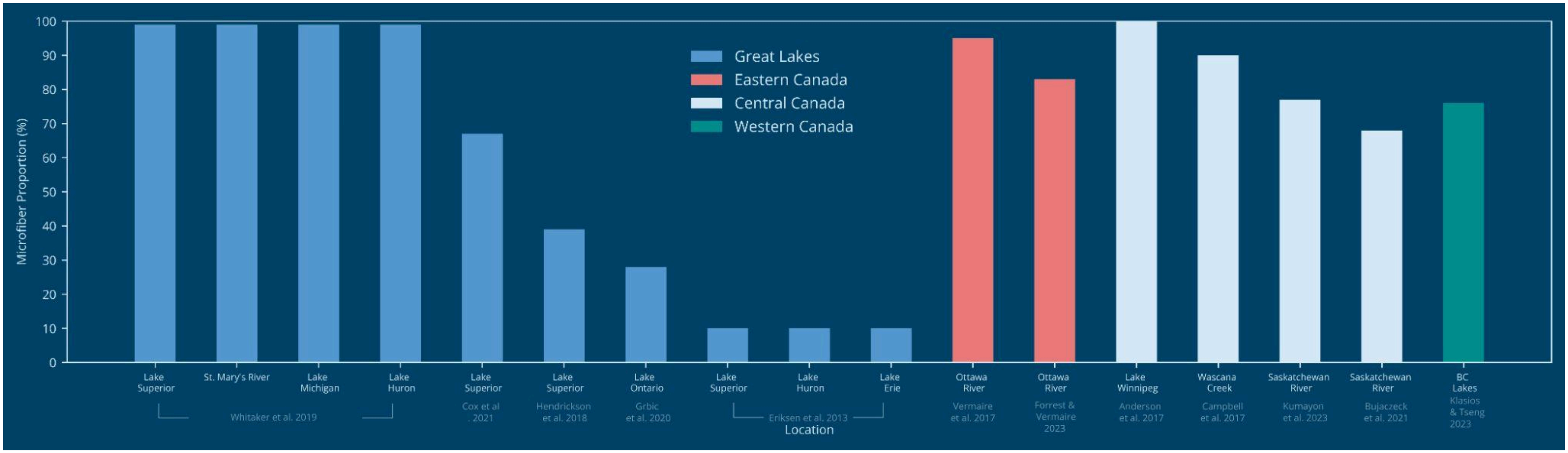


Table 6. Comparative overview of studies on microplastic and microfibres in Canadian river and lake samples

Retrieved from fourteen peer-reviewed scientific publications *Microfibre levels were explicitly reported in the paper, whereas remaining entries are calculated concentrations; n-number of samples; n/a- data/information not available.

Location	n	Year	Reported microplastic abundance (count L^{-1} or km^{-2})	Microfibre proportion (%)	Calculated or reported microfibre abundance (count L^{-1} or km^{-2})	Dominant polymer type		Laboratory method		Reference
						Synthetic	Natural (cotton) or semi-synthetic (e.g. rayon)	Digestion and/or extraction	Characterization and quantification	
Great Lakes										
Lake Superior	3	2017	119 ± 40 L^{-1}*	99%	118 ± 40 L^{-1}	n/a	n/a	n/a	Melt test, light microscopy and FTIR spectroscopy	Whitaker et al., 2019
St. Mary's River	1									
Lake Michigan	1									
Lake Huron	2									
Lake Superior	187	2014	30,000 particle km^{-2}	67%	2680 - 67,000 microfibres km^{-2}	Polyethylene (51%)	n/a	Wet peroxide digestion	Light microscopy and FTIR spectroscopy	Cox et al., 2021
Lake Superior	12	2016-2017	37,000 ± 27,000	39%	14430 ± 10530 microfibres km^{-2}	Polyvinyl chloride, polypropylen	Cotton	Fenton oxidation,	Melt test, pyrolysis-gas chromatography mass spectrometry;	Hendrickson et al., 2018

			particles km^{-2}*			e, polyethylene		NaCl density separation	light microscopy FTIR spectroscopy	
Lake Ontario	4	2015	0.8 ± 0.7 L^{-1}	28%	0.22 ± 0.20 L^{-1}	Polyethylene terephthalat e	Cellulose	$CaCl_2$ density separation	Micro-Raman spectroscopy; FTIR spectroscopy (Attenuated Total Reflection)	Grbic et al., 2020
Lake Superior, Lake Huron, Lake Erie	21	2012	43,157 particles km^{-2}*	10%	4349.8 particles km^{-2}	n/a	n/a	NaCl density separation, acidic digestion using HCl	SEM (Scanning Electron Microscopy), Energy Dispersive X-ray Spectroscopy (EDS)	Eriksen et al., 2013
Eastern Canada										
St. Lawrence River	10	2017	0.12 ± 0.01 L^{-1}	n/a	n/a	n/a	n/a	Canola oil extraction	Fluorescent microscopy	Crew et al., 2020
Ottawa River	7	2016	0.05 - 0.24 L^{-1}	> 95%	0.04 - 0.23 L^{-1}	n/a	n/a	Hydrogen peroxide oxidation	Light microscopy	Vermaire et al. 2017
Ottawa River	105	2019-2021	0.528 L^{-1}	83%	0.438 L^{-1}	n/a	n/a	Hydrogen peroxide oxidation	Light microscopy	Forrest and Vermaire, 2023

Central Canada										
Lake Winnipeg	12	2014-2016	193,420 ± 115,567 particles km^{-2}	Majority of MPs identified as fibres	n/a	n/a	n/a	Wet peroxide oxidation	SEM, Energy Dispersive X-ray Spectroscopy (EDS)	Anderson et al., 2017
Wascana Creek, SK	15	2015 - 2016	0.0031 ± 0.0008 L^{-1}	90%	0.0028 ± 0.0008 L^{-1}	n/a	n/a	Iron sulfate heptahydrate and hydrogen peroxide digestion	Light microscopy and hot needle test	Campbell et al., 2017
Saskatchewan River	7	2020	0.063 L^{-1}	77%	0.05 L^{-1}	Polyethylene terephthalate (49%)	Natural textiles (77%)	n/a	Light microscopy and Raman spectroscopy	Kumayon et al., 2023
Saskatchewan River	22	2017	0.026 ± 0.018 L^{-1}	68%	0.018 ± 0.013 L^{-1}	Polyester (30%)	Cotton (30%)	Hydrogen peroxide digestion and zinc chloride separation	Light microscopy and Raman spectroscopy	Bujaczeck et al., 2021
Western Canada										
8 BC lakes	32	2021	0.607 ± 0.153 L^{-1}	76%	0.46 - 0.12 L^{-1}	Polyester (78%)	n/a	KOH digestion	Light microscopy and Raman spectroscopy	Klasios and Tseng, 2023

3.3.3 Seawater

The majority of studies on microplastics and microfibres in seawater have been conducted in the Canadian Arctic (n = 4) and on the west coast of Canada (n = 5, **Table 7, Figure 7**). In marine studies, microfibres account for approximately 75% to 100% of the total microplastics.

Huntington et al. 2020 investigated microplastics in waters spanning the Hudson Bay and the Canadian Archipelago, finding concentrations of microfibres of up to 300 particles m^{-3}. Polyester and polypropylene were the dominant synthetic types of microfibres while natural anthropogenic microfibres (e.g. cotton) comprised ~14% of the particles (Huntington et al., 2020). A lack of correlation between microplastic concentrations and population densities in the study suggested that long-range transport via atmosphere or currents was a more important source than local sources.

Ross et al. (2021) sampled 71 stations across the European and North American Arctic - including the North Pole, as well as down to 1,015 m depth at several locations in the Beaufort Sea. Between 92% to 94% of all microplastics consisted of microfibres, primarily polyester (73%). The study found three times more microfibres in the eastern Arctic compared to the west, with an east-to-west shift in infra-red signatures pointing to a potential weathering of microfibres away from the source. The results suggested that polyester microfibres may be delivered to the eastern Arctic Ocean, via Atlantic Ocean inputs and/or atmospheric transport from the South.

Jones-Williams et al. (2021) explored the role of shipping as a potential source of microfibres through untreated greywater discharge. With the increase in shipping activity in the Canadian Arctic, the volume of greywater discharge is expected to increase from 33 million L in 2016 to more than 60 million L in 2035 (Vard, 2018). Using the 2016 discharge volume, the study estimated an annual release of 3.8 to 84.5 billion plastic microfibres into the Canadian Arctic from Arctic shipping.

In coastal British Columbia, approximately 80%-100% of microplastics detected in seawater samples were microfibres (Desforges et al., 2014; Collicut et al., 2019; Covernton et al., 2019; Mahara et al., 2022). Desforges et al. (2014) found that their abundances were lowest 1,200 km offshore in the remote North East Pacific Ocean, and increased 6-, 12- and 27-fold near Vancouver Island and into Strait of Georgia and Queen Charlotte Sound, respectively. This pattern was attributed to the influence of cities and urban areas, as well as oceanographic conditions that trap microplastics in the Queens Charlotte Sound (Desforges et al., 2014).

Figure 7. Microfibres dominate microplastic composition in Canadian seawater

Shown below are microfibre proportions, as a percentage (%) of total microplastics, from nine peer-reviewed studies focusing on marine ecosystems. Study information and data underlying the figures are consolidated in **Table 7**.

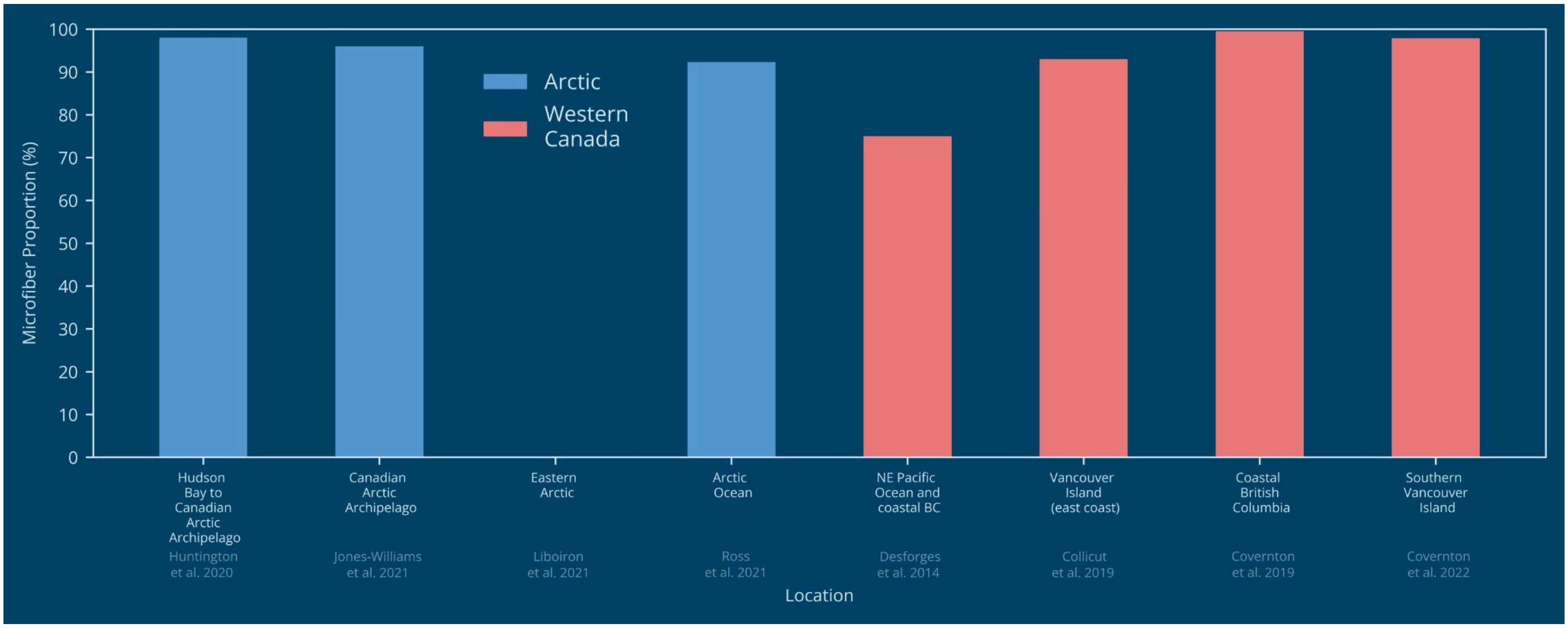


Table 7. Comparative overview of studies on microplastic and microfibres in Canadian seawater samples

Retrieved from nine peer-reviewed scientific publications. *microfibre levels were explicitly reported in the paper; **water was collected from the beach as opposed to a boa; n: number of samples; n/a: data/information not available.

Location	n	Reported particle abundance (count L^{-1})	Microfibre proportion (%)	Calculated or reported microfibre abundance (count L^{-1})	Dominant polymer type		Laboratory method		Reference
					Synthetic	Natural (cotton) or semi-synthetic (e.g. rayon)	Digestion and/or extraction	Characterization and quantification	
Arctic									
Hudson Bay to the Canadian Arctic Archipelago	21	0.07*	98%	0.07*	Polyester and polypropylene	Unspecified natural fibres (14%)	Filtration	Light microscopy and Raman spectroscopy	Huntington et al., 2020
Canadian Arctic Archipelago	16	0.031 ± 0.017	96%	0.029 ± 0.016	Polyester and acrylics (71%)	n/a	Sodium dodecyl sulfate digestion	Light microscopy and FTIR spectroscopy	Jones-Williams et al., 2021
Eastern Arctic	12	0.018*	0	0	0	0	H_2O_2 (hydrogen peroxide) digestion and bleach	Light microscopy and FTIR spectroscopy	Liboiron et al., 2021
Arctic Ocean	71	0.0405 ± 0.004	92%	0.037 ± 0.003	Polyester (73.3%)	Natural and semi-synthetic (41%)	Canola oil extraction	Light microscopy an FTIR spectroscopy	Ross et al., 2021

Western Canada									
Northeast Pacific and coastal British Columbia	34	0.008 - 9.2	75%	0.006 - 6.9	n/a	n/a	HCl digestion	Light microscopy	Desforges et al., 2014
Vancouver Island, British Columbia	5	0.65 ± 0.52	93%	0.61 ± 0.48	n/a	n/a	KOH digestion, $CaCl_2$ density separation	Light microscopy	Collicut et al., 2019
Baynes Sound, British Columbia	11	0.59	83%	0.49	Polyester	Cellulose acetate	KOH and H_2O_2 digestion	Light microscopy and Raman spectroscopy	Mahara et al., 2022
Coastal British Columbia	16	0.63 ± 0.68	99.5%	0.63 ± 0.68	Polyester (6.3%)	Cotton (6.3%)	KOH digestion	Light microscopy and FTIR spectroscopy	Covernton et al., 2019
Southern Vancouver Island, British Columbia**	3	0.0000425	97.9	0.0000416	Polyester (26.1%)	Natural anthropogenic (e.g., wool, dyed cellulose) (54%)	Hydrogen peroxide and KOH digestions, NaI density separation	Light microscopy and Raman spectroscopy	Covernton et al., 2022

3.3.5 Soil

Terrestrial systems have been significantly less studied than aquatic environments in terms of microplastic pollution. However, research in this area is experiencing rapid growth due to increasing evidence of the widespread presence of these particles. For instance, in 2020 the proportion of terrestrial studies on microplastics constituted 43% of marine studies compared to 19% in 2016 (He et al. 2020). The main sources of microplastics, and likely microfibres, in these systems are wastewater irrigation, biosolid and compost application as soil improvers, atmospheric deposition, and transport from landfills by wind and water (Nizzetto et al., 2016, Steinmetz et al., 2016).

In Canada, limited investigations are available on this topic. Crossman et al., 2020 examined microplastics in the upper soil at four agricultural fields as well as from two biosolid suppliers in Ontario. Three of the four fields had been previously treated with biosolids, while one field had no history of biosolid treatment and acted as a control. Polyester microfibres were abundant in field soils comprising 41%–45% of the total microplastics, but were lower in biosolid application where they comprised 8%–21% of the total microplastics. The study observed that after applying biosolids, microfibre levels increased in two of the three treated sites, while the prevalence of fragment microplastics decreased. This pattern implied that microfibres, due to their elongated and flexible structure, may be more likely to become entangled and persist in the soil matrix, whereas fragments could be more readily exported or degraded.

3.3.6 Biota

Assessing the presence and ingestion of microfibres in biota represents a great challenge due to the difficulty in isolating these particles from digestive tracts and tissues of animals. Scientific research conducted in both freshwater and marine ecosystems have consistently identified synthetic microfibres in range of organisms, including in species of invertebrates, whales, and birds (McGoran et al., 2017, Moore et al., 2020, Moore et al. 2021, Weyman et al., 2024). Between 2011 and 2020, at least 133 studies documented microfibres in biota, including 58 studies that reported microfibres in various fish species and 49 that reported microfibres in invertebrates (Athey & Erdle, 2021).

In Canada, microplastics contamination has been examined in species of coastal zooplankton, fish, mussels, birds, and Beluga whales from Canadian Arctic (Brookson et al., 2019, Desforges et al., 2015, Huntington et al., 2020, Moore et al., 2020, Moore et al., 2021,Noël et al., 2022). These studies often point to the transfer of microfibres across the food webs, highlighting their ubiquity and potential to accumulate at higher trophic levels. For instance, Desforges et al. (2015) found evidence for ingestion of microplastics and microfibres by wild zooplankton from coastal British Columbia, and estimated that consumption of microplastic-containing zooplankton could lead to ingestion of 2–7 microplastic particles per day by individual juvenile salmon, and ≤91 microplastic particles per day in returning adults. A different study focused on Arctic Beluga food web found that various fish species, which are part of the diet of the Beaufort Sea beluga whales, were commonly contaminated with microfibres (Moore et al., 2022). It was estimated that individual beluga may ingest between 3,800 and 145,000 microplastics annually through trophic transfer, with authors highlighting uncertain health implications.

3.4 Gaps in the scientific literature

We identified the following knowledge gaps in the scientific understanding of microfibre pollution sources, transport and fate:

- **Microfibre contributions from textile uses in different sectors.** While understanding of microfibre releases from textile home laundry has significantly advanced, the extent to which non-clothing products contribute to the microfibre pollution problem remains limited. Specifically, we find gaps in data for microfibre releases related to uses in healthcare, agricultural, construction and fishing industries.

- **Commercial laundry releases.** Only one preliminary study was identified on microplastics releases from commercial laundry operations. There is a lack of foundational data on microfibre concentrations and composition in this sector.

- **Electric drying of clothing.** Emerging research indicates that domestic electric drying of clothing could be a significant source of microfibres. However, few studies are available and more information, particularly on the role of appliance design and types of garments, would enhance the understanding of this microfibre pollution source.

- **Natural anthropogenic microfibres**. Microplastics research has been largely focused on synthetic microfibres, possibly due to the conception that natural microfibres are thought to be biodegradable (Ladewig et al., 2015, Wieshu et al., 2016), although methodological limitations are likely influencing this trend (e.g. degradation of natural microfibres in treatments that are suitable for plastic polymers or dye interferences in spectroscopic analysis, Dehaut et al., 2016, Treilles et al., 2020, Lenz et al., 2015). Some research suggests that anthropogenic natural microfibres may be similar or higher in their abundance in the environment (Stanton et al., 2019, Dris et al., 2016, Liu et al. 2023). For instance, a recent global review of seawater studies reported that modified cellulosic and animal protein-based microfibres accounted for 91% of the total microplastic composition (Suaria et al., 2020).

- **Sewage sludge and biosolids.** There is evidence that biosolid application represents a significant risk for microfibre pollution in terrestrial ecosystems, however, more research is needed. This is especially important as the amount of treated wastewater is projected to grow in the future (Gavigan et al., 2020).

- **Stormwater.** Although wastewater treatment plants have been identified as a significant conduit for microfibres into aquatic environments, recent research demonstrates the presence of microfibres in urban runoff. There is a need to better understand this diffuse source, which may differ depending on local infrastructure and population density.

- **Groundwater.** Research on freshwater systems has often focused on lakes, rivers and streams, yet emerging studies revealed that microfibres can also migrate through soil strata (Engdahl, 2018, Goeppert and Goldscheider, 2021). Despite this, it remains uncertain whether these microfibres can reach and contaminate groundwater (Re, 2019; Goeppert and Goldscheider, 2021).

- **Snow and ice**. Little research is available on microplastics in snow and ice. Since snowpacks are likely receiving microfibres from long-range atmospheric transport and deposition. Further research on the role of atmospheric transport in delivering microfibres to remote environments (including Canada's Arctic) is needed.

- **Terrestrial environments**. A recent study suggests that synthetic microfibre emissions to terrestrial environments and landfills rival those to aquatic environments (Gavigan et al., 2020). Yet, terrestrial studies significantly lag behind aquatic research on microplastics and microfibres, leading to gaps in our understanding of their concentrations, fate and wider impacts.

- **Indigenous foods**. The long-range transport of persistent organic pollutants (POPs) to the Canadian Arctic via atmospheric and ocean currents highlights the vulnerability of Indigenous foods to pollution and lays the foundation for the science-to-policy success of the Stockholm Convention. A better understanding of microfibres and microplastics in Indigenous foods is critically important and will benefit from a blend of western science and Indigenous Knowledge.

3.5 Estimates of generation, releases and fate of microfibres globally and in Canada

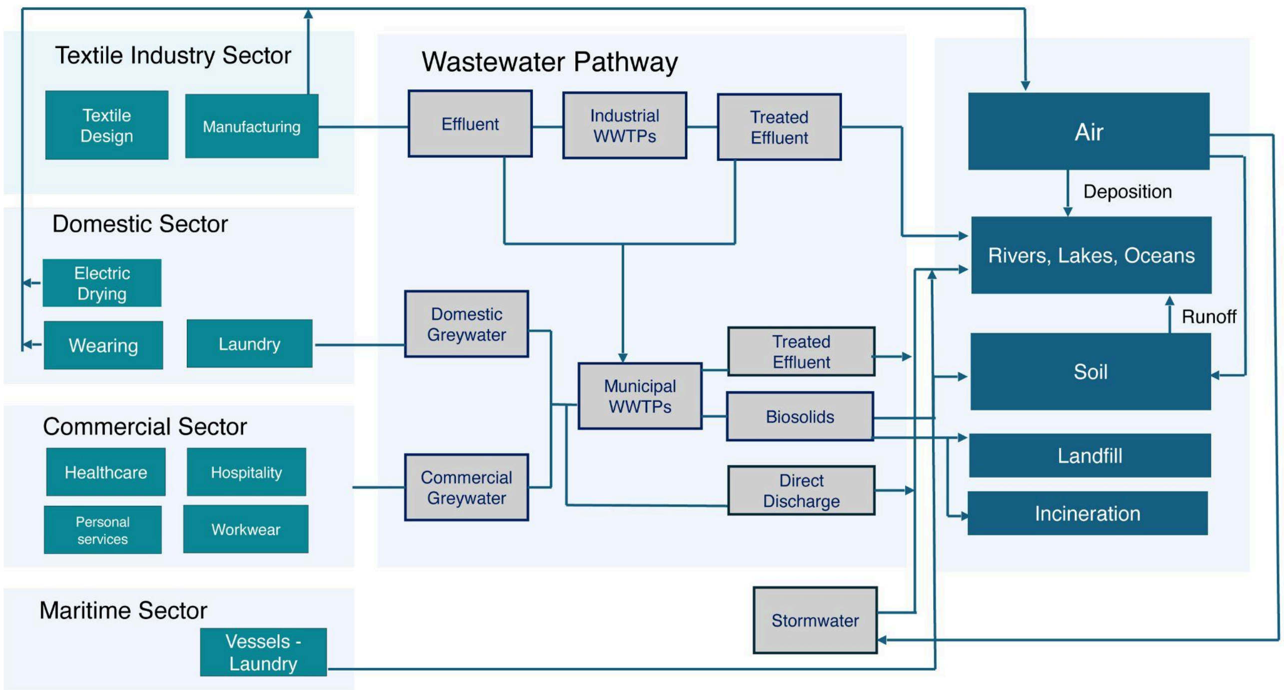
Estimating the global and regional releases and fate of microfibres is complex due to significant data variabilities, leading to a wide range of estimates (**Table 8**). Despite this variance, the substantial scale of microfibre releases into the environment is evident. This underscores the importance of developing prevention and management strategies, while expanding research into microfibre emissions from different pathways and their exposure to humans and the environment.

A recent global flow analysis provides a comprehensive view of the releases and fate of microfibres derived from washing of synthetic apparel (Gavigan et al., 2020). The study reported that between 1960-2016, 2.9 million tonnes of synthetic microfibres entered waterbodies, which is equivalent to over 7 billion fleece jackets by mass, while 1.9 million tonnes were applied to terrestrial environments, 0.6 million tonnes landfilled, and 0.3 million tonnes incinerated. The majority of waterborne microfibres (88%) resulted from the discharge of untreated wastewater, primarily in Asian countries. Although North America and Western Europe contributed 2-6% of microfibres to water bodies, almost half of microfibres produced in those regions entered the terrestrial environment through the application of contaminated biosolids. The study indicates that while wastewater infrastructure can reduce the release of microfibres into aquatic environments, it is not a silver bullet solution. The significant transfer of microfibres to land through biosolids application and to landfills (1.96 million tonnes) points to the need for comprehensive solutions that minimize the generation of microfibres at the source.

To better understand Canada's microfibre pollution challenge, we mapped out the relevant sector sources and pathways by which microfibres enter water, soil and atmospheric compartments (**Figure 8**, Flow Map of Microfibre Pollution). This diagram focuses on microfibres from clothing, an area where understanding has significantly advanced in recent years. Utilizing the methodology established in our prior research (Vassilenko et al. 2021), we also estimated microfibre releases from laundering textiles in Canada by domestic and commercial sectors, and their inputs into water and soil ecosystems (detailed methodology is provided in Appendix A).

Figure 8. Microfibre pollution flow map: how are microfibres generated and where do they go?

This microfibre pollution flow map illustrates the sectors and activities generating microfibres, their downstream transfer and their ultimate destination in the environment.



We estimate that:

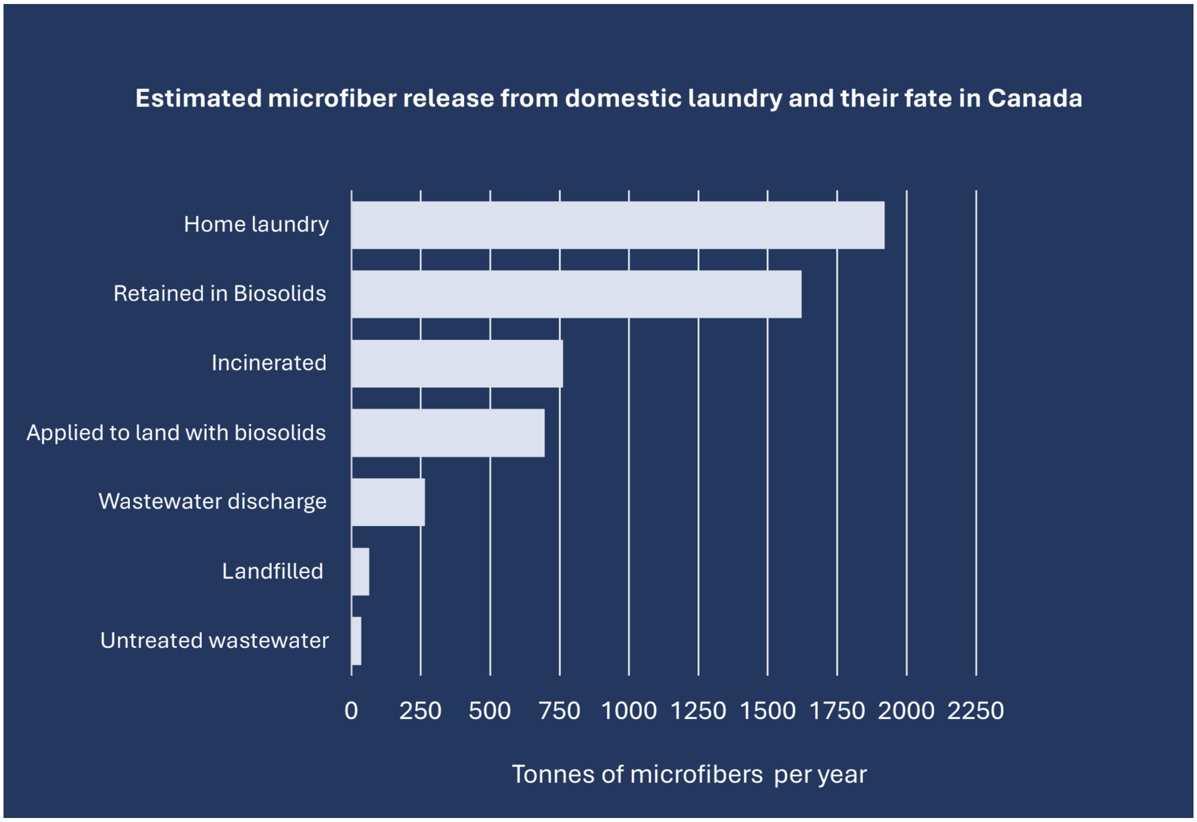
Canadian households generate **1,920 tonnes** of microfibres annually by laundering textiles (**Figure 9**). Technical and behavioural interventions to prevent the release of microfibres at the consumer level have been researched extensively and are discussed in Chapter 5, Section 5.2.

Wastewater discharge is estimated to contribute **264 tonnes** via treated effluents, with an additional **35 tonnes** via untreated effluents to aquatic environments each year. Wastewater treatment facilities are crucial, capturing up to 99% of microfibres and significantly reducing domestic microfibre discharges into the aquatic receiving environment. This existing efficiency suggests that source control measures are essential in complementing wastewater treatment works. The efficiencies of conventional treatment and emerging technologies for removing microfibres are reviewed in Chapter 5, Section 5.3.

Despite the considerable reduction of microfibres by treatment processes, the accumulation of **1,621 tonnes of microfibres in biosolids annually** poses a significant risk to soil and human health. An estimated **795 tonnes are distributed into Canadian soil** ecosystems each year through the application of biosolids for agriculture, forestry and land reclamation purposes. This finding further emphasizes the importance of reducing microfibre entry into wastewater systems through source control. Microfibres persist in the environment; they are simply relocated through biosolid application practices or through landfill deposition. Improvements in biosolid management can reduce the dispersion of microfibres across Canadian soil and water systems through runoff, as discussed in Chapter 5, Section 5.3.2.

Figure 9. What happens to microfibres released from Canadian homes during textile laundering?

Estimates of microfibres released during home laundry of textiles and their loads in wastewater, biosolids, soil, landfill and amounts incinerated. Detailed methodology is provided in Appendix (Appendix A).



Electric drying of clothing represents a potentially significant additional source of microfibres to the Canadian environment. A recent study by Tao et al. (2022) estimated that an average Canadian household releases between 90 to 120 million microfibres from a dryer appliance annually (based on polyester and cotton fabrics, respectively). Our conversion of the count data from Tao et al. (2022) to mass of microfibres (using an average polyester and cotton microfibre weights from Vassilenko et al. 2021), suggests that electric drying could be contributing between 287 to 371 tonnes of microfibres to the atmosphere annually, which is similar to our estimated releases of microfibres to water environments via wastewater treatment facilities.

Preliminary estimates suggest that **commercial laundry operations** are releasing up to **1,099 tonnes** of microfibres annually to the Canadian environment, possibly doubling the microfibre contributions to Canadian soils and aquatic environments. However, there are significant uncertainties in these estimates due to data gaps. Further research is recommended to refine the understanding on the scale of microfibre contribution from commercial laundry in Canada.

Furthermore, there is insufficient data to evaluate the domestic **manufacturing process** releases of microfibres. Canada imports 95% of its clothing, underscoring the importance of addressing the microfibre problem on a global scale.

We estimate that by 2030, marking a critical timeline for Canada's ambitious zero plastic waste objectives, laundering of textiles will contribute **6, 558 tonnes of microfibres to Canadian soil and water combined**. This is equivalent to approximately 44 million T-shirts.

Table 8. Summary global microfibre release estimates to the environment from scientific and technical literature

Scope	Amount (annual)	Study	Details
Global	0.26 million tonnes to water bodies	UNEP (2018)	Synthetic fibre releases assuming 2% of microplastics in clothing are lost via washing during the lifetime and an annual consumption of about 25 Mt of plastic fibres for clothing. Emissions via wastewater treatment plants.
Global	0.48-4.48 million tonnes to water bodies and air combined (combined sources)	First Sentier MUFG Sustainable Investment Institute Report (2022)	Residential & commercial laundry, wear, and textile manufacturing; including natural and synthetic microfibres.

Global	0.0178 million tonnes	Belzagui et al. 2019	Estimates based on annual laundry cycles per capita, load per wash and regional wastewater treatment.
Global	~140 quadrillion particles to water bodies	Pew Charitable Trust & SYSTEMIQ (2020)	Model based on domestic hand and machine washing of textiles.
US & Canada	898 tonnes to water bodies, 3.5 quadrillion microfibres	Vassilenko et al. (2021)	Domestic laundry and synthetic clothing only; based on data from laundry experiments of commercial products and an average Canadian and US household laundry rate.
Global	0.12 million tonnes from manufacturing, the equivalent of ~500 T-shirts 0.53 million tonnes from consumer laundry	The Nature Conservancy (2021)	Estimates based on synthetic textiles.
Europe	18,430 - 46,175 tonnes to water bodies (100-600 quadrillion fibres)	Hann et al. (2018)	Releases from domestic laundry only.
Global	0.525 million tonnes or 35% of primary microplastics (tires, city dust, pellets, road markings, personal care products) to water bodies	Boucher and Friot (2017)	Releases of synthetic microfibres from domestic laundry. Estimated using the central model scenario of 1.5 million tonnes of primary microplastics per year and 35% proportion of microfibres provided in the study.
Global	0.167 million tonnes to water 0.142 million tonnes to land 0.035 million tonnes to water bodies 0.017 million tonnes incinerated	Gavigan et al. (2021)	Synthetic microfibre releases from washing machines. Based on global apparel production, regionalized consumption, apparel end of life and wastewater treatment. Emissions from washing machines were derived using an average microfibre loss of 0.34 kg per tonne washed.

Table 9. Estimates of microfibre releases from domestic and commercial laundry in Canada.

Details of the methodology are provided in the Appendix (Appendix A).

Source/pathway/compartment	Annual contributions (tonnes per year)	Description
Domestic laundry	1,920	Microfibres released from washing of textiles by all Canadian households combined
Commercial laundry	1,099	Microfibres released from washing of textiles by Canadian commercial laundry businesses
Municipal Wastewater Treatment Plants	264	Releases of domestic microfibres after treatment into rivers, lakes and oceans
Untreated wastewater	35	Releases of domestic microfibres into rivers, lakes and oceans due to lack of wastewater treatment
Microfibres in biosolids	1,621	Microfibres retained in biosolids
Biosolid application of microfibres to soil and for forestry, reclamation purposes	795	Microfibres added to soil ecosystems through the application of biosolids
Incinerated	762	Microfibres incinerated with biosolids
Landfilled	65	Microfibres landfilled with biosolids

Chapter 4: Methods and technologies to measure microfibres

Innovation in Canadian science, regulatory and industry circles will benefit from a blend of flexible and standardized methods and protocols for microfibre sampling and determination.

4.0 Key messages

- **Microfibre methods can be categorized based on their application**, including testing microfibre releases from textile products and measuring microfibres in various environmental sample types.
- **Microfibres are often studied within the broader category of microplastics**. Their unique properties complicate sampling and analysis, leading to challenges in accurately representing microfibre pollution in the environment.
- **Currently, there are limited guidelines or regulations for monitoring or controlling microfibre pollution**, partly due to gaps in standardized measurement methods. However, while a variety of methodological protocols are used in research, standardized methods are being advanced at international level.

The field of microplastic research has significantly advanced in recent years, with a diverse range of analytical techniques developed for collection of microplastic samples and their analysis. This encompasses determination of their size, morphology, polymer type, and abundance. These methods aim to identify and quantify microplastics, of which microfibres are a subset. However, the broad diversity of microplastics, lack of standardized definitions, combined with the varying strengths and limitations of different techniques, results in microfibres not being consistently represented in existing research. Moreover, while methods for analyzing microfibres in water samples have advanced significantly, the development and refinement of methodologies for more complex matrices, such as soil, and biota, is still ongoing (Athey & Erdle, 2021).

Concurrently, industry and cross-sector efforts have led to the recent introduction of international standard methods to measure microfibre releases from textile products and in samples from textile sources. Standard methodologies for environmental microplastic monitoring and testing, particularly in water, have also been the focus of international standardization efforts, however many of these methods are still under development. This effort towards standardization represents a critical step forward in the systematic assessment of microplastics in the environment, including microfibres.

The alignment of different microplastic research methodologies through harmonization has been a key objective of several international and regional initiatives, such as EuroQCharm, the Marine Litter Group of the Arctic Monitoring and Assessment Programme (AMAP), the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), and projects within the State of California. These efforts aim to improve the comparability of different techniques by rigorously testing them, identifying their limitations, and establishing reporting standards (AMAP, 2021).

This harmonization process is critical for the effective implementation of monitoring programs and the assessment of microplastic risks. Moreover, recommendations and best practices for microplastic analysis from these initiatives will aid in addressing existing challenges within microplastic research, particularly the prevalent issue of insufficient quality control and assurance (QA/QC) measures (as analyzed in Primpke et al. 2023, Provencher et al. 2022). The field of microplastics has been developing rapidly in recent years, which may explain why latest methodological recommendations are not always followed in recent literature (Primpke et al. 2023, Provencher et al. 2020).

4.1 Research methods for environmental microfibre analysis

4.1.1 Considerations

There are several important considerations for sampling, characterizing and quantifying microfibres in the environment. Microfibres are very fine and elongated particles, typically between 10-20 µm in the shortest dimension (width), that are ubiquitous and subject to transport processes in the environment. These unique characteristics pose specific challenges for accurate detection and quantification in environmental studies.

Contamination and positive controls

Microfibres are prevalent in both indoor and outdoor air, including some of the most remote regions (Allen et al. 2019, Sharaf Din et a. 2024). Preventing contamination during field and laboratory procedures is an essential aspect of microfibre analyses, particularly when determining low concentrations is critical. Established best practices for controlling microfibre contamination include the design of field equipment, avoidance of synthetic clothing and microfibre shedding materials during procedures, regular laboratory cleaning and monitoring, use of cleanrooms and HEPA filtered bench spaces, and collection of field and procedural blanks (Brander et al. 2020).

However, some on-going challenges include suitable methods for correcting for contamination during procedures in microplastic datasets and interpreting control data. Microplastics, including microfibres, are discrete entities characterized by heterogeneity and stochastic distribution. These characteristics pose a challenge to the adoption of established detection and quantification procedures typically employed for environmental contaminants (Lao and Wong, 2023). However, studies are increasingly exploring this question and new statistical methods for treatment of control samples in microplastic research are being evaluated (Dawson et al., 2023, Lao & Wong, 2023, Covernton et al, 2022).

Sample size

Given the relatively low abundance of microfibres in environmental matrices compared to natural particles, selection of adequate sample size, replication, and spatial coverage are critical aspects of study design to ensure the collection of statistically robust and representative data (Kolemans et al. 2019). Their concentrations vary by over 1,000 orders of magnitude across different environmental matrices (Athey and Erdle, 2022) depending on locations, and seasons, which significantly complicates the standardization of sample sizes for microfibre research. Municipal wastewater and sediments, for instance, are often found to have high concentrations of microfibres and other microplastics, while sources of drinking water, remote ocean areas, and waterbodies distant from urbanized areas typically exhibit lower abundances of these contaminants.

As outlined in a systematic review of Koelmans et al. 2019, the benchmark for microplastic detection is a method's ability to detect at least one particle with statistical rigor. Sampling too low reduces the probability of finding particles, which may lead to incorrect conclusions about the absence of microplastics in the study area. On the other hand, large sample sizes require significant field and lab effort, while often facing technical limitations like filter clogging. The question of the representative sample size for microplastic detection across different environmental matrices continues to be investigated (e.g. Watkins et al., 2021) but targeting large sampling volumes has been recommended for detecting microfibres in water environments (Athey & Erdle 2022). Conducting pilot studies and refining approaches based on preliminary findings can aid in enhancing the detection and quantification of microplastics in studies (Brander et al., 2021, Miller et al., 2021).

Microfibre recovery

For reliable detection and quantification of microfibres in the environment, field methods need to be able to capture and efficiently recover microfibres from various matrices with good precision. This requires using filters with a porosity fine enough to retain microfibres during both field collection and laboratory processing. Given that microfibres are typically between 10-20 microns in their smallest dimensions, filters with pore sizes in this range or lower should result in effective microfibre recovery (Covernton et al., 2019). Additionally, recovery is also influenced by sample preparation, which often consists of several steps during which particle losses can occur.

The isolation of microfibres, especially in complex samples, typically requires pre-concentration of the sample (e.g., via filtration) and reduction of organic and inorganic matrix constituents (Ivleva, 2021). To verify the efficacy of microplastic recovery through filtration, digestion, transfer, and analytical identification steps, the use of positive controls is essential (Hermsen et al., 2018, Brander et al., 2021, Kolemans et al., 2019). However, in microplastic research recovery rates are not consistently assessed, and rarely include microfibres (Athey and Erdle, 2022).

Recent interlaboratory studies have started to include microfibre recoveries in their evaluation of microplastic method performance for drinking water, surface water, sediment, and fish tissue (De Frond et al. 2022, Thornton Hampton et al., 2023). These studies reported mean microfibre recovery rates ranging from 294-106 % (PET fibres, 300-500 µm in length) for these matrices, indicating potential contamination issues. It would be advantageous to conduct further interlaboratory assessments of microfibre recoveries across a broader spectrum of sizes and polymer types. In addition, there is a need for more method testing and development involving natural anthropogenic microfibres, which are underrepresented in scientific literature and susceptible to damage or destruction using digestive methods designed for synthetic polymers (Athey and Erdle, 2022).

Certified Reference Materials

Certified Reference Materials (CRMs) are essential for ensuring the accuracy, reliability, and comparability of analytical methods across different studies and laboratories. However, creating microplastic CRMs is an on-going challenge due to the diversity of particle sizes, chemistries, varying effects of environmental weathering and difficulties in creating homogeneous suspensions (Seghers et al. 2022, Martinez-Frances et al. 2023). CRMs are important tools for validating the capabilities of a method to both extract and identify microplastics polymers. Recent advances include a cryo-milling method combined with immobilizing micro particles in solid NaCl (Seghers et al. 2022), aluminum strips (Van Mourik et al. 2021), and use of soda tablets (Martinez-Frances et al. 2023). The soda tablets demonstrated good repeatability for polyethylene terephthalate microfibres across various laboratories (Martinez-Frances et al. 2023), indicating their potential as microfibre CRMs.

Sample collection

Approaches to the collection of microplastic samples vary depending on sample matrix. Methods for water samples have evolved most significantly in scientific research, each presenting unique advantages and challenges for microfibre collection (**Table 9**). Broadly, these techniques fall into two categories: grab sampling and volume-reduced sampling. Grab sampling entails the direct collection of water samples into containers, which are then transported to a laboratory for filtration and analysis. In contrast, volume-reduced sampling is conducted on-site and involves the immediate filtration of water samples through in-situ filtration systems, sieves, or nets.

Grab sampling is generally restricted to a small volume of water (1-2 L), thus is best suited to environments where microplastic pollution is expected to be relatively high, such as near-urban or industrial areas. Given that the concentrations of microfibres in aquatic environments can be low, high-volume sampling is preferred over grab sampling (Athey and Erdle, 2022). One challenge of this form of collection is filter clogging and extensive field collection times.

Net sampling, particularly using manta trawls with mesh sizes larger than 300 µm, is the most commonly referenced technique in microplastics research, accounting for over 60% of the methodologies (Primpke et al., 2023; Athey & Erdle, 2022). However, it is widely acknowledged that this method can lead to considerable losses of microfibres, and finer meshes are recommended for use (Covernton et al., 2022, Barrows et al., 2017). Given the frequent identification of microfibres as either a significant or the dominant form of microplastics in studies, refining and implementing methodologies tailored for microfibre capture would markedly enhance both our understanding of, and our ability to mitigate, microplastic pollution.

In the past decade, there has been a significant increase in the sampling and analysis of microplastics in biota, with the majority of studies focusing on fish, followed by non-bivalve invertebrates, bivalves, and birds (De Witte et al., 2023). Typically, for fish and birds, the analysis concentrates on the gastro-intestinal tract (GIT) and/or stomach contents, while for bivalves, the entire organism is used for examination. The study of microplastics in aquatic food webs has gained importance, aiming to understand their transfer and ecological impacts better. For example, Moore et al. (2022) found that microfibres constituted 78% of the microplastics consumed by fish species that are crucial to the diet of Beluga whales in the Beaufort Sea.

Research into microfibre pollution within the atmosphere is still in its nascent stages, with only a handful of studies available on the subject. These initial investigations reveal that microfibres are the predominant form of microplastics detected in air samples (Luo et al., 2022, Wright et al., 2020). Air sample collection for microplastic analysis is categorized into two main methodologies: active and passive sampling. The choice between these methods largely depends on the specific objectives of the research and the type of airborne contaminants under scrutiny (Enyoh et al., 2019).

Table 9. Summary of different water sampling techniques and considerations for microfibre detection

Approach	Filtration	Sample size (volume)	Considerations for microfibre analysis
Net sampling using manta trawls, bongo, and neuston nets	50, 100, 330 µm	>100 L	• Underrepresentation of microfibres • Potential for airborne microfibre contamination is high during sampling and handling
Bulk water sample Seawater intake, *In-situ* or on-board pumping, *FerryBox*	1 µm- 5 mm	>100 L	• Large volumes of water afford a greater probability of microfibre detection. • These systems can be designed to eliminate exposure to air during collection, which is recommended for microfibres. • Requires electric energy and vessel infrastructure. • Extensive sampling times may be involved, which can limit spatial resolution. • Cascade filtration is generally employed to allow high volumes of water to be processed. Microfibres can get trapped across filters of varying sizes, thus requiring the processing of all filter fractions for accurate representation. • Types of pumps, their placement and filtration speeds are important considerations in the configuration of the sampling system. Microfibres are likely to fragment under high pressure and turbulence conditions.
Niskin bottles	1 µm- 5 mm	10 L	• Potential for airborne microfibre contamination is high during transfer and processing of collected water. It is recommended for filtration to be performed in a protected environment, such as under a HEPA bench. • Relatively small sample size.
Grab samples	1 µm- 5 mm	1-2 L	• Less representative than high volume approaches in terms of detection in most waters. • Typically, it does not require significant sample preparation. • Due to the low sample size, this collection practice is generally not suitable for detecting microfibres in water bodies but may be adequate in places with elevated levels of microfibres.

Sample preparation

For microplastic analysis in environmental samples, chemical digestion serves as a key pre-treatment step to reduce sample matrix and facilitate efficient identification and characterization. This method encompasses the use of a variety of reagents and chemicals—acids, bases, oxidizing agents, and enzymes—under varied temperature conditions, and is frequently combined with filtration, sieving, ultracentrifugation, and continuous flow centrifugation (Ivleva, 2021).

The choice of the method largely depends on sample type, with more complex matrices like soil, biota and wastewater typically requiring one or more digestive steps, whereas drinking water and surface water samples requiring fewer steps or no pre-treatment. These treatments can, however, impact and modify polymer characteristics. Partial or substantial destruction of polyamide (PA, also known as nylon), polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyurethane (PUR) which are common microfibre polymers, has been reported for some of these treatments, especially under high temperatures **(Table 10**, Munno et al., 2018, Enders et al., 2017, Pfeiffer and Fischer, 2020, Savino et al., 2022, Schrank et al., 2022). This can lead to fragmentation of microplastics, affect their spectral signatures, and cause discoloration, which may hinder subsequent identification (Pfeiffer and Fischer, 2020, Savino et al., 2022).

These considerations are likely applicable for microfibre analysis, however evaluations of digestive treatment effects specifically on various microfibre polymer types and sizes are rare. Moreover, since these treatments aim to degrade natural particles, microfibres derived from natural feedstocks (e.g., cotton, rayon) can be compromised, resulting in potential underrepresentation.

Digestion using H_2O_2 (hydrogen peroxide) represents the most common method used for preparation of seawater, terrestrial water, wastewater, and sediments for microplastics analysis (Primpke et al., 2023, Athey and Erdle, 2022). In this category, iron catalyzed H_2O_2 digestion, also known as Fenton reagent or wet peroxide oxidation, has been reported to have minimal effects on polyethylene terephthalate (PET), nylon, and polyurethane (PU) polymers (Munno et al., 2017, Schrank et al., 2022) and can accelerate processing times. In contrast, alkaline digestion involving KOH has been more frequently reported in studies involving fish, birds, and mussels, and can significantly affect polyester and natural microfibres (De Witte et al., 2023).

Extraction techniques are a common step in microplastic analysis workflow and can be categorized into buoyancy-based methods using saturated salt solutions, and oil extraction methods that exploit the oleophilic characteristics of microplastics for selective isolation from other particles. Both approaches are commonly used in microplastic studies of soil and sediment, as these matrices are characterized by high inorganic content that is not reduced through digestive treatments (Constant et al., 2021, Crichton et al., 2017, Mani et al., 2019, Reineccius et al., 2021; Rodrigues et al., 2018; Scopetani et al., 2020).

Extraction techniques can also be integrated into analytical procedures for less complex samples such as river water, which tends to contain high suspensions of sediment. Sodium chloride is the most common agent for density separation in water sample analysis, representing up to 66% of cases, while $ZnCl_2$ (zinc chloride) and NaI (sodium iodide) are used less commonly (Primpke et al., 2023). However, the use of NaCl, which has a density range of 1.15-1.3 g cm^{-3}, can lead to the loss of polyester and modified natural fibres like rayon, lyocell, and modal, which have higher densities (1.3-1.63 g cm^{-3} for polyester and 1.53 g cm^{-3} for the modified fibres). The differential effects of digestive treatments and extraction protocols highlight the importance of using microfibre spikes to determine the methods capabilities as part of research studies.

Table 10. Digestive treatments used in environmental microplastic analysis and considerations for microfibres

Information based on reviews of Athey and Erdle (2022), Primpke et al. (2023), De Witte et al. (2023).

Preparation method	Considerations
Alkaline digestion Potassium hydroxide (KOH, 10%) Sodium hydroxide (NaOH) Temperatures: 40, 50, 60 °C Exposure times 24 hr to 7 days	• Typically applied for preparation of biota tissues, including fish, mussel, and bird GI tracts. • Polyethylene terephthalate (polyester) and polyamide (nylon) can be significantly affected, particularly at high temperatures. Polyester is more affected by KOH, while polyamide by NaOH (Pfeiffer and Fischer, 2020, Treilles et al., 2020). • Natural/semi-synthetic fibres are often degraded (Prata et al. 2020, Treilles et al. 2020).
Oxidative digestion Hydrogen peroxide (<15-30%, v/v) Hydrogen peroxide (30%, v/v) and Fe (II) – Fenton reagent Exposure times 15 minutes to 7 days	• Most common for preparation of water, wastewater, sediments, and soil/sludge samples. • Fenton reagent accelerates the digestion process. • High temperatures should be avoided. Polyamide (nylon) polymers can be affected at temperatures of over 50°C (Savino et al. 2022, Pfeiffer and Fischer, 2020). • Natural/semi-synthetic fibres are often degraded (Prata et al. 2020, Treilles et al. 2020).
Acid digestion HCl, HNO_3, NaClO, $NaClO_4$, HF	• Acid digestion is generally not advised for microplastic analysis as it has been reported to dissolve or degrade a wide range of plastic polymers (Enders et al. 2018, Schrank et al. 2022).

Enzymatic digestion Cellulase, lipase, chitinase, protease, Schweizer reagent	• Require careful temperature control and can involve extensive incubation times. • These treatments are often integrated with alkaline or oxidative digestion in biota and wastewater analysis. • Effects of enzymatic treatments on microfibres have not been fully evaluated. • Cellulase and Schweizer reagents are expected to destroy natural microfibres.

Identification and quantification

The objective of microplastic studies is to quantify and characterize particles in terms of their chemistry, morphology, and size. Vibrational spectroscopy has emerged as the leading technique for detecting and identifying the polymer types of microplastics and has been successfully applied to identify microfibres. This technique is generally coupled with morphological analysis, as the polymers in microfibres are also found in various other products. The most common techniques are Fourier Transform Infrared spectroscopy (FTIR) and spontaneous Raman spectroscopy, although FTIR has seen the greatest application in the last decade (> 60% for water samples, Primpke et al. 2023). Other emerging spectroscopy techniques include quantum cascade laser induced spectroscopy (QCL-IR) and near or short-wave infrared spectroscopy (NIR, SWIR).

Processing samples using these techniques can take various forms, each with its advantages and disadvantages, in terms of cost, throughput and detection. Typically, visual microscopy is employed initially to locate potential microplastics in a processed sample for isolation and subsequent spectroscopic analysis. Anthropogenic microfibres, both natural and synthetic, exhibit distinct physical characteristics that can facilitate their identification (Ross et al., 2021, Hidalgo-Ruz et al. 2012), with complementary staining and density methods enhancing the ability to differentiate them (Zhu et al. 2019).

However, certain digestive treatments may bleach microfibres, complicating their distinction from naturally occurring cellulosic fibres found in environmental samples. Furthermore, particles smaller than 100 μm, including microfibres, are challenging to recognize visually (Lenz et al., 2015) and transfer for instrumental analysis, leading to potential misrepresentation. Given the variable amounts of suspect microplastics identified during microscopy analysis, spectroscopy is usually performed on a subsample of particles (De Frond et al., 2023), with variable approaches to selection of microfibres for spectroscopy analysis amongst the studies.

Vibrational spectroscopy techniques are susceptible to the effects of environmental weathering, which can change the chemical properties and thus spectroscopic fingerprints of microfibres. Enhancing identification accuracy can be achieved by incorporating spectra of experimentally weathered microfibre polymers into reference libraries (Cowger et al. 2021). Another challenge in microfibre identification is the presence of pigments and dyes in microfibres, especially in application of Raman spectroscopy where they can induce high fluorescence, leading to false positives or insufficient quality spectra for reliable identification (Dong et al. 2020, Liu et al. 2023). Furthermore, the identification of anthropogenic natural microfibres, such as cotton and rayon, is complicated by their spectral resemblance to natural cellulose (Cai et al. 2019) and thus relies on the use of complementary visual observations (color, structures).

In recent years, there has been a trend towards automating spectroscopy techniques, leading to the development of several methods for application to environmental microplastic analysis (Primpke et al., 2017, Renner et al., 2020, Whiting et al., 2022). These can produce varying results given their differences in size detection capabilities, interferences, spectral library designs and data processing algorithms (Dong et al. 2022, Song et al. 2021). There is a need for further refinement and interlaboratory comparisons for automated spectroscopy techniques. Microfibres, due to their complex shapes and tendency to protrude from sample substrates, require special consideration to avoid misrepresentation in automated analytical routines.

4.2 Method standardization and harmonization efforts

EuroQCharm, (EUROpean quality Controlled Harmonization Assuring Reproducible Monitoring and assessment of plastic pollution), coordinates the validation of available methods for macro-, micro-, and nanoplastics, and is developing harmonized protocols for their assessment at an EU level. It brings together experts from various scientific disciplines—including marine, surface, and groundwater, drinking and wastewater, soil, air, and analytical chemistry—industry stakeholders such as instrument manufacturers, plastic producers, and commercial laboratories, regulators from the United Nations, the EU, national levels, and standardization bodies, professional associations and societies, policymakers, and NGOs at national and international levels.

Some recent outcomes of the EuroQCharm initiative include a systematic review of state-of-the-art measurement methods and the development of the 'reproducible analytical pipelines' (RAPs) concept. This concept assesses the readiness of methods for international monitoring or identifies further research and development needs. EuroQCharm has recently developed a new soda tablet microplastic reference material preparation (particles > 50 micron), validated through an interlaboratory comparison study and soon to be commercially available. Furthermore, EuroQCharm has contributed to the development of the ISO/CEN standard for analyzing microplastics in drinking water and surface water with low organic material content. It also supports several EU Directives as part of the EU Green Deal, including the Urban Wastewater Treatment Directive (UWWTD), the

Sewage Sludge Directive (SSD), the Environmental Quality Standards Directive (EQSD), and the upcoming recast of the Drinking Water Directive (DWD) at the beginning of 2024.

The Arctic Monitoring and Assessment Programme (AMAP) Litter and Microplastics Expert Group is part of the Arctic Council, which is mandated to monitor and assess the Arctic region's status regarding pollution and climate change issues. Established in 2019, the group aims to develop a monitoring plan and program for microplastic and litter in the Arctic environment, along with technical guidelines to support these efforts. Their focus encompasses harmonized sampling of biotic and abiotic matrices, guidance on matrix and site selection, standardized sample processing and analytical methods, quality assurance/quality control (QA/QC) procedures, data management, and reporting guidance.

The "AMAP Litter and Microplastics Monitoring Guidelines, Version 1.0," focuses on general recommendations for size fractions of microplastics and study design requirements, such as frequency of sampling, replicates, and reporting units (AMAP, 2021). However, it does not provide specific guidelines or standards for the assessment of microfibres. Microfibres are recognized as significant components of microplastic research and monitoring in the Arctic, especially in compartments such as air, where they tend to dominate due to their mobility.

The State of California Water Resources Control Board, the California Ocean Protection Council, University of Toronto, Southern California Coastal Water Research (SCCWRP) and HORIBA Inc. In the State of California inter-laboratory comparison studies involving twenty-two laboratories from six countries were conducted in support of the legislative mandates to develop standardized microplastics monitoring methods for both ocean and drinking waters. These efforts led to two methods for testing drinking water sources for microplastics, including microfibres (Raman and μ-FTIR, Wong and Coffin, 2021). The State Water Resources Control Board (SWRCB) will test water supplies for microplastics over the period of four years as required by the California Senate Bill 1422 passed in 2018 (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.

European Union. The Joint Research Centre of the European Commission conducted an interlaboratory comparison (ILC) study in cooperation with BAM (Bundesanstalt für Materialforschung undprüfung, Germany) to investigate the methods used for the analysis of microplastics in water. The study involved nearly 100 laboratories from the EU and worldwide, and focused on the analysis of polyethylene terephthalate (PET) particles in types of water mimicking bottled water, tap water, and groundwater matrices (Belz et al. 2021). The European Commission has proposed a new methodology for the measurement of microplastics in drinking water, as part of the Drinking Water Directive that came into effect on January 12, 2021. This development aims to facilitate the inclusion of microplastics on the “watch list” of substances of concern to the public or scientific community. The methodology, published on March 11, 2024, was developed with support of the Joint Research Centre and experts from the Member States.

The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP). The GSAMP established a Working Group (WG40) in 2012, with the objective to provide a comprehensive, independent, and global assessment of the sources, fate, and effects of microplastics in the environment. In 2019, GESAMP released the “Guidelines for the Monitoring and Assessment of Plastic Litter in the Ocean” recommendations, advice, and practical guidance, for the establishment of programmes to monitor and assess the distribution and abundance of plastic litter.

The International Atomic Energy Agency has conducted harmonization workshops under its flagship initiative to address plastic pollution, NUTEC Plastics. Through the IAEA’s NUTEC Plastics initiative, sixty-three countries are participating in marine monitoring of microplastics. The laboratories will form a network of NUTEC Plastic Monitoring Laboratories to support the harmonization of sampling and analysis protocols and the sharing of experience, best practices, and data on marine microplastic pollution (IAEA, 2022).

UNEP Global Partnership on Marine Litter (GPML). The GPML is a multi-stakeholder partnership that brings together different actors working to share knowledge and work together to create solutions for marine plastic pollution. The UNEP Global Partnership on Plastic Pollution and Marine Litter (GPML) Community of Practice on Data Harmonization and the Integrated Marine Debris Observing System (IMDOS) aims to promote the harmonization of data acquisition and processing methods, in collaboration with the Ministry of the Environment, Japan (MOEJ), EU MSFD Technical Group on Marine Litter, EMODnet Chemistry, and the NOAA NCEI to establish interoperability to support UNEP’s GPML Digital Platform.

Standardization organizations. Several organizations are developing industry standard test methods for microplastic and microfibres. These efforts are leading to the creation of standards and guidelines for environmental analyses utilizing different measurement techniques, rather than proposing a single approach to testing. The ISO (International Organization for Standardization) is developing several international standards covering key aspects of microplastic analysis, including terminology, sampling, identification, and quantification methodologies (**Table 11**).

Recent publications by ISO provide guidelines for evaluating microplastics originating from the textile industry across various matrices, including textile process wastewater, clothes washwater, textile process air, and solid waste (ISO 2284-2:2023(E)), as well as for assessing microfibre losses under standardized laundering conditions (ISO 44840-1). Similarly, the American Association of

Textile Chemists and Colorists (AATCC) has released a test method for assessing microfibre releases during laundering of textiles (AATCC TM212-2021).

ASTM International has been focused on standardized analysis and practices for the collection, sample preparation, and quantification of microplastics in water and wastewater (Committee D10). Published standards include practices for collection and preparation of water samples with variable suspended solids for analysis of microplastics and fibres using Raman, IR Spectroscopy or pyrolysis GC/MS (ASTM D8332-20, D8333-20). Furthermore, the US NIST (National Institute of Standards and Technology) is developing reference materials and guidelines that help in the calibration of analytical instruments and validation of methods for microplastics analysis.

Table 11. Summary of published or under development standards relevant to microfibre measurement.

Standard	Title	Description
European Commission	"Methodology to measure microplastics in drinking water intended for human consumption"	Method to measure microplastics in drinking water between 20 μm and 5 mm for particles and 20 μm and 15 mm for microfibres.
ISO 4484- 1:2023	"Microplastics from textile sources. Part 1: Determination of material loss from fabrics during washing"	Method for systematically collecting material lost from fabrics under laundering test conditions, applicable to all material types
ISO 4484- 2:2023	"Microplastics from textile sources. Part 2: Qualitative and quantitative analysis of microplastics"	Provides guidance on determination of microplastics (from the textile sector) collected in various matrices (for example textile process wastewater, clothes washing water, textile process air emissions, textile process solid waste).
ISO 4484- 3:2023	"Microplastics from textile sources. Part 3: Measurement of collected material mass released from textile end products by domestic washing method"	Method for measuring the mass of material released from the outlet hose of a standard domestic washing machine, applicable to textile and home end products.

ISO 24187:2023	"Principles for the analysis of microplastics present in the environment".	This document lists several methods and provides general guidelines for all key aspects of microplastic analysis workflow.
ISO/DIS 16094-2	"Analysis of microplastic in water. Part 2: Vibrational spectroscopy methods for waters with low content of suspended solids including drinking water"	Under development. A method for the qualitative and quantitative analysis of microplastics in water using a microscopy technique coupled with micro-Raman or FTIR spectroscopy. The method defines microplastics as solid plastic or synthetic polymer particles insoluble in water with the largest dimension between 1 μm and 5 mm.
ISO/CD 16094-1	"Analysis of microplastic in water. Part 1: General and sampling for waters with low content of suspended solids including drinking water"	Under development. This standard lays out the general principles for the design of sampling programmes and sampling techniques for plastics in waters with low contents of total suspended. The limitations and advantages of different sampling approaches including grab sampling, cascade filtration and net sampling, with respect to different microplastic size categories are evaluated.
AATCC TM212-2012	"Test method for fibre fragment release dring home laundry"	Determines the mass of fibre fragments released in an accelerated laundering testing machine. Accelerated laundering is expected to provide a relative approximation of fibre fragment release in full-scale home laundering, but an exact correlation has not been determined.
ASTM-D8332-20	"Standard Practice for Collection of Water Samples with High, Medium, or Low Suspended Solids for Identification and Quantification of Microplastic Particles and fibres"	This practice involves the collection of 1,500 L of water and is applicable for the collection of samples from drinking water, surface waters, wastewater influent and effluent (secondary and tertiary), and marine waters.

ASTM-D8333-20	"Standard Practice for Preparation of Water Samples with High, Medium, or Low Suspended Solids for Identification and Quantification of Microplastic Particles and fibres Using Raman Spectroscopy, IR Spectroscopy, or Pyrolysis-GC/MS"	This practice consists of wet peroxide oxidation followed by progressive enzymatic digestion to the extent necessary to remove interfering organic constituents such as cellulose, lipids and chitin that are typically found in abundance in water matrices of samples with high to medium suspended solids such as wastewater influent.
ATM-D8489-23e1	"Standard Test Method for Determination of Microplastics Particle and Fibre Size, Distribution, Shape, and Concentration in Waters with High to Low Suspended Solids Using a Dynamic Image Particle Size and Shape Analyzer"	The method describes the procedures for characterizing fibre concentration, size, and shape using image analysis of sample extracts containing particles between 10 and 100 μm.
ASTM WK87463	"Spectroscopic Identification and Quantification of Microplastic Particles and fibres in all High and Low Turbidity Water Matrices including Municipal Wastewater Using IR and Raman Spectroscopy"	Under development
ASTM WK67788	"New Test Method for Identification of Polymer Type and Quantity (Mass) Measurement of Microplastic Particles and fibres in Waters with High-to-Low Suspended Solids Using Pyrolysis-Gas Chromatography/Mass Spectrometry"	Under development
ASTM WK83681	"New Test Method for Microplastics Capture for stormwater control measures"	Under development

Chapter 5: Solutions to reduce textile microfibre pollution in Canada

Meaningful and lasting reductions in microfibre pollution will require a systems change approach that recognizes the interconnected role of the textile value chain and the ways in which the environment is being contaminated. Such a system prioritizes waste reduction at all stages, and acknowledges the individual roles of textile design, production, sale, laundry, waste capture and waste management.

5.0 Key messages

- **Concerted efforts are needed** in the public and private sectors to curtail the release of large quantities of microfibres to the Canadian environment.
- **Solutions to microfibre pollution need to be integrated throughout the entire textile value chain.** This includes upstream interventions, such as the design of materials and clothing that releases fewer microfibres, improvements in manufacturing processes, and interventions that reduce the releases from domestic and commercial streams.
- **The mitigation of microfibre pollution is interwoven with strategies to reduce other environmental impacts**. Ancillary, but important, impacts including energy and water usage, chemical pollution, and waste generation could be addressed concurrently with microfibre pollution mitigation strategies.
- **Tackling the microfibre pollution problem in Canada requires a team approach**, with strong leadership by Ottawa through the following:
    - Research and Development, tax or policy incentives to textile designers, material suppliers, wastewater infrastructure engineers and natural resource managers
    - Standards, guidelines and regulation
    - The strengthening of national frameworks through CCME, recycling systems or other approaches that contribute to textile circularity

Microfibre pollution has emerged as a critical environmental challenge, shedding light on the broader challenges associated with current textile industry practices. The production and disposal patterns of the global fashion sector, representative of a linear economic model, contribute to this pollution. This model, predicated on the 'take-make-dispose' approach, leads to excessive resource use and waste generation, with textiles often being discarded after limited use and less than one percent of these materials being recycled back into the clothing industry (Ellen MacArthur Foundation, 2017).

’Fast fashion’, which accelerates the cycle of consumption, promotes the rapid production of cheap, trend-driven garments. This industry trend is marked by the continuous introduction of new materials, and microfibres, into the economy without adequate recycling systems in place. This practice likely exacerbates microfibre release during the production and use phases, and poses challenges in managing these materials at their end-of-life.

The pervasive issue of microfibre pollution underscores the inefficiencies and environmental costs of the linear economic systems that dominate global industries, including fashion. The United Nations Environment Programme has highlighted how such linear practices in the global fashion industry exacerbate climate change, biodiversity loss, and pollution, driving significant alterations in both oceanic and terrestrial ecosystems (UNEP, 2023). In contrast, the circular economy model offers a sustainable alternative, focusing on resource efficiency, waste reduction, and the closure of material loops through the design of products for extended use, promotion of repair and reuse, and ensuring recyclability of materials.

There is a growing interest among governments and industry leaders worldwide to foster a transition towards circular economy principles. This shift is particularly relevant to addressing microfibre pollution, where the adoption of circular strategies—such as developing durable textiles that are less prone to shedding microfibres, enhancing recycling processes, and implementing improved washing machine design—can play a significant role.

In this chapter, we summarize and evaluate these solutions, identifying those most relevant to the Canadian textile system to curb microfibre pollution. Our analysis aims to highlight strategies that are particularly applicable and effective within the unique context of Canada's textile industry and environmental policies. This analysis underscores that effective strategies against microfibre pollution are closely linked to the principles of circularity. Implementing these strategies successfully will require a synergistic approach, combining policy support, industry innovation, and consumer education to create meaningful change.

We propose three categories of textile microfibre pollution solutions:

1. **Upstream interventions:** The material science, sourcing, design and manufacture of textiles provide important opportunities to create more sustainable textile products that release fewer microfibres. These solutions include new practices and business models that encourage waste reduction, re-use and recyclability of materials. Canada will have to reconcile what it can do domestically and internationally to ensure that the Canadian environment and the health of Canadians benefit.
2. **Consumer interventions:** Consumer awareness, behaviour and decisions will improve the ability of Canadians to make informed consumer choices and reduce their microfibre pollution footprint during the purchase, use and laundering of textile products.
3. **Environmental management interventions:** Downstream technical and engineering infrastructure provide additional opportunities to reduce the release and spread of microfibres emanating from consumers and businesses. These solutions include wastewater treatment plant designs, biosolids practices.

5.1 Upstream solutions

Upstream solutions are practices centered on textile and apparel production, which encompass everything from the initial design phase to the provision of products to users. Such solutions focus on root causes and the prevention of textile and microfibre waste in the first place, lessening the burden to waste capture and management. These solutions are important in steering the textile economy towards greater sustainability. However, there are several challenges to the implementation of such solutions in the short term because of the complexity of the sector, its global nature, the high costs of innovation and consumer preferences for affordability.

5.1.1 Sustainable textile design

Textile design encompasses fibre and yarn selection, fabric construction, and finishing techniques that vary extensively amongst different types of textiles and their application. Scientific research suggests that textile design can greatly influence microfibre releases when consumers launder, dry, wear and use the textiles.

Defining sustainable textile design

Sustainable textile design means making choices that result in minimal environmental footprints during the life cycle of a product. This approach is intricately linked with textile manufacturing, as every decision made during the design phase directly influences the environmental impact during production.

Examples of considerations in sustainable textile design to reduce microfibres:

- The selection of fibres and yarns not only determines the properties of the textile but also influences the scale of microfibre releases when consumers use the products.
- Construction techniques that enhance durability and longevity of textiles can reduce the need for frequent replacement, thereby lowering production demand, while minimizing microfibre releases during their use.
- Minimizing chemical usage and avoiding toxic chemicals reduces the immediate occupational and environmental impact during manufacturing but can also affect the recyclability and circularity of the final product.

To better understand the impact of textile properties on microfibre releases, researchers have been quantitatively assessing microfibres shed from different types of clothing during use or laundry. Microfibre shedding can vary up to 1,000 fold among different garments during a laundry cycle (Vassilenko et al. 2021, **Figure 10**). The release primarily occurs due to the mechanical and chemical stresses when consumers launder, dry, wear and use the textiles.

Understanding these processes and fabric properties can inform the development of more durable and less microfibre shedding textiles. The diversity in experimental methodologies, laundering conditions, and domestic washing machine designs (Tiffin et al., 2022) complicates the direct comparison of data from available scientific studies. Additionally, there are considerable differences in clothing manufacturing techniques used in the industry making examination of this problem highly complex. For instance, a study of 37 fabrics from five different outdoor retailers, reported an extensive variability in microfibre releases for similar fabric categories (Vassilenko et al. 2021). The key observations on the role of textile design in microfibre shedding from scientific literature are summarized in **Table 12**.

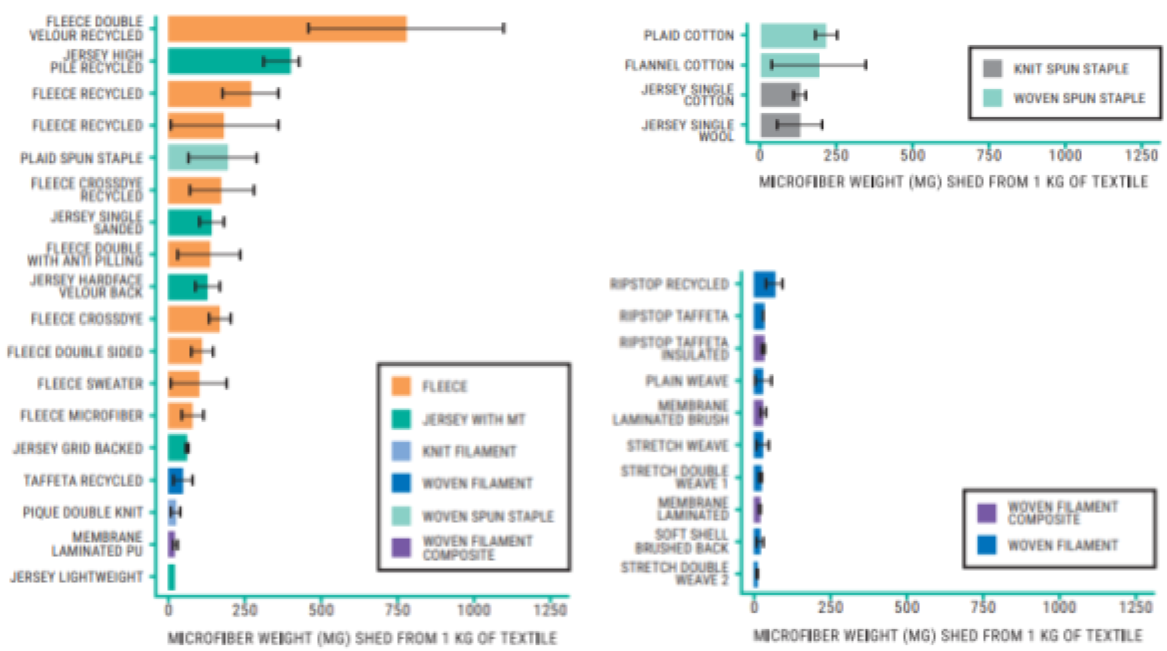
Table 12. Textile design parameters influence microfibre releases

Properties such as yarn type, textile construction and finishing methods influence rates of microfibre loss in textiles. The consideration of these features offers opportunities to design textiles that shed fewer microfibres.

Property	Research highlights
Yarn Type	Fabrics made from spun-staple yarns, with their shorter, irregular fibres, tend to shed more in the wash compared to those made from long, continuous filamentous yarns (Vassilenko et al., 2021, de Falco et al. 2020). The amount of microfibre shedding is also influenced by yarn characteristics like count, length, tenacity, tightness, and irregularity (Hartline 2016, Zambrano et al., 2019, Cesa et al. 2020). High-quality yarns, marked by strength, consistency, and regularity, will likely result in textiles with lower tendencies to shed microfibres (OECD, 2020)
Textile Finishing	Mechanical finishing is often used to enhance the texture and appearance of textiles but also promotes microfibre releases (Cai et al. 2020a, 2020b, Vassilenko et al. 2021). The abrasion caused by finishig techniques tends to loosen the fibres, especially in fabrics with short or exposed fibres. Recent studies have focused on developing coatings and finishes that could reduce the shedding of microfibres from textiles. For instance, Lahiri et al. 2023 developed a two-layer coating for nylon fabrics, which uses polydimethylsiloxane (PDMS, also known as silicone) brushes to significantly reduce microfibre shedding during laundering. The coating resulted in 93 ± 2% reduction in microfibres compared to non-treated fabrics.
Fabric density	Thicker fabrics tend to release more microfibres due to increased fibre density (Vassilenko et al., 2021, Peryasami et al., 2021)
Synthetic versus natural fibres	Use of natural fibres in textiles has been advocated as a better alternative to synthetic materials (e.g. Henry et al., 2019) . However, studies have shown that natural textiles can release as many if not more microfibres as their synthetic counterparts (Vassilenko et al., 2021, Zambrano et al., 2022, Figure 10). Anthropogenically modified “natural” and semi-synthetic fibres (cotton, wool, rayon, viscose) are increasingly being detected in the environment (Athey and Erdle, 2022).
Additional considerations	Commercial products can also be a source of microplastic particles other than microfibres, which could be resulting from chemical treatments or contamination in the manufacturing process (Vassilenko et al., 2021). Even minor differences in fabric quality and design can significantly influence microfibre release within similar material categories (Vassilenko et al., 2021). This complexity calls for comprehensive R&D by brands and manufacturers to understand the specific factors influencing microfibre shedding in their products.

Figure 10. Textile design influences microfibre release during laundry

Shown are microfibre shed rates per kg of textile washed in a typical domestic laundry cycle (Vassilenko et al. 2019, Vassilenko et al., 2021).



Recent developments in the textile industry have led to the publication of industry standard test methods by organizations including the American Association of Textile Chemists and Colorists (AATCC), The Microfibre Consortium (TMC) and International Standards Organization (ISO). These methods are designed to quantify microfibre loss from end textiles during laundering, providing a crucial tool for brands and manufacturers to address microfibre pollution. These advancements reflect a growing recognition within the industry of the need for standardized testing methods to quantify and address microfibre shedding.

While there are currently no regulatory requirements to control textile microfibre shedding from finished products, the development of these standards suggests that the industry is preparing for potential future regulations, particularly in light of the European Union's Ecodesign for Sustainable Products Regulation and the broader EU textile strategy. The EU Strategy for Sustainable and Circular Textiles launched in 2022 focuses on ensuring textiles in the EU market by 2030 are durable, recyclable, made largely from recycled fibres, free of hazardous substances, and produced ethically (European Commission, 2022). Ecodesign regulations under development aim to minimize the unintentional release of microplastics from textiles, through measures such as setting design standards and enhancing product transparency with a Digital Product Passport. These efforts are also proposed to target manufacturing processes, mandating pre-washing at industrial plants, product labeling, and encouraging the adoption of innovative materials to mitigate environmental impacts.

There is a growing recognition for the need to address the extensive use of chemicals in textile production. Many of the chemicals used can be hazardous to human and environmental health, and may pose risks during the manufacturing process as well as through exposure of biota to fibre-containing chemicals in the environment.

Modern textile making processes employ lubricants, solvents, dyes, bleaches and stain repellents (Niinimäki et al., 2020, NRDC, 2021). The number of chemicals used in the global textile industry is estimated at 8,000 to as many as 20,000 (Niinimäki et al., 2020). These include substances that have been categorized as carcinogenic, toxic, and harmful to human health and the environment, such as phthalates and per- and polyfluoroalkyl substances (PFAS) (NRDC, 2021).

Health research has been mainly centered on the occupational exposure to chemicals during production processes (Rovira and Domingo, 2019), while research on exposure of consumers is beginning to emerge. For instance, epidemiological studies have revealed associations between exposure to specific PFAS and immune and thyroid function, liver disease, lipid and insulin dysregulation, kidney disease, adverse reproductive and developmental outcomes, and cancer (Fenton et al. 2020). To what extent such chemicals may be leaching from microfibres once in the environment and adversely affecting is unclear (Athey et al., 2022). A recent investigation by the Canadian Broadcasting Corporation with the support of University of Toronto researchers, found elevated levels of lead and phthalates in children's clothing from fast fashion retailers sold in Canada. The levels of lead were almost 20 times the amount that Health Canada sets as safe for children.

Box 4. Cross-sector research and development initiatives to combat microfibre pollution

There is a need for more industry data on microfibre releases from textiles, with some initiatives underway to fill this need through standard test method development and research on microfibre releases in textiles. Some of the major efforts include:

Textile Microfibre Consortium (TMC), a research-led sustainable textiles NGO, is working to convene the global textiles sector through the Microfibre 2030 Commitment and Roadmap. It currently consists of 92 organisations, which comprise brands and retailers, manufacturers, NGOs, laboratories, and researchers. The microfibre Consortium's Data Portal was developed to consolidate industry data from the testing of finished fabrics using a test method developed by the consortium. The TMC Test Method was developed to quantify microfibre loss from fabrics through a simulated domestic laundering process and has been validated by 10 independent global laboratories and is performed at a TMC-accredited laboratory. The consortium's most recent reports provide general data on microfibre releases from 687 fabrics.

Cross Industry Agreement (CIA) is a voluntary collaboration for the prevention of microplastic releases into the aquatic environment during the washing of synthetic textiles. The signatories are five European industry associations representing the global value chain of garments and their associated maintenance (AISE, CIRFS, EOG, EURATEX and FESI). The focus of the CIA is on supporting the development of standardized methods for measuring and reducing microfibre releases during the manufacture and use of textile products. The work of the CIA also involves research, sharing best practices, and advocating for sustainable manufacturing processes.

Ocean Wise Microfibre Partnership is a cross-sector initiative of a Canadian ocean conservation NGO focused on informing science-based solutions to microfibres through research on their sources, transfer to and fate in the ocean. The Partnership includes apparel retailers MEC, Patagonia, REI, Arc'teryx, Aritzia, and Joe Fresh. Research conducted under the partnership is published in peer-reviewed scientific literature and publicly available Ocean Wise reports. Their work includes examining the effects of textile design (Vassilenko et al., 2021) and impact of wash cycles (Ocean Wise, 2022) on microfibre shedding.

Outdoor Industry Association and the European Outdoor Group (EOG), collectively representing over 1500 companies, have created a Microfibre Toolkit and facilitate a unified effort among their member companies – as well as among other key industries and sectors, including the fashion industry, the textile industry, chemical manufacturers, the home appliance industry, and water treatment facilities – to drive the collection of data that is necessary to better understand the sources and causes of microfibre release, and to implement appropriate solutions that are based on sound science.

Cascale (formerly Sustainable Apparel Coalition) is a global, non-profit alliance of 300 leading apparel, footwear, and textile brands, retailers, manufacturers, sourcing agents, service providers, trade associations, NGOs and academic institutions. The coalition launched the **Higgs Index** - a suite of five tools that assess and measure the social and environmental performance of the value chain and the environmental impacts of apparel and footwear industry products. The coalition also announced its intention to implement microfibre shedding into the index.

5.1.2 Improved manufacturing processes

Textile manufacturing is a complex process that converts raw fibres into finished fabrics. It starts with synthetic fibre production from raw materials including cotton, natural gas, oil, and coal (Tier 3). The next stage is yarn and fabric production, where yarn is tufted, woven, or knitted, and includes abrasive and water-intensive dyeing processes (Tier 2). The final stage is garment production that involves cutting, sewing, finishing and distribution (Tier 1, **Figure 11**).

Textile and apparel production involves a complex web of stakeholders and is largely concentrated in the Asia-Pacific (APAC) economies (The Nature Conservancy Report, 2021). Major textile production countries include China, India, Vietnam, and Bangladesh (Leal Filho et al., 2022), but other countries including Brazil and the United States are significant contributors to the global yarn and fabric production (The Nature Conservancy Report, 2021).

There is increasing awareness amongst some industry players that textile production chains are significantly contributing to the global microfibre pollution problem (Euratex, 2021, FFA, 2023, The Nature Conservancy, 2020). However, retailers, particularly the large fashion brands, are more aware of this, and are more active in research on microfibre pollution compared to manufacturers (FFA, 2023). The problem is twofold: the extensive releases of microfibres at various manufacturing stages, including dyeing, cutting and sewing, and the impact of production techniques on the final product's quality, which in turn affects microfibre shedding during consumer phase. This indicates that improvements in manufacturing represent a key solution for reducing microfibre pollution globally.

In Canada, 95% of apparel sold is imported, with the majority coming from China, Bangladesh, Vietnam, Cambodia, and the US (ISED, 2023). The larger retail sector compared to textile product manufacturing, makes retailers the major decision makers in enhancing the sustainability of fashion in Canada (Cybis and Bernard, 2021).

In 2022, Statistics Canada reported 588 textile mills (comprises establishments manufacturing yarns or textile fabrics, or finishing yarn, textile fabrics or clothing), 994 textile product mills (comprises establishments primarily engaged in manufacturing textile products, except clothing) and 3369 clothing manufacturing establishments (Statistic Canada, 2022), with the majority located in Québec and Ontario (FTA, 2021).

Industrial wastewater treatment systems in Canadian textile mills generally only have pre-treatment, which consists of a fibre removal system, an equalization basin, a pH measurement and control system, and a flow measurement chamber. Further treatment of the effluent takes place at publicly-owned wastewater treatment facilities (Health Canada, nd). Most wet processing mills in Canada (96%) discharge to municipal wastewater systems, and 99% of these municipal wastewater systems have primary, secondary, or tertiary wastewater treatment prior to release into receiving water (CEPA Annual Report, 2002-2003). Data on microfibre in Canadian textile facilities is not available at present, leaving a knowledge gap on the industrial contributions of microfibres in Canada.

How are microfibres generated in textile manufacturing processes?

The two key sources of microfibres originating from the textile manufacturing process are:

- Production processes that influence microfibre shedding when consumers use the material.
- Microfibre waste that is generated during manufacturing and released into factory air and effluents. This can result in exposure of factory workers to microfibres, and the environment through discharge of treated, or in some cases, untreated effluent. Some estimates place global microfibre release from textile factories (fibre to end product) at 0.12-2.14 million tonnes (The Nature Conservancy, 2021, First Sentier MUFG, 2022).

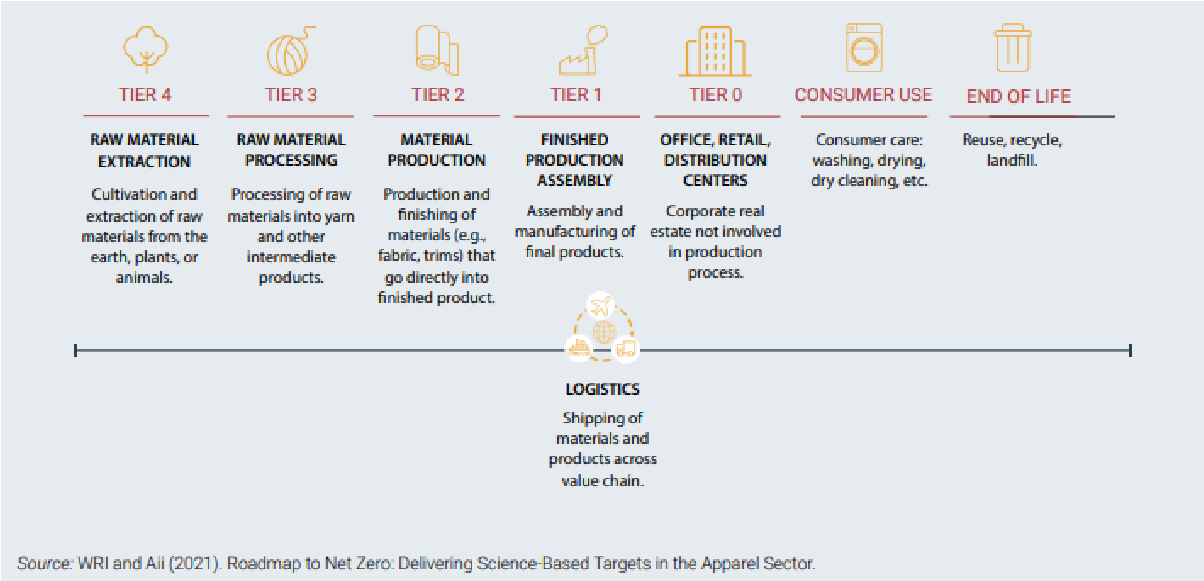
Wastewater discharged from the wet-processing manufacturing stages

Wet processing is a series of steps where fabrics are treated with water and various chemicals to get them ready for use, and includes dyeing, sizing, post-processing, and finishing.

- Textile printing and dyeing wastewater in an industrial park in China was found to contain as much as 54,100 microfibres L^{-1}, and 430 billion microfibres were estimated to be released from the park annually (e.g. Zhou et al. 2020). For comparison, a secondary WWTP in Vancouver, B.C., Canada was estimated to release approximately 18 billion microfibres per year (Gies et al., 2018).
- Globally, wet textile processing was estimated to produce 6,400 tonnes of microfibres in 2020, with China, India, and the US as significant contributors (Wang et al., 2023).

Figure 11. The tiers in the textile value chain

Graphic: United Nations Environmental Programme (2023). Sustainability and Circularity in the Textile Value Chain. Adapted from WRI & Aii (2022). Roadmap to Net Zero: Delivering Science-Based Targets in the Apparel Sector.



Recent research provides insights into strategies that could address microfibre pollution stemming from manufacturing:

- **Microfibre removal at manufacturing sites**. Many studies report that microfibre shedding from garments is often greatest when consumers first wash them. This initial release is likely due to the presence of loose fibres and/or particles left over from the manufacturing process. Therefore, it has been suggested that garment manufacturers could implement pre-washing of final garments at production sites (Roos et al., 2017; OECD, 2020). As this strategy would require significant uses of water, alternative means including the modification of a production process or the use of dry technologies (e.g. vacuuming), should be explored.

- **Modifications to existing dying processes.** One study suggested that microfibre release during the dying processes could be reduced by lowering temperature and decreasing dyeing process duration (Wang et al., 2023). This could also help prevent fibre irregularities and preserve fibre yarn strength (OECD, 2020). It has also been reported that thinner and denser yarns were associated with higher microfibre releases during dying processes than tightly twisted fibres (Wang et al., 2023).

- **Innovative dying technology** with reduced water usage compared to conventional heating baths and tanks have the potential to drastically reduce microfibre waste (FFA, 2022). Such technologies include dope dyeing, cold pad-batch dyeing, supercritical $C0_2$ dyeing, ultrasonic assisted dyeing and dry digital printing (**Table 13**),
- **Fabric preparation and construction techniques.** Research shows that certain fabric preparation techniques exacerbate microfibre release during production. For instance, scissor cutting was found to release up to 30 times more microfibres from textiles than ultrasonic cutting methods (Cai et al. 2020a, Cai et al. 2020b). Furthermore, rotor spinning in yarn preparation is a critical point at which microfibres are formed (Cai et al. 2020a).

Table 13. Comparison of proposed technical solutions to mitigate the release of microfibres during textile manufacturing

Source: Forum for Future, Asia (2023). "Tackling microfibres at Source: Investigating opportunities to reduce microfibre pollution from the fashion industry through textile design and manufacturing innovation". Validation of these approaches is recommended as a next step in tackling manufacturing microfibre sources.

Solution	Strengths	Drawbacks	Potential for positive impact on the environment and workers	Potential for reducing microfibre pollution	Potential for transforming textile system
Wastewater treatment	Tackles several environmental problems	Significant financial investment	High	High. Already considered a requirement in many countries, though enforcement and requirements may vary	Low
Dope dying	Proven technology High quality product No water used	Significant financial investment Shade limitations Prior brand commitment required Only applicable for synthetic fibres	High	High	High
Cold pad-batch dyeing	Proven technology Reduced water use Reduced energy use High product quality	Some financial investment Applicable only to natural fibres	Medium	High. Low abrasion of fibres	Medium
Supercritical CO_2 dyeing	No water used during dyeing step Applicable for both natural and synthetic fibres	Significant investment Not yet scaled Potential high energy use	Medium-energy use remains high	High	High
Ultrasonic assisted dyeing	Less water used in the process Minimizes fibre breakage High quality product	Not yet scaled Potentially high energy use	Low. Energy use potentially high	High	High
Dry digital printing	Little to no water required in the process	Significant investment Potentially high energy use Requirement for dyes Costly to operate Varying quality of product Involves product preparation for printing Applicable to only polestar fibres and polyester blends Requires consumer acceptance of the look of the products due to print-only style	Medium	High	Low. Cannot replace conventional wet dying

Box 5. Initiatives and resources for tracking and reducing microfibre releases in textile manufacturing supply chains and final products

Forum for Future Asia's Project: "Tackling Microfibre at Source: Investigating opportunities to reduce microfibre pollution from the fashion industry through textile design and manufacturing innovation". Forum for Future Asia is an international sustainability NGO. The organization led a 21-month research project to assess the textile manufacturing role in the microfibre pollution problem. The project involved a Tier-1 manufacturer of apparel products headquartered in Singapore - Ramatex Group, serving some of the world's leading global sportswear and fashion brands. The objectives were to evaluate which processes act as greatest sources of microfibres and why; role of material type, and what innovations are available today that can help mitigate microfibre generation in the production processes. The study was shared via a publicly available report.

Key findings

- Wet processing stages released most microfibres, but alternative and tested technologies exist on the market. The project team emphasized the need for the textile industry to accelerate the move away from processing in heated baths and tanks to dry processes and evaluated the strengths and weaknesses of these alternative technologies.
- The footprint of different textile production techniques in microfibre pollution is understudied. The knowledge and data in this area are needed to drive solutions in the industry, emphasizing the need for further research. Policymakers can play an important role in promoting research by industry players through funding and innovation mechanisms.
- "The impetus for suppliers to adopt more sustainable practices is often driven by the need to comply with their customers' low-cost and speed demands rather than through their own agency to contribute to a more sustainable fashion industry. This hinders the shift towards a more just and regenerative industry as suppliers are not able to fully tap on their potential as change agents. One key reason for this apparent lack of supplier agency is the absence of collaboration between brands and their suppliers that would place risk equally between both parties".

Flora and Fauna International has developed a fibre Loss Risk Assessment (FLoRA) to provide companies across textile manufacturing supply chains with an entry-level insight into the risk that their operations face with respect to fibre loss, with the aim of helping companies identify where mitigation measures are needed. The toolkit is designed to help yarn, textile and garment manufacturers understand and address microplastic fibre loss at any given facility and across a broad range of processes. It takes a holistic view of possible sources of microplastic fibre loss and pathways to the environment and provides an indication of the risk of fibre loss from different processes, for different businesses and facilities. The FLoRA toolkit has been created in collaboration with textile manufacturers and professionals and provides the user with an indicative risk rating for both facility-level assessments and individual process-based assessments.

Plastic Footprint Network (PFN) consists of a broad spectrum of stakeholders including: brand owners, product manufacturers, environmental consultants, sustainability activators, plastics researchers, footprint specialists, and NGOs who are leading global plastic pollution mitigation efforts. PFN developed an open access tool with a standardized method for establishing the amounts of microplastic leakage from textile fibres when conducting a comprehensive plastic footprint assessment.

5.1.3 Creating textile circularity

The concept of a circular economy can vary in definition and interpretation among organizations, industries, and regions (Ekins et al. 2019). The Organization for Economic Development (OECD) identifies the following key features in the concept of material circularity— increased product repair and remanufacture, material recycling, the design of long-lived products, reuse and repair, material productivity, improved asset utilization, and modified consumer behaviour. These strategies collectively aim to reduce the demand for new goods (and thus virgin materials), promote the use of secondary raw materials in production, expand the secondary sector, and foster more durable and repairable products, alongside encouraging the growth of sharing and service economies (McCarthy et al., 2018).

What is textile circularity?

The Organization for Economic Cooperation and Development (OECD) identifies circularity as a system that is characterized by (McCarthy et al., 2018):

- increased product repair and remanufacture,
- increased material recycling, more robust long-lived products through design, increased produce re-use and repair,
- increased material productivity,
- improved asset utilisation, and modified consumer behaviour.

The intended effects of these features include decreased demand for new goods (and virgin materials), substitution of secondary raw materials in production, expanded secondary sector, more durable and repairable products, and expanded sharing and service economies.

Textile circularity can play an important role in mitigating microfibre pollution, by lowering the demand for new materials through increased reuse and repair of textiles (Syberg et al. 2022, Manshoven et al, 2022). It has also been suggested that increasing consumer preference for repurposed or recycled textiles is important in driving reductions in their consumption (Henry et al., 2018). This concept also entails adequate textile waste collection and “end-of-life” treatment, which in turn is crucial in preventing the release or leakage of microfibres from landfills (Manshoven et al., 2022), although this is expected to be of relevance in jurisdictions outside of Canada where waste infrastructure is weak.

Globally, only about 12% of used clothing is recycled, and this can be attributed to such factors as the complexity of textile waste, lack of adequate recycling technologies, and limited systems for collection and sorting (Ellen MacArthur Foundation, 2017, UNEP, 2023). In practice, the term recycling amounts to downcycling of clothing for products that are used in other industries, as opposed to new clothing (Shirvanimoghaddam et al. 2020). Additionally, the blended composition of many modern fabrics makes recycling more challenging, as it requires separation of different fibres (NIST, 2021). Consumer awareness and behaviour also play a role, as there is often a lack of knowledge about proper disposal and recycling options for textiles. Fibre-to-fibre recycling, which involves transforming textile waste back into new fibres, is still limited and represents only about 1% of global textile recycling (Ellen MacArthur Foundation, 2017).

Consequently, 73% of textile waste ends up in landfills or is incinerated, despite being reusable or in good condition. This also includes unsold merchandise (Ellen MacArthur Foundation, 2017).

In Canada, the production and fate of textile waste is not well understood. However, recent research on this topic from Fashion Takes Action (2021) has revealed a major gap in Canada's 'end-of-life' management of textiles. It has been estimated that 480,576 tonnes of textile accumulates in Canadian landfills each year, which translates to 12 kg per person, with over 60% of this waste being in good enough condition for re-use. Furthermore, textile waste is estimated to account for 7% of total plastic waste, or 233 ktonnes, in Canada (ECCC, 2019).

A study by Cybis and Bernard (2021) investigated why some firms decide to destroy their unsold inventory in Canada, noting that currently little sustainable alternatives exist to landfills and incineration centers. Furthermore, large-scale textile reuse and repair is hindered by high transportation and labor costs and decreasing quality and cost of new clothing. Similarly, the cost to collect and recycle textiles exceeds the price end users are willing to pay for the product. Re-use and repair programs are not economical in the current global textile system (Schumacher and Forster, 2022).

While capacity for mechanical textile recycling exists in Canada, this process results in fibres of low quality that are primarily used for insulation purposes (ECCC, 2019). A handful of companies are pioneering fibre-to-fibre textile waste technologies. Loop Industries in Terrebonne, Québec, and Duvaltex in Québec, for example, have developed methods to produce recycled polyester from pre- and post-consumer textile waste. General Recycled in Vancouver, BC, specializes in recycling polyamide fibres, primarily from fire-resistant garments. In Europe, a ban on ban the destruction of unsold apparel, clothing accessories and footwear was recently introduced (European Parliament, 2023)

Collectively, there is a need to develop infrastructure and business models that facilitate enhanced reuse, repair, and recycling in Canada. A study on the feasibility of textile recycling in Canada by Fashion Takes Action concluded that considering feedstock, investment costs, and technology readiness, the most promising technology to start a textile recycling industry in Canada is mechanical recycling. The study also provided several recommendations to facilitate development of post-consumer recycling and circular textile systems in Canada.

These activities should be integrated with practices in textile design and manufacturing phases to ensure that materials are designed for low microfibre releases, reuse and recyclability from the outset whenever possible. As highlighted by a workshop led by the U.S. National Institute of Standards Technology (Schumacher and Forster, 2022), current textile design practices fail to consider the full lifecycle of products, while achieving the balance between the durability of materials with design for recyclability is one of the key challenges to textile circularity.

Case Study: Estimate of textile waste in Canada: Dumpster Dive in Ontario

Source: Fashion Takes Action study: Feasibility of Textile recycling in Canada, 2021.

Ten municipalities in Ontario were selected for an assessment of textile waste trends between 2018-2019.

- Different municipality sizes, from large urban, medium urban, rural, and regional to a Township
- Different waste management programs with weekly or bi-weekly collected waste and 'bring your own waste' to a depot.

All textiles were separated from the waste stream and sorted into six categories, including clothing, home textiles, shoes, accessories, and soft toys.

2,846 family households and 35 multi-residential complexes were sampled in 36 waste audits which resulted in the collection of 11,000 pieces of textiles (slightly over 1,800 kg).

Residential waste

- 176,343 tonnes of textile waste were sent for disposal in Ontario in 2018.
- It was estimated that 480,576 tonnes of textile waste may be generated across Canada each year.

Non-residential waste

- 64% of this waste was found to be in a condition good enough for reuse, 22% could be recycled and only 14% was considered actual waste
- Clothing and home textiles (primarily bedding and towels) were the dominant textile waste categories, accounting for 57.8% of total textiles (~277,773 tonnes Canada-wide)
- Of this textile waste, approximately 50% was mainly constructed with natural fibres, 22.4% of synthetic fibres, and 27.6% were made with blended fibres.

5.1.4 Reducing overproduction

The fashion industry has seen a rapid increase in production, with a doubling in the past 15 years and an anticipated 81% increase by 2030 (Global Fashion Agenda & Boston Consulting Group, 2017). Low-cost, fast fashion trends lead to clothing that is designed for short-term use and high turnover, which in turn results in a significant amount of textile waste material (Ellen MacArthur Foundation, 2017). As a result, fast fashion likely exacerbates the microfibre pollution issue through the introduction of new materials and microfibres into the economy. Microfibre concentrations in the environment have been increasing alongside textile production and consumption since the 1950s (Gavigan et al, 2021). As production is a significant source of microfibres globally, fewer new textiles means fewer instances of cutting, sewing, and finishing and releases of microfibres that accompany these processes.

Fast fashion is characterized by quickly bringing high fashion designs to market at affordable prices (Cachon and Swinney, 2011), and caters to consumer demand for newness (Cybis & Bernard, 2021). Retailers introduce new products at an increasing frequency to align with up to 52 micro seasons per year (Pulitzer Centre, 2022). This trend, fueled by aggressive marketing and social media, encourages overconsumption (Binet et al. 2019). It has been estimated that consumers spent up to 60% more on clothing between 2000 and 2014, while keeping the garments for only half the time (Remy et al., 2016). The lowest utilization rates of clothing in the U.S.A. (Ellen MacArthur Foundation, 2017).

Although Canada lacks robust textile waste tracking, it can be expected that the Canadian population displays a similar rate of consumption (Cybis & Bernard, 2021). A recent investigation by CBC Marketplace suggested that Canadians are buying 70 new articles of clothing a year, and contributing 12 million tonnes of textile waste to landfills annually.

Consumers' attitudes towards sustainability in fashion have been changing, and vary among regions and demographics. For instance, European consumers have become more engaged in sustainability, with two-thirds considering it crucial to limit climate change impacts and 88% stressing the need to reduce pollution. European consumers are increasingly opting for sustainable materials and brands with strong social and environmental commitments. This shift includes a growing interest in purchasing more durable fashion items, keeping them longer, and exploring second-hand options, especially among younger members of the population (survey was conducted on over 2,000 UK and Germany respondents, McKinsey and Company, n.d.). The Swedish Environmental Protection Agency found that 57% of respondents surveyed think about the impact of textiles on the environment when buying clothes, while 70% think about microplastic emissions when washing. However, almost half of the respondents stated that they lacked knowledge of the underlying issues (Naturvårdsverket, 2020).

A household survey of Metro Vancouver residents conducted by Barsen (2021) in 2020 revealed that young people and young parents drive the demand for low-cost fashion in the region, regardless of income brackets. Environmental sustainability was not viewed as a priority when purchasing a new piece of clothing or washing machine for consumers in Vancouver, in contrast to the European studies. While these findings are considered representative of BC, they may not accurately represent the rest of Canada. More research is needed to better understand the attitudes of the Canadian public towards textile and microfibre sustainability.

5.1.5 Policy and other tools to drive upstream change

Diverse strategies are currently being explored by governments worldwide to foster circularity in the textile industry and reduce microfibre pollution arising from the sector. These are summarized in Section 5.4. Here, we provide an overview of various mechanisms and examine their relevance and potential benefits for tackling microfibre pollution.

Extended Producer Responsibility is when producers are given the responsibility – financial and/or operational – to treat or dispose of post-consumer products. EPR can play a multifaceted role by incentivizing retailers and manufacturers to design or sell more sustainable garments, develop efficient textile recycling systems and invest in consumer education on responsible product use and disposal.

In Canada, EPR schemes for textiles are not yet well established. Nova Scotia offers a textile recycling option when one brings end of life textiles to a recycling depot (https://divertns.ca/find-depot). The province of British Columbia plans to include textiles in its future EPR program (McDonald, 2017). In 2009, the Canadian Council for the Ministers of the Environment published a Canada-wide Action Plan for Extended Producer Responsibility on priority products, including packing, electronics, automotive items and others (CCME, 2009). Upon adoption of the plan, Canadian jurisdictions commit to working towards the development of EPR framework legislation and/or regulations to allow for action on products and materials. Textiles, carpets, and furniture were identified as priority products for EPR in Phase 2 of the plan and classified as not ready to progress to EPR due to lack of data, engagement with industry, and gaps in recycling technologies (Giroux, 2014). Phase 2 Action Plan involves an 8-year timeline for the development of EPR schemes for textiles.

Case Study: France's Extended Producer Responsibility program

France has a well-established EPR program for textiles. Launched in 2017, the French EPR policy requires producers, distributors and importers to responsibly manage end-of-life products by either creating their own approved recycling program, or by contributing financially to an accredited producer responsibility organization (PRO). 'Refashion' is currently the only eco-organization accredited by French authorities to cover the textile industry's legal obligation to manage waste sustainably under the EPR scheme. Refashion is financed by the marketers (brands, importers, etc.) to manage end-of-life support for products.

- EPR policy has contributed to a threefold increase in collection and recycling rates of post-consumer textiles between 2006 and 2018 (Buckhari et al. 2018).
- There has been a 13% annual increase in post-consumer textiles collection since implementation. In 2016, the French PRO collected €17.2 million in tariffs from fashion retailers.
- The funds generated have supported recycling organizations in promoting increased collection and recycling rates, maintaining transparent material and financial flows, funding research and development projects to identify solutions for textile producers and recyclers, and supporting inclusion for socially excluded workers (Eco TLC, 2016).

Currently, EPR schemes are primarily focused on reducing textile waste in landfills and establishing collection and recycling infrastructures, which indirectly contribute to mitigating microfibre pollution. However, these schemes could also address the issue of microfibre release more directly during the manufacturing and consumer usage phases. Policymakers could adapt EPR schemes by incentivizing producers to develop products with lower microfibre shedding and encouraging appliance manufacturers to design washing machines that minimize or capture microfibres. Financial incentives and reduced EPR fees are possible levers that could encourage these developments.

Bans on textile materials that don't meet sustainability standards (e.g. low microfibre shedding). Bans are common policy instruments to prohibit or limit use of hazardous substances in the manufacturing of products. However, the successful implementation of such bans in the context of microfibres would require industry data on microfibre releases and product performance standards (microfibre shed thresholds). Currently, such systems are still under development.

Eco-modulated fees are an approach where financial charges levied on products are adjusted based on their environmental impact. This system has been suggested as a method to enhance the use of recycled content in textiles (Schumacher and Forster, 2022). By implementing lower fees on products with a high percentage of recycled textiles compared to those made with virgin materials, producers are financially incentivized to increase the use of recycled content in their products. In theory, this approach encourages manufacturers to shift towards more sustainable practices, in manufacturing and creation of textiles, by making the use of recycled materials more economically attractive. Similar to bans, this system could be adapted to account for the microfibre shedding footprint of textile products. In the absence of testing standards, manufacturers could be encouraged to conduct comprehensive life cycle assessments of their products. Eco-modulated fees could be adjusted based on the overall environmental footprint of the product, which would include considerations of microfibre shedding as part of broader sustainability criteria.

Tax incentives can be used to alleviate cost pressures and reward brands and retailers for sustainable practices, like sourcing sustainably, using eco-friendly materials, producing fewer new products, and managing repair programs. An example is the proposal of a chemicals tax on clothing and shoes by the Government of Sweden in 2021. This tax, set at €4 per kilogram of product weight, aims to phase out hazardous substances from these items. It offers fee reductions of up to 95% for products that have no harmful chemicals.

Business-to-business (B2B) information systems have been developed in the textile sector to address various sustainability challenges (OECD, 2021). Examples of leading systems are the manufacturing restricted substances list (MRSL) of the ZDHD Foundation (Zero Discharge of Hazardous Chemicals), the Oeko-Tex Standards, and the Higgs Index from Cascale. These systems adopt an integrated approach to environmental impacts, offering an opportunity to include microfibre release assessments in their sustainability evaluations (OECD, 2021). The Higg Materials Sustainability Index (MSI), for instance, allows retailers and manufacturers to understand the cradle-to-grave environmental impacts of textile materials, from resource extraction, production, all the way to their end of use based on metrics on hazardous chemicals, water use, energy and deforestation.

Business-to-Consumer (B2C) schemes: Eco-labels. This option targets consumer purchasing decisions with the aim of shifting clothing manufacturing towards products that shed less (Hann et a., 2018). Labelling schemes could be designed to map the resistance of products to microplastics shedding on a scale or B2C certification labels can be employed to indicate that a product meets certain predetermined environmental criteria (e.g. European Union Eco-Label, Nordic Swan Ecolabel, OECD, 2020). In addition to labelling schemes, information on the shedding propensity of products could also be included via other information provision tools, such as product packaging and garment tags or stickers. However, in the absence of information on the shedding propensity of garments available on the market consumers' ability to discern products based on their environmental performance is currently limited. As part of its textile eco labelling legislation, the French Ministry of the Environment is developing an environmental assessment tool called Ecobalyse, which considers microfibre releases. The French Decree 2022-748, part of the Anti-Waste for Circular Economy Law, mandates that companies inform consumers about the risk of microfibre release associated with the use of textiles.

While Canada currently has no specific regulations addressing microfibre pollution in manufactured textiles, the *Canada Consumer Product Safety Act*, along with the *Textile Labelling Act and the Textile Labelling and Advertising Regulations*, could provide a framework for future standards.

The *Canada Consumer Product Safety Act* ensures the safety of consumer products, including textiles. The Act requires that consumer products undergo testing for various safety aspects, such as chemical toxicity, flammability, and electrical hazards.

The *Textile Labelling Act* and *the Textile Labelling and Advertising Regulations* mandate accurate labeling of textiles, including fibre content and care instructions. While they primarily focus on consumer information and advertising accuracy, these regulations could extend to include environmental impact, including microfibre shedding properties.

5.2 Consumer interventions

The solutions discussed here center on strategies to reduce microfibre releases at consumer level, particularly during textile laundering.

We estimate that Canadian households generate **1,920 tonnes** of microfibres each year by laundering textiles. Although the majority of domestic liquid waste effluents are treated (minimum of primary treatment is 86% nation-wide), **264 tonnes** of microfibres are estimated to inadvertently end up in aquatic environments from treated effluent, with an additional **35 tonnes** coming from untreated effluents.

The majority of microfibres retained by wastewater treatment facilities are estimated to accumulate in sludge and biosolids. We further estimate that **795 tonnes of microfibres** are added to Canadian terrestrial ecosystems each year through the application of biosolids.

Tested technologies to significantly reduce microfibre releases from homes are available. External washing machine filters, for instance, can capture up to **90% of microfibres** released in laundry**.** If washing machines in every household in Canada were equipped with a filter with such efficiency, we estimate that **983 tonnes** of microfibres could be **diverted** from aquatic receiving environments and biosolid-amended soils each year.

5.2.1 Laundry solutions

Much of the research in recent years has focused on after-market devices that can be used with existing washing machines. This research underscores the importance of integrating filtration in washing machines in domestic and commercial sectors.

Residential sector

Aftermarket devices designed to mitigate microfibre in laundry release can be categorized into in-drum capturing devices and add-on external filters. Due to various factors affecting microfibre shedding, including the device used, the type of garment tested, and the filter's mesh size, there is a significant variability in reported efficiencies of aftermarket devices (McIlwraith et al., 2019; Napper et al., 2020; Browne et al., 2020, Vassilenko et al. 2021). Studies have shown that capture rates can range from 26-90% of microfibres (**Table 14**). Devices installed in the washing machines appear to have lower effectiveness compared to external filters (**Table 14**).

In a study of McIlwraith et al. (2019) the efficiency of "Cora Ball'' and "Lint LUV-R" filters were evaluated using 100% polyester blankets in the wash. Both devices were found to have significant reductions in microfibres in laundry effluents, however, "Lint LUV-R" captured 86.5% (648 ± 165 microfibres L^{1}) compared to 25% captured by "Cora Ball" (3,580 ± 390 microfibres L^{-1}). Microfibres in effluents following filtration by "Lint LUV-R" device were significantly shorter than in the control samples, suggesting that small microfibres can still wind up in domestic waste effluents.

Napper et al. (2020) conducted extensive tests on a variety of devices using a mixed laundry load (100% polyester jumpers, 100% acrylic or 60% polyester/40% cotton). The "XFiltra" filter was most effective, reducing microfibres in laundry effluents by 78% on average, owing to its smallest pore size compared to the other devices tested. In contracts, the capture rate for the "Guppyfriend" was 54%, the "Fourth Element" bag 21%, the "Cora Ball" 31%, and 29% for the "Lint LUV-R" (Napper et al., 2020). The capture rate for the "Lint LUV-R" was lower than those reported by McIlwraith et al. (2019) possibly reflecting differences in study design and quantification methods.

The role of filter design in microfibre mitigation was explored in the study of Vassilenko et al. (2021). The tested devices included Lint "LUV-R" and "Filtrol ', with filter pore sizes spanning 100–1500 µm. The authors found that pore size was critical to microfibre retention, with larger pores capturing fewer fibres. Moreover, retention rates varied among textile fibres, with polyester fibres being captured more efficiently (80–90%) than nylon fibres (~40%).

In addition to laboratory testing, after-market filters have also been tested at a community scale in Parry Sound, Ontario (Erdle et al. 2021). The study involved installation of "Filtrol 160" devices in 10% of households in the town and monitoring of microfibre levels at a local WWTPs for 17 months.

Significant reductions of over two-fold were observed in wastewater effluent microfibre concentrations after installation of the devices, and it was estimated that 934 million to 14.1 billion of microfibres were diverted from the environment during the course of the study.

The pilot study of Erdle et al. (2021) and a range of laboratory studies demonstrate that aftermarket washing machine filtration can be an effective strategy to reduce microfibre releases from homes. However, there are several considerations for a broad implementation of this solution:

1. **Consumer awareness and willingness to change behaviour.** A US consumer survey of attitudes towards microfibre filtration devices found that while 68% of respondents are aware of plastic pollution, only 37% recognize the role of laundry in microfibre pollution. Despite acknowledging the importance of solutions for capturing microfibres, there was a discrepancy in willingness to invest time in using these products. Respondents valued the idea of sacrificing time for environmental benefits but showed reluctance towards the actual daily time commitment required for maintenance (Herweyers et al. 2020).

2. **Varying effectiveness of devices**. The effectiveness of different microfibre catching devices, sometimes for the same device, has varied considerably among studies due to a number of factors (**Table 14**). The effectiveness of such devices was found to be the key factor influencing consumer decision on washing habits to cut microfibres (Herweyers et al. 2020). Filter cleaning and appropriate disposal of retained microfibres have not been fully examined but may represent a barrier to scaling after-market filtration solutions (Erdle et al. 2021).

3. **Need for clear information on consumer maintenance needs**. Some devices require specific maintenance or replacement to prevent potential clogging or malfunctioning in the washing machine.

4. **Lack of endorsement by the appliance sector**. There is a lack of information on the compatibility of the devices with the different washing machine brands and models and the impacts of these devices on the normal functioning of the machine, such as energy/water consumption and cleaning effectiveness.

Given the challenges with broad implementation of the after-market devices, there has been a growing emphasis on built-in appliance innovations and requirements for new washing machines. France is the first country to introduce a mandatory requirement that all new professional and household washing machines be equipped with a microfibre filter, with a deadline of January 1, 2025 (France, 2020).

Two appliances manufacturers have introduced innovations to address microfibre releases during laundry. The UK-based Grundig now offers a washing machine with an integrated microfibre filter, the “Grundig fibreCatcher”, with a reported 90% capture rate for synthetic wash cycles (Grundig, 2024). Samsung’s recent washing machine with the built-in “The Less Microfibre™ Filter”, is reported to reduce microplastics released during laundry by up to 98% when used four times a week. In addition, the company offers a standalone mountable Less Microfibre™ Filter that can be used with standard washing machine models (Samsung, 2023).

Commercial sector

Commercial laundry machines should also be targeted for filtration capture. In Canada, commercial laundry facilities are generally required to treat their wastewater before discharging it, either to municipal sewage systems or directly into the environment, depending on their location and the specific regulations that apply. However, the lack of data on microfibre concentrations in effluents from these commercial laundries complicates the task of determining their contributions to microfibre pollution. We estimate that commercial laundry releases could be contributing approximately **1,099 tonnes of microfibres per year**, which would nearly double the current estimates for microfibre releases to the environment in Canada from laundry.

While the filtering devices listed in **Table 14** have been designed primarily for household use, several models could easily be adapted to commercial settings (OECD, 2021). Notably, the PlanetCare filter has been marketed to hotels, hospitals, laundromats and marinas stating that it can process effluent from up to ten washing machines (PlanetCare, 2020). The Filtrol filter has been used in government facilities and laundromats (Wexco Environmental, 2020). In addition, commercial laundry facilities generally have systems in place to remove oils or suspended solids (Fijan et al., 2008), based on precipitation/coagulation and flocculation or adsorption on granular-activated carbon, or oxidation with ozone, UV treatment, chlorination. Such processes are employed in tertiary or advanced treatment processes and have been shown to remove microfibres (Section 5.3.1). There is therefore potential to optimize these technologies for microplastic removal in commercial laundry effluents (UNEP, 2020).

Case Study: Washing machine filters reduce microfibre releases in Parry Sound, Ontario (Erdle et al., 2021)

Study design

- Installation of washing machine filters in 10% of households connected to municipal WWTP in Parry Sound Ontario.
- Use of Filtrol 160 (Wexco Environmental, USA): 100 µm mesh, 89% MF retention rate in lab studies.
- Collection of lint samples four times between March 2019 and October 2020.
- Evaluation of microfibres in WWTP effluent before and after filter installation.

Key findings

Households:

- The average mass of microfibres released per household was 6.4 ± 6.0 g, representing 45.5 ± 21.4 microfibres mg^{-1} of lint.

WWTP effluent:

- Contained 4.6 ± 1.6 microfibres L^{-1} before filter installation compared to 1.9 ± 0.7 microfibres L^{-1} after. There were no seasonal differences in microfibre abundances.
- Blue microfibres were the most common (32%).
- Anthropogenic cellulose was the dominant polymer (52%).
- An estimated 934 million to 14.1 billion of microfibres were diverted from WWTP over the course of the study.
- Extrapolation to the Toronto population suggested that 12 – 166 trillion of microfibres could be diverted from WWTPs if all washing machines were equipped with filters.

Table 14. The effectiveness of microfibre capture devices varies depending on experimental conditions

A review of marketed devices, study conditions and reduction of microfibres based on weight and count. Also included are evaluations of pros and cons of each device from Organisation for Economic Cooperation (OECD, 2021).

Device	Type	Pore size	Cost	Experimental Design			Microfibre reduction in effluent		Pros (OECD, 2021)	Cons (OECD, 2021)	References
				Garment	Washing Machine	Wash Cycle	Weight	Count			
Cora Ball	In-drum	na	~$40	100% polyester fleece blankets	Top loading	No adjustment of T settings	↓ 5%	↓ 26%	Easy to use; Reduce overall shedding	Cannot be used with delicate; Significant cleaning process	McIlwraith et al., 2019
				Mixed load of 100% polyester jumpers, 100% acrylic or 60% polyester/40% cotton	Front loading	45 minutes, 30°C, 1000 RPM	↓ 31 ± 8%	na			Napper et al., 2020
Lint LUV-R	External filter	1580 µm	~$200	100% polyester fleece blankets	Top loading	No adjustment of T settings	↓ 80%	↓ 87%		Unclear cleaning and maintenance	McIlwraith et al., 2019
				Mixed load of 100% polyester jumpers, 100% acrylic or 60% polyester/40% cotton	Front loading	45 minutes , 30°C, 1000 RPM	↓ 29 ± 15%	na			Napper et al., 2020

				Cotton and polyester T shirts	Front loading	30°C, 600 RPM for polyester; 30°C, 1000 RPM for cotton	No effect for cotton; ↓ 65% for polyester	na			Browne et al, 2020
		50 μm 100 μm 200 μm		Polyester fleece Nylon stretch woven	Top-loading	12 mins/41°C/ 645 RPM	↓ 88% (150 μm -polyester) ↓ 14% (150 μm - nylon)	na			Vassilenko et al. 2021
Guppy friend	In-drum	50 μm	~$45				↓ 86%		Reduce overall shedding; Protects fabrics during washing potentially extending their lifetime; Low price	Can limit the maximum washing load	Guppyfriend 2020
				Mixed load of 100% polyester jumpers, 100% acrylic or 60% polyester/40% cotton	Front loading	45 minutes, 30°C, 1000 RPM	↓ 54 ± 14%	na			Napper et al., 2020
X-filtra (prototype)	Built-in	60 μm	na	Mixed load of 100% polyester jumpers, 100% acrylic or 60% polyester/40% cotton	Front loading	45 minutes, 30°C, 1000 RPM	↓ 78 ± 5%	na	Remove the need for the user to purchase, install and operate an external filter unit; No need	Unclear maintenance needs for consumers	Napper et al., 2020

				na	na	na	↓ 90%	na	for cartridge replacement		Xeros Technologies, 2020
Indi	External filter	na	~$220	na	na	na	↓ 90%	na	Easy maintenance	Used cartridges need to be sent back to producers	CleanerSeas, 2024
Fourth Element washing bag	In-drum	50 µm	~$25	Mixed load of 100% polyester jumpers, 100% acrylic or 60% polyester/40% cotton	Front loading	45 minutes, 30°C, 1000 RPM	↓ 21 ± 9%	na	na	na	Napper et al., 2020
PlanetCare	External filter	> 175 µm	~$15	Mixed load of 100% polyester jumpers, 100% acrylic or 60% polyester/40% cotton	Front loading	45 minutes, 30°C, 1000 RPM	↓ 25 ± 20%	na	Easy installation	Does not retain the smallest particles; Cannot be used with fabric softener or excessive detergent	PlanetCare, 2020
Filtrol 160	External filter	100 µm	~$170	na	na	na	↓ 89%	na	na	na	Filtrol, 2021

		50 µm 100 µm 200 µm		Polyester fleece Nylon stretch woven	Top loading	12 mins,41°C, 645 RPM	↓ 88-89% (50-200 µm -polyester) ↓ 44-46% (50-200 µm -nylon)				Vassilenko et al. 2021
Microplastics LUV-R	External filter	150 µm	~$270	na	na	na	↓ 87%	na	na	na	Environmental Enhancements, 2021
				Cotton and polyester T shirts	Front loading	30°C, 600 RPM for polyester; 30°C, 1000 RPM for cotton	↓ 67% for cotton; ↓ 74% for polyester	na	na	na	Browne et al., 2020

5.2.2 Electric dryers

Electric drying of clothing represents a source of microfibres. Although electric drying appliances are typically equipped with a filter, recent studies have detected significant amounts of microfibres in dryer vents (Tao et al., 2022, Kapp et al., 2020). The degree of microfibre release from a dryer is influenced by its type, age, vent installation and lint trap characteristics (Kapp et al., 2020). Tao et al. (2022) reported releases of 561,810 ± 102,156 microfibres from an electric dryer per synthetic clothing load (7kg) and 433,128 ± 70,878 for cotton load (6 kg) after 15 minutes of drying cycle. The estimated annual microfibre dryer contribution was reported at 9×10^7 to 12×10^7 (assuming 219 loads per year, NRC, 2021).

To compare microfibre dryer releases to those from laundry, we calculated an average mass per microfibre shed from synthetic and cotton textiles using data presented in Vassilenko et al. (2021). Converting annual dryer releases by all Canadian households to mass results in an estimated 287 and 371 tonnes of microfibres released from drying synthetic and natural textiles, respectively, each year. In comparison, Canada-wide domestic laundry is estimated to generate significantly more microfibres - 1,920 tonnes per year. Of those 14% are estimated to enter water bodies with treated and untreated wastewater (270 tonnes per year), while 37% (710 tonnes per year) are estimated to enter Canadian terrestrial environments through biosolid application.

These preliminary estimates suggest that the electric drying of clothes provides an additional and significant mechanism for microfibre environmental contamination. As this is a relatively new topic, there is a need to advance research and encourage exploration of innovations in electric dryer appliances.

5.2.2 Textile product care practices

Various studies have examined how laundry and drying practices impact the release of microfibres from clothing. These investigations have revealed that factors such as water temperature, type of washing machine, detergent used, and the frequency and intensity of wash cycles can significantly influence the number of microfibres shed during laundering (**Table 15**).

Laundry and drying practices that result in lower microfibre releases can be encouraged through public awareness campaigns. For instance, Metro Vancouver in British Columbia conducts information campaigns via their website and social media on ways to reduce microfibres released from fabrics, such as washing in cold, air drying clothes and wearing them longer. Similarly, the U.S National Park Service provides several microfibre recommendations to the public, including washing less, installing a filter, and lowering the temperature of drying or air drying. Various NGOs globally have been conducting educational campaigns for microfibres, including the Ocean Conservancy, 5Gyres, Plastic Soup and Ocean Wise. The success of effectively influencing consumer habits to cut microfibre pollution overall relies on significant engagement and outreach efforts.

In 2023, Samsung Electronics introduced a "Less Microfibre Cycle" for their new washing machines, which utilizes gentle, low agitation wash conditions. This cycle, which reduces microfibre release by 54%, employs gentle, low agitation wash cycles (Samsung Electronics, 2023). The impact of various washing conditions on microfibre releases was assessed through a study conducted in collaboration with Patagonia and Ocean Wise Plastics Lab (Ocean Wise, 2023). These results informed identification of specific conditions to reduce microfibres for the South Korea style and European style washing machines. The effectiveness of this solution is contingent on consumers opting for the wash program, which could be facilitated by appliance labelling that promotes microfibre friendly practices (Ocean Wise, 2022).

Table 15. Best practices in textile care to reduce microfibre loss in laundry

Overview of textile care best practices that can be utilized by consumers to reduce the releases of microfibres during home laundry.

Practice	Description	Study
Reduce Washing Frequency	Decreasing the frequency of washing can lower the overall release of microfibres. This approach not only reduces wear and tear on fabrics but also limits the quantity of fibres entering water systems. An average Canadian household performs 4 laundry cycles per week (NRC, 2021).	Pirc et al. (2016)
Use Gentle and Shorter Wash Cycles	Gentler wash settings result in less agitation and stress on fabrics.	Hartline et al. 2016 Ocean Wise, 2022
Use Low-Temperature Washing	Washing at lower temperatures appears to be less aggressive on textiles, thereby minimizing fibre breakage and subsequent microfibre release	Sillanpää et al. 2017 Yang et al. 2019b Ocean Wise, 2022 Lant et al., 2020
Modify Wash load	Larger wash load size usually result in less microfibres released due to the lower water-to-fabric ratio.	Lant et al., 2020

Detergents and softeners	The effects of detergent and softener use on microfibre generation have been variable between the studies. There is a need for more research and innovation for this area.	De Falco et al., 2018 O'Brien et al.,2020 Cesa et al., 2020 Yang et al., 2019 Carney-Almroth et al., 2018
Use Air drying	Tumble drying can increase microfibre shedding due to mechanical action. Air drying is a preferable alternative and helps to extend the products' lifetime.	Hernandez et al., 2017

5.3. Environmental management interventions

Wastewater treatment plants, biosolids and stormwater represent important pathways through which microfibres enter the environment. We estimate that **264 tonnes** of microfibres are released annually to Canadian water bodies after treatment, with an additional **35 tonnes** coming from untreated effluents. Although wastewater treatment prevents an estimated **1,621 tonnes** of microfibres from entering the aquatic environment (up to 98%, as reviewed in Section 5.3.1), a significant portion of captured microfibres (**795 tonnes**) is estimated to be distributed in terrestrial environments through biosolid applications.

The detection of persistent microfibres that do not readily degrade in stormwater, wastewater and biosolids underscores the importance of implementing solutions closer to the source and preventing microfibre entry into the liquid waste stream and the urban environment. Interventions may be considered at the textile design and manufacturing stage, as well as in washing machines, to reduce the loads of microfibres in municipal waste streams. While stormwater has been identified as an important route for microfibres in international studies, data gaps for Canada limit our ability to evaluate its contribution. By discussing various strategies for stormwater microplastic reduction, we highlight the many opportunities environmental managers could apply that are already successful in managing other contaminants.

5.3.1 Wastewater treatment

Wastewater treatment can remove large proportions of microplastics and microfibres, ranging from 76% to 98% of the influent quantities (Carr et al., 2016; Murphy et al., 2016; Gies et al., 2018; Conley et al., 2019; Talvitie et al., 2017; Gasperi et al., 2015; Blair et al., 2019; Zhang et al., 2023; Zhou et al., 2020). Microfibres often constitute the dominant form of microplastics in wastewater studies. It is important to note that while this section centres on microfibres, we use the term microplastics broadly, as many wastewater studies often examine microplastics as a uniform category.

A significant fraction (up to 90%) of the microplastics entering a wastewater treatment plant is removed during **preliminary/primary treatment** (Lares et al., 2018; Talvitie et al., 2015). Wastewater treatment processes that may contribute to the removal of microplastics include skimming, screening, grit removal, flotation and primary settlement.

Microplastics can be removed by skimming in addition to being adsorbed and entrapped in flocculating particles and separated by sedimentation (Sun et al., 2019; Wei et al., 2020). Xu et al. (2019) found that long microfibres (>1,000 μm) were most effectively removed during primary treatment compared to short microfibres (500-1000 μm). Similarly, Dris et al. (2015) found that particles between 1,000 and 5,000 μm were being removed by primary treatment. When considering particle shape, removal rates were generally higher for particles and fragments compared to microfibres (Claessens et al., 2013). For example, while 91% and 83% of granules/fragments and pellets were, respectively, removed in a study of a WWTP in China, 79% of microfibres were eliminated (Long et al., 2019).

During **secondary treatment**, soluble organic matter is removed, mainly through biological processes, followed by sedimentation of activated sludge (Tang et al. 2021). During this treatment, microplastics get trapped within the aeration tanks and are further settling into the sludge (Sun et al., 2019). Membrane bioreactors (MBRs) allow for microfiltration or ultrafiltration aided by organic catalysts such as enzymes or microorganisms to produce effluent of high quality (Iorhemen et al., 2016). Membrane filtration (0.4 μm) and biologically active filters have been shown to remove an additional 98-99% of particles after secondary treatment (Lares et al., 2018; Talvitie et al., 2017). There are reports that MBR is more efficient in treating microplastics compared to conventional active sludge (CAS) technology (Leslie et al., 2017, Lares et al., 2018).

Tertiary treatment may employ dissolved air flotation which uses bubbles to carry suspended solids to the surface to allow removal by skimming, or filtration using different media such as sand filters, disc filters, biologically active filters and gravity filters to further remove suspended particles in addition to coagulation or ozone treatment (Bhandari et al., 2014). Reverse osmosis (RO) has also been used as part of tertiary treatment in Australia and China (Ziajahromi et al., 2017, Zhou et al., 2020). Reverse osmosis forces liquid across a semipermeable membrane to eliminate the impurities from the flow.

When investigating microfibres in effluents from three textile mills in China, Zhou et al. (2020) found that the plants equipped with a membrane bioreactor (MBR) and reverse osmosis (RO) had the lowest levels of microfibres in the final effluent. In an Australian WWTP equipped with RO technology microplastics discharge was reduced from 0.28 to 0.21 microplastics L^{-1} of effluent (Ziajahromi et al., 2017). Additionally, Talvitie et al. (2017) found that 40 – 98.5% of microplastics (between 20-300 μm) were removed by disc filter, 95% by dissolved air flotation and 97% by rapid sand filter. High treatment efficiencies were also reported for membrane disc filters (91% removal rate), rapid sand filtration (98.6% removal rate), coagulation (92.2% and 95.7%) and ozone treatments (99.2%) in a study by Hidayaturrahman and Lee (2019).

These overall rates were in line with those reported for a WWTP in Spain (99% and 95% for MBR and rapid sand filtering, respectively). However, when the authors considered microfibre specifically, the removal rates were lower, between 79% and 75% (Bayo et al., 2020). In some studies, lower removal rates were observed for similar technologies (e.g. France with 69% for disc filters and even an increase by 58% in microplastics when using rapid sand filter, OECD, 2021; 71.7% removal of microplastics with advanced treatment consisting of denitrification, ultrafiltration, ozonation and ultraviolet, Yang et al. 2019b). These variabilities may be attributed to differences in operational conditions, population, influent characteristics, and measurement methodologies.

In general, these studies and others observe that smaller and fibre-shaped particles are more likely to escape initial treatment stages due to their longitudinal shape and small diameters (Li et al., 2020; Raju et al., 2020, Hamidian et al., 2021, Edo et al., 2020). Tertiary effluents are often dominated by microfibres (Yuan et al., 2021; Li et al., 2020; Raju et al., 2020; Hamidian et al., 2021; Edo et al., 2020), with sizes 20-190 μm being frequent as reported in some studies (Ziajahromi et al., 2017).

In Canada, the *Wastewater Systems Effluent Regulations* came into force in 2012 under the *Fisheries Act* to manage wastewater released by facilities that collect an average daily influent volume of 100 m^3 or more (Government of Canada, 2012). However, these regulations do not apply to wastewater systems located on the site of an industrial, commercial or institutional facility (Government of Canada, 2012). There were 1,866 publicly-owned WWTPs in Canada in 2020 with varying degrees of treatment (Statistics Canada, 2020). The proportion of populations served by municipal WWTP systems varied from 54.3% in Prince Edward Island to 91% in British Columbia with a national average of 86%. This ranked Canada 14th out of 24 countries from the Organisation for Economic Co-operation and Development for which data was available for the year 2020 (ECCC, 2023). When taking into account the different treatment options, 13.6% of the population was served by primary treatment facilities, 42.7% by secondary treatment facilities and 28.1% by tertiary treatment facilities (ECCC, 2023). The availability of extensive wastewater infrastructure in Canada thus offers substantial prevention against microfibre pollution in water environments.

Emerging technologies to reduce microplastics and microfibres in wastewater

Scientific research clearly demonstrates the significance of wastewater treatment in reducing waterborne microplastic pollution. However, despite the 78-98% retention rates, significant amounts of microplastics can still be released to the environment over long time scales. Consequently, new technologies and processes are being investigated to provide additional removal of microplastics from final effluents. While research on these technologies has mainly focused on fragment-shaped microplastics, this overview can benefit the optimization and development of technologies, as well as support further validation efforts to treat microfibres in wastewater systems.

Electrocoagulation

During electrocoagulation, electrochemical reactions lead to the formation Fe^{3+} and Al^{3+} and the formation of micro-flocs. Removal efficiency for microplastics was reported >90% and up to 99.2% for polyethylene microbeads with pH 7.5 (Perren et al., 2018, Garcia-Segura, 2017). When using polyesters in synthetic solution, the removal efficiency of microplastics was 99% and 96.5% in experiments utilizing wastewater samples (Elkhatib et al., 2021).

Magnetic extraction

Fe nanoparticles coated with hexadecyltrimethoxysilane can be used for magnetic extraction of microplastics. Removal efficiency for medium-sized microplastics (200 – 1000 μm) was reported at 84% for freshwater samples, 78% for sediment and 92% for small polyethylene and polystyrene particles in seawater. The recovery efficiency in sediment suggested good potential for application to sludge (Grbić et al., 2019).

Sol-gel method

pH-induced sol-gel process leads to agglomeration and formation of microplastic flocculates that can then be more easily removed from wastewater through separation mechanisms such as sand traps (Collivignarelli et al., 2017). Microplastic removal efficiency of up to 99% was reported and was strongly affected by the chemical composition and surface properties of the particles (Herbog et al., 2018; Sturm et al., 2023).

Organosilane agglomeration

Organosilanes can be used alongside chemically-induced agglomeration to trap particles in large agglomerates making their removal easier. High rates of agglomeration of 75% have been reported for C4 silane, over a gelation time of 120 s (Sturm et al., 2021).

Biofilter

Biofilters made of three filtration layers (stone wool, 40 cm Filtralite layer, 10 cm granite gravel) were reported to remove 79% of microplastics from the secondary effluent of a WWTP in Denmark (Liu et al., 2020).

Bioremediation

While this research is in its infancy, several species have been considered for mitigating microplastic release via wastewater effluents. For example, some groups of bacteria and fungi have the ability to degrade different classes of plastics (Zhang et al., 2021, Al Hosni et al., 2019). Marine seagrasses have been shown to bind microplastics via encrustation, to macrophyte-associated epibionts, and to the mucus layer, with 75% and 94% of seagrass blades reported to have accumulated microplastics in samples collected close to urban agglomerations (Goss et al., 2018, Jones et al., 2020).

Suspended microplastics can also be retained on the membranes of certain species of seaweeds such as brown seaweed, (*Fucus vesiculosus)* (Bonanno and Orlando-Bonaca, 2020; Gutow et al., 2016). Finally, several marine invertebrates such as blue mussels (*Mytilus edulis*), lugworms (*Arenicola marina)* or sea cucumbers (*Apostichorus japonicus*) have all been reported to ingest microplastics and have been suggested as potential organisms for remediation (Mohsen et al., 2019, Van Cauwenberghe et al., 2015, Murano et al., 2020). However, more research is needed to properly evaluate the harmful effects of microplastics on these organisms (Krishnan et al., 2023).

5.3.2 Sludge and biosolid treatment

Following wastewater treatment, a significant amount of microfibres (69 – 99%) accumulates in sludge which is then treated by lime stabilization, composting, anaerobic digestion or thermal drying to produce biosolids (Mahon et al., 2017). We estimate that up to **1,651 tonnes** of microfibres may be trapped in sludge and biosolids annually, with **795 tonnes** redirected to the terrestrial ecosystem through biosolid application.

A pan-Canadian study involving 22 wastewater treatment plants found elevated levels of microplastics in biosolids, with an average of 636 particles g^{-1} of dry weight and the majority consisting of microfibres (86%, Sivarajah et al. 2023). Additionally, it was estimated that between 410-1,300 billion microplastics were added to agricultural soils in Ontario in 2017 (Crossman et al. 2020). The study found that agricultural soils have limited capacity to store microplastics, therefore promoting their migration into nearby water courses. This suggests that biosolid application contributes not only to microplastic pollution of land systems, but also to their wider dispersal. However, there was evidence that microfibres, due to their elongated and flexible structure, may be more likely to become entangled and persist in the soil matrix, whereas fragments could be more readily exported or degraded.

There are limited examinations on the role of sludge treatment processes in reducing microplastics or management practices that could alleviate their entry into soil systems with biosolids. Long-term storage of biosolids and syphoning of supernatant liquid could be one strategy to reduce biosolid microplastic content as suggested in an Ontario study (Crossman et al. 2020). Mahon et al. (2017)

reported that mesophilic anaerobic digestion of sludge has little effect on microplastics, although some small-sized particles were higher in lime-stabilized sludge compared to anaerobically digested and thermally dried sludge, likely due to higher pH and mechanical mixing. Some researchers have suggested that microplastics could be destabilized during the thermal treatment of sludge or potentially broken down through enzymatic activity of microorganisms (Talvitie et al., 2015; Tang and Hadibarata, 2021) but further research is needed.

The Mohajerani & Karabatak 2020 study estimated that biosolid applications in European Union, the United States, China, Canada and Australia, result in the addition of approximately 26,042, 21,249, 13,660, 1,518 and 1,241 tonnes of microplastics to farmlands, respectively. The Canadian estimates are twice those of estimates for microfibre additions derived in our study, possibly due to the inclusion of other types of microplastics. The authors identified the utilization of biosolids in brick manufacturing as a feasible alternative to address microplastic pollution and other micropollutants such as pharmaceuticals and heavy metals.

In Canada, the Canadian Council of Ministers of the Environment (CCME) developed a framework to guide biosolids management (CCME, 2012). In order to capitalize on the high nutrient, organic material and energy content of biosolids, the framework promotes the beneficial use of biosolids such as composting, certain land applications and combustion for energy production (CCME, 2012). Regulations for processing, management and use of biosolids are province/territory specific and even municipality specific. Emerging research on microplastics in biosolids underscores the need to integrate microplastic and microfibre management into biosolids management strategies to protect soil and water environments in Canada, with CCME guidelines offering an important avenue.

5.3.3 Stormwater treatment

Stormwater represents a significant yet complex vector for transporting microfibres to the environment. Treatment and management systems already in use for other pollutants can prevent and manage microplastics and may alleviate microfibre pollution, but more research is needed.

Detention/Retention ponds

Sedimentation ponds are artificial ponds used commonly to manage stormwater runoff by removing particulate material via sedimentation processes. They are considered the most effective stormwater management solutions for particulates. In detention ponds, runoff is retained for a period of time and then clean water is released gradually. In contrast, in retention ponds, a permanent pool is maintained with water being replaced/released with the following runoff water (EPA, 1999). Many studies report on microplastic settling into stormwater pond sediment (Liu et al., 2019, Olesen et al., 2019, Ziajahromi et al., 2020, Liu et al., 2022).

Rasmussen et al. (2024) evaluated microplastics in stormwater retention ponds from a small residential area and industrial areas including one pond having a plastic recycling facility in its catchment. The number of particles smaller than 500 µm ranged from 0.3 to 1,200 microplastics L^{-1} in pond effluent and 65 to 35,000 microplastics g^{-1} in pond sediment with the highest levels being reported in the pond receiving runoff from the plastic recycling factory (Rasmussen et al., 2024). Tyre wear particles dominated in all ponds except the one associated with the plastic recycling facility. Polyethylene and polypropylene dominated in the pond water samples due to their lower densities and therefore their retention rate was lower (77 – 95%) than those reported for denser particles (97 – 97%).

High removal efficiency of microplastics in stormwater retention ponds was reported in studies conducted in Denmark (85%, Olesen et al., 2019) and Sweden (90 – 99%, Jonsson and Ockerman, 2017) with microplastic concentrations in water 270 and 5.4 – 10 microplastics L^{-1}, respectively (Olesen et al., 2019; Jonsson and Ockerman, 2017). Levels in sediment of the retention pond in Denmark were estimated at 950,000 microplastics kg^{-1}.

Limited studies are available on detention ponds. A study in Brazil reported 57,542 microplastics kg^{-1} in the sediment of the detention pond but no removal efficiency was calculated (Braga Moruzzi et al., 2020). This result suggests that detention ponds can also facilitate a significant treatment of stormwater runoff for microplastics and possibly microfibres.

Infiltration systems

These systems are designed for water to infiltrate into the ground and the soil or a membrane to remove particulates from stormwater runoffs. They include infiltration basins (drain accumulated water within 3 days), porous pavement systems (can reduce runoff by 45% compared to traditional fully asphalt pavement) and infiltration trenches or wells. They are often used in combination with detention/retention ponds due to their limited capacity (OECD, 2021). These systems require extensive maintenance to prevent clogging and are not suitable in all areas. Current research suggests that they may not be highly effective in removing microplastics from stormwater (Karlsson, 2009).

Filtration and bioretention

Filtration consists of passing stormwater through a filter media that retains pollutants and allows the water to pass through to the discharge (Wang et al., 2023). It has been reported to offer over 80% of microplastic retention (Lange et al., 2021). Bioretention cells are depressions filled with engineered porous media covered with mulch and vegetation and are used to mitigate flooding (Roy-Poirier et al., 2010).

Limited studies have been conducted in Canada on stormwater management and their potential for microplastic removal. However, one study focused on stormwater treatment from parking lots made of recycled tyres with bioretention cells, reported between 38-84% microplastic retention efficiencies (Smyth et al., 2021). These efficacies were in the lower range of what has been reported in San Francisco (91 – 95%; Gilbreath et al., 2019, Werbowski et al., 2021) and Sweden (76 – 97%; Lange et al., 2021).

In the Swedish study, vegetated and non-vegetated systems were explored, with vegetated systems found more effective at removing microfibres, fragments and paint particles specifically (76% *vs* 42% for non-vegetated, Lange et al., 2021). Polyurethane and polypropylene were shown to be efficiently retained in retention cells as opposed to polyester and acrylic (Smyth et al., 2021; Werbowski et al., 2021). Werbowski et al. (2021) suggested that this pattern was likely linked to the fact that polyester and acrylic particles were likely microfibres, which, due to their elongated shape may have variable retention efficiencies in bioretention and filtration. While high removal efficiencies have been reported, bioretention and filtration tended to remove more fragments than microfibres (Wang et al., 2022, Smyth et al., 2021, Werbowski et al., 2021). Studies on microplastic treatment of stormwater using these treatment systems have focused on microfibres over 100 μm in length, but smaller particles are commonly found in stormwater (Wang et al., 2022).

Gully pots/catch basins

Roadside gully pots/catch basins are small sumps that act as run-off inlet points and are designed to retain sediments from road run-off water that would otherwise enter drains and sewer systems (UNEP, 2020). They can vary in diameter and depths and are made of various materials. They require regular cleaning to prevent blockage and flooding. If well maintained, a gully pot can remove up to 80% of microplastics from road run-offs (UNEP, 2020).

Wetlands

Wetlands are known to improve water quality through natural processes involving wetland vegetation, soil and their associated microbial communities (OECD, 2021). Constructed wetlands are engineered wetlands, which are constructed to mimic natural wetlands, and have been effective in microplastic removal. For instance, they have been reported to remove up to 99.7% of microplastics larger than 20 μm (Liu et al., 2022). However, removal rates can vary significantly: a constructed wetland in Melbourne, Australia, reported only a 28% removal rate (Pramanik et al., 2020), while those in Belgium and Sweden achieved 88% and more than 99% removal, respectively.

In contrast, floating wetlands use small artificial platforms to grow plants on floating mats in open water. Plant roots spread through the mat and into the water. Of note is that such mats can be made from plastic materials and therefore could contribute to microplastic pollution (Ziajahromi et al., 2020; Townsend et al., 2019). In some studies, however, polymers from the mat materials were not detected, suggesting high durability of some mat materials (Ziajahromi et al. 2020). Similar to ponds and bioretention/filtration systems, larger microplastics were preferentially retained in sediment from wetlands. Ziajahromi et al., (2020) suggested similar removal efficiencies for fragments and microfibres. In their review of stormwater management, Stang et al. (2022) suggested that wetlands may be a better option for stormwater with high concentrations of microfibres.

5.3.4 Maritime effluents

Greywater from ships, which includes water from laundry, showers, and kitchen operations, can contain substantial amounts of microfibres shed from textiles and other materials. However, data on microfibres in vessel effluents are limited in scientific literature. As these vessels operate within and across delicate marine ecosystems, the potential impacts of this source poses ecological concerns.

In 2022, Canada's commercial fleet, which includes ships of 1,000 gross tonnage and above, numbered 201 vessels with a total gross tonnage of about 2.3 million. This fleet comprised 46 cargo ships, 42 dry bulk carriers, 24 tankers, and 89 vessels classified under other categories. Additionally, passenger ferries, numbering 69 in 2022, serve as vital links for coastal, island, and remote communities across Canada. The Canadian Ferry Association's members, representing major ferry operators, annually transport over 60 million passengers and more than 22 million vehicles (Transport Canada, 2022).

Cruise ships, with their large passenger capacities and extensive onboard amenities, represent a particularly significant source of greywater that potentially contains microfibres. These vessels, often described as floating cities, generate vast amounts of greywater from laundry, showers, and kitchen operations. Unlike commercial fleets or ferries, cruise ships have a unique operational profile that includes longer durations at sea and a high density of occupants. For instance, in 2022 Port Vancouver reportedly welcomed 307 cruise ships, with 815,000 passengers (Port Vancouver, 2022).

More research is needed to better understand microplastic and microfibre pollution contributions from large vessels. Despite knowledge gaps in this area, the Government of Canada has already taken a proactive approach to develop a wastewater system that can capture and extract microplastics from vessel greywater prior to discharge through the Innovation, Science and Economic Development Canada and Transport Canada challenge, launched in 2020. In their preliminary scan, Transport Canada noted that while it was unable to determine whether or not treatments are being used to treat a ship's greywater, the ship's blackwater and greywater is currently not regulated through the International Maritime Organization under MARPOL Annex IV (ISED, 2020). Furthermore, in the event that the ship's wastewater systems combine black and grey waters for treatment, the treatment standards under MARPOL Annex IV do not account for the capture and extraction of microplastics and therefore treatment systems installed on ships would not present this function.

5.4 Jurisdictional initiatives to address microfibres pollution

Over the last decade, policymakers across the world have been developing and implementing measures to address plastic pollution (Nielsen et al. 2023). Despite ongoing debates and uncertainties about the full effects and risks of plastics to human health and the environment, many countries are adopting a precautionary principle (Nielsen et al. 2023). This approach prioritizes preventive action in the face of potential risks, reflecting a growing awareness and concern about the environmental impacts of plastic. While macro-plastics, particularly single-use items, have been the main focus of environmental regulations, microplastics have recently started receiving attention. Current initiatives are concentrated on advancing research into their environmental impact, banning microplastic additions to consumer personal care products, and developing standardized methodologies for analysis. Regarding microfibres, existing policies and efforts have been aimed at mitigating microfibre releases from textiles during laundry and influencing consumer purchases (**Table 16**), as well as establishing a circular economy for textiles, as discussed below and summarized in **Appendix B**.

United Nations

In 2015, the United Nations created the Sustainable Development Goals (SDGs) to address global challenges from poverty to environmental degradation (UN, 2015). SDG 14.1 calls for actions to "prevent and significantly reduce marine pollution of all kinds, particularly from land-based activities, including marine debris and nutrient pollution". To align with this goal, member states and organizations will need to consider actions to reduce microfibres in the environment.

The United Nations also created the Global Partnership on Marine Litter (GPML), a global multi-stakeholder platform where partners can share knowledge and experience and work together to create solutions to plastic pollution. In turn, The Plastic Waste Partnership (PWP) established under the Basel Convention aims to mobilize business, government, academic and civil society resources, interests and expertise to improve and promote the environmentally sound management of plastic waste at the global, regional and national levels and to prevent and minimize its generation. The G20 Action Plan on Marine Litter released in 2017 sets out policy principles to prevent marine litter, and through the voluntary Global Network of the Committed, connects the G20 to aligned global initiatives such as the UNEP Global Partnership on Marine Litter (GPML) and the Plastic Waste Partnership.

On March 2, 2022, the UN Environment Assembly adopted a historic resolution to develop a global plastics treaty (UNEP, 2022). The goal is to reduce plastic pollution, including ocean pollution and microplastics, across the entire plastic life-cycle. Mandated by the United Nations Environmental Agency 5/14 resolution, the INC met in Uruguay and France, and will convene twice in the coming year to complete negotiations by the end of 2024 (UN, 2023). Although the Zero Draft text of the international legally binding instrument on plastic pollution published on September 3, 3023, includes intentionally created and added microplastics (e.g. microbeads), it does not cover unintentionally created microplastics like microfibres (UNEP, 2023). It is beneficial for future negotiations to also consider the implications and specific actions needed to address microfibres, the most prevalent form of microplastic pollution.

The United Nations Environment Programme (UNEP) also provides strategic leadership and encourages sector-wide collaboration to accelerate a just transition towards a sustainable and circular textile value chain. In 2023, UNEP released Sustainability and Circularity in the Textile Value Chain - A Global Roadmap. This report was launched in May 2023 and outlines what each stakeholder group can do individually and collectively to reach the shared destination of a circular textile sector, including actions to reduce microfibre pollution stemming from the sector.

Canada

As part of its G7 presidency, Canada launched the Ocean Plastics Charter in 2018 and proposed targets and solutions in five areas: 1) sustainable plastic design, production, and markets, 2) waste collection, management and infrastructure, 3) sustainable lifestyles and education, 4) research and innovation and 5) coastal and shoreline clean up. In addition, Canada signed the Paris Agreement and the Agenda 2030 that establishes the Sustainable Development Goals, one of which is responsible consumption and production of products (Department of Economic and Social Affairs, n.d.). These international commitments collectively promote sustainable plastic product design and waste management, which is relevant to reducing microfibre release into the environment.

Consistent with the priority areas identified in the Ocean Plastics Charter, the Canadian Council of Ministers of the Environment developed the Zero Plastic Waste Strategy in 2018 to conduct and support microplastic research "to effect change across the plastics lifecycle to increase waste collection, improve value recovery, and prevent and remove plastic pollution" (CCME, 2018). Phase 2 of the strategy was published in 2020. While this strategy focuses mainly on single-use plastics, the government also provided funding to support research on microfibre release during laundry, design dedicated test methods and develop sampling methods for microfibre in laundry effluent and wastewaters (Government of Canada, 2022).

In 2020, the government of Canada published an order to add plastics to Schedule 1 (List of Toxic Substances) to the Canadian Environmental Protection Act (CEPA), building the case on scientific evidence in its report "Canada Science Assessment of Plastic Pollution". This inclusion was intended to enable regulations that target sources of plastic pollution and change behaviour at key stages in the plastic product lifecycle, such as design, manufacture, use, disposal, and recovery in order to reduce pollution and create the conditions for achieving a circular plastics economy (Canada, 2021). Plastics were listed as toxic in 2021 and a ban on single-use manufactured plastic items, covering 6 product categories, went into effect on June 20, 2023. However, the Federal Court overturned this decision in November 2023.

Some provincial and regional governments have launched research and other initiatives for microplastics. For instance, researchers at Ontario's Ministry of Environment and Climate Change found significant quantities of microplastics in water samples from Lake Erie and Lake Ontario, with microbeads comprising 14% of the total (Government of Ontario 2016). In response, the Ontario government began to work with communities, local NGOs and manufacturers to phase out microbeads from personal care products sold in the province. In the province of British Columbia, MetroVancouver is educating residents about how to reduce microfibres shed in laundry and is involved in research on their sources and releases through initiatives like Ocean Wise's Microfibre Partnership and University of British Columbia studies. Additionally, the Yukon Government's Water Resources Branch (WRB) has been investigating microplastics in freshwater systems and, so far, has conducted two sampling programs in the Yukon River (Government of Yukon, 2022).

Textile waste and microfibres

As part of the broader nation-wide zero waste strategy, federal, provincial, and local governments are acting to reduce textile waste. The federal government has funded several projects to better understand the drivers and extent of textile waste in Canada through the Fashion Takes Action Initiative. To enable prevention and better management of textiles, there are efforts to develop EPR schemes, with CCME listing textiles under Phase 2 of the Canada-wide Action Plan for EPR. However, as discussed in Section 5.1.3, such schemes are currently hampered by a lack of collection, reuse, and recycling infrastructure.

On June 6, 2023, a private members bill, Bill C-337, was introduced in the Canadian House of Commons to establish a national strategy to reduce textile waste. The Bill emphasizes that Canadians send nearly 500 million kilograms of textile waste to the landfill each year and that textiles are a significant source of microplastics to the environment. The required elements of such a strategy include measures to enhance the reusability, sustainability, and chemical safety of textiles, as well as requirements for design and production to control microplastic emissions. At the time of completion of this report, the Bill had completed its first reading.

In 2021, Bill 279 was introduced in Ontario to amend the Environmental Protection Act with respect to microplastic filters for washing machines. The bill would require all new residential washing machines in Ontario to be equipped with microfibre filter technology of 100 microns or smaller.

In 2022, the National Zero Waste Council (NZWC), an initiative of Metro Vancouver, released their Strategic Plan. NZWC is "leading Canada's transition to a circular economy by bringing together governments, business and NGOs to advance a waste prevention agenda that maximizes economic opportunities for the benefit of all Canadians," and has included textiles in their list of priority items (NZWC, 2023). Its latest report encourages further landfill bans for textiles, apparel resale programs, and research to support EPR programs for textiles (NZWC, 2023). In addition, several municipalities have put into place textile diversion programs where they partner with charity organizations to set up semi-private textile collection systems to try to reduce the amount of textiles in the waste stream. This includes programs in Markham (Ontario), and Colchester (Nova Scotia). The City of Markham was the first municipality to ban textiles from their landfill in 2017.

With the increase of plastic and microfibre pollution related to PPE during and following the COVID-19 pandemic, Canada's first recycling program for PPE was launched in February 2021. This program applied to long-term care and urgent care facilities in Vancouver and targeted single-use face masks and N95 respirators. Since then, other PPE recovery programs have been developed such as the PPE Recovery Initiative by RecycleSmart, and Green Circle which is making PPE collection also accessible to the general public.

In 2018, the IMO's Maritime Environmental Protect Committee adopted the IMO Action Plan to Address Marine Plastic Litter from Ships. This action plan aims to enhance existing regulations and introduce new supporting measures to reduce marine plastic litter from ships. Canada contributed to developing this action plan and is participating in the development of a strategy for its implementation. In support of this in 2020, Innovation, Science and Economic Development Canada and Transport Canada launched a wastewater treatment system challenge to capture and extract microplastics in quantifiable amounts from ships' greywater prior to discharge (ISED, 2020).

United States

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 activities or provided funding for research and monitoring related to microplastics, with some of these efforts tackling microfibres specifically.

Under the Trash Free Waters program, the US EPA engages with industry and commissions research projects to identify and assess solutions to microfibre pollution. Several governmental agencies have sponsored research on the risks of microplastics in the environment. The US government has a multi-agency micro and nanoplastics information-sharing group to share knowledge gathered via existing research projects. In 2017, Ocean Conservancy and Bren School of Environmental Sciences and Management convened a Microfibre Leadership Summit, a multi-stakeholder workshop to share knowledge and create a roadmap to address the sources and risks posed by microfibres. In 2021, the EPA released a follow-up report to document the progress since the 2017 Microplastics Expert Workshop and the current research gaps.

In 2018, California proposed Microfibre Bill AB 129, which would have required the State Water Resources Control Board to develop a standard methodology to evaluate the effectiveness of microfibre filtration systems and to identify best manufacturing practices for clothing. California State has also introduced mandatory testing of microplastics, including microfibres, in drinking water in 2022 and developed a standard definition and methodology for this purpose (California Water Board, 2020). It adopted a Statewide Microplastics Strategy, developed by the California Ocean Protection Council, which outlines a research plan to better understand the impacts of microplastics on California's marine environment and identifies policy options to prevent and reduce microplastic pollution. Additionally, Bill AB 1952 proposed in 2020 in California aims to implement a pilot program to assess the efficacy of microfibre filtration systems in removing microfibre from waste washwater from state-owned laundry facilities. The bill would require the department to monitor the presence of microfibre in waste washwater from 10 state-owned laundry facilities chosen to participate in the pilot program for one year (California State Assembly, 2020).

In 2022, EPA and NOAA released a draft report on Microfibre Pollution to the U.S. Congress. The report was prepared on on behalf of the interagency Marine Debris Coordinating Committee (IMDCC) as part of the Save our Oceans Act 2.0 Section 132 requirement, and consists of 1) a definition of microfibre; (2) an assessment of the sources, prevalence, and causes of microfibre pollution; (3) a recommendation for a standardized methodology to measure and estimate the prevalence of microfibre pollution; (4) recommendations for reducing microfibre pollution; and (5) a plan for how Federal agencies, in partnership with other stakeholders, can lead on opportunities to reduce microfibre pollution during the five-year period beginning on the date of the Act's enactment.

Europe

In Europe, microplastics have been subject to intense research initiatives and increasing regulations. The European Union adopted a Europe Plastics Strategy in January 2018, this is part of the European Green Deal and Circular Economy Action Plan, which includes several strategic actions related to microplastics, including i) examination of policy options to reduce unintentional microplastics releases from tires and textiles, ii) restrictions of intentionally added microplastics in products, iii) development of methods to quantify microplastic emissions, iv) targeted R&D funding, v) minimum design requirements and information requirements.

The EU has also recently adopted the Drinking Water Directive (EU) 2020/2184, which identifies microplastics as contaminants of emerging concern that must be regularly monitored in water bodies used for the abstraction of drinking water (EIB, 2023). The Drinking Water Directive enables the Commission to develop a methodology to measure microplastics to include them on the watch list of priority contaminants (European Commission, 2020). To support this directive, the Joint Research Centre, a science and knowledge center for the EU, has led interlaboratory studies and conducted projects to harmonize methods for microplastic measurement in water (European Commission, 2020). It is also anticipated that microplastics will be included in the EU's Water Framework and Urban Wastewater Framework Treatment Directive in the near future (EIB, 2023), which would enable regulatory measures to address microplastic releases via in wastewater and their entry into water environments.

The European Commission has already started the process of restricting the use of intentionally added microplastics. European Chemicals Agency (ECHA), which is an independent European executive agency funded by the European Union, addresses the safety assessment of chemicals and materials under European Chemical legislation REACH – a system to register, evaluate, authorise, and restrict chemicals. In September 2023, the European Commission adopted ECHA's proposal to restrict intentionally added microplastics under Annex XVII REACH (EC, 2023). To enable these regulations, ECHA established definitions of microplastics to be included in restrictions (Annex to Regulation (EU) 2023/2055), which includes fibre-like particles.

In 2022, the EU developed a strategy for sustainable and circular textiles which, amongst many actions, includes preventive measures for microplastics originating from synthetic textiles (EC, 2022). In June 2023, the European Parliament adopted recommendations for the EU strategy for sustainable and circular textiles, with 600 votes in favour, 17 against and 16 abstentions.

The key areas of the EU's Circular Textiles Strategy are:

1. Textile eco-design requirements to make products last longer and easier to repair and recycle, and provide requirements on minimum recycled content.
2. Clear and transparent product information for consumers via a Digital Product Passport.
3. Reverse overproduction and overconsumption and discourage the destruction of unsold or returned textiles.
4. Address the unintentional release of microplastics from synthetic textiles. In addition to product design, measures will target manufacturing processes, pre-washing at industrial manufacturing plants, labelling and promoting innovative materials. Further options considered include filters on washing machines, mild detergents, end-of-life textile waste management, and regulations to improve wastewater and sewage sludge treatment.

5. Measures to tackle greenwashing to empower consumers and raise awareness about sustainable fashion.
6. Introduce mandatory and harmonised Extender Producer Responsibility rules for textiles in all Member States and incentivize producers to design more sustainable products.
7. Restrict the export of textile waste and promote sustainable textiles globally.

France

In 2020, the French National Assembly adopted an anti-waste law to promote a circular economy. This law included measures such as a ban on certain plastic items, aligning with France's goals to phase out single-use plastic packaging by 2040 and recycle 100% of plastics by 2025 (MacArthur Foundation, 2021). More recently, France adopted a law that requires new professional and household washing machines sold by January 1, 2025, to be equipped with filters to catch plastic microfibres shed during washing. The measure will affect around 2.7 million washing machines sold in the country each year (PlanetCare, 2021). This initiative is part of France's broader efforts to tackle microplastic pollution, particularly those stemming from the textile industry, and aligns with the European Strategy for Plastics.

Sweden

In Sweden, governments have been primarily focused on research, with the Environmental Protection Agency funding various studies on microplastic releases into the environment. This includes research on microplastic contributions from geotextiles, which estimates that geotextiles release 2-32 tonnes of microplastics per year in Sweden (Gustavsson et al., 2022), and studies on microfibres and commercial laundry businesses (Bordin et al., 2018).

United Kingdom

The Department of Environment, Food and Rural Affairs funds research on microplastics releases from textiles and tires (DEFRA, 2021). Other actions have targeted the elimination of microbeads in rinse-off cosmetic products or restrictions on single-use plastics including bags, cotton butts and straws.

Australia

The Australian Federal Government, as part of the national plastics plan, pledged to work on an industry-led phase-in of microfibre filters on new residential and commercial washing machines by July 1, 2023 (UNEP, 2024). It has also invested $100 million over four years in projects dedicated to the prevention and recovery of plastics from the environment and has successfully phased out microbeads from personal care and cosmetic products (Department of Climate Change, Energy, the Environment and Water, 2023).

Table 16. Summary of microfibre-specific policies and regulations proposed or adopted in different jurisdictions

Country	Year	Level	Name of the Law	Goal
United States - California	2018	Subnational	SB 1422 Safe Water Drinking Act: microplastics	State Water Board is required to adopt a standard methodology to test drinking water annually, for four years, for microplastics, including microfibres.
	2020	Subnational	Bill AB 1952	This bill would require the Department of General Services, in coordination with the California Environmental Protection Agency and as soon as feasible, to implement a pilot program for one year to assess the efficacy of microfibre filtration systems in removing microfibre from waste washwater from state-owned laundry facilities.
United States - Connecticut	2018	Subnational	House Bill 5360	State Department of Energy and Environmental Protection to convene a working group with representatives of the apparel industry and the environmental community to develop a consumer awareness and education program about synthetic microfibre pollution.
United States	2020	National	S. 1982 Save our Seas Act 2.0	Conduct studies on the effects of microplastics, including microfibres, on human health and the environment.
France	2020	National	Anti-Waste Law for a Circular Economy	All new professional and household machines are to be equipped with a microfibre filter by January 1, 2025.

Australia	2021	National	National Plastics Plan	Phase-in microfibre filters on all washing machines sold in Australia by 2030.
United States - California	2022	Subnational	Assembly Bill 622	All new washing machines sold in California must be fitted with a microfibre filtration system with a 100 microns or smaller mesh size by January 1, 2024. The Bill was vetoed by the Governor of California on October 8, 2023.
Canada - Ontario	2021	Subnational	Bill 279	The Bill would require all new residential washing machines in Ontario to be equipped with a microfibre filter technology of 100 microns or smaller. The Bill is still in development.

Chapter 6: Summary and recommendations

We have identified the following key opportunities for science, policy, and solution initiatives that will contribute to microfibre pollution reductions in Canada. These elements lay the groundwork for a strategic blueprint to tackle this urgent issue.

1. **Innovation in textile design and production techniques can reduce microfibre releases by industry and consumers in Canada and internationally**. Standards or guidelines for environmentally-friendly textile design and manufacturing represent a key way to achieve microfibre releases reductions from Canadian sources. Since the majority of textile products sold in Canada are imported, Canadian fashion brands and retailers play an important role in driving innovation in practices and processes needed to protect the Canadian environment from microfibre contamination. This report consolidates the latest technical solutions and strategic approaches that can transform textile industry practices and reduce its contribution to microfibre pollution.

2. **Widespread washing machine filtration could dramatically reduce (up to 90%) microfibre discharges from domestic and commercial wastewater effluent in Canada**. Evidence from scientific studies of aftermarket devices underscores the effectiveness of this measure. Recent policy and regulatory initiatives introduce mandatory filtration in new washing machines to reduce microfibre pollution. Promoting best practices for product care and further innovation by appliance manufacturers to minimize microfibre releases during laundry can offer additional benefits towards mitigating the issue.

3. **Electrical drying of clothing represents a relatively recent concern with research pointing to significant releases of microfibres into the air**. The majority of Canadian households utilize electrical drying for laundry, underscoring the need for targeted solutions, such as improved lint capture and consumer education.

4. **The accumulation of microfibres in biosolids, with the subsequent release into terrestrial ecosystems through land application, underscores the potential for significant and widespread distribution of microfibres in agricultural, forestry and land reclamation areas.** Reductions in liquid waste microfibre content through source control practices (as above) and new approaches to biosolids processing should be explored.

5. **A national textile circularity and sustainable fashion strategy, emphasizing reducing overproduction and combating microfibre pollution, should be a top priority for Canada. Such a strategy would position Canada alongside a growing cadre of nations**

actively developing or implementing circular textile initiatives. Enhancing the utilization and durability of our clothing and lowering the demand for new products indirectly contributes to microfibre pollution mitigation.

6. **Increasing awareness amongst industry players and the public.** Across all Canadian sectors, there continues to be a lack of fulsome awareness of what microfibres are, where they come from, and what we can do about them. Clear, concise and widely available information on the topic would enable solution-oriented actions at all levels in Canada and contribute to the 'team approach' required to fix the microfibre problem.

7. **Advancing knowledge through research and collaboration initiatives will improve data availability, build consensus and contribute to decision-making across the board**. Leadership through Ottawa will not only aid in a better understanding of the stakes and position Canada as the leader in the global effort to combat microfibre pollution.

6.1 Recommendations to Environment and Climate Change Canada

Specific actions that Environment and Climate Change Canada could consider to support this blueprint and address Canadian microfibre pollution arising from textiles include:

Upstream solutions: textile design and manufacturing

- Concerted efforts will be key to enabling microfibre pollution reductions in Canada. ECCC could consider creating or supporting initiatives that facilitate information exchange and collaboration amongst Canadian microfibre stakeholders, such as a Task Force, while engaging with international jurisdictions to share best practices and innovative solutions.
- Our research suggests that developing standards for microfibre releases from textile products can begin in Canada. As setting benchmarks for release is an evolving challenge ECCC might consider establishing **Environmental Performance Agreements** with companies that have the greatest influence over the global supply chain. These agreements could target microfibre product release testing and identification of best practices for textile design to inform the development of standards and labelling requirements in Canada.
- Integrating microfibre release standards into the **Extended Producer Responsibility (EPR) schemes** for textiles under the Phase 2 plan of the Canadian Council of Ministers of the Environment (CCME) offers an avenue to synergize/harmonize circular textile policies with microfibre pollution strategies.
- Although we suspect domestic manufacturing releases of microfibres may not be as significant as domestic releases, there is a notable lack of data on the contribution of textile manufacturing to microfibre pollution in Canada. Supporting research and development in this area will not only result in a stronger understanding of microfibre sources and exposure, but it could also inform innovations in global manufacturing processes.
- To foster sustainable supply chains and collaboration among stakeholders within the textile supply chain, ECCC could explore trade agreements that encourage microfibre reduction strategies.

Consumer-level interventions

- Implement microfibre filtration in new washing machines sold in Canada. This could be enabled through a regulatory approach (e.g. European Commission) or voluntary phase-in of filtration technology (e.g. Government of Australia).
- Considering the long replacement cycle for new washing machines (typically around ten years), incentivizing aftermarket devices for use in existing domestic washing machines is

important to address microfibre releases in the short-term. Government rebate programs for consumers or incentives for industry players, such as appliance manufacturers and textile retailers to offer these devices at a discount, are some options that could be explored.

- Investigating the treatment of commercial laundry effluents in Canada is recommended to enhance the understanding of the sector's contribution to microfibre pollution and to evaluate the effectiveness of current technologies used in the sector.
- Support for research into microfibre emissions from electric dryers and developing dryer innovations represents another critical area for federal action.

Environmental and waste management

- To our knowledge, there are currently no tested and validated treatment methods for removing microfibres from biosolids. Our research, and that of others, indicates that biosolid application is a major source of microfibres in the Canadian environment. Research on microfibres in Canadian biosolids and soil, and exploration of mitigation approaches with key stakeholders represents a priority.
- National guidelines and leadership for microplastic and microfibre monitoring is needed. The substantial progress in analytical standards and methods for measurement means that Canada is now well positioned to create a national research and monitoring framework for microplastics and microfibres. Monitoring data will enable a deeper understanding of microfibre impacts and evaluation of the effectiveness of strategies to protect the environment and public health from this form of pollution.

Additionally, we recommend further research and solution development projects targeting microfibers from fishing gear, but the evaluation of their specific contributions within Canada is challenging due to limited data availability.

References

AATCC Committee RA100. (2021). *AATCC TM212-2021, Test Method for Fiber Fragment Release During Home Laundering.* American Association of Textile Chemists and Colorists. https://www.aatcc.org/tm212/

Adams, J. K., Dean, B. Y., Athey, S. N., Jantunen, L. M., Bernstein, S., Stern, G., Diamond, M. L., & Finkelstein, S. A. (2021). Anthropogenic particles (including microfibers and microplastics) in marine sediments of the Canadian Arctic. *Science of the Total Environment, 784,* 147155. https://doi.org/10.1016/j.scitotenv.2021.147155

Ahmad, S., Ullah, T., & Ziauddin. (2020). Fibres for technical textiles (pp. 21–47). *Springer International Publishing.*

Akhbarizadeh, R., Dobaradaran, S., Parhizgar, G., Schmidt, T. C., & Mallaki, R. (2021). Potentially toxic elements leachates from cigarette butts into different types of water: A threat for aquatic environments and ecosystems? *Environmental Research, 202,* 111706.

Akyildiz, S. H., Bellopede, R., Sezgin, H., Yalcin-Enis, I., Yalcin, B., & Fiore, S. (2022). Detection and analysis of microfibers and microplastics in wastewater from a textile company. *Microplastics, 1(4),* 572–586.

Al Hosni, A. S., Pittman, J. K., & Robson, G. D. (2019). Microbial degradation of four biodegradable polymers in soil and compost demonstrating polycaprolactone as an ideal compostable plastic. *Waste Management, 97,* 105–114.

Alava, J. J., Kazmiruk, T. N., Douglas, T., Schuerholz, G., Heath, B., Flemming, S. A., Bendell, L., & Drever, M. C. (2021). Occurrence and size distribution of microplastics in mudflat sediments of the Cowichan-Koksilah Estuary, Canada: A baseline for plastic particles contamination in an anthropogenic-influenced estuary. *Marine Pollution Bulletin, 173(Pt A),* 113033.

Allen, S., Allen, D., Phoenix, V., Le Roux, G., Durántez Jiménez, P., et al. (2019). Atmospheric transport and deposition of microplastics in a remote mountain catchment. *Nature Geoscience, 12,* 339–344.

Ambrosini, R., Azzoni, R. S., Pittino, F., Diolaiuti, G., Franzetti, A., & Parolini, M. (2019). First evidence of microplastic contamination in the supraglacial debris of an alpine glacier. *Environmental Pollution, 253,* 297–301.

Amélineau, F., Bonnet, D., Heitz, O., Mortreux, V., Harding, A. M. A., Karnovsky, N., Walkusz, W., Fort, J., & Grémillet, D. (2016). Microplastic pollution in the Greenland Sea: Background levels and selective contamination of planktivorous diving seabirds. *Environmental Pollution, 219,* 1131–1139.

Anderson, P. J., Warrack, S., Langen, V., Challis, J. K., Hanson, M. L., & Rennie, M. D. (2017). Microplastic contamination in Lake Winnipeg, Canada. *Environmental Pollution, 225,* 223–231.

Arctic Monitoring and Assessment Programme. (2017). *Chemicals of Emerging Arctic Concern.* Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. 353p.

Arctic Monitoring and Assessment Programme (AMAP). (2021). *AMAP litter and microplastics monitoring guidelines* (Version 1.0). https://www.amap.no/documents/doc/amap-litter-and-microplastics-monitoring-guidelines.257pp

ASTM International. (2020). *ASTM D8332-20, Standard Practice for Collection of Water Samples with High, Medium, or Low Suspended Solids for Identification and Quantification of Microplastic*

Particles and Fibres. https://www.astm.org/d8332-20.html

ASTM International. (2020). *ASTM D8333-20, Standard Practice for Preparation of Water Samples with High, Medium, or Low Suspended Solids for Identification and Quantification of Microplastic Particles and Fibers Using Raman Spectroscopy, IR Spectroscopy, or Pyrolysis-GC/MS.* https://www.astm.org/d8333-20.html

ASTM International. (2023). *ASTM D8489-23e1, Standard Test Method for Determination of Microplastics Particle and Fibre Size, Distribution, Shape, and Concentration in Waters with High to Low Suspended Solids Using a Dynamic Image Particle Size and Shape Analyzer.* https://www.astm.org/d8489-23.html

ASTM International. (Under development). *ASTM WK67788, New Test Method for Identification of Polymer Type and Quantity of Microplastic Particles and Fibres in Waters with High-to-Low Suspended Solids Using Pyrolysis-Gas Chromatography/Mass Spectrometry.* https://www.astm.org/workitem-wk67788

ASTM International. (Under development). *ASTM WK83681, New Test Method for Microplastics Capture for Stormwater Control Measures.* https://www.astm.org/workitem-wk83681

ASTM International. (Under development). *ASTM WK87463, New Test Method for Spectroscopic Identification and Quantification of Microplastic Particles in Water Using Infrared (IR) Spectroscopy.* https://www.astm.org/workitem-wk87463

Au, S. Y., Bruce, T. F., Bridges, W. C., & Klaine, S. J. (2015). Responses of *Hyalella azteca* to acute and chronic microplastic exposures. *Environmental Toxicology and Chemistry, 34(11),* 2564–2572.

Athey, S. N., & Erdle, L. M. (2022). Are we underestimating anthropogenic microfibre pollution? A critical review of occurrence, methods, and reporting. *Environmental Toxicology and Chemistry, 41(4),* 822–837.

Athey, S. N., Carney Almroth, B., Granek, E. F., Hurst, P., Tissot, A. G., & Weis, J. S. (2022). Unraveling physical and chemical effects of textile microfibres. *Water, 14(23),* 3797.

Bai, X., Li, F., Ma, L., & Li, C. (2022). Weathering of geotextiles under ultraviolet exposure: A neglected source of microfibers from coastal reclamation. *Science of The Total Environment, 804,* 150168.

Ballent, A., Corcoran, P. L., Madden, O., Helm, P. A., & Longstaffe, F. J. (2016). Sources and sinks of microplastics in Canadian Lake Ontario nearshore, tributary and beach sediments. *Marine Pollution Bulletin, 110(1),* 383–395.

Bartsen. (2021). *Vancouver's Dirty Laundry: Policy considerations and interventions to address synthetic (plastic) microfiber ocean pollution in a large urban center.* Master's Thesis, Simon Fraser University.

Barrows, A. P. W., Cathey, S. E., & Petersen, C. W. (2018). Marine environment microfiber contamination: Global patterns and the diversity of microparticle origins. *Environmental Pollution, 237,* 275–284.

Bayo, J., López-Castellanos, J., & Olmos, S. (2020). Membrane bioreactor and rapid sand filtration for the removal of microplastics in an urban wastewater treatment plant. *Marine Pollution Bulletin, 156,* 111211.

Belontz, S. L., Corcoran, P. L., de Haan-Ward, J., Helm, P. A., & Marvin, C. (2022). Factors driving the spatial distribution of microplastics in nearshore and offshore sediment of Lake Huron, North America. *Marine Pollution Bulletin, 179,* 113709.

Belz, S., Bianchi, I., Cella, C., Emteborg, H., Fumagalli, F., Geiss, O., Gilliland, D., Held, A., Jakobsson, U., La Spina, R., Mėhn, D., Ramaye, Y., Robouch, P., Seghers, J., Sokull-Kluettgen, B., Stefaniak, E., & Stroka, J. (2021). Current status of the quantification of microplastics in water - Results of a JRC/BAM inter-laboratory comparison study on PET in water. *EUR 30799 EN,* Publications Office of the European Union, Luxembourg. ISBN 978-92-76-40957-1.

Belzagui, F., Buscio, V., Gutierrez-Bouzan, C., & Vilaseca, M. (2021). Cigarette butts as a microfiber source with a microplastic level of concern. *Science of the Total Environment, 762,* 144165.

Belzagui, F., Crespi, M., Álvarez, A., Gutiérrez-Bouzán, C., & Vilaseca, M. (2019). Microplastics' emissions: Microfibers' detachment from textile garments. *Environmental Pollution, 248,* 1028–1035.

Bhandari, V. M., & Ranade, V. V. (2014). Advanced physico-chemical methods of treatment for industrial wastewaters. In *Industrial wastewater treatment, recycling and reuse* (pp. 81–140).

Blair, R. M., Waldron, S., & Gauchotte-Lindsay, C. (2019). Average daily flow of microplastics through a tertiary wastewater treatment plant over a ten-month period. *Water Research, 163,* 114909.

Bonanno, G., & Orlando-Bonaca, M. (2020). Marine plastics: What risks and policies exist for seagrass ecosystems in the Plasticene? *Marine Pollution Bulletin, 158,* 111425.

Boucher, C., Morin, M., & Bendell, L. I. (2016). The influence of cosmetic microbeads on the sorptive behavior of cadmium and lead within intertidal sediments: A laboratory study. *Regional Studies in Marine Science, 3,* 1–7.

Boucher, J., & Friot, D. (2017). *Primary Microplastics in the Oceans: A Global Evaluation of Sources.* Gland, Switzerland: IUCN. https://portals.iucn.org/library/sites/library/files/documents/2017-002-En.pdf

Braga Moruzzi, R., Galileu Speranza, L., Tomazini da Conceição, F., Teodoro de Souza Martins, S., Busquets, R., & Cintra Campos, L. (2020). Stormwater detention reservoirs: An opportunity for monitoring and a potential site to prevent the spread of urban microplastics. *Water, 12(7),* 1994.

Brander, S. M., Renick, V. C., Foley, M. M., Steele, C., Woo, M., Lusher, A., Carr, S., Helm, P., Box, C., Cherniak, S., Andrews, R. C., & Rochman, C. M. (2020). Sampling and quality assurance and quality control: A guide for scientists investigating the occurrence of microplastics across matrices. *Applied Spectroscopy, 74(9),* 1099–1125.

Brodin, M., Norin, H., Hanning, A.-C., Persson, C., & Okcabol, S. (2018). *Microplastics from industrial laundries: A laboratory study of laundry effluents.* EnviroPlanning AB & RISE IVF AB for The Swedish Environmental Protection Agency. Retrieved from https://www.naturvardsverket.se/4ac403/globalassets/media/publikationer-pdf/ovriga-pub/978-91-620-6867-7.pdf

Brookson, C. B., de Solla, S. R., Fernie, K. J., Cepeda, M., & Rochman, C. M. (2019). Microplastics in the diet of nestling double-crested cormorants (*Phalacrocorax auritus*), an obligate piscivore in a freshwater ecosystem. *Canadian Journal of Fisheries and Aquatic Sciences, 76(11),* 2156–2163.

Browne, M. A., Ros, M., & Johnston, E. L. (2020). Pore-size and polymer affect the ability of filters for washing-machines to reduce domestic emissions of fibres to sewage. *PLOS ONE, 15(6),* e0234248.

Bruce, N., Hartline, N., Karba, S., Ruff, B., & Sonar, S. (2016). *Microfiber pollution and the apparel industry.* Bren School of Environmental Science and Management. Retrieved from https://bren.ucsb.edu/projects/microfibre-pollution-and-apparel-industry

Bukhari, M. A., Carrasco-Gallego, R., & Ponce-Cueto, E. (2018). Developing a national programme for textiles and clothing recovery. *Waste Management & Research, 36(4),* 321–331.

Bujaczek, T., Kolter, S., Locky, D., & Ross, M. S. (2021). Characterization of microplastics and anthropogenic fibres in surface waters of the North Saskatchewan River, Alberta, Canada. *Facets, 6(1),* 26–43.

Cable, R. N., Beletsky, D., Beletsky, R., Wigginton, K., Locke, B. W., & Duhaime, M. B. (2017). Distribution and modeled transport of plastic pollution in the Great Lakes, the world's largest freshwater resource. *Frontiers in Environmental Science, 5,* 45.

Cachon, G. P., & Swinney, R. (2009). Purchasing, pricing, and quick response in the presence of strategic consumers. *Management Science, 55(3),* 497–511.

Cai, H., Du, F., Li, L., Li, B., Li, J., & Shi, H. (2019). A practical approach based on FT-IR spectroscopy for identification of semi-synthetic and natural celluloses in microplastic investigation. *Science of The Total Environment, 669,* 692–701.

Cai, L., Wang, J., Peng, J., Tan, Z., Zhan, Z., Tan, X., & Chen, Q. (2017). Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: Preliminary research and first evidence. *Environmental Science and Pollution Research, 24,* 24928–24935.

Cai, Y., Mitrano, D. M., Heuberger, M., Hufenus, R., & Nowack, B. (2020a). The origin of microplastic fibre in polyester textiles: The textile production process matters. *Journal of Cleaner Production, 267,* Article 121970.

Cai, Y., Yang, T., Mitrano, D. M., Heuberger, M., Hufenus, R., & Nowack, B. (2020b). Systematic study of microplastic fibre release from 12 different polyester textiles during washing. *Environmental Science & Technology, 54(8),* 4847–4855.

California State Assembly. (2020). AB-1952 Microfiber pollution: Pilot program (2019–2020). Retrieved from https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201920200AB1952.

California State Water Resources Control Board. (n.d.). Retrieved on December 15, 2023, from https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/microplastics.html.

California State Water Resources Control Board. (2020). Proposed definition of 'Microplastics in Drinking Water'. Retrieved from https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/docs/stffrprt_jun3.pdf.

Campbell, S. H., Williamson, P. R., & Hall, B. D. (2017). Microplastics in the gastrointestinal tracts of fish and the water from an urban prairie creek. *FACETS, 2,* 395–409.

Canada. (2021). Order Adding a Toxic Substance to Schedule 1 to the Canadian Environmental Protection Act, 1999: SOR/2021-86. *Canada Gazette, Part II, 155(10).* P.C. 2021-316. April 23, 2021. https://canadagazette.gc.ca/rp-pr/p2/2021/2021-05-12/html/sor-dors86-eng.html.

Canadian Council of Ministers of the Environment. (2009). Canada-wide action plan for extended producer responsibility. Retrieved from https://ccme.ca/en/res/cap-epr_e.pdf.

Canadian Council of Ministers of the Environment. (2012). Canada-wide approach for the management of wastewater biosolids (PN 1477). https://ccme.ca/en/res/biosolids_cw_approach_e.pdf.

Canadian Environmental Protection Act, 1999 (CEPA) annual report for April 2002 to March 2003. Retrieved on February 20, 2024, from https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/historical/annual-reports/canadian-environmental-protection-act-annual-report-2002-2003.html.

Carlsson, P., Singdahl-Larsen, C., & Lusher, A. L. (2021). Understanding the occurrence and fate of microplastics in coastal Arctic ecosystems: The case of surface waters, sediments, and walrus

(*Odobenus rosmarus*). *Science of The Total Environment, 792,* 148308.

Carney Almroth, B. M., Åström, L., Roslund, S., Petersson, H., Johansson, M., & Persson, N. K. (2018). Quantifying shedding of synthetic fibres from textiles: A source of microplastics released into the environment. *Environmental Science and Pollution Research International, 25(2),* 1191–1199.

Carr, S. A., Liu, J., & Tesoro, A. G. (2016). Transport and fate of microplastic particles in wastewater treatment plants. *Water Research, 91,* 174–182.

Castañeda, R. A., Avlijas, S., Simard, M. A., & Ricciardi, A. (2014). Microplastic pollution in St. Lawrence River sediments. *Canadian Journal of Fisheries and Aquatic Sciences, 71(12),* 1767–1771.

Cesa, F. S., Turra, A., & Baruque-Ramos, J. (2017). Synthetic fibres as microplastics in the marine environment: A review from textile perspective with a focus on domestic washings. *Science of The Total Environment, 598,* 1116–1129.

Cesa, F. S., Turra, A., Checon, H. H., Leonardi, B., & Baruque-Ramos, J. (2020). Laundering and textile parameters influence fibres release in household washings. *Environmental Pollution, 257.*

Chan, C. K., Park, C., Chan, K. M., Mak, D. C., Fang, J. K., & Mitrano, D. M. (2021). Microplastic fibre releases from industrial wastewater effluent: A textile wet-processing mill in China. *Environmental Chemistry, 18(3),* 93–100.

Chan, C. K. M., Fang, J. K. H., Fei, B., & Kan, C. W. (2023). Microfibres release from textile industry wastewater effluents are underestimated: Mitigation actions that need to be prioritised. *Fibers, 11(12),* 105.

Chen, H., Jia, Q., Zhao, X., Li, L., Nie, Y., Liu, H., & Ye, J. (2020). The occurrence of microplastics in water bodies in urban agglomerations: Impacts of drainage system overflow in wet weather, catchment land-uses, and environmental management practices. *Water Research, 183,* 116073.

Claessens, M., Van Cauwenberghe, L., Vandegehuchte, M. B., & Janssen, C. R. (2013). New techniques for the detection of microplastics in sediments and field collected organisms. *Marine Pollution Bulletin, 70(1–2),* 227–233.

Cole, M., Lindeque, P., Fileman, E., Halsband, C., & Galloway, T. S. (2015). The impact of polystyrene microplastics on feeding, function, and fecundity in the marine copepod *Calanus helgolandicus*. *Environmental Science & Technology, 49,* 1130–1137.

Collicutt, B., Juanes, F., & Dudas, S. E. (2019). Microplastics in juvenile Chinook salmon and their nearshore environments on the east coast of Vancouver Island. *Environmental Pollution, 244,* 135–142.

Collivignarelli, M. C., Abbà, A., Benigna, I., Sorlini, S., & Torretta, V. (2017). Overview of the main disinfection processes for wastewater and drinking water treatment plants. *Sustainability, 10(1),* 86.

Conley, K., Clum, A., Deepe, J., Lane, H., & Beckingham, B. (2019). Wastewater treatment plants as a source of microplastics to an urban estuary: Removal efficiencies and loading per capita over one year. *Water Research X, 3,* 100030.

Constant, M., Billon, G., Breton, N., & Alary, C. (2021). Extraction of microplastics from sediment matrices: Experimental comparative analysis. *Journal of Hazardous Materials, 420,* 126571.

Courtene-Jones, W., Quinn, B., Ewins, C., Gary, S. F., & Narayanaswamy, B. E. (2020). Microplastic accumulation in deep-sea sediments from the Rockall Trough. *Marine Pollution Bulletin, 154,* 111092.

Covernton, G. A., Collicutt, B., Gurney-Smith, H. J., Pearce, C. M., Dower, J. F., Ross, P. S., & Dudas, S. E. (2019). Microplastics in bivalves and their habitat in relation to shellfish aquaculture proximity in coastal British Columbia, Canada. *Aquaculture Environment Interactions, 11,* 357–374.

Covernton, G. A., Pearce, C. M., Gurney-Smith, H. J., Chastain, S. G., Ross, P. S., Dower, J. F., & Dudas, S. E. (2019). Size and shape matter: A preliminary analysis of microplastic sampling technique in seawater studies with implications for ecological risk assessment. *Science of The Total Environment, 667,* 124–132.

Covernton, G. A., Cox, K. D., Fleming, W. L., Buirs, B. M., Davies, H. L., Juanes, F., Dudas, S. E., & Dower, J. F. (2022). Large size (>100-μm) microplastics are not biomagnifying in coastal marine food webs of British Columbia, Canada. *Ecological Applications, 32(7).*

Cowger, W., Steinmetz, Z., Gray, A., Munno, K., Lynch, J., Hapich, H., Primpke, S., De Frond, H., Rochman, C., & Herodotou, O. (2021). Microplastic spectral classification needs an open-source community: Open Specy to the rescue! *Analytical Chemistry, 93(21),* 7543–7548.

Crew, A., Gregory-Eaves, I., & Ricciardi, A. (2020). Distribution, abundance, and diversity of microplastics in the upper St. Lawrence River. *Environmental Pollution, 260,* 113994.

Crichton, E. M., Noël, M., Gies, E. A., & Ross, P. S. (2017). A novel, density-independent and FTIR-compatible approach for the rapid extraction of microplastics from aquatic sediments. *Analytical Methods.*

Crossman, J., Hurley, R. R., Futter, M., & Nizzetto, L. (2020). Transfer and transport of microplastics from biosolids to agricultural soils and the wider environment. *Science of The Total Environment, 724,* 138334.

Cybis, P., Bernard, S. (2021). Fast fashion: Why firms incinerate deadstock, and public policies. Smart Prosperity Institute. *Clean Economy Working Papers.* Retrieved from https://institute.smartprosperity.ca/sites/default/files/Fashion_WP_report.pdf.

Dai, Z., Zhang, H., Zhou, Q., Tian, Y., Chen, T., Tu, C., Fu, C., & Luo, Y. (2018). Occurrence of microplastics in the water column and sediment in an inland sea affected by intensive anthropogenic activities. *Environmental Pollution, 242*(Pt B), 1557–1565.

D'Angelo, A., Trenholm, N., Loose, B., Glastra, L., Strock, J., & Kim, J. (2023). Microplastics distribution within Western Arctic seawater and sea ice. *Toxics, 11*(9), 792.

Dawson, A. L., Santana, M. F. M., Nelis, J. L. D., & Motti, C. A. (2023). Taking control of microplastics data: A comparison of control and blank data correction methods. *Journal of Hazardous Materials, 443*(Part A), 130218.

Dean, B. Y., Corcoran, P. L., & Helm, P. A. (2018). Factors influencing microplastic abundances in nearshore, tributary and beach sediments along the Ontario shoreline of Lake Erie. *Journal of Great Lakes Research, 44*(5), 1002–1009.

De Falco, F., Cocca, M., Avella, M., & Thompson, R. C. (2020). Microfibre release to water, via laundering, and to air, via everyday use: A comparison between polyester clothing with differing textile parameters. *Environmental Science & Technology, 54*(6), 3288–3296.

De Falco, F., Di Pace, E., Cocca, M., & Avella, M. (2019). The contribution of washing processes of synthetic clothes to microplastic pollution. *Scientific Reports, 9*(1), 6633.

De Falco, F., Gullo, M. P., Gentile, G., Di Pace, E., Cocca, M., Gelabert, L., Brouta-Agnésa, M., Rovira, A., Escudero, R., Villalba, R., Mossotti, R., Montarsolo, A., Gavignano, S., Tonin, C., & Avella, M. (2017). Evaluation of microplastic release caused by textile washing processes of synthetic fabrics. *Environmental Pollution, 231*, 1112–1119.

De Frond, H., Thornton Hampton, L., Kotar, S., Gesulga, K., Matuch, C., Lao, W., Weisberg, S. B., Wong, C. S., & Rochman, C. M. (2022). Monitoring microplastics in drinking water: An interlaboratory study to inform effective methods for quantifying and characterizing microplastics. *Chemosphere, 298*, 134282.

Dehaut, A., Cassone, A.-L., Frère, L., Hermabessiere, L., Himber, C., Rinnert, E., Rivière, G., Lambert, C., Soudant, P., Huvet, A., Duflos, G., & Paul-Pont, I. (2016). Microplastics in seafood: Benchmark protocol for their extraction and characterization. *Environmental Pollution, 215*, 223–233.

De Witte, B., Vanavermaete, D., Lusher, A., Strand, J., Holgado, E. A., Farré Urgell, M., Kallenbach, E., Dekimpe, M., & Verle, K. (2023). Short report on methods and protocols for the analysis of nano-, micro-, and macroplastic in biota. *Zenodo*. Retrieved from: https://zenodo.org/records/8417585

Department for Environment, Food & Rural Affairs. (2022). DEFRA response to microplastics coverage. Retrieved from https://deframedia.blog.gov.uk/2021/11/08/defra-response-to-microplastics-coverage/

Department of Climate Change, Energy, the Environment and Water. (2023). *Environment Restoration Fund: Protecting Australia's environment for future generations*. Australian Government. Retrieved from https://www.dcceew.gov.au/environment/biodiversity/conservation/environment-restoration-fund

Desforges, J. P. W., Galbraith, M., Dangerfield, N., & Ross, P. S. (2014). Widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean. *Marine Pollution Bulletin, 79*(1–2), 94–99.

Desforges, J. P., Galbraith, M., & Ross, P. S. (2015). Ingestion of microplastics by zooplankton in the Northeast Pacific Ocean. *Archives of Environmental Contamination and Toxicology, 69*(3), 320–330.

Dong, M., Luo, Z., Jiang, Q., Xing, X., Zhang, Q., & Sun, Y. (2020). The rapid increases in microplastics in urban lake sediments. *Scientific Reports, 10*, Article 848.

Dris, R., Gasperi, J., Saad, M., Mirande, C., & Tassin, B. (2016). Synthetic fibres in atmospheric fallout: A source of microplastics in the environment? *Marine Pollution Bulletin, 104*(1–2), 290–293.

Edo, C., González-Pleiter, M., Leganés, F., Fernández-Piñas, F., & Rosal, R. (2020). Fate of microplastics in wastewater treatment plants and their environmental dispersion with effluent and sludge. *Environmental Pollution, 259*, 113837.

EFSA CONTAM Panel (EFSA Panel on Contaminants in the Food Chain). (2016). Statement on the presence of microplastics and nanoplastics in food, with particular focus on seafood. *EFSA Journal, 14*(6), 4501. https://doi.org/10.2903/j.efsa.2016.4501

Ekins, P., Domenech, T., Drummond, P., Bleischwitz, R., Hughes, N., & Lotti, L. (2019). The Circular Economy: What, why, how and where. Background paper for an OECD/EC Workshop on 5 July 2019 within the workshop series "Managing environmental and energy transitions for regions and cities", Paris. Retrieved from https://www.oecd.org/cfe/regionaldevelopment/Ekins-2019-Circular-Economy-What-Why-How-Where.pdf

Elkhatib, D., Oyanedel-Craver, V., & Carissimi, E. (2021). Electrocoagulation applied for the removal of microplastics from wastewater treatment facilities. *Separation and Purification Technology, 276*, 118877.

Ellen MacArthur Foundation. (2017). *A new textiles economy: Redesigning fashion's future*. Retrieved from https://www.ellenmacarthurfoundation.org/a-new-textiles-economy

Enders, K., Lenz, R., Beer, S., & Stedmon, C. A. (2017). Extraction of microplastic from biota: Recommended acidic digestion destroys common plastic polymers. *ICES Journal of Marine Science, 74*(1), 326–331.

Engdahl, N. B. (2018). Simulating the mobility of microplastics and other fiber-like objects in saturated porous media using constrained random walks. *Advances in Water Resources, 121*, 277–284.

Enyoh, C. E., Verla, A. W., Verla, E. N., Ibe, F. C., & Amaobi, C. E. (2019). Airborne microplastics: A review study on method for analysis, occurrence, movement, and risks. *Environmental Monitoring and Assessment, 191*(11).

Environment and Climate Change Canada. (2019). *Economic study of the Canadian plastic industry, markets and waste: Summary report to Environment and Climate Change Canada*. Retrieved from https://publications.gc.ca/collections/collection_2019/eccc/En4-366-1-2019-eng.pdf

Environment and Climate Change Canada. (2023). *Canadian Environmental Sustainability Indicators: Municipal wastewater treatment*. Consulted on January 8, 2024. Retrieved from https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/municipal-wastewater-treatment.html

Environment Canada. (2002, Revised July 2005). *Risk management strategy in respect of effluents from textile mills that use wet processing (TMEs) and nonylphenol (NP) and its ethoxylates (NPEs) under CEPA 1999*. Retrieved from https://publications.gc.ca/collections/collection_2014/ec/En14-167-2005-eng.pdf

Environmental Enhancements. (n.d.). *MicroPlastics LUV-R*. Retrieved on November 12, 2023, from https://environmentalenhancements.com/store/index.php/products/products-micro-plastics

Eriksen, M., Mason, S., Wilson, S., Box, C., Zellers, A., Edwards, W., Farley, H., & Amato, S. (2013). Microplastic pollution in the surface waters of the Laurentian Great Lakes. *Marine Pollution Bulletin, 77*(1–2), 177–182.

Erdle, L. M., Nouri Parto, D., Sweetnam, D., & Rochman, C. M. (2021). Washing machine filters reduce microfibre emissions: Evidence from a community-scale pilot in Parry Sound, Ontario. *Frontiers in Marine Science, 8*, 777865.

European Chemicals Agency (ECHA). (2020). Committee for Risk Assessment (RAC) & Committee for Socio-economic Analysis (SEAC): Opinion on an Annex XV dossier proposing restrictions on intentionally-added microplastics. Retrieved from https://echa.europa.eu/documents/10162/23665416/rest_microplastics_opinion_rac_16339_en.pdf/b4d383cd-24fc-82e9-cccf-6d9f66ee9089

European Commission. (2020). *Joint Research Centre activities on microplastic measurement in water: Interlaboratory studies and method harmonization*. Retrieved from https://ec.europa.eu/jrc

European Commission. (2022). *EU strategy for sustainable and circular textiles*. Retrieved from https://environment.ec.europa.eu/strategy/textiles-strategy_en

European Commission. (2023). *Commission Regulation (EU) 2023/2055 of 25 September 2023 amending Annex XVII to Regulation (EC) No 1907/2006 of the European Parliament and of the Council concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as regards synthetic polymer microparticles (Text with EEA relevance)*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2023.238.01.0067.01.ENG&toc=OJ%3AL%3A2023%3A238%3ATOC

European Commission. (2024, March 11). *Commission Delegated Decision supplementing Directive (EU) 2020/2184 of the European Parliament and of the Council by laying down a methodology to measure microplastics in water intended for human consumption (C(2024) 1459 final)*. Retrieved from https://environment.ec.europa.eu/publications/delegated-act-measure-microplastics-water_en

European Investment Bank. (2023). *Microplastics and micropollutants in water: Contaminants of emerging concern*. Retrieved from https://www.eib.org/en/publications/20230042-microplastics-and-micropollutants-in-water

European Parliament. (2023, December 5). Deal on new EU rules to make sustainable products the norm. *ENVI Press Releases*. Retrieved from https://www.europarl.europa.eu/news/en/press-ro

EURATEX. (2021, September 6). Textile and apparel industry alliance moves closer to release of an international microfibre shedding standard. Retrieved from https://euratex.eu/news/textile-and-apparel-industry-alliance-moves-closer-to-release-of-an-international-microfibre-shedding-standard/

Evangeliou, N., Grythe, H., Klimont, Z., Heyes, C., Eckhardt, S., Lopez-Aparicio, S., & Stohl, A. (2020). Atmospheric transport is a major pathway of microplastics to remote regions. *Nature Communications, 11*(1), Article 3381.

Fang, C., Zheng, R., Zhang, Y., Hong, F., Mu, J., Chen, M., Song, P., Lin, L., Lin, H., Le, F., & Bo, J. (2018). Microplastic contamination in benthic organisms from the Arctic and sub-Arctic regions. *Chemosphere, 209*, 298–306.

Fashion Takes Action. (2021). *Feasibility study of textile recycling in Canada*. By Kelly Drennan, Sabine Weber, Colin Jacob-Vaillancourt, Anika Kozlowski, and Laurence Fiset-Sauvageau.

Fenton, S. E., Ducatman, A., Boobis, A., DeWitt, J. C., Lau, C., Ng, C., Smith, J. S., & Roberts, S. M. (2020). Per- and polyfluoroalkyl substance toxicity and human health review: Current state of knowledge and strategies for informing future research. *Environmental Science & Technology, 54*(15), 11420–11429.

Filtrol. (n.d.). *The Filtrol solution*. Retrieved November 12, 2023, from https://filtrol.net/about/

Fijan, S., Fijan, R., & Šostar-Turk, S. (2008). Implementing sustainable laundering procedures for textiles in a commercial laundry and thus decreasing wastewater burden. *Journal of Cleaner Production, 16*(12), 1258–1263.

First Sentier MUFG Sustainable Investment Institute. (2022). *Microfibres: The invisible pollution from textiles*. Retrieved from https://www.firstsentier-mufg-sustainability.com/content/dam/sustainabilityinstitute/assets/research/FSI-Sustainability-Investment-Institute-Report-January2022-final.pdf

Fischer, E. K., Paglialonga, L., Czech, E., & Tamminga, M. (2016). Microplastic pollution in lakes and lake shoreline sediments–A case study on Lake Bolsena and Lake Chiusi (Central Italy). *Environmental Pollution, 213*, 648–657.

Finnegan, A. M. D., Süsserott, R., Gabbott, S. E., & Gouramanis, C. (2022). Man-made natural and regenerated cellulosic fibres greatly outnumber microplastic fibres in the atmosphere. *Environmental Pollution, 310*, Article 119808.

Forrest, S. A., McMahon, D., Adams, W. A., & Vermaire, J. C. (2022). Change in microplastic concentration during various temporal events downstream of a combined sewage overflow and in an urban stormwater creek. *Frontiers in Water, 128*.

Forum for the Future (FFA). (2023). *Tackling microfibres at source: Investigating opportunities to reduce microfibre pollution from the fashion industry* *through textile design and manufacturing innovation*. Retrieved from https://www.forumforthefuture.org/Handlers/Download.ashx?IDMF=c3a474ee-5ceb-4945-b5f0-96823b7007fb

France. Ministère de la Transition écologique. (2022). Décret n° 2022-748 relatif à la lutte contre le gaspillage et à l'économie circulaire [Decree No. 2022-748 on the fight against waste and the circular economy]. Retrieved from https://www.legifrance.gouv.fr/

Gao, G. H. Y., Helm, P., Baker, S., & Rochman, C. M. (2023). Bromine content differentiates between construction and packaging foams as sources of plastic and microplastic pollution. *ACS ES&T Water, 3*(3), 876–884.

Garcia-Segura, S., Eiband, M. M. S. G., de Melo, J. V., & Martínez-Huitle, C. A. (2017). Electrocoagulation and advanced electrocoagulation processes: A general review about the fundamentals, emerging applications and its association with other technologies. *Journal of Electroanalytical Chemistry, 801*, 267–299.

Gasperi, J., Dris, R., Bonin, T., Rocher, V., & Tassin, B. (2014). Assessment of floating plastic debris in surface water along the Seine River. *Environmental Pollution, 195*, 163–166.

Gavigan, J., Kefela, T., Macadam-Somer, I., Suh, S., & Geyer, R. (2020). Synthetic microfiber emissions to land rival those to waterbodies and are growing. *PLOS ONE, 15*(9), e0237839. https://doi.org/10.1371/journal.pone.0237839

GESAMP. (2016). Sources, fate and effects of microplastics in the marine environment: Part two of a global assessment (Kershaw, P. J., & Rochman, C. M., Eds.). *IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection*. (Rep. Stud. GESAMP No. 93, 220 p.).

Gewert, B., Plassmann, M. M., & MacLeod, M. (2015). Pathways for degradation of plastic polymers floating in the marine environment. *Environmental Science: Processes and Impacts, 17*(9), 1513–1521.

Gies, E. A., LeNoble, J. L., Noël, M., Etemadifar, A., Bishay, F., Hall, E. R., & Ross, P. S. (2018). Retention of microplastics in a major secondary wastewater treatment plant in Vancouver, Canada. *Marine Pollution Bulletin, 133*, 553–561.

Gilbreath, A., McKee, L., Shimabuku, I., Lin, D., Werbowski, L. M., Zhu, X., Grbic, J., & Rochman, C. (2019). Multi-year water quality performance and mass accumulation of PCBs, mercury, methylmercury, copper, and microplastics in a bioretention rain garden. *Journal of Sustainable Water in the Built Environment, 5*(4). SFEI Contribution No. 872.

Giroux, L. (2014). *State of waste management in Canada*. Prepared for the Canadian Council of Ministers of Environment. Giroux Environmental Consulting. In association with Duncan Bury Consulting, René Drolet Consulting Services, and Ecoworks Consulting.

Goeppert, N., & Goldscheider, N. (2021). Experimental field evidence for transport of microplastic tracers over large distances in an alluvial aquifer. *Journal of Hazardous Materials, 408*, 124844.

Goss, H., Jaskiel, J., & Rotjan, R. (2018). *Thalassia testudinum* as a potential vector for incorporating microplastics into benthic marine food webs. *Marine Pollution Bulletin, 135*, 1085–1089.

Government of Canada. (2012). *Wastewater systems effluent regulations*. Retrieved from https://laws-lois.justice.gc.ca/eng/regulations/sor-2012-139/fulltext.html

Government of Yukon. (2022). *Microplastics in Yukon freshwater: 2021–2022 sampling report*. Retrieved from https://open.yukon.ca/sites/default/files/microplastics-yukon-freshwater-2021-2022-sampling-report.pdf

Grbić, J., Helm, P., Athey, S., & Rochman, C. M. (2020). Microplastics entering northwestern Lake Ontario are diverse and linked to urban sources. *Water Research, 174*, 115623.

Grbić, J., Nguyen, B., Guo, E., You, J. B., Sinton, D., & Rochman, C. M. (2019). Magnetic extraction of microplastics from environmental samples. *Environmental Science & Technology Letters, 6*(2), 68–72.

Green, D. S., Kregting, L., & Boots, B. (2020). Smoked cigarette butt leachate impacts survival and behaviour of freshwater invertebrates. *Environmental Pollution, 266*(Pt 3), 115286.

Green, D. S., Tongue, A. D. W., & Boots, B. (2022). The ecological impacts of discarded cigarette butts. *Trends in Ecology & Evolution, 37*(2), 183–192.

Grundig. (n.d.). *FiberCatcher® - World's 1st integrated microfibre filter*. Retrieved February 11, 2024, from https://www.grundig.co.uk/fiber-catcher

Guppyfriend. (n.d.). *Guppyfriend washing bag*. Retrieved November 12, 2023, from http://guppyfriend.com/

Gutow, L., Eckerlebe, A., Giménez, L., & Saborowski, R. (2016). Experimental evaluation of seaweeds as a vector for microplastics into marine food webs. *Environmental Science & Technology, 50*(2), 915–923.

Gustavsson, N., Bylund, A., Grabo, L., Grönholdt Palm, J., Nordzell, H., & Snöbohm, S. (2022). *Geotextiles and microplastics in Sweden – An assessment*. Ramboll, Perstop, Sweden. Retrieved October 10, 2023, from https://www.diva-portal.org/smash/get/diva2:1722263/ATTACHMENT01.pdf

Hamidian, A. H., Ozumchelouei, E. J., Feizi, F., Wu, C., Zhang, Y., & Yang, M. (2021). A review on the characteristics of microplastics in wastewater treatment plants: A source for toxic chemicals. *Journal of Cleaner Production, 295*, 126480.

Hamilton, B. M., Bourdages, M. P., Geoffroy, C., Vermaire, J. C., Mallory, M. L., Rochman, C. M., & Provencher, J. F. (2021). Microplastics around an Arctic seabird colony: Particle community composition varies across environmental matrices. *Science of the Total Environment, 773*, 145536.

Hamilton, B. M., Jantunen, L., Bergmann, M., Vorkamp, K., Aherne, J., Magnusson, K., Herzke, D., Granberg, M., Hallanger, I. G., Gomiero, A., & Peeken, I. (2022). Microplastics in the atmosphere and cryosphere in the circumpolar North: A case for multicompartment monitoring. *Arctic Science, 8*(4), 1116–1126.

Hann, S., Sherrington, C., Jamieson, O., Hickman, M., Kershaw, P., Bapasola, A., & Cole, G. (2018). *Investigating options for reducing releases in the aquatic environment of microplastics emitted by (but not intentionally added in) products*. Final Report. London/Bristol.

Hartline, N. L., Bruce, N. J., Karba, S. N., Ruff, E. O., Sonar, S. U., & Holden, P. A. (2016). Microfibre masses recovered from conventional machine washing of new or aged garments. *Environmental Science & Technology, 50*(21), 11532–11538.

He, D., Bristow, K., Filipović, V., Lv, J., & He, H. (2020). Microplastics in terrestrial ecosystems: A scientometric analysis. *Sustainability, 12*(20), 8739.

Health Canada. (n.d.). *Tobacco smoke: Toxic substances*. Retrieved from https://www.canada.ca/en/health-canada/services/health-concerns/tobacco/legislation/tobacco-product-labelling/tobacco-smoke-toxins.html

Health Canada. (n.d.). *Priority Substances List assessment report: Textile mill effluents.* Retrieved on Aug 9, 2023 from https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/environmental-contaminants/canadian-environmental-protection-act-1999-priority-substances-list-assessment-report-textile-mill-effluents.html

Hendrickson, E., Minor, E. C., & Schreiner, K. (2018). Microplastic abundance and composition in western Lake Superior as determined via microscopy, Pyr-GC/MS, and FTIR. *Environmental Science & Technology, 52*(4), 1787–1796.

Herbort, A. F., & Schuhen, K. (2017). A concept for the removal of microplastics from the marine environment with innovative host-guest relationships. *Environmental Science and Pollution Research, 24*(12), 11061–11065.

Henry, B., Laitala, K., & Klepp, I. G. (2019). Microfibres from apparel and home textiles: Prospects for including microplastics in environmental sustainability assessment. *Science of the Total Environment, 652*, 483–494.

Hermsen, E., Mintenig, S. M., Besseling, E., & Koelmans, A. A. (2018). Quality criteria for the analysis of microplastic in biota samples: A critical review. *Environmental Science & Technology, 52*(18), 10230–10240.

Hernandez, E., Nowack, B., & Mitrano, D. M. (2017). Polyester textiles as a source of microplastics from households: A mechanistic study to understand microfibre release during washing. *Environmental Science & Technology, 51*(12), 7036–7046.

Herweyers, L., Catarci Carteny, C., Scheelen, L., Watts, R., & Du Bois, E. (2020). Consumers' perceptions and attitudes toward products preventing microfibre pollution in aquatic environments as a result of the domestic washing of synthetic clothes. *Sustainability, 12*(6), 2244.

Hidayaturrahman, H., & Lee, T. G. (2019). A study on characteristics of microplastic in wastewater of South Korea: Identification, quantification, and fate of microplastics during treatment process. *Marine Pollution Bulletin, 146*, 696–702.

Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., & Thiel, M. (2012). Microplastics in the marine environment: A review of the methods used for identification and quantification. *Environmental Science & Technology, 46*(6), 3060–3075.

Huang, Y., He, T., Yan, M., Yang, L., Gong, H., Wang, W., Qing, X., & Wang, J. (2021). Atmospheric transport and deposition of microplastics in a subtropical urban environment. *Journal of Hazardous Materials, 416*, 126168.

Huntington, A., Corcoran, P. L., Jantunen, L., Thaysen, C., Bernstein, S., Stern, G. A., & Rochman, C. M. (2020). A first assessment of microplastics and other anthropogenic particles in Hudson Bay and the surrounding eastern Canadian Arctic waters of Nunavut. *Facets, 5*(1), 432–454.

Innovation, Science and Economic Development Canada (ISED). (2020). *Plastics challenge: Filtration of microplastics in ship greywater*. Retrieved January 10, 2024, from https://ised-isde.canada.ca/site/innovative-solutions-canada/en/plastics-challenge-filtration-microplastics-ship-greywater

Innovation, Science and Economic Development Canada. *Apparel industry profile*. Retrieved December 10, 2023, from https://ised-isde.canada.ca/site/consumer-products/en/industry-profiles/apparel

Interagency Marine Debris Coordinating Committee (IMDCC). (2024). *Report on microfiber pollution* (149 pp.). Retrieved from https://marinedebris.noaa.gov/interagency-marine-debris-coordinatingcommittee-reports/report-microfiber-pollution

International Organization for Standardization. (2023). *ISO 4484-1:2023, Textiles and textile products – Microplastics from textile sources – Part 1: Determination of material loss from fabrics during* *washing*. Retrieved from https://www.iso.org/standard/82238.html

International Organization for Standardization. (2023). *ISO 4484-2:2023, Textiles and textile products – Microplastics from textile sources – Part 2: Qualitative and quantitative analysis of microplastics*. Retrieved from https://www.iso.org/standard/80011.html

International Organization for Standardization. (2023). *ISO 4484-3:2023, Textiles and textile products – Microplastics from textile sources – Part 3: Measurement of collected material mass released from textile end products by domestic washing method*. Retrieved from https://www.iso.org/standard/81035.html

International Organization for Standardization. (2020). *ISO/TR21960:2020 – Plastics – Environmental aspects – State of knowledge and methodologies*. Retrieved from https://www.iso.org/standard/72300.html

International Organization for Standardization. (Under development). *ISO 16094-1, Water quality – Analysis of microplastic in water – Part 1: General and sampling for waters with low content of suspended solids including drinking water*. Retrieved from https://www.iso.org/standard/84459.html

International Organization for Standardization. (Under development). *ISO 16094-2, Water quality – Analysis of microplastic in water – Part 2: Vibrational spectroscopy methods for waters with low content of suspended solids including drinking water*. Retrieved from https://www.iso.org/standard/84460.html

Iorhemen, O. T., Hamza, R. A., & Tay, J. H. (2016). Membrane bioreactor (MBR) technology for wastewater treatment and reclamation: Membrane fouling. *Membranes, 6*(2), 33.

Ivleva, N. P. (2021). Chemical analysis of microplastics and nanoplastics: Challenges, advanced methods, and perspectives. *Chemical Reviews, 121*(19), 11886–11936.

Iyare, P. U., Ouki, S. K., & Bond, T. (2020). Microplastics removal in wastewater treatment plants: A critical review. *Environmental Science: Water Research & Technology, 6*(10), 2664–2675.

Jabeen, K., Li, B., Chen, Q., Su, L., Wu, C., Hollert, H., & Shi, H. (2018). Effects of virgin microplastics on goldfish (*Carassius auratus*). *Chemosphere, 213*, 323–332.

Jemec, A., Horvat, P., Kunej, U., Bele, M., & Kržan, A. (2016). Uptake and effects of microplastic textile fibres on freshwater crustacean *Daphnia magna*. *Environmental Pollution, 219*, 201–209.

Jones, K. L., Hartl, M. G., Bell, M. C., & Capper, A. (2020). Microplastic accumulation in a *Zostera marina* L. bed at Deerness Sound, Orkney, Scotland. *Marine Pollution Bulletin*, *152*, 110883.

Jones-Williams, K., Galloway, T. S., Peck, V. L., & Manno, C. (2021). Remote, but Not Isolated—Microplastics in the Sub-surface Waters of the Canadian Arctic Archipelago. *Frontiers in Marine Science, 8*, 666482.

Kane, I. A., & Clare, M. A. (2019). Dispersion, accumulation, and the ultimate fate of microplastics in deep-marine environments: A review and future directions. *Frontiers in Earth Science, 7*, 80.

Kapp, K. J., & Miller, R. Z. (2020). Electric clothes dryers: An underestimated source of microfibre pollution. *PLOS ONE, 15*(10), e0239165. https://doi.org/10.1371/journal.pone.0239165

Kazmiruk, T. N., Kazmiruk, V. D., & Bendell, L. I. (2018). Abundance and distribution of microplastics within surface sediments of a key shellfish growing region of Canada. *PLOS ONE, 13*(5), e0196005.

Khatmullina, L., & Isachenko, I. (2017). Settling velocity of microplastic particles of regular shapes. *Marine Pollution Bulletin, 114*(2), 871–880.

Kim, D., Kim, H., & An, Y.-J. (2021). Effects of synthetic and natural microfibres on *Daphnia magna* – Are they dependent on microfibre type? *Aquatic Toxicology, 240*, 105968.

Kim, S. K., Kim, J. S., Kim, S. Y., Song, N. S., La, H. S., & Yang, E. J. (2023). Arctic Ocean sediments as important current and future sinks for marine microplastics missing in the global microplastic budget. *Science Advances, 9*(27).

Klasios, N., & Tseng, M. (2023). Microplastics in subsurface water and zooplankton from eight lakes in British Columbia. *Canadian Journal of Fisheries and Aquatic Sciences, 80*(8), 1248–1267.

Klein, M., & Fischer, E. K. (2019). Microplastic abundance in atmospheric deposition within the Metropolitan area of Hamburg, Germany. *Science of the Total Environment, 685*, 96–103.

Koelmans, A. A., Mohamed Nor, N. H., Hermsen, E., Kooi, M., Mintenig, S. M., & De France, J. (2019). Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. *Water Research, 155*, 410–422.

Kosuth, M., Mason, S. A., & Wattenberg, E. V. (2018). Anthropogenic contamination of tap water, beer, and sea salt. *PLOS ONE, 13*(4), e0194970.

Krishnan, R. Y., Manikandan, S., Subbaiya, R., Karmegam, N., Kim, W., & Govarthanan, M. (2023). Recent approaches and advanced wastewater treatment technologies for mitigating emerging microplastics contamination – A critical review. *Science of The Total Environment, 858*, 159681.

Kumar, R., Sharma, P., Manna, C., & Jain, M. (2021). Abundance, interaction, ingestion, ecological concerns, and mitigation policies of microplastic pollution in riverine ecosystem: A review. *Science of The Total Environment, 782*, 146695.

Kumayon, I., Prajapati, S., Brinkmann, M., & Kahan, T. T. (2023). Levels and composition of microplastics and microfibers in the South Saskatchewan River and stormwater retention ponds in the City of Saskatoon, Canada. *Environmental Science and Pollution Research, 30*(42), 95367–95375.

Kutralam-Muniasamy, G., Pérez-Guevara, F., Elizalde-Martínez, I., & Shruti, V. C. (2020). An overview of recent advances in micro/nano beads and microfibres research: Critical assessment and promoting the less known. *Science of The Total Environment, 740*, 139991.

Kye, H., Kim, J., Ju, S., Lee, J., Lim, C., & Yoon, Y. (2023). Microplastics in water systems: A review of their impacts on the environment and their potential hazards. *Heliyon, 9*(3), e14359.

Ladewig, S. M., Bao, S., & Chow, A. T. (2015). Natural fibers: A missing link to chemical pollution dispersion in aquatic environments. *Environmental Science & Technology, 49*(21), 12609–12610.

Lahiri, S. K., Azimi Dijvejin, Z., & Golovin, K. (2023). Polydimethylsiloxane-coated textiles with minimized microplastic pollution. *Nature Sustainability, 6*, 559–567.

Lange, K., Magnusson, K., Viklander, M., & Blecken, G. T. (2021). Removal of rubber, bitumen and other microplastic particles from stormwater by a gross pollutant trap-bioretention treatment train. *Water Research, 202*, 117457.

Lant, N. J., Hayward, A. S., Peththawadu, M. M., Sheridan, K. J., & Dean, J. R. (2020). Microfibre release from real soiled consumer laundry and the impact of fabric care products and washing conditions. *PLOS ONE, 15*(6), e0233332.

Lao, W., & Wong, C. S. (2023). How to establish detection limits for environmental microplastics analysis. *Chemosphere, 327*, 138456.

Lares, M., Ncibi, M. C., Sillanpää, M., & Sillanpää, M. (2018). Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology. *Water Research, 133*, 236–246.

Lavoy, M., & Crossman, J. (2021). A novel method for organic matter removal from samples containing microplastics. *Environmental Pollution, 286*, 117357.

Leal Filho, W., Perry, P., Heim, H., Pimenta Dinis, M. A., Moda, H., Ebhuoma, E., & Paço, A. (2022). An overview of the contribution of the textiles sector to climate change. *Frontiers in Environmental Science, 10.*

Lechner, A., & Ramler, D. (2015). The discharge of certain amounts of industrial microplastic from a production plant into the River Danube is permitted by the Austrian legislation. *Environmental Pollution, 200*, 159–160.

Lenaker, P. L., Corsi, S. R., & Mason, S. A. (2020). Spatial distribution of microplastics in surficial benthic sediment of Lake Michigan and Lake Erie. *Environmental Science & Technology, 55*(1), 373–384.

Lenz, R., Enders, K., Stedmon, C. A., Mackenzie, D. M. A., & Nielsen, T. G. (2015). A critical assessment of visual identification of marine microplastic using Raman spectroscopy for analysis improvement. *Marine Pollution Bulletin, 100*(1), 82–91.

Leslie, H. A., Brandsma, S. H., Van Velzen, M. J. M., & Vethaak, A. D. (2017). Microplastics en route: Field measurements in the Dutch river delta and Amsterdam canals, wastewater treatment plants, North Sea sediments and biota. *Environment International, 101*, 133–142.

Liboiron, M., Zahara, A., Hawkins, K., Crespo, C., de Moura Neves, B., Wareham-Hayes, V., Edinger, E., Muise, C., Walzak, M. J., Sarazen, R., Chidley, J., Mills, C., Watwood, L., Arif, H., Earles, E., Pijogge, L., Shirley, J., Jacobs, J., McCarney, P., & Charron, L. (2021). Abundance and types of plastic pollution in surface waters in the Eastern Arctic (Inuit Nunangat) and the case for reconciliation science. *Science of The Total Environment, 782*, 146809.

Licina, D., et al. (2019). Clothing-mediated exposures to chemicals and particles. *Environmental Science & Technology, 53*(10), 5559–5575.

Li, Y., Lu, Q., Xing, Y., Liu, K., Ling, W., Yang, J., Yang, Q., Wu, T., Zhang, J., Pei, Z., Gao, Z., Li, X., Yang, F., Ma, H., Liu, K., & Zhao, D. (2023). Review of research on migration, distribution, biological effects, and analytical methods of microfibres in the environment. *Science of the Total Environment, 855*, 158922.

Liu, F., Nord, N. B., Bester, K., & Vollertsen, J. (2020). Microplastics removal from treated wastewater by a biofilter. *Water, 12*(4), 1085.

Liu, H., Kwak, J. I., Wang, D., & An, Y.-J. (2021). Multigenerational effects of polyethylene terephthalate microfibers in *Caenorhabditis elegans*. *Environmental Research, 193*, 110569.

Liu, J., Yang, Y., Ding, J., Zhu, B., An, L., & Xu, Y. (2019). Microfibers: A preliminary discussion on their definition and sources. *Environmental Science and Pollution Research, 26*, 29497–29501.

Liu, Q., Hu, H., Xiong, X., Zhao, E., Wang, K., & Wu, C. (2022). Urban natural wetland as a sink for microplastics: A case from Lalu Wetland in Tibet, China. *Science of The Total Environment, 828*, 154399.

Liu, Y., Hu, J., Lin, L., Yang, B., Huang, M., Chang, M., Huang, X., Dai, Z., Sun, S., Ren, L., & Li, C. (2023). Overcoming the fluorescent interference during Raman spectroscopy detection of microplastics. *Science of The Total Environment, 897*, 165333.

Liu, Z., Wang, W., & Liu, X. (2023). Automated characterization and identification of microplastics through spectroscopy and chemical imaging in combination with chemometrics: Latest developments and future prospects. *TrAC Trends in Analytical Chemistry, 160*, 116956.

Long, Z., Pan, Z., Wang, W., Ren, J., Yu, X., Lin, L., Lin, H., Chen, H., & Jin, X. (2019). Microplastic abundance, characteristics, and removal in wastewater treatment plants in a coastal city of China. *Water Research, 155*, 255–265.

Luo, X., Wang, Z., Yang, L., Gao, T., & Zhang, Y. (2022). A review of analytical methods and models used in atmospheric microplastic research. *Science of The Total Environment, 828*, 154487.

Lv, X., Dong, Q., Zuo, Z., Liu, Y., Huang, X., & Wu, W. M. (2019). Microplastics in a municipal wastewater treatment plant: Fate, dynamic distribution, removal efficiencies, and control strategies. *Journal of Cleaner Production, 225*, 579–586.

Maaß, S., Daphi, D., Lehmann, A., & Rillig, M. C. (2017). Transport of microplastics by two collembolan species. *Environmental Pollution, 225,* 456-459.

Mahara, N., Alava, J. J., Kowal, M., Grant, E., Boldt, J. L., Kwong, L. E., & Hunt, B. P. V. (2022). Assessing size-based exposure to microplastic particles and ingestion pathways in zooplankton and herring in a coastal pelagic ecosystem of British Columbia, Canada. *Marine Ecology Progress Series, 683*, 139–155.

Mahon, A. M., O'Connell, B., Healy, M. G., O'Connor, I., Officer, R., Nash, R., & Morrison, L. (2017). Microplastics in sewage sludge: Effects of treatment. *Environmental Science & Technology, 51*(2), 810–818.

Mani, T., Frehland, S., Kalberer, A., & Burkhardt-Holm, P. (2019). Using castor oil to separate microplastics from four different environmental matrices. *Analytical Methods, 11*(13), 1788–1794.

Mani, T., Hauk, A., Walter, U., & Burkhardt-Holm, P. (2015). Microplastics profile along the Rhine River. *Scientific Reports, 5*(1), 17988.

Manshoven, S., Smeets, A., Malarciuc, C., Tenhunen, A., & Mortensen, L. F. (2022). *ETC/CE Report 1/2022: Microplastic pollution from textile consumption in Europe*. European Topic Centre on Circular Economy and Resource Use. Retrieved from https://www.eionet.europa.eu/etcs/etc-ce/products/etc-ce-products/etc-ce-report-1-2022-microplastic-pollution-from-textile-consumption-in-europe

Martínez-Francés, E., van Bavel, B., Hurley, R., et al. (2023). Innovative reference materials for method validation in microplastic analysis including interlaboratory comparison exercises. *Analytical and Bioanalytical Chemistry, 415*, 2907–2919.

Martynova, A., Genchi, L., Laptenok, S. P., Cusack, M., Stenchikov, G. L., Liberale, C., & Duarte, C. M. (2024). Atmospheric microfibrous deposition over the Eastern Red Sea coast. *Science of the Total Environment, 907*, 167902.

McCarthy, A., Dellink, R., & Bibas, R. (2018). The macroeconomics of the circular economy transition: A critical review of modelling approaches. *OECD Environment Working Papers, No. 130*. OECD Publishing. https://doi.org/10.1787/4a39e5f3-en

McDonald, B. (2017). *Extended Producer Responsibility Overview of British Columbia*. British Columbia Ministry of Environment and Climate Change Strategy.

McGoran, A. R., Clark, P. F., Smith, B. D., & Morritt, D. (2020). High prevalence of plastic ingestion by *Eriocheir sinensis* and *Carcinus maenas* (Crustacea: Decapoda: Brachyura) in the Thames Estuary. *Environmental Pollution, 265*(Part A), 114972.

McIlwraith, H. K., Lin, J., Erdle, L. M., Mallos, N., Diamond, M. L., & Rochman, C. M. (2019). Capturing microfibres: Marketed technologies reduce microfibre emissions from washing machines. *Marine Pollution Bulletin, 139*, 40–45.

McIntyre, J., Duncan, K., Fulton, L., Smith, A., Goodman, A. J., Brown, C. J., & Walker, T. R. (2023). Environmental and economic impacts of retrieved abandoned, lost, and discarded fishing gear in Southwest Nova Scotia, Canada. *Marine Pollution Bulletin, 192*, 115013.

McKenna, H. A., Hearle, J. W. S., & O'Hear, N. (2004). *Handbook of fibre rope technology*. Woodhead Publishing.

McKinsey & Company. (n.d.). *Survey: Consumer sentiment on sustainability in fashion*. Retrieved from https://www.mckinsey.com/industries/retail/our-insights/survey-consumer-sentiment-on-sustainability-in-fashion

Micevska, T., Warne, M. S., Pablo, F., & Patra, R. (2006). Variation in, and causes of, toxicity of cigarette butts to a cladoceran and microtox. *Archives of Environmental Contamination and Toxicology, 50*(2), 205–212.

Mikkola, O. (2020). Estimating microplastic concentrations and loads in cruise ship grey waters. (Master's thesis, Aalto University).

Miller, E., Sedlak, M., Lin, D., Box, C., Holleman, C., Rochman, C. M., & Sutton, R. (2021). Recommended best practices for collecting, analyzing, and reporting microplastics in environmental media: Lessons learned from comprehensive monitoring of San Francisco Bay. *Journal of Hazardous Materials, 409*, 124770.

Milojevic, N., & Cydzik-Kwiatkowska, A. (2021). Agricultural use of sewage sludge as a threat of microplastic (MP) spread in the environment and the role of governance. *Energies, 14*(19), 6293.

Mohajerani, A., & Karabatak, B. (2020). Microplastics and pollutants in biosolids have contaminated agricultural soils: An analytical study and a proposal to cease the use of biosolids in farmlands and utilize them in sustainable bricks. *Waste Management, 107*, 252–265.

Mohsen, M., Wang, Q., Zhang, L., Sun, L., Lin, C., & Yang, H. (2019). Microplastic ingestion by the farmed sea cucumber *Apostichopus japonicus* in China. *Environmental Pollution, 245*, 1071–1078.

Moore, R. C., Noel, M., Etemadifar, A., Loseto, L., Posacka, A. M., Bendell, L., & Ross, P. S. (2022). Microplastics in beluga whale (*Delphinapterus leucas*) prey: An exploratory assessment of trophic transfer in the Beaufort Sea. *Science of The Total Environment, 806*(Part 1), 150201.

MSFD Technical Group on Marine Litter. (2023). *Guidance on the monitoring of marine litter in European seas: An update to improve the harmonized monitoring of marine litter under the Marine Strategy Framework Directive (EUR 31539 EN; JRC133594).* Luxembourg, Publications Office of the European Union. https://doi.org/10.2760/59137

Mitrano, D. M., & Wohlleben, W. (2020). Microplastic regulation should be more precise to incentivize both innovation and environmental safety. *Nature Communications, 11*, 5324.

Munno, K., Helm, P. A., Jackson, D. A., Rochman, C., & Sims, A. (2018). Impacts of temperature and selected chemical digestion methods on microplastic particles. *Environmental Toxicology and Chemistry, 37*(1), 91–98.

Murano, C., Agnisola, C., Caramiello, D., Castellano, I., Casotti, R., Corsi, I., & Palumbo, A. (2020). How sea urchins face microplastics: Uptake, tissue distribution and immune system response. *Environmental Pollution, 264*, 114685.

Murphy, F., Ewins, C., Carbonnier, F., & Quinn, B. (2016). Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. *Environmental Science & Technology, 50*(11), 5800–5808.

Napper, I. E., & Thompson, R. C. (2016). Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions. *Marine Pollution Bulletin, 112*(1-2), 39-45.

Napper, I. E., Barrett, A. C., & Thompson, R. C. (2020). The efficiency of devices intended to reduce microfibre release during clothes washing. *Science of the Total Environment, 738,* 140412.

Naturvårdsverket. (2020). *Konsumentundersökning 2020.* Retrieved from https://www.naturvardsverket.se/4a4394/globalassets/amnen/textil/konsumentundersokning-2020.pdf

National Resources Canada. (2021). *Survey of household energy use.* Accessed on October 15, 2023. https://publications.gc.ca/collections/collection_2015/rncan-nrcan/M144-120-2-2011-eng.pdf

Natural Resources Defense Council. (2021). *Encourage textile manufacturers to reduce pollution.* Retrieved from https://www.nrdc.org/issues/encourage-textile-manufacturers-reduce-pollution

National Zero Waste Council. (2023). *National Zero Waste Council 2022-2025 strategic plan.* https://nzwc.ca/Documents/NationalZeroWasteCouncil2022-2025StrategicPlan.pdf

Nelms, S. E., Duncan, E. M., Patel, S., Badola, R., Bhola, S., Chakma, S., Chowdhury, G. W., Godley, B. J., Haque, A. B., Johnson, J. A., Khatoon, H., Kumar, S., Napper, I. E., Niloy, M. N. H., Akter, T., Badola, S., Dev, A., Rawat, S., Santillo, D., Sarker, S., Sharma, E., & Koldewey, H. (2021). Riverine plastic pollution from fisheries: Insights from the Ganges River system. *Science of the Total Environment, 756,* 143305.

Ng, E. L., Lwanga, E. H., Eldridge, S. M., Johnston, P., Hu, H. W., Geissen, V., & Chen, D. (2018). An overview of microplastic and nanoplastic pollution in agroecosystems. *Science of the Total Environment, 627,* 1377-1388.

Nielsen, M. B., Clausen, L. P. W., Cronin, R., Hansen, S. F., Oturine, N. G., & Syberg, K. (2023). Unfolding the science behind policy initiatives targeting plastic pollution. *Microplastics and Nanoplastics, 3,* 3.

Niinimäki, K., Peters, G., Dahlbo, H., et al. (2020). The environmental price of fast fashion. *Nature Reviews Earth and Environment, 1,* 189–200.

Nizzetto, L., Futter, M., & Langaas, S. (2016). Are agricultural soils dumps for microplastics of urban origin? *Environmental Science & Technology, 50*(20), 10777–10779.

Noël, M., Wong, C., Ross, P. S., Patankar, S., Etemadifar, A., Morales-Caselles, C., Lyons, S., & Delisle, K. (2022). Microplastics distribution in sediment and mussels along the British Columbia Coast, Canada. *Marine Pollution Bulletin, 185*(Pt A), 114273.

Nørup, N., Pihl, K., Damgaard, A., & Scheutz, C. (2018). Development and testing of a sorting and quality assessment method for textile waste. *Waste Management, 79,* 8-21.

Novotny, T. E., Lum, K., Smith, E., Wang, V., & Barnes, R. (2009). Cigarettes butts and the case for an environmental policy on hazardous cigarette waste. *International Journal of Environmental Research and Public Health, 6*(5), 1691-1705.

Obbard, R. W., Sadri, S., Wong, Y. Q., Khitun, A. A., Baker, I., & Thompson, R. C. (2014). Global warming releases microplastic legacy frozen in Arctic Sea ice. *Earth's Future, 2*(6), 315-320.

O'Brien, S., Okoffo, E. D., O'Brien, J. W., Ribeiro, F., Wang, X., Wright, S. L., Samanipour, S., Rauert, C., Alajo Toapanta, T. Y., Albarracin, R., & Thomas, K. V. (2020). Airborne emissions of microplastic fibres from domestic laundry dryers. *Science of The Total Environment, 747,* 141175.

Ocean Protection Council. (2023). *Statewide Microplastics Strategy. Understanding and Addressing*

Impacts to Protect Coastal and Ocean Health. Retrieved from https://opc.ca.gov/webmaster/ftp/pdf/agenda_items/20220223/Item_6_Exhibit_A_Statewide_Microplastics_Strategy.pdf

Ocean Wise. (2022). *The Great Canadian Shoreline Cleanup Report.* Retrieved from: https://ocean.org/blog/ditching-the-dirty-dozen/

Ocean Wise Report. (2022). *Smart wash cycle design can reduce microfiber shedding.* Retrieved from: https://ocean.org/app/uploads/2022/12/OceanWise-WashingReport.pdf

OECD. (2021). *Policies to reduce microplastics pollution in water: Focus on textiles and tyres.* OECD Publishing, Paris. Retrieved from: https://doi.org/10.1787/7ec7e5ef-en

Olesen, K. B., Stephansen, D. A., van Alst, N., & Vollertsen, J. (2019). Microplastics in a stormwater pond. *Water, 11*(7), 1466.

Österlund, H., Blecken, G., Lange, K., Marsalek, J., Gopinath, K., & Viklander, M. (2023). Microplastics in urban catchments: Review of sources, pathways, and entry into stormwater. *Science of The Total Environment, 858*(Part 1), 159781.

Peng, G., Xu, B., & Daoji, L. (2022). Gray water from ships: A significant sea-based source of microplastics? *Environmental Science & Technology, 56*(1), 4. Periyasamy, A. (2021). Evaluation of microfiber release from jeans: The impact of different washing conditions. *Environmental Science and Pollution Research, 28,* 58570–58582.

Perren, W., Wojtasik, A., & Cai, Q. (2018). Removal of microbeads from wastewater using electrocoagulation. *ACS Omega, 3*(3), 3357-3364.

Pfeiffer, F., & Fischer, E. K. (2020). Various digestion protocols within microplastic sample processing—Evaluating the resistance of different synthetic polymers and the efficiency of biogenic organic matter destruction. *Frontiers in Environmental Science, 8,* 572424.

Pirc, U., Vidmar, M., Mozer, A., & Kržan, A. (2016). Emissions of microplastic fibres from microfibre fleece during domestic washing. *Environmental Science and Pollution Research, 23,* 22206-22211.

PlanetCare. (n.d.). *Test results.* Retrieved on January 1, 2024, from https://planetcare.org/pages/test-results

Postma, J. V. (2022). An inexpensive atmospheric microplastic collector for use in remote areas. *Atmospheric Pollution Research, 13*(10), 101550.

Port Vancouver. (2022). Record cruise ship visits to the Port of Vancouver in 2022, as cruise returns to Canada's west coast. Retrieved from https://www.portvancouver.com/news-and-media/news/record-cruise-ship-visits-to-the-port-of-vancouver-in-2022-as-cruise-returns-to-canadas-west-coast/

Prajapati, S., Beal, M., Maley, J., & Brinkmann, M. (2021). Qualitative and quantitative analysis of microplastics and microfiber contamination in effluents of the City of Saskatoon wastewater treatment plant. *Environmental Science and Pollution Research, 28,* 32545-32553.

Pramanik, B. K., Roychand, R., Monira, S., Bhuiyan, M., & Jegatheesan, V. (2020). Fate of road-dust associated microplastics and per- and polyfluorinated substances in stormwater. *Process Safety and Environmental Protection, 144,* 236-241.

Prasittisopin, L., Ferdous, W., & Kamchoom, V. (2023). Microplastics in construction and built environment. In *Developments in the Built Environment (Vol. 15).* Elsevier Ltd.

Primpke, S., Lorenz, C., Rascher-Friesenhausen, R., & Gerdts, G. (2017). An automated approach for microplastics analysis using focal plane array (FPA) FTIR microscopy and image analysis. *Analytical Methods, 9*(9), 1499–1511.

Primpke, S., Aliani, S., Lusher, A. L., Roscher, L., Suaria, G., & Paluselli, A. (2023). Short report on methods and protocols for the analysis of nano-, micro-, and macroplastic in water samples. *Zenodo.* Retrieved from: https://doi.org/10.5281/zenodo.8417563

Provencher, J. F., Vermaire, J. C., Avery-Gomm, S., Braune, B. M., & Mallory, M. L. (2018). Garbage in guano? Microplastic debris found in faecal precursors of seabirds known to ingest plastics. *Science of The Total Environment, 644,* 1477-1484.

Provencher, J. F., Covernton, G. A., Moore, R. C., Horn, D. A., Conkle, J. L., & Lusher, A. L. (2020). Proceed with caution: The need to raise the publication bar for microplastics research. *Science of The Total Environment, 748,* 141426.

Pulitzer Center. (2024). *What fast fashion costs the world.* Retrieved from: https://pulitzercenter.org/stories/what-fast-fashion-costs-world

Raju, S., Carbery, M., Kuttykattil, A., Senthirajah, K., Lundmark, A., Rogers, Z., & Palanisami, T. (2020). Improved methodology to determine the fate and transport of microplastics in a secondary wastewater treatment plant. *Water Research, 173,* 115549.

Rasmussen, L. A., Liu, F., Klemmensen, N. D. R., Lykkemark, J., & Vollertsen, J. (2024). Retention of microplastics and tyre wear particles in stormwater ponds. *Water Research, 248,* 120835.

Re, V. (2019). Shedding light on the invisible: Addressing the potential for groundwater contamination by plastic microfibers. *Hydrogeology Journal, 27,* 2719–2727.

Rech, S., Macaya-Caquilpán, V., Pantoja, J. F., Rivadeneira, M. M., Madariaga, D. J., & Thiel, M. (2014). Rivers as a source of marine litter–a study from the SE Pacific. *Marine Pollution Bulletin, 82*(1-2), 66-75.

Reineccius, J., Appelt, J. S., Hinrichs, T., Kaiser, D., Stern, J., Prien, R. D., & Waniek, J. J. (2020). Abundance and characteristics of microfibres detected in sediment trap material from the deep subtropical North Atlantic Ocean. *Science of the Total Environment, 738,* 140354.

Reineccius, J., Bresien, J., & Waniek, J. J. (2021). Separation of microplastics from mass-limited samples by an effective adsorption technique. *Science of The Total Environment, 788,* 147881.

Renner, G., Schmidt, T. C., & Schram, J. (2020). Automated rapid & intelligent microplastics mapping by FTIR microscopy: A Python-based workflow. *MethodsX, 7,* 100742.

Rillig, M. C., Ingraffia, R., & de Souza Machado, A. A. (2017). Microplastic incorporation into soil in agroecosystems. *Frontiers in Plant Science, 8,* Article 1805.

Roblin, B., Ryan, M., Vreugdenhil, A., & Aherne, J. (2020). Ambient atmospheric deposition of anthropogenic microfibers and microplastics on the western periphery of Europe (Ireland). *Environmental Science & Technology, 54*(18), 11100-11108.

Rochman, C. M., Brookson, C., Bikker, J., Djuric, N., Earn, A., Bucci, K., Athey, S., Huntington, A., McIlwraith, H., Munno, K., De Frond, H., Kolomijeca, A., Erdle, L., Grbic, J., Bayoumi, M., Borrelle, S. B., Wu, T., Santoro, S., Werbowski, L. M., Zhu, X., Giles, R. K., Hamilton, B. M., Thaysen, C., Kaura, A., Klasios, N., Ead, L., Kim, J., Sherlock, C., Ho, A., & Hung, C. (2019). Rethinking microplastics as a diverse contaminant suite. *Environmental Toxicology and Chemistry, 38*(4), 703-711.

Rodrigues, M. O., Abrantes, N., Gonçalves, F. J. M., Nogueira, H., Marques, J. C., & Gonçalves, A. M. M. (2018). Spatial and temporal distribution of microplastics in water and sediments of a freshwater system (Antuã River, Portugal). *Science of The Total Environment, 633,* 1549-1559.

McIlwraith, H., Munno, K., De Frond, H., Kolomijeca, A., Erdle, L., Grbic, J., Bayoumi, M., Borrelle, S. B., Wu, T., Santoro, S., Werbowski, L. M., Zhu, X., Giles, R. K., Hamilton, B. M., Thaysen, C., Kaura, A., Klasios, N., Ead, L., Kim, J., Sherlock, C., Ho, A., & Hung, C. (2019). Rethinking microplastics as a diverse contaminant suite. *Environmental Toxicology and Chemistry, 38(4): 703-711.*

Ross, P. S., Chastain, S., Vassilenko, E., Etemadifar, A., Zimmermann, S., Quesnel, S.-A., Eert, J., Solomon, E., Patankar, S., Posacka, A. M., & Williams, B. (2021). Pervasive distribution of polyester fibres in the Arctic Ocean is driven by Atlantic inputs. *Nature Communications, 12*, Article 106.

Roder Green, A. L., Putschew, A., & Nehls, T. (2014). Littered cigarette butts as a source of nicotine in urban waters. *Journal of Hydrology, 519*(Part D), 3466-3474.

Roos, S., Arturin, O. L., & Hanning, A. (2017). *Microplastics Shedding From Polyester Fabrics*. Mistra Future Fashion. Report number: 2017:1.

Ross, M. S., Loutan, A., Groeneveld, T., Molenaar, D., Kroetch, K., Bujaczek, T., Kolter, S., Moon, S., Huynh, A., Khayam, R., Franczak, B. C., Camm, E., Arnold, V. I., & Ruecker, N. J. (2023). Estimated discharge of microplastics via urban stormwater during individual rain events. *Frontiers in Environmental Science, 11*, Article 1090267.

Roy-Poirier, A., Champagne, P., & Filion, Y. (2010). Review of bioretention system research and design: past, present, and future. *Journal of Environmental Engineering*, *136*(9), 878-889.

Saliu, F., Veronelli, M., Raguso, C., Barana, D., Galli, P., & Lasagni, M. (2021). The release process of microfibers: From surgical face masks into the marine environment. *Environmental Advances, 4,* 100042.

Samsung Electronics. (2023, June 7). Samsung launches Less Microfiber™ Filter to protect oceans from laundry plastics. *Samsung Newsroom.* https://news.samsung.com/global/samsung-launches-less-microfiber-filter-to-protect-oceans-from-laundry-plastics

Savino, I., Campanale, C., Trotti, P., Massarelli, C., Corriero, G., & Uricchio, V. F. (2022). Effects and impacts of different oxidative digestion treatments on virgin and aged microplastic particles. *Polymers, 14,* 1958.

Schernewski, G., Radtke, H., Hauk, R., Baresel, C., Olshammar, M., & Oberbeckmann, S. (2021). Urban microplastics emissions: Effectiveness of retention measures and consequences for the Baltic Sea. *Frontiers in Marine Science, 8,* Article 594415.

Scheurer, M., & Bigalke, M. (2018). Microplastics in Swiss floodplain soils. *Environmental Science & Technology, 52*(6), 3591-3598.

Schrank, I., Möller, J. N., Imhof, H. K., Hauenstein, O., Zielke, F., Agarwal, S., Löder, M. G. J., Greiner, A., & Laforsch, C. (2022). Microplastic sample purification methods—Assessing detrimental effects of purification procedures on specific plastic types. *Science of The Total Environment, 833,* 154824.

Schumacher, K., & Forster, A. L. (2022). Facilitating a circular economy for textiles: Workshop report (NIST Special Publication 1500-207). *National Institute of Standards and Technology.* Retrieved from: https://doi.org/10.6028/NIST.SP.1500-207

Scopetani, C., Chelazzi, D., Mikola, J., Leiniö, V., Heikkinen, R., Cincinelli, A., & Pellinen, J. (2020). Olive oil-based method for the extraction, quantification and identification of microplastics in soil and compost samples. *Science of the Total Environment, 733,* 139338.

Seghers, J., Stefaniak, E. A., La Spina, R., & others. (2022). Preparation of a reference material for microplastics in water—Evaluation of homogeneity. *Analytical and Bioanalytical Chemistry, 414,* 385–397.

Sharaf Din, K., Khokhar, M. F., Butt, S. I., Qadir, A., & Younas, F. (2024). Exploration of microplastic concentration in indoor and outdoor air samples: Morphological, polymeric, and elemental analysis. *Science of The Total Environment, 908,* 168398.

Shirvanimoghaddam, K., Motamed, B., Ramakrishna, S., & Naebe, M. (2020). Death by waste: Fashion and textile circular economy case. *Science of The Total Environment, 718,* 137317.

Siddique, K., Rizwan, M., Shahid, M. J., Ali, S., Ahmad, R., & Rizvi, H. (2017). Textile wastewater treatment options: A critical review. In N. Anjum, S. Gill, & N. Tuteja (Eds.), *Enhancing Cleanup of Environmental Pollutants* (pp. 183-202). Springer, Cham.

Sillanpää, M., & Sainio, P. (2017). Release of polyester and cotton fibers from textiles in machine washings. *Environmental Science and Pollution Research, 24*(21), 19313–19321.

Sivarajah, B., Lapen, D. R., Gewurtz, S. B., Smyth, S. A., Provencher, J. F., & Vermaire, J. C. (2023). How many microplastic particles are present in Canadian biosolids? *Environmental Science and Pollution Research, 52*(5), 1037-1048.

Slaughter, E., Gersberg, R. M., Watanabe, K., Rudolph, J., Stransky, C., & Novotny, T. E. (2011). Toxicity of cigarette butts, and their chemical components, to marine and freshwater fish. *Tobacco Control, 20*(Suppl 1), i25-i29.

Smyth, K., Drake, J., Li, Y., Rochman, C., Van Seters, T., & Passeport, E. (2021). Bioretention cells remove microplastics from urban stormwater. *Water Research, 191,* 116785.

Song, Y., Cao, C., Qiu, R., Hu, J., Liu, M., Lu, S., Shi, H., Raley-Susman, K. M., & He, D. (2019). Uptake and adverse effects of polyethylene terephthalate microplastics fibres on terrestrial snails (*Achatina fulica*) after soil exposure. *Environmental Pollution, 250,* 447–455.

Song, Y. K., Hong, S. H., Eo, S., & Shim, W. J. (2021). A comparison of spectroscopic analysis methods for microplastics: Manual, semi-automated, and automated Fourier transform infrared and Raman techniques. *Marine Pollution Bulletin, 173*(Part B), 113101.

Spennemann, D. H. R. (2022). Environmental decay of single-use surgical face masks as an agent of plastic microfiber pollution. *Environments, 9*(7), 94.

Stang, C., Mohamed, B. A., & Li, L. Y. (2022). Microplastic removal from urban stormwater: Current treatments and research gaps. *Journal of Environmental Management, 317,* 115510.

Stanton, T., Johnson, M., Nathanail, P., MacNaughtan, W., & Gomes, R. L. (2019). Freshwater and airborne textile fiber populations are dominated by ‘natural’, not microplastic, fibers. *Science of The Total Environment, 666,* 377-389.

Statistics Canada. (2009). Table 8-1 Household equipment at the time of interview, Canada, provinces and territories, recent years — Canada. *Statistics Canada.* Retrieved from: https://www150.statcan.gc.ca/n1/en/pub/62-202-x/2008000/t006-eng.pdf?st=sSup02i

Statistics Canada. (2023). Table 38-10-0124-01 Wastewater volumes discharged from municipal sewage systems by treatment category (x 1,000,000). *Statistics Canada.* Retrieved from: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3810012401

Statistics Canada. *Textile and product manufacturing.* Retrieved on Dec 7, 2022, from https://www23.statcan.gc.ca/imdb/p3VD.pl?Function=getVD&TVD=201401&CVD=201403&CPV=313310&CST=01012012&MLV=2&CLV=2&adm=0&dis=0

Steinmetz, Z., Wollmann, C., Schaefer, M., Buchmann, C., David, J., Tröger, J., Muñoz, K., Frör, O., & Schaumann, G. E. (2016). Plastic mulching in agriculture: Trading short-term agronomic benefits for long-term soil degradation? *Science of The Total Environment.*

Stohl, A. (2006). Characteristics of atmospheric transport into the Arctic troposphere. *Journal of Geophysical Research: Atmospheres, 111*(D11).

Strady, E., Kieu-Le, T. C., Tran, Q. V., & Thuong, Q. T. (2021). Microplastic in atmospheric fallouts of a developing Southeast Asian megacity under tropical climate. *Chemosphere, 272,* 129874.

Sturm, M. T., Horn, H., & Schuhen, K. (2021). Removal of microplastics from waters through agglomeration-fixation using organosilanes—Effects of polymer types, water composition, and temperature. *Water, 13*(5), 675.

Sturm, M. T., Myers, E., Schober, D., Korzin, A., Thege, C., & Schuhen, K. (2023). Comparison of AOP, GAC, and novel organosilane-based process for the removal of microplastics at a municipal wastewater treatment plant. *Water, 15*(6), 1164.

Suaria, G., Achtypi, A., Perold, V., Lee, J. R., & Ryan, P. G. (2020). Microfibers in oceanic surface waters: A global characterization. *Science Advances, 6*(23),

Sun, J., Dai, X., Wang, Q., Van Loosdrecht, M. C., & Ni, B. J. (2019). Microplastics in wastewater treatment plants: Detection, occurrence, and removal. *Water Research, 152,* 21-37.

Syberg, K., Nielsen, M. B., Oturai, N. B., Clausen, L. P. W., Ramos, T. M., & Hansen, S. F. (2022). Circular economy and reduction of micro(nano)plastics contamination. *Journal of Hazardous Materials Advances, 5,* 100044.

Szewc, K., Graca, B., & Dołęga, A. (2021). Atmospheric deposition of microplastics in the coastal zone: Characteristics and relationship with meteorological factors. *Science of The Total Environment, 761,* 143272.

Talvitie, J., Heinonen, M., Pääkkönen, J. P., Vahtera, E., Mikola, A., Setälä, O., & Vahala, R. (2015). Do wastewater treatment plants act as a potential point source of microplastics? Preliminary study in the coastal Gulf of Finland, Baltic Sea. *Water Science and Technology*, *72*(9), 1495-1504.

Talvitie, J., Mikola, A., Koistinen, A., & Setälä, O. (2017). Solutions to microplastic pollution–Removal of microplastics from wastewater effluent with advanced wastewater treatment technologies. *Water Research*, 123, 401-407.

Tang, K. H. D., & Hadibarata, T. (2021). Microplastics removal through water treatment plants: Its feasibility, efficiency, future prospects and enhancement by proper waste management. *Environmental Challenges*, *5*, 100264.

Tao, D., Zhang, K., Xu, S., Lin, H., Liu, Y., Kang, J., Yim, T., Giesy, J. P., & Leung, K. M. Y. (2022). Microfibres released into the air from a household tumble dryer. *Environmental Science & Technology Letters, 9*(2), 120–126.

Textile Exchange. (2023). *Preferred fibre & materials market report 2023*. Retrieved from: https://textileexchange.org/app/uploads/2023/11/Materials-Market-Report-2023.pdf

Textile Microfibre Consortium. (n.d.). *Glossary of terms*. Retrieved from: https://www.microfibreconsortium.com/resources-1

Thompson, R. C., Olsen, Y., Mitchell, R. P., Davis, A., Rowland, S. J., Jhon, A. W. G., McGonigle, D., & Russel, A. E. (2004). Lost at sea: Where is all the plastic? *Science, 304*, 838.

Thornton Hampton, L. M., De Frond, H., Gesulga, K., Kotar, S., Lao, W., Matuch, C., Weisberg, S. B., Wong, C. S., Brander, S., Christansen, S., Cook, C. R., Du, F., Ghosal, S., Gray, A. B., Hankett, J., Helm, P. A., Ho, K. T., Kefela, T., Lattin, G., Lusher, A., Mai, L., McNeish, R. E., Mina, O., Minor, E. C., Primpke, S., Rickabaugh, K., Renick, V. C., Singh, S., van Bavel, B., Vollnhals, F., & Rochman, C. M. (2023). The influence of complex matrices on method performance in extracting and monitoring for microplastics. *Chemosphere*, *334*, 138875.

The Nature Conservancy & Bain & Company. (2021). *Toward eliminating pre-consumer emissions of microplastics from the textile industry*. Retrieved from https://www.nature.org/content/dam/tnc/nature/en/documents/210322TNCBain_Pre-ConsumerMicrofibreEmissionsv6.pdf

The Textile Institute. (n.d.). Technical terms and definitions. Retrieved Nov 2, 2023 from https://www.textileinstitute.org/ttd/

The Pew Charitable Trusts & SYSTEMIQ. (2020). *Breaking the plastic wave: A comprehensive assessment of pathways towards stopping ocean plastic pollution*. Retrieved from: https://www.pewtrusts.org/-/media/assets/2020/10/breakingtheplasticwave_distilledreport.pdf.

Tibbetts, J., Krause, S., Lynch, I., & Sambrook Smith, G. H. (2018). Abundance, distribution, and drivers of microplastic contamination in urban river environments. *Water, 10*(11), 1597.

Townsend, K. R., Lu, H. C., Sharley, D. J., & Pettigrove, V. (2019). Associations between microplastic pollution and land use in urban wetland sediments. *Environmental Science and Pollution Research*, *26*, 22551-22561.

Transport Canada. (2022). *Key Traffic and Volume Statistics*. Retrieved from https://tc.canada.ca/en/corporate-services/transparency/corporate-management-reporting/transportation-canada-annual-reports/transportation-canada-2022/key-traffic-volume-statistics-0

Treilles, R., Cayla, A., Gaspéri, J., Strich, B., Ausset, P., & Tassin, B. (2020). Impacts of organic matter digestion protocols on synthetic, artificial and natural raw fibers. *Science of the Total Environment*, 748, Article 141230.

United Nations Environment Programme (2018). Mapping of global plastics value chain and plastics losses to the environment (with a particular focus on marine environment). Ryberg, M., Laurent, A., Hauschild, M. United Nations Environment Programme. Nairobi, Kenya. Retrieved from https://wedocs.unep.org/handle/20.500.11822/26745.

United Nations Environment Programme (2020). *Water Pollution by Plastics and Microplastics: A Review of Technical Solutions from Source to Sea*. Retrieved from https://wedocs.unep.org/20.500.11822/34424.

United Nations Environment Programme. (2022, March 7). End plastic pollution: Towards an international legally binding instrument. Retrieved from: https://wedocs.unep.org/bitstream/handle/20.500.11822/39812/OEWG_PP_1_INF_1_UNEA%20resolution.pdf

United Nations Environment Programme (2023). Sustainability and Circularity in the Textile Value Chain - A Global Roadmap. Paris. Retrieved from https://www.unep.org/resources/publication/sustainability-and-circularity-textile-value-chain-global-roadmap

United Nations Environment Programme. (2023). Zero draft text of the international legally binding instrument on plastic pollution, including in the marine environment. Retrieved from https://wedocs.unep.org/bitstream/handle/20.500.11822/43239/ZERODRAFT.pdf. Date: September 4, 2023, Accessed: January 4, 2024.

van Mourik, L. M., Crum, S., Martinez-Frances, E., van Bavel, B., Leslie, H. A., de Boer, J., & Cofino, W. P. (2021). Results of WEPAL-QUASIMEME/NORMAN's first global interlaboratory study on microplastics reveal urgent need for harmonization. *Science of The Total Environment, 772,* 145071.

Van Cauwenberghe, L., & Janssen, C. R. (2014). Microplastics in bivalves cultured for human consumption. *Environmental Pollution, 193,* 65–70.

Vassilenko, E., Watkins, M., Chastain, S., Mertens, J., Posacka, A. M., Patankar, S., & Ross, P. S. (2021). Domestic laundry and microfibre pollution: Exploring fibre shedding from consumer apparel textiles. *PLOS ONE, 16*(7), Article e0250346.

Vermaire, J. C., Pomeroy, C., Herczegh, S. M., Haggart, O., & Murphy, M. (2017). Microplastic abundance and distribution in the open water and sediment of the Ottawa River, Canada, and its tributaries. *Facets, 2*(1), 301-314.

Vianello, A., Jensen, R. L., Liu, L., & others. (2019). Simulating human exposure to indoor airborne microplastics using a Breathing Thermal Manikin. *Scientific Reports, 9,* 8670.

Wang, M., Sun, C., & Zhang, D. (2023). Opportunities and challenges in green stormwater infrastructure (GSI): A comprehensive and bibliometric review of ecosystem services from 2000 to 2021. *Environmental Research, 116701.*

Wang, M., Yang, J., Zheng, S., Jia, L., Yong, Z. Y., Yong, E. L., See, H. H., Li, J., Lv, Y., Fei, X., & Fang, M. (2023). Unveiling the microfibre release footprint: Guiding control strategies in the textile production industry. *Environmental Science & Technology, 57*(50), 21038–21049.

Watkins, L., Sullivan, P. J., & Walter, M. T. (2021). What you net depends on if you grab: A meta-analysis of sampling method's impact on measured aquatic microplastic concentration. *Environmental Science & Technology, 55*(19), 12930–12942.

Wei, S., Luo, H., Zou, J., Chen, J., Pan, X., Rousseau, D. P., & Li, J. (2020). Characteristics and removal of microplastics in rural domestic wastewater treatment facilities of China. *Science of the Total Environment, 739,* 139935.

Welk, B., Aherne, J., Paterson, A. M., Yao, H., & McConnell, C. (2022). Atmospheric deposition of anthropogenic particles and microplastics in south-central Ontario, Canada. *Science of the Total Environment, 835,* 155426.

Werbowski, L. M., Gilbreath, A. N., Munno, K., Zhu, X., Grbic, J., Wu, T., Sutton, R., Sedlak, M. D., Deshpande, A. D., & Rochman, C. M. (2021). Urban stormwater runoff: A major pathway for anthropogenic particles, black rubbery fragments, and other types of microplastics to urban receiving waters. *ACS EST Water, 1*(6), 1420–1428.

Whitaker, J. M., Garza, T. N., & Janosik, A. M. (2019). Sampling with Niskin bottles and microfiltration reveals a high prevalence of microfibres. *Limnologica, 78,* 125711.

Whiting, Q. T., O'Connor, K. F., Potter, P. M., & Al-Abed, S. R. (2022). A high-throughput, automated technique for microplastics detection, quantification, and characterization in surface waters using laser direct infrared spectroscopy. *Analytical and Bioanalytical Chemistry, 414*(29), 8353-8364.

Wiesheu, A. C., Anger, P. M., Baumann, T., Niessner, R., & Ivleva, N. P. (2016). Raman microspectroscopic analysis of fibers in beverages. *Analytical Methods, 8*(28), 5722–5725.

Wong, C. S., & Coffin, S. (2021). Standard operating procedures for extraction and measurement by infrared spectroscopy of microplastic particles in drinking water. *State Water Resources Control Board.* Retrieved from https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/microplastics/mcrplstcs_ir.pdf

World Health Organization. (2022). *Dietary and inhalation exposure to nano- and microplastic particles and potential implications for human health.* Retrieved from https://www.who.int/publications/i/item/9789240054608

Woodward, J., Li, J., Rothwell, J., et al. (2021). Acute riverine microplastic contamination due to avoidable releases of untreated wastewater. *Nature Sustainability,* 4, 793–802.

Wright, L. S., Napper, I. E., & Thompson, R. C. (2021). Potential microplastic release from beached fishing gear in Great Britain's region of highest fishing litter density. *Marine Pollution Bulletin, 173,* 113115.

Wright, S. L., Ulke, J., Font, A., Chan, K. L. A., & Kelly, F. J. (2020). Atmospheric microplastic deposition in an urban environment and an evaluation of transport. *Environment International, 136,* 105411.

Wexco Environmental. (2020). *Filtrol 160: Washing machine lint filter.* Retrieved from https://wexcoenvironmental.com/filtrol-160/

Xu, X., Hou, Q., Xue, Y., Jian, Y., & Wang, L. (2018). Pollution characteristics and fate of microfibres in the wastewater from textile dyeing wastewater treatment plant. *Water Science and Technology, 78*(10), 2046-2054.

Xu, X., Jian, Y., Xue, Y., Hou, Q., & Wang, L. (2019). Microplastics in the wastewater treatment plants (WWTPs): Occurrence and removal. *Chemosphere, 235,* 1089-1096.

Yang, L., Li, K., Cui, S., Kang, Y., An, L., & Lei, K. (2019). Removal of microplastics in municipal sewage from China's largest water reclamation plant. *Water Research, 155,* 175-181.

Yang, L., Qiao, F., Lei, K., Li, H., Kang, Y., Cui, S., & others. (2019). Microfibre release from different fabrics during washing. *Environmental Pollution, 249,* 136–143.

Yuan, F., Zhao, H., Sun, H., Zhao, J., & Sun, Y. (2021). Abundance, morphology, and removal efficiency of microplastics in two wastewater treatment plants in Nanjing, China. *Environmental Science and Pollution Research, 28,* 9327-9337.

Zambrano, M. C., Pawlak, J. J., Daystar, J., Ankeny, M., & Venditti, R. A. (2021). Impact of dyes and finishes on the microfibres released on the laundering of cotton knitted fabrics. *Environmental Pollution, 272,* 115998.

Zambrano, M. C., Pawlak, J. J., Daystar, J., Ankeny, M., Goller, C. C., & Venditti, R. A. (2020). Aerobic biodegradation in freshwater and marine environments of textile microfibres generated in clothes laundering: Effects of cellulose and polyester-based microfibres on the microbiome. *Marine Pollution Bulletin, 151,* 110826.

Zemke, J. J., Pöhler, J., & Stegmann, S. (2019). Modeling runoff-formation and soil erosion after pumice excavation at forested Andosol-sites in SW-Germany using WEPP. *Soil Systems, 3*(3), 48.

Zhang, B., Wu, Q., Gao, S., Ruan, Y., Qi, G., Guo, K., & Zeng, J. (2023). Distribution and removal mechanism of microplastics in urban wastewater plants systems via different processes. *Environmental Pollution, 320,* 121076.

Zhang, L., Liu, J., Xie, Y., Zhong, S., & Gao, P. (2021). Occurrence and removal of microplastics from wastewater treatment plants in a typical tourist city in China. *Journal of Cleaner Production, 291,* 125968.

Zhang, Y., Kang, S., Allen, S., Allen, D., Gao, T., & Sillanpää, M. (2020). Atmospheric microplastics: A review on current status and perspectives. *Earth-Science Reviews, 203,* Article 103118.

Zhou, H., Zhou, L., & Ma, K. (2020). Microfibre from textile dyeing and printing wastewater of a typical industrial park in China: Occurrence, removal and release. *Science of the Total Environment, 739,* 140329.

Zhu, X., Nguyen, B., You, J. B., Karakolis, E., Sinton, D., & Rochman, C. (2019). Identification of microfibers in the environment using multiple lines of evidence. *Environmental Science & Technology, 53*(20), 11877–11887.

Ziajahromi, S., Drapper, D., Hornbuckle, A., Rintoul, L., & Leusch, F. D. (2020). Microplastic pollution in a stormwater floating treatment wetland: Detection of tyre particles in sediment. *Science of the Total Environment, 713,* 136356.

Ziajahromi, S., Neale, P. A., Rintoul, L., & Leusch, F. D. (2017). Wastewater treatment plants as a pathway for microplastics: Development of a new approach to sample wastewater-based microplastics. *Water Research, 112,* 93-99.

Zubris, K. A. V., & Richards, B. K. (2005). Synthetic fibres as an indicator of land application of sludge. *Environmental Pollution, 138*(2), 201-211.

Appendix A: Methodology for estimating the emissions, pathways and fate of microfibres in Canada

Units: Metric weight (g or kg) of microfibres per year

1. **Domestic laundry microfibre generation**

   a. Microfibre releases based on average laundry load of **7 kg** (Vassilenko et al. 2021)

   b. **219 washes per year** per household (Natural Resources Canada, 2011)

   c. Number of Canadian households of **14,072,080** (Statistics Canada, 2016)

   d. Median microfibre release of **136.43 mg kg^{-1}** from a study of Vassilenko et al. (2021) calculated using synthetic and natural textile products.

2. **Microfibre releases via WWTPs**

   a. average retention rate for different types of WWTP treatment of **86%** (Sun et al. 2019)

   b. **86%** of Canadian population served by WWTPs (Government of Canada, Municipal wastewater treatment, 2010-2020 Statistics)

   c. **1.80%** of wastewater in Canada is untreated (Government of Canada, Municipal wastewater treatment, 2010-2020 Statistics).

3. **Microfibre application to land**

   a. **43%** of the 388,700 tonnes of biosolids are applied to land across Canada, **47%** are incinerated and **4%** are sent to landfill, the remaining **6%** is used in land reclamation and other purposes (CH2MHill Canada. 2000)

4. **Commercial releases**

We made significant assumptions when calculating the contribution of commercial laundry establishments to microfibre pollution. These businesses vary in size and operations, with types of textiles and effluent amounts depending on the sector these businesses serve (e.g. healthcare, hotel, and public). Furthermore, the available statistics from Statistics Canada on the number of establishments available include dry cleaning businesses, which results in an overestimate.

a. **27,897** number of commercial laundry and dry-cleaning businesses in Canada (2022, Statistics Canada)

b. Median microfibre release of **89 mg kg^{-1}** from a textile sample from Vassilenko et al. 2021

c. **13 kg** of average load and **5 loads** per machine, with **20 machines** per establishment.

Sources

National Resources Canada, 2021. Survey of Household Energy Use. Accessed on October 15, 2023. Available at https://publications.gc.ca/collections/collection_2015/rncan-nrcan/M144-120-2-2011-eng.pdf.

CH2MHill Canada. Biosolids Generation, Treatment, Use and Disposal in Canada. Opportunities for Energy Recovery and Greenhouse Gas Reduction Report. Prepared for Environment Canada, 2000.

Sun, J., Dai, X., Wang, Q., van Loosdrecht, M. C. M., & Ni, B.-J. (2019). Microplastics in wastewater treatment plants: Detection, occurrence and removal. *Water Research, 152*, 21-37.

Statistics Canada, 2016. Number of households, median income and median income rank, Canada, provinces, and territories. Accessed on October 20, 2023 https://www150.statcan.gc.ca/n1/daily-quotidien/170913/t001a-eng.htm)

Statistics Canada. Municipal wastewater treatment. Accessed Nov 2023 from https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/municipal-wastewater-treatment.html

Statistics Canada. Business Counts, 2022. Accessed on October 15, 2023. Available at: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3310056801&pickMembers%5B0%5D=2.1&pickMembers%5B1%5D=3.1332)

Vassilenko E, Watkins M, Chastain S, Mertens J, Posacka AM, Patankar S, et al. (2021). Domestic laundry and microfibre pollution: Exploring fibre shedding from consumer apparel textiles. PLoS ONE 16(7): e0250346. https://doi.org/10.1371/journal.pone.0250346

Appendix B: Summary of proposed strategies to establish circularity and minimize microfibre pollution across the entire textile value chain

Example of a strategy	Key stakeholders
Upstream solutions	
Textile waste prevention ● Design requirements for increased durability, re-use and recyclability ● Accessible information on the environmental sustainability characteristics of products ● Ban on destruction of unsold or returned textiles goods ● Regulating the number of fashion cycles ● Extended Producer Responsibility schemes to fund infrastructure for collection, reuse, and recycling of textiles ● Eco-design to facilitate end-of-life management and efficient recycling of garments, for instance by avoiding the use of multi-material textiles, which are more challenging to recycle ● New circular business models and technologies ● Preventing unintentional generation of microfibre waste during textile waste recycling processes ● Encourage the domestic development of recovery infrastructure and supply chains through grants, low- interest loans, tax incentives, zoning allowances, etc.	Fashion brands and retailers Recyclers Collectors Sorters
Microfibre release prevention from finished products ● Set textile shedding thresholds ● Disclosure of shedding rates on product labels ● Test methods, standardized reporting and data disclosure requirements for prioritization and accountability ● Levy on high microfibre emitting products ● B2B product certification systems (e.g. Higgs Index) ● B2C schemes (e.g. Europe's Ecolabel, France's Ecolabyse) ● Credits and certification ● Pre-washing/removal of excess microfibres at industrial manufacturing plants	Fashion brands and retailers Consumers Manufacturers

Microfibre release prevention during manufacturing ● De-risking and blended finance mechanisms to lower capital costs for new technology. ● Incentivise manufacturer-brand collaboration. ● Replace wet processing dying with processes that involve no to minimal water use. ● Identify and implement the best technical practices for production sites and prioritize on-site improvements and innovation for environmental impact reduction.	Fashion brands and retailers Manufacturers
Consumer-level interventions	
● Encourage microfibre friendly laundry practices ● Mandatory or voluntary filtration in domestic and professional washing machines ● Subsidize after market microfibre capture technologies through provincial programs (e.g. Clean BC)	Consumer Provincial governments Washing machine manufacturers

Consolidated from:
European Commission (2022) Circular Textiles Strategy.
NOAA and EPA.(2022). Report on Microfibre Pollution
First Sentier MUFG (2022). Water Pollution by Plastics and Microplastics: A review of Technical Solutions from Source to Sea.
UNEP (2020). Technical solutions to reduce microplastic pollution in water.
Bartsen (2021). Vancouver's Dirt Laundry Policy considerations and interventions to address synthetic (plastic) microfibre ocean pollution in a large urban centre.
Forum for Future Asia (2023). Tackling microfibres at the source. Investigating opportunities to reduce microfibre pollution from the fashion industry through textile design and manufacturing innovation.
OECD (2021). Policies to Reduce Microplastic Pollution in Water.
Schumacher, K., & Forster, A. L. (2022). Facilitating a Circular Economy for Textiles: Workshop Report (NIST Special Publication 1500-207)
UNEP (2023). Sustainability and Circularity in the Textile Value Chain - A Global Roadmap.

Tackling microfibre pollution through science, policy, and innovation

A framework for Canadian leadership

2024 November 12

Anna M. Posacka, Peter S. Ross. 2024. Tackling microfibre pollution through science, policy, and innovation: A framework for Canadian leadership. https://doi.org/10.70766/47.9973

www.oceandiagnostics.com
www.raincoast.org