Reducing microfiber shedding: A multi-criteria evaluation framework for solutions to address microfiber pollution in the textile industry.

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Reducing microfiber shedding: A multi-criteria evaluation framework for solutions to address microfiber pollution in the textile industry.

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Executive Summary

Each year, millions of metric tons (MMT) of microfibers enter the environment from both textile manufacturing and consumer use. Downstream mitigation is fragmented and hard to scale, while wastewater treatment plants struggle to capture fine microfibers under 100 µm. Wet processing stages—like washing, dyeing, and finishing— result in the release of large quantities of microfiber, while upstream solutions combining process innovation and treatment remain underexplored. Growing concern has drawn attention from researchers, regulators, and industry leaders. Apparel brands are now launching voluntary initiatives to control microfiber pollution, underscoring the urgent need for scalable, upstream solutions and a framework to assess them.

While upstream product development, such as fiber and fabric material innovation, is essential for a broader impact to reduce microfiber pollution, this project specifically targets manufacturing-stage technologies. It identifies and evaluates upstream technologies in textile manufacturing and wastewater treatment that can reduce microfiber pollution during wet processing. The study introduces a multi-criteria evaluation framework incorporating performance, sustainability, cost, and integration dimensions, providing a flexible and adaptable approach for ongoing comparison as technologies evolve, and offering a consistent basis for evaluating existing, emerging, and new technologies. It includes a baseline scenario to benchmark improvements and a horizon scan covering 38 existing technologies across 11 manufacturing and wastewater classes.

Microfiber shedding is highly process-dependent, with average microfiber (MF) release per kilogram of processed fabric estimated at 0.58 g MF/kg for washing, 0.54 g MF/kg for dyeing, and 0.53 g MF/kg for finishing. Together, these wet processing stages account for most of the microfiber release during manufacturing. Average microfiber concentrations in textile effluent were estimated at 37.3 mg/L resulting in a global release of over 0.5 MMT in 2023. In addition to optimization of existing on-site processes to remove microfibers, innovative manufacturing technologies, especially waterless dyeing methods such as dope, pigment, and chemically-engineered dyeing, show strong potential to reduce shedding, with additional co-benefits such as reductions in water, energy, and chemical use. More advanced wastewater treatment technologies such as membrane-based systems (ultrafiltration, microfiltration) and membrane bioreactors also show promise and have the potential to capture over 80% of fibers.

For brands and textile manufacturers, the findings highlight the strategic importance of addressing microfiber pollution at its source. Upstream interventions, particularly in high-shedding wet processing stages, offer the opportunity for measurable impact. Brands should prioritize adopting low-shedding solutions, especially in high-volume operations where economies of scale offset capital costs. Regulatory action is needed to set microfiber emission limits for wastewater and sludge, with stricter sludge disposal requirements such as lined landfills or incineration. Sustained investment in research and development for integrated treatment systems will be key to delivering scalable, affordable solutions for diverse production contexts. Addressing microfiber pollution at

the manufacturing stage can also lead to substantial co-benefits including cost savings by improving process efficiency and minimizing material losses. It also helps advance sustainability goals and brand positioning, though reputational and financial benefits will vary by case. Finally, to drive meaningful progress, brands, policymakers, and technology developers must cooperate to close existing data gaps, improve microfiber testing protocols, and support full-scale interventions.

Technologies were selected based on sustainability benefits (e.g., reduced water, energy, or chemical use), demonstrated or potential effectiveness in microfiber control, stage of adoption, and risk of microfiber fragmentation. Sources included published data, vendor materials, and expert interviews. Technologies were grouped into manufacturing and wastewater classes and sub-classes for consistent, brand-neutral comparison. In summary, this report offers an evaluation framework that is used to assess 19 wastewater and 19 manufacturing solutions for reducing microfiber pollution in upstream textile processes. Using the best available data and assessing baseline conditions, the techno-economic feasibility and sustainability of interventions are evaluated. Given the emerging nature of the field and technologies, data gaps remain, hence, assumptions were made where necessary (e.g., microfiber reduction). However, the evaluation of technologies relies on robust and credible sources available, e.g., textile industry reports, LCAs, vendor & expert interviews, and peer-reviewed literature. Key conclusions include:

- The effectiveness of microfiber mitigation is contingent upon addressing both the generation and release pathways, with upstream process optimization and advanced wastewater treatment playing equally critical roles.
- The most microfiber-intensive stages—namely washing, dyeing, finishing, and printing—were identified as key contributors, responsible for over 50% of microfiber emissions. These stages therefore represent high-priority targets for intervention.
- Ultrafiltration and microfiltration were most effective for microfiber removal in wastewater, with MBRs, cartridge filtration, flotation, and even simple basket strainers offering scalable, stage-specific options. Evidently, microfiber control requires a range of solutions rather than a one-size-fits-all approach.
- Chemically-engineered dyeing had the highest impact across the dyeing chain. Pigment and dope dyeing showed strong potential for sustainability and microfiber reduction, while spray, supercritical, ultrasonic, digital, and biological dyeing offer promising alternatives. Spray finishing, digital printing, and microfiber air removal also help reduce microfiber release pre-distribution.
- Combining treatment and manufacturing solutions is essential, as approaches that pair source reduction with advanced capture technologies have demonstrated promising outcomes in terms of both environmental impact and implementation feasibility.
- The microfiber control framework developed here offers a flexible, data-driven approach to guide decision-making and scale impact—positioning microfiber reduction as a strategic opportunity for innovation in the textile industry.
- Efforts to maximize mitigation performance must be balanced against cost and scalability, as overly complex or expensive solutions may hinder industry-wide adoption.
- Industry collaboration and shared standards are essential to scale solutions effectively, drive innovation, and foster knowledge transfer through education and training programs.

- Further research and development should prioritize the creation of practical, microfiber monitoring protocols, particularly at the mill level, to enable continuous performance evaluation and data-informed decision-making.

Although still in the early stages of implementation, this evaluation framework represents a promising pathway for the textile sector to significantly reduce its microfiber footprint through targeted interventions, informed decision-making, and collaborative action.

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1. Introduction

The dynamics of the textile industry and the population's need for access to clothing, home furnishings, and other industrial uses, make it one of the most industrialized and diverse sectors within manufacturing (Kumar & Pavithra, 2019). The textile industry drives economic progress in developed and developing nations at local, regional, and global levels due to its extensive job creation and strong relationship with multiple economic sectors, e.g., agriculture and chemical manufacturing to produce raw materials (i.e., natural and synthetic fibers), semi-finished goods, and final products (Adane et al., 2021; Kumar & Pavithra, 2019).

However, beyond its industrial and economic significance, the textile industry is one of the most polluting sectors globally (Mia et al., 2019). The extensive use of water and energy resources has led to significant emissions of greenhouse gases (Leal Filho et al., 2022), as well as large production volumes of wastewater containing toxic dyes and other hazardous pollutants (Wang et al., 2022). Within fabric production, large amounts of water are used for textile wet processing, e.g., pretreatment, dyeing, printing, and finishing, typically requiring 100 to 200 liters of water per kilogram of textile produced (Yin et al., 2017). The wastewater of such processes is a major source of chemical pollution due to wide pH variability, high concentrations of color, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total dissolved solids (TDS; due to the use of $NaCl$ and Na_2SO_4 in the dyeing process), and the presence of heavy metals, and its treatment also emits greenhouse gases (Samanta et al., 2019; Uddin et al., 2023; X. Wang et al., 2022).

1.1. Global Microfiber Production

In the last decade, the global community has become increasingly aware of an additional contaminant resulting from textile production and use: microfiber pollution. Microfibers are a staple fiber or a filament with a linear density ranging from 0.3 dtex to 1 dtex lengths ranging from 1 µm to 5000 µm, and a diameter generally <10 µm (Liu et al., 2019; G. Song, 2011); they are the fibers that are shed or separated, detached, or disentangled from textile surfaces and enter the environment as smaller particles (Rathinamoorthy & Raja Balasaraswathi, 2020).

As the textile industry is constantly growing, so too is microfiber pollution. Since 2000, global fiber production has doubled from 58 to 124.4 million metric tons (MMT) and is projected to reach 160 MMT by 2030 if current trends continue (Textile Exchange, 2024). Table 1 provides a detailed breakdown of global fiber production by fiber type, highlighting the industry's reliance on synthetic materials and the distribution of various natural and regenerated fibers. Synthetic fibers dominate the market, accounting for 67.4% of the total production, with polyester as the most widely produced fiber. Natural fibers, including cotton, wool, and other plant-based sources, contributed 26.3%, while manmade cellulosic fibers such as viscose and lyocell made up 6.3%.

Table 1. Global Fiber Production in 2023 (Textile Exchange, 2024).

Fiber Type	Production (MMT)
Total Global Production	124.4
Natural Fibers	**32.6**
Cotton	24.7
Other fibers (Flax, Hemp, etc.)	6.7
Wool (sheep)	1.1
Other animal fibers (Silk & Others)	0.1
Manmade Cellulosic Fibers	**7.9**

Viscose	6.3
Other (Acetate, Lyocell, Modal, Cupro)	1.6
Synthetic Fibers	**83.9**
Polyester	71.1
Polyamide (Nylon)	6.7
Other (Polypropylene, Acrylics, Elastane)	6.1

Polyester and cotton, the two most produced fibers, have distinct production geographies influenced by raw material availability, industrial capabilities, and agricultural conditions. Polyester, a petroleum-based synthetic fiber, dominates the textile industry for its durability, cost efficiency, and versatility. In 2023, global polyester fiber production reached 71.1 MMT, with China accounting for 72% (Figure 1a), driven by its strong petrochemical base and integrated supply chains (IVC, 2024). India followed with 8%, while the U.S., South Korea, Europe, and Japan contributed smaller, specialized shares. In contrast, cotton is an agricultural commodity with a more distributed production profile. Global cotton output in 2023 totaled 24.7 MMT, led by China (24.11%) and India (22.39%) (Figure 1b; USDA, 2024). Brazil (12.84%) and the U.S. (10.64%) are key exporters, while countries like Pakistan, Australia, Turkey, and Uzbekistan also play significant roles in a diversified global supply chain.

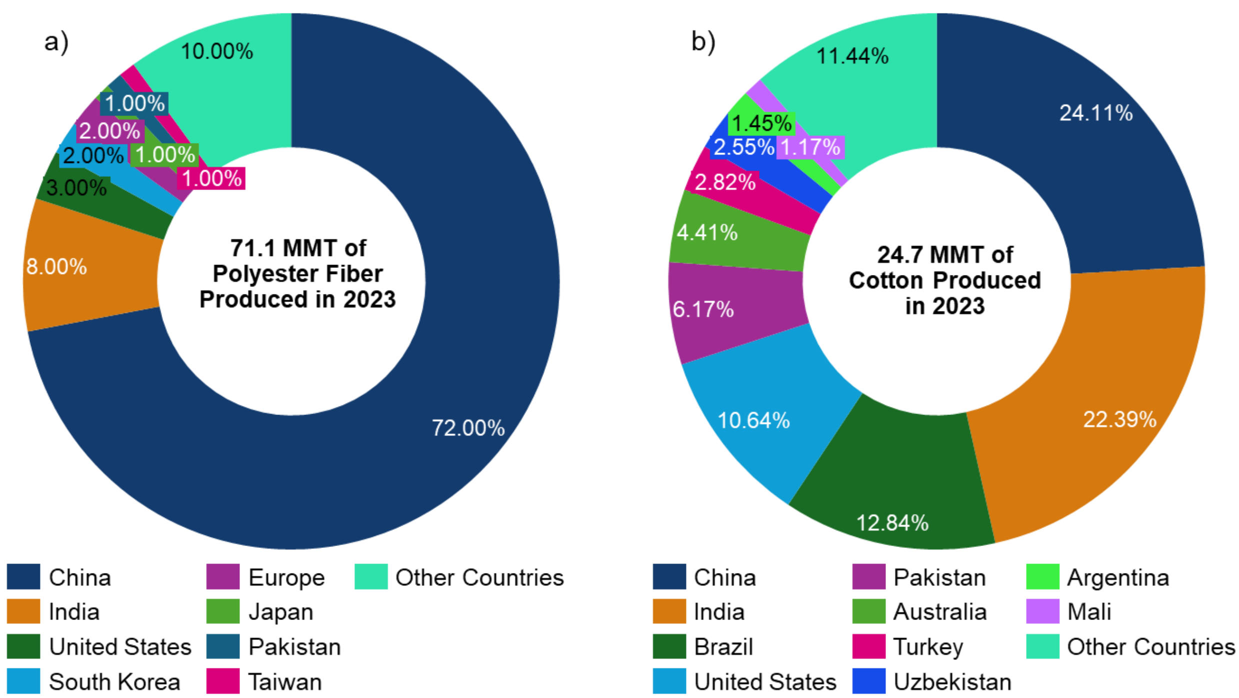

Figure 1. Country-level production of main textile fibers in 2023 for a) polyester production (IVC, 2024) and b) cotton production (Foreign Agricultural Service USDA, 2024).

The global production of fiber carries important environmental implications, as all fiber categories—synthetic, natural, and manmade cellulosic—contribute to microfiber pollution (Figure 2). Once released into the environment, microfibers can pose various risks, including plastic pollution, persistence in ecosystems, chemical leaching of dyes and additives, the potential to transport other pollutants, and the possibility of bioaccumulation in the food chain.

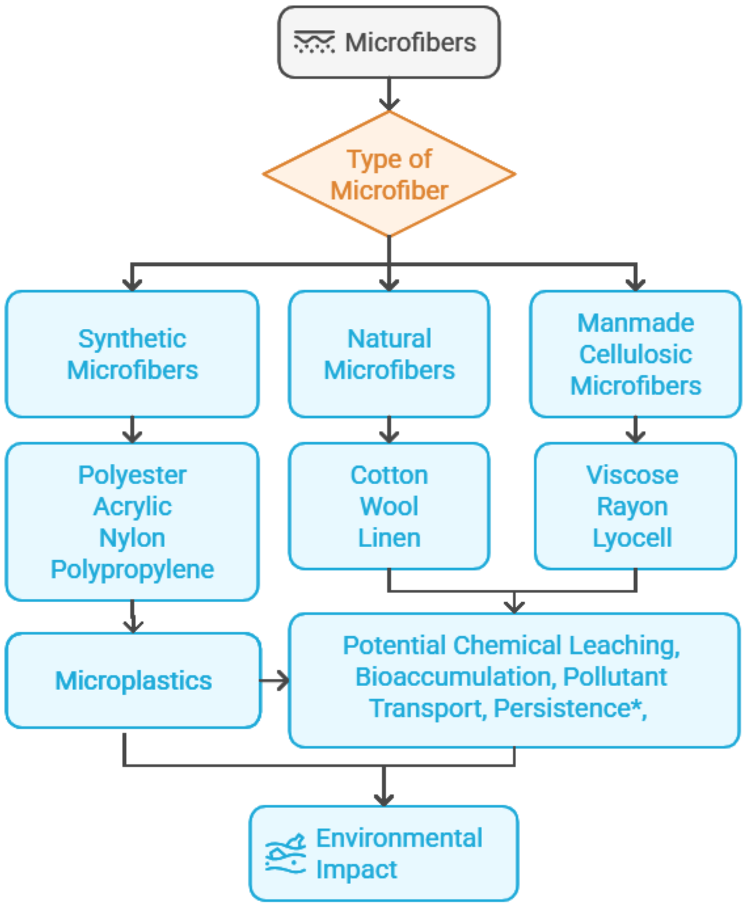

Figure 2. Microfiber classification and environmental impact. Persistence is exacerbated in synthetic microfibers.*

1.2. Microfiber Pollution in the Environment

Microfibers are considered an emerging contaminant, and due to the dominance of synthetic fiber production, are now generally recognized as a prevailing type of microplastic (Liu et al., 2022). Microfibers have been detected in diverse environmental settings, ranging from freshwater bodies, such as lakes and rivers, to soil, and even atmospheric dust (Kwak et al., 2022; Suaria et al., 2020); in the ocean, they consistently represent the most common type of microplastic (Belzagui et al., 2019; Mishra et al., 2019; Salvador Cesa et al., 2017; Suaria et al., 2020). Synthetic microfibers, a type of microplastic, persist in the environment due to their non-biodegradable nature and break down over time into smaller and smaller fragments (Singh et al., 2020).

However, all types of microfibers, not just synthetics, threaten the environment and human health. Notably, in some geographies, natural and manmade cellulosic fibers were the dominant type of microfibers found in the atmosphere and freshwater bodies (Finnegan et al., 2022; Stanton et al., 2019). Although most manmade and natural fibers degrade relatively quickly compared to synthetic fibers due to their cellulosic nature, their degradation process can lead to the release of toxic compounds such as dyes, additives, and flame retardants into the environment (Ladewig et al., 2015; Popoola, 2000; Subasinghe et al., 2018).

Once in the environment, microfibers spread rapidly across different ecosystems due to their small size and lightweight nature, easily dispersing through air and water pathways (Carr, 2017; Napper et al., 2023). The widespread presence of microfibers in all environments tested has raised serious concerns about their impact on aquatic and terrestrial biota and human health (Priya et al., 2023). These impacts include physical risks due to the shape of the fibers, chemical risks from the release of manufacturing-related chemicals or their absorption into the environment, and biological risks associated with enhanced transport of pathogens and microbes (Reisser et al., 2014; Kirstein et al., 2016; Henry et al., 2019) as well as heavy metals and other pollutants (Sørensen et al., 2021).

Consequently, the pollutant-laden microfibers can travel across different environments and be consumed by living organisms, where they accumulate in tissues through bioaccumulation and become more concentrated at higher trophic levels through biomagnification (Zambrano et al., 2019). Unfortunately, natural and synthetic microfibers can leach the sorbed pollutants, whereas natural fibers may leach the chemical additives more readily than synthetic fibers (Sørensen et al., 2021). This chemical leaching results in additional bioaccumulation and biomagnification phenomena because of the chemical buildup. When microfibers are ingested, the leaching of adsorbed contaminants and additives could represent a source of toxic substances that affect the organisms and enter the food chain that ultimately feeds humans (Sharma & Krupadam, 2022; Sørensen et al., 2021; Zambrano et al., 2019).

Microfibers have been documented in the digestive tract and gills of small aquatic organisms (Liu et al., 2022). The chronic consumption of microfibers, particularly synthetic ones, can lead to nutrient depravation, starvation, and physical injury of the digestive tract of aquatic organisms due to respiratory and gastrointestinal blockages (Malinowski et al., 2023; Mizraji et al., 2017; Wang et al., 2020). In humans, microfiber exposure occurs through ingestion and inhalation via multiple pathways, including drinking water, seafood, table salt, tea bags, and other food items contaminated by airborne microfibers, as well as direct inhalation of airborne microfibers released from textiles, household dust, and industrial emissions (Liu et al., 2022; Nawab et al., 2024). As a result, humans ingest or inhale between 75,000 and 120,000 synthetic microfibers each year—roughly the weight of a paper clip—mainly through seafood consumption (Harvey et al., 2022).

Once inside the body, microfibers can migrate beyond the digestive system and reach deeper tissues. Recent studies have detected synthetic microfibers in human stool, placenta, and meconium, indicating their ability to translocate to various organs (Braun et al., 2021; Mohamed Nor et al., 2021; Prata, 2018; Schwabl et al., 2019). Similar behavior is expected for all microfiber types, though further research is needed to confirm this. Moreover, chemicals leached from microfibers may disrupt hormones and contribute to cytotoxicity, immune responses, oxidative stress, respiratory issues, and the breakdown of cellular barriers (Rahman et al., 2021; S. Song et al., 2024).

These impacts from microfibers are ubiquitous, because textiles shed microfibers throughout their life cycle, polluting water, air, and soil, through wastewater, atmospheric emissions, and terrestrial discharge of microfiber-laden waste (sludge) or decomposition of garments in landfills (Athey & Erdle, 2022). In the textile industry, microfiber shedding occurs in both upstream and downstream sectors, i.e., during textile manufacturing and in the consumption phase, respectively. Recent estimates suggest that between 0.48 - 4.28 MMT of microfibers are released into the environment each year (Harvey et al., 2022). Of this total, approximately half (0.24 - 2.14 MMT) originates upstream during manufacturing (Belzagui et al., 2019; EMAF, 2017; Gavigan Jenna AND Kefela, 2020; Harvey et al., 2022) and half (0.24 - 2.14 MMT) comes from consumption (i.e., everyday activities such as clothing wear, washing clothes, etc.). Textiles shed additional microfibers post-consumption (i.e., after disposal), but this is not captured in current microfiber estimates.

1.3. Microfiber Pollution Interventions

In the textile industry, microfiber pollution can be addressed along the entire textile lifecycle – from creation to disposal. However, solutions in the downstream phase are fragmented, as emission control largely depends on technology in washing machines and dryers as well as consumer behavior and their knowledge about how to reduce microfiber pollution. Focusing on reducing microfiber shedding upstream is more strategic, as the sources—mainly textile mills—are fewer in number and the shedding is concentrated at specific focal points. Furthermore, some "upstream" actions have the potential to reduce fiber fragmentation or textile shedding during the downstream phase. Consequently, a necessary first step toward addressing microfiber pollution is identifying interventions that help reduce microfiber shedding during manufacturing or remove microfiber emissions from upstream discharges to prevent them from entering the environment.

Microfiber shedding in the industrial textile sector is strongly influenced by fiber/fabric composition and structure, as well as process setup, mechanical interactions, and chemical treatments applied during manufacturing (Figure 3). Mechanical actions such as abrasion from friction during wet and dry processing stages can cause fiber breakage and surface damage (De Falco et al., 2018; M. Wang et al., 2023; Yang et al., 2023). Additionally, severance and pressure exerted during cutting and sewing have also resulted in microfiber shedding (Cai et al., 2020; Rathinamoorthy & Raja Balasaraswathi, 2023b). Chemical treatments, including alkaline scouring, bleaching, dyeing, and finish agents, can further degrade fiber integrity, thereby increasing microfiber shedding (M. Wang et al., 2023; Zambrano et al., 2021). Finally, process setup—including temperature, liquor ratio, chemical concentration, and water composition significantly affects microfiber release, with poor control increasing fiber stress and shedding (Rathinamoorthy & Balasaraswathi, 2022).

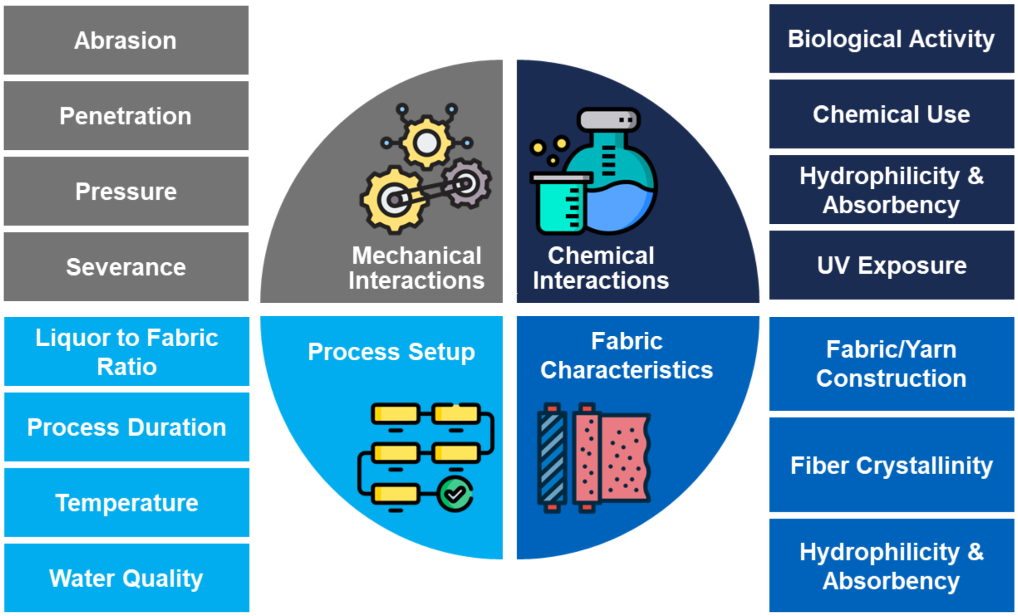

Figure 3. Drivers of microfiber emissions during textile manufacturing including mechanical and chemical interactions, process setup, and fabric characteristics.

Microfiber shedding occurs at various stages of textile manufacturing and can enter the environment through air emissions, wastewater, and solid waste. Wet processing stages are especially significant contributors to microfiber release into wastewater, where the fibers are often difficult to remove using conventional treatment methods. As the industry shifts toward more sustainable practices, technologies must not only reduce water, energy, and chemical use but also limit fiber damage and shedding. To meet these sustainability goals, textile brands and manufacturers should explore targeted solutions to prevent fiber fragmentation. While not the focus of this report, it's important to highlight that optimizing existing production processes—such as reducing agitation, fine-tuning cycles, using gentler chemicals, and managing temperatures—can further lower microfiber shedding while preserving fabric quality (Periyasamy, 2024; Periyasamy & Tehrani-Bagha, 2022).

Textile wastewater treatment plants (WWTPs) are essential to prevent microfiber and other pollutants from escaping into local environments, but they require adequate specification and handling of the millions of microfibers that are discharged daily. While a significant portion of these microfibers are captured sludge, sludge is not always disposed of properly. Proper or effective disposal includes incineration or a lined landfill, but currently, sludge is often landfilled without lining or open-dumped, shifting the microfiber emissions to a land or aquatic pathway via groundwater and posing equivalent environmental risks (Rathinamoorthy et al., 2022). Smaller fibers (<100 µm) often escape removal during wastewater treatment because they behave similarly to fine suspended solids (Zhou et al., 2020). Because conventional treatment focuses on standard discharge limits, microfibers are often overlooked, allowing effluent reuse or discharge, or sludge disposal despite their microfiber content. These issues call for targeted treatment solutions like screens, membranes, filters, and separation technologies to cope with microfibers effectively (Akarsu et al., 2020; Bayo et al., 2020; Talvitie et al., 2017; Zhou et al., 2020).

Multiple stakeholders are actively addressing microfiber pollution in the textile industry through coordinated efforts in research, innovation, education, and regulation. Initiatives include the development of standardized testing protocols, collaborative data platforms, and commitments to reduce fiber shedding across the value chain (The Microfiber Consortium, 2022). Apparel companies are supporting research into advanced manufacturing technologies, promoting low-shedding product design, backing textile recycling efforts, investing in consumer-use solutions to capture microfibers during laundry using washing bags or external filters, and exploring low-emission processing techniques, among others (Forum for the Future, 2023; HKRITA, 2024; The Microfiber Consortium, 2022; Thodges, 2019; Tim Somheil, 2014; UC Santa Barbara, 2017).

At the same time, several jurisdictions are introducing or pursuing legislation requiring microfiber filtration, product testing, and labeling, alongside broader calls for international regulatory alignment (e.g., Assembly Bill A10599, 2018; California Assembly Bill AB2379, 2018; Connecticut Department of Energy and Environmental Protection, 2020; European Commission, 2023). Collectively, these actions reflect a growing commitment to sustainable manufacturing practices and are helping to drive public awareness, scientific research, and policy development across the textile sector.

1.4. Report Objectives

While several promising upstream microfiber control technologies exist, evaluating their effectiveness and benefits remains challenging due to significant data gaps around performance and key decision-making metrics. This report seeks to address these challenges by using the best available data to develop a holistic evaluation framework that captures the combined impact of upstream interventions, providing a clearer understanding of their effectiveness. Ideally, this framework could be adapted and refined as additional data becomes available. Product development changes (e.g., fiber type modifications or fabric construction improvements) represent a critical class of interventions but are beyond the scope of this study.

Here, an innovative framework is presented to evaluate the potential of technology solutions in textile manufacturing and wastewater treatment to address microfiber pollution. The framework consists of (1) defining the baseline conditions for textile manufacturing and wastewater treatment operations, (2) developing a broad set of evaluation criteria that represent key categories of information required for decision-making, (3) a technology horizon scan to identify textile manufacturing and wastewater treatment technologies and collect relevant data, and (4) scoring each selected technology against the evaluation criteria. This integrated approach is expected to assist in the decision-making process of stakeholders to address the sustainability challenges facing the textile industry, centered on microfiber pollution, while also considering water scarcity, energy efficiency, and other forms of environmental pollution.

2. Methods

We first provide a high-level overview of the four main steps in the evaluation framework, followed by a comprehensive explanation of the method used for each step. Lastly, we build on the data collected as part of the baseline scenario to estimate the total annual microfiber pollution from textile manufacturing.

2.1. Evaluation Framework Overview

The framework's development and application include four key processing steps (see Figure 4):

1. Construct a baseline scenario for microfiber emissions in textile manufacturing and wastewater generation.

2. Development of the framework fundamentals, including defining the criteria used to assess each technology solution.
3. Complete a technology horizon scan to identify manufacturing and wastewater treatment technologies that have the potential to reduce microfiber emissions and collect data to populate the framework.
4. Apply the framework to assess each technology solution against the established criteria, using the baseline scenario to assess potential microfiber emission reductions.

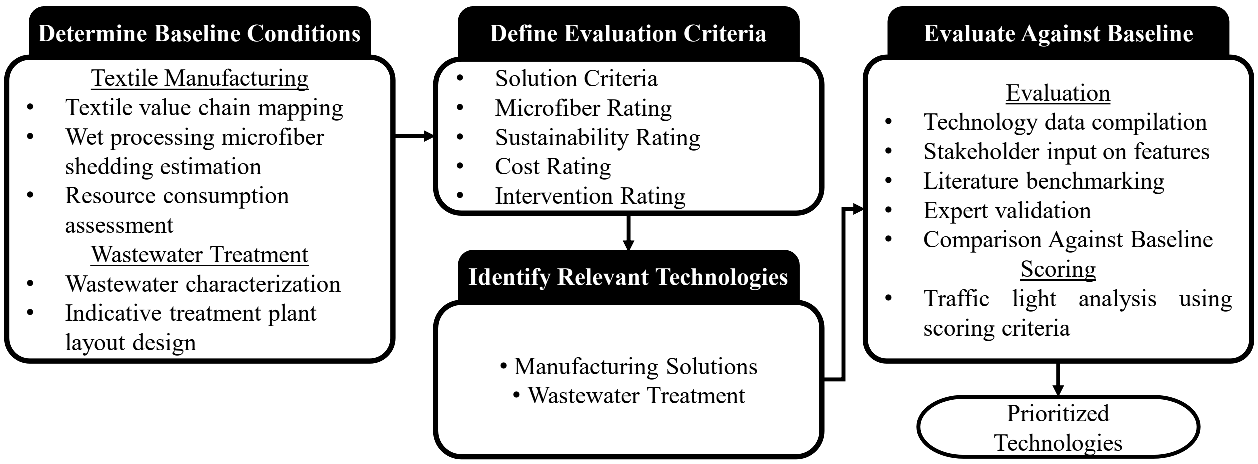

Figure 4. Proposed framework for evaluation of microfiber control in the textile industry.

This framework was designed to provide a structured methodology for evaluating technologies capable of reducing microfiber shedding or capturing and removing microfibers from wastewater, ensuring a clear, consistent, and systematic assessment process. The following sections describe the methods and assumptions in each step of the process.

2.2. Baseline Conditions

To enable an assessment of how wastewater treatment and manufacturing technologies can be used to control microfiber pollution within the textile industry, it is crucial to establish a high-level understanding of the industry's baseline conditions. This scenario served as a reference that accounted for technical, operational, economic, and sustainability factors influencing current facility practices, though, it is acknowledged that specific configurations may vary across regions and facility types.

The evaluation focused on three key pillars: (1) microfiber pollution, (2) water use, and (3) energy consumption. As such, the baseline scenario was constructed to reflect a representative textile manufacturing facility by capturing data and process descriptions across the following domains:

- Textile manufacturing process
- Baseline operating conditions
  - Microfiber shedding
  - Water use and effluent generation
  - Energy intensity
  - Chemical usage
- Wastewater characterization and treatment layout

To establish a baseline scenario, the key steps in the textile manufacturing process were first outlined with an emphasis on wet processing. A review of peer-reviewed and gray literature was conducted to gather estimates of microfiber shedding (Grillo et al., 2023; Rathinamoorthy & Raja Balasaraswathi, 2023a; M. Wang et al., 2023; Zambrano et al., 2021), water use (Kumar & Pavithra, 2019; Marzoug & Cheriaa, 2023; Roth et al., 2023), energy consumption (Koç & Çinçik, 2010; Roth et al., 2023), and wastewater production and composition (Samanta et al., 2019; X. Wang et al., 2022), for each stage of the manufacturing process. The methods used for each estimate are described in more detail in the following sections.

Textile Manufacturing Process

A textile manufacturing workflow was pieced together using a combination of sources to ensure both technical accuracy and real-world relevance. It drew on published literature detailing standard processing steps, such as dry and wet processes, as well as technical manuals and industry reports that outlined process sequences. Additionally, the workflow was informed by on-site observations and discussions during visits to textile mills, which helped validate the devised textile manufacturing process matched both the planned design and how things work in practice.

Baseline Operating Conditions

Microfiber Shedding

Although both dry and wet processes contribute to microfiber shedding, this study focuses on wet processes. Dry process emissions are typically managed through exhaust and ventilation systems which capture microfiber-laden air and direct it to rotary drum lint filters, where the lint can be recycled or disposed of properly, reducing environmental discharge.

To develop the baseline conditions for microfiber pollution, microfiber shedding was estimated across the wet processing stages in textile manufacturing. A comprehensive literature review of peer-reviewed articles and technical reports was completed to inform estimates of microfiber emissions during each stage of wet processing. Microfiber shedding values were reported as both counts (number of microfibers per kilogram of fabric) and mass (grams of microfibers per kilogram of fabric). All count estimates were converted to mass using a standardized conversion factor (4.364×10^{-4} mg MF/ # MF) accounting for fiber dimensions and density (M. Wang et al., 2023; Zhou et al., 2020). Microfiber shedding data was found for all stages of wet-processing. When more than one shedding estimate was available for a given processing stage, estimates were averaged across the studies to develop representative mass-based shedding values (in g MF/kg fabric) for each stage. For the finishing stage, the average value was adjusted by 50% to reflect the variability and partial application of finishing agents across different textile products. These values were then summed across all stages to estimate the total microfiber shedding from wet processing.

To further understand the drivers of microfiber release, microfiber shedding was assessed in relation to four broad categories of influencing factors (1) Mechanical Interactions, (2) Process Setup, (3) Chemical Interactions, and (4) Fabric Properties (see Figure 3). Each category includes specific factors known to increase or control microfiber loss, based on textile behavior under wet processing conditions (Table 2). These were adapted from the literature and structured into a matrix to guide the interpretation of how processing and material decisions impact fiber release. This understanding was used to inform the relevance and potential effectiveness of various intervention strategies.

Table 2. Factors influencing microfiber shedding. Adapted to fundamental factors from literature (Rathinamoorthy & Balasaraswathi, 2022a).

Category	Factor	Impact on Microfiber Shedding
Mechanical	Abrasion	Physical wear from agitation releases fibers.
	Penetration	Sewing disrupts fabric, creating micro-holes that release fibers.
	Pressure	Excess pressure compacts and weakens fibers.
	Severance	Cutting and impacts directly break fibers.
Process Setup	Liquid-to-fabric ratio	Imbalanced ratios increase fiber stress from uneven processing.
	Process Duration	Longer exposure to heat and chemicals degrades fibers.
	Temperature	High heat weakens fibers, making them prone to shedding.
	Water Quality	Hard water and pH variations stiffen or degrade fibers.
Chemical	Biological Activity	Enzymes or microbes can degrade fiber integrity.
	Chemical Use	Harsh or excessive chemicals weaken fibers.
	Hydrophilicity/Absorbency*	Water absorption swells fibers; hydrophobic treatments can make them brittle.
	UV Exposure	Sunlight weakens especially synthetic fibers through photodegradation.
Fabric Properties*	Fabric/Yarn Construction	Dense, strong fabrics shed less; loose, light ones shed more.
	Fiber Crystallinity	High-crystallinity fibers resist shedding; low-crystallinity swell and shed more.

*Factor tied to fabric properties and chemical interactions due to natural hydrophilicity & absorbency or enhanced by finishing processes.

Water Use and Effluent Generation

To define baseline water usage and wastewater generation profiles, water balance estimates were developed for individual wet processing stages. Process-specific data were sourced from international references such as industry reports on the best available techniques (BAT) for textile manufacturing and supplemented with peer-reviewed data. Water consumption and wastewater production estimates are reported in liters per kilogram of fabric processed. Literature-based estimates were found for all wet processing steps except sizing. While water consumption data for sizing/desizing is commonly reported jointly due to the functional interlinkage of both processes, sizing consumption is generally lower than that of desizing, which involves removing all sizing agents and therefore generates more wastewater. In this analysis, 20% of the desizing water use was estimated for the sizing stage, reflecting the limited water required primarily for cleaning the sizing bath. Wastewater production was assumed to occur predominantly during the desizing process, as this is when the sizing agents are fully removed from the fabric and discharged with the effluent. The cumulative water footprint and wastewater discharge rate per unit of fabric were established by summing the values across all stages.

Energy Intensity

To establish energy-related baseline conditions, specific energy consumption (SEC) values were gathered for individual wet processing steps. Estimates for each step were gathered through a literature review and reported in kilowatt-hours per kilogram of fabric. Values for the most analogous process were used to estimate the SEC for stages that were not reported. SEC values were summed across all stages to get a total SEC value for the wet processing sequence. This aggregated SEC value served as a benchmark for evaluating energy-efficient technologies and estimating potential savings through equipment upgrades.

Chemical Usage

The textile industry relies on a wide range of chemicals to achieve desired fabric properties during wet processing. These chemicals serve various purposes, including fiber preparation, dye fixation, and fabric finishing. The chemical inputs vary depending on the process, fabric type, and end-use requirements. Many of these chemicals contribute to wastewater pollution, making chemical management and wastewater treatment essential components of sustainable textile manufacturing. The number and type of chemicals commonly used in each stage of wet processing were identified through a literature review of peer-reviewed studies, industry reports, and process manuals.

While specific quantities of chemical inputs were not estimated due to high variability across fabric types and dye formulations, the qualitative inventory of chemical types was used to inform environmental impact assessments and comparisons with alternative technologies. Each chemical was categorized by process stage, and its functional role (e.g., lubricant, dye, enzyme, softener, binder) was recorded. Data on chemical usage was found for every wet processing stage. This chemical inventory supported the assessment of technologies that aim to reduce or substitute harmful chemical inputs as part of microfiber mitigation or wastewater minimization strategies. Baseline comparisons evaluated whether technologies reduce the number of chemicals required during wet processing thereby minimizing chemical loads and improving sustainability in the sector, based on high-level estimates informed by company reports, interviews, and peer-reviewed literature.

Wastewater Characterization and Treatment Layout

Wastewater technologies are one unit within a broader system and assessing the effectiveness of wastewater treatment technologies for the removal of microfibers in textile mill effluent requires characterization of the broader wastewater treatment system. To ensure a consistent basis for comparison, a baseline scenario was developed to serve as the standard reference WWTP in our evaluation. First, a wastewater characterization was put together to provide a representation of the types of pollutants and typical pollutant loads generated by textile manufacturing. Second, an indicative wastewater treatment plant layout, (i.e., a diagram showing the sequence of the unitary treatment used in wastewater treatment) was devised. This indicative plant layout presents a typical treatment train based on a set of standardized conditions—including wastewater generation volumes and pollutant loading (i.e., wastewater characterization) and common industry practices for facilities with onsite treatment, based on a set of standardized conditions—including wastewater generation volumes and pollutant loading (i.e., wastewater characterization) and common industry practices for facilities with onsite treatment.

Textile wet processing generates large volumes of complex effluents with varying compositions depending on the stage, but they are generally characterized by high levels of BOD, COD, TSS, TDS, and a wide range of organic and inorganic pollutants (Kumar & Pavithra, 2019). A wastewater characterization was completed using literature-based estimates of the concentration of key contaminants—specifically pH, COD, BOD, and TSS—from different wet processing stages (Table 3). These values reflect the distinct pollution loads associated with each wet processing stage. In practice, treatment plants often receive a combined effluent stream, where discharges from different wet processes are mixed. Therefore, to estimate the average influent characteristics for treatment design purposes, a weighted average approach was applied, considering both the wastewater production volume and typical pollutant concentrations from each process stage (see Table A 2 and Table 3, respectively). This provides a representative characterization of combined textile effluent. It is recognized that other pollutants—including color, nutrients, oils, and heavy metals—are also present in textile wastewater. For these parameters, average concentrations reported in the literature were used to complete the indicative wastewater characterization (see Table 4). This characterization is not an actual wastewater sample but an indicative representation of expected conditions, that served as a reference for designing a semi-hypothetical treatment plant layout to compare microfiber removal technologies.

Table 3. Wastewater composition of different textile wet processes (Samanta et al., 2019).

Process	pH	TSS (mg/L)	BOD_5 (mg/L)	COD (mg/L)
Sizing/Desizing	8.6 - 10	2290 - 2670	1000 - 1080	1650 - 1750
Scouring	10.9 - 11.8	1960 - 2080	2500 - 3480	12800 - 19600
Bleaching	8.4 - 10.9	200 - 340	87.5 - 535	1350 - 1575
Mercerizing	8.1 - 9.2	160 - 430	100 - 1222	246 - 381
Dyeing	9.2 - 11	360 - 370	130 - 820	465 - 1400
Printing/Finishing	6.7 - 8.2	250 - 390	135 - 1380	410 - 4270

Table 4. Indicative wastewater characterization for a combined textile effluent.

Parameter	Average Value	Reference
pH [a]	9	(Samanta et al., 2019)
Temperature, °C	40	(X. Wang et al., 2022)
Total dissolved solids (TDS) mg/L	3000	(X. Wang et al., 2022)
Biological Oxygen Demand (BOD) mg/L [a]	1000	(Samanta et al., 2019)
Chemical Oxygen Demand (COD) mg/L [a]	2200	(Samanta et al., 2019)
Total suspended solids (TSS), mg/L [a]	500	(Samanta et al., 2019)
Chloride, mg/L	1000	(X. Wang et al., 2022)
Free chlorine, mg/L	<10	(X. Wang et al., 2022)
Oil & Grease, mg/L	15	(X. Wang et al., 2022)
Total Kjeldahl Nitrogen (TKN) mg/L	75	(X. Wang et al., 2022)
Nitrate (NO_3) mg/L	<15	(X. Wang et al., 2022)
Free ammonia, mg/L	<10	(X. Wang et al., 2022)
Color (Pt-Co)	1,250	(X. Wang et al., 2022)
Sulphate (SO_4) mg/L	600	(X. Wang et al., 2022)
Heavy metals, mg/L	<10	(X. Wang et al., 2022)

a) Average values estimated for combined effluent based on wastewater production (Table A 2) and pollutant load (Table 3).

The high costs and operational complexities associated with onsite treatment prevent many textile facilities from investing in dedicated treatment infrastructure and as a result, they often adopt alternative approaches:

- **Wastewater Hauling & Disposal:** Many textile facilities transport their wastewater to centralized treatment plants equipped with advanced technologies capable of handling industrial effluents.
- **Partial Onsite Treatment:** Some facilities implement partial treatment before discharging wastewater into municipal sewer systems. This approach helps ensure compliance with local regulations while reducing overall treatment costs.

For estimating baseline conditions, a partial onsite treatment scenario was assumed which includes the following treatment stages (Figure 5):

- **Pre-Treatment:** This stage includes screening to remove large solids and debris.
- **Equalization:** A tank is used to balance variations in flow rate and pollutant concentrations, ensuring stable conditions for downstream treatment.
- **Coagulation & Flocculation:** Coagulants and flocculants are added to aggregate fine particles, dyes, and heavy metals into larger flocs for easier separation. Dyes are only partially removed.
- **Biological Treatment:** This step, often using an activated sludge process, facilitates the microbial degradation of organic pollutants.
- **Tertiary Filtration:** The final polishing step removes any remaining suspended solids before discharge or further treatment.

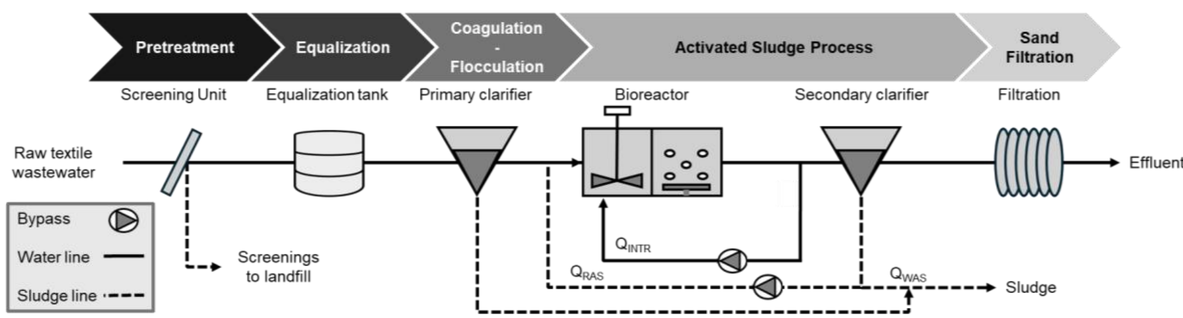

Figure 5. Indicative reference of a textile WWTP plant layout for onsite treatment.

While this WWTP configuration is representative of the process for onsite treatment, it provides a foundation for treatment but is not meant to be a recommendation. Many textile industry pollutants, such as synthetic dyes and surfactants, are resistant to biological degradation, leading to persistent non-biodegradable COD. Additionally, highly soluble and chemically stable dyes often remain in the treated effluent, causing color and dissolved pollutant issues. The activated sludge process generates excess biomass, which requires proper disposal. Without advanced treatment, the effluent may not comply with increasingly strict regulations for COD, color, and emerging contaminants.

Lastly, the total daily wastewater output was estimated based on the wastewater production per kilogram of fabric and the amount of fabric produced each day. The estimated wastewater production is 110 liters per kilogram of fabric (see Table A 2). Production rates were estimated to range from 5-20 tons of fabric per day (Nasir et al., 2025; Textile Commissioner's Organization, 2023); for calculation purposes a median value of 10 tons per day was used, resulting in a total of approximately 1000 m³ of wastewater per day. To ensure consistency, cost estimates for the treatment technologies under evaluation were based on a design capacity of 1000 m³/day. However, cost considerations are influenced by economies of scale and facility size plays an important role in cost efficiency, so these are likely underestimating costs for small facilities (less than 5 tons/day) and overestimating costs for large facilities (more than 20 tons/day).

2.3. Evaluation Criteria

The evaluation criteria were developed from general principles of technology adoption and adapted to the specific context of textile manufacturing and microfiber pollution control. Each category reflects key considerations such as technology fundamentals, microfiber control, broader environmental impact, cost, technical effectiveness, and ease of implementation, ensuring a balanced and practical assessment aligned with industry needs. The evaluation criteria were selected to include multiple dimensions that are relevant for informed decision-making across five major rating categories:

- **Solution Criteria** – Provides a more general high-level assessment of the technology solution, such as the type of intervention, where it occurs in the textile manufacturing process, and what processes it directly influences.
- **Microfiber Rating** – Evaluates technology performance specifically related to how effectively it controls microfiber pollution across the textile manufacturing process through shedding reduction or fiber capture and removal from wastewater.
- **Sustainability Rating** – Assesses technology performance across a suite of environmental performance indicators centered on resource efficiency, i.e., conservation of water, energy, and chemicals along with ancillary benefits.
- **Cost Rating** – Delves into cost considerations of each technology solution such as capital expenditures (CAPEX), operational expenses (OPEX), and return on investment (ROI).
- **Intervention Rating** – Looks at current technology adoption and evaluates how easily the technology can be implemented based on the scale of intervention, integration into existing processes, operational disruption (risk factors), infrastructure needs, and required user or operator behavior changes.

Within each rating category, a specific set of parameters was used to evaluate each technology solution (Table 5). The definitions provided ensure clarity and consistency in how each technology is compared throughout the evaluation process. Each category captures distinct but complementary performance dimensions, allowing for a holistic assessment of the technologies across their technical, environmental, economic, and practical attributes.

Table 5. Definition of Evaluation Criteria Used in the Microfiber Control Framework

Category	Parameter	Definition
Solution Criteria	Intervention Class	The broader stage or zones where microfiber control is implemented.
	Stage	Stages in textile manufacturing and product use where microfiber control is applied.
	Technology Class	The category of technology in terms of its underlying scientific/engineering principles.
	Technology	Solution to reduce microfiber shedding in manufacturing or microfiber removal from wastewater.
	Definition	Description of the Technology

	Intervention Mechanism	Fundamentals of the process to control microfiber release.
	Influenced Processes	Specifies which stages of textile production the technology affects, such as the textile wet processes or wastewater treatment plant stages.
Microfiber Rating	Control Efficiency	Effectiveness in the control of microfiber release.
	Downstream Effect	Refers to the impact a technology has on reducing microfiber shedding during the consumer phase,
	Overall Reduction (%)	Total percentage of microfiber reduction achieved across all stages of textile processing.
	Control Mechanism	Means for microfiber release control either by capture/removal in wastewater or shedding reduction.
	Microfiber Fate	The fate of microfibers post-intervention.
	Microfiber Composition	Microfiber types controlled—natural, synthetic, or blends.
	Particle Size Range	The range of sizes of microfiber particles that the technology can effectively capture or reduce.
Sustainability Rating	By-product Management	The handling and disposal of any by-products generated during the microfiber control process.
	Energy Consumption	The amount of energy required for the operation of the technology.
	Energy Savings	The potential reduction in energy usage compared to baseline operations.
	Water Savings	The potential water conserved compared to baseline operations.
	Water Savings Method	The approach by which technology achieves water conservation.
	Chemical Usage	Types of chemicals required for the operation and maintenance of a technology.
	Chemical Savings	Reduction of chemicals required for operation compared to BASELINE operations.
	Additional Benefits	Additional advantages offered by the technology.
Cost Rating	CAPEX	Benchmark capital costs to procure and implement the technology for early-stage evaluations.
	OPEX	Benchmark operation and maintenance costs of the technology for early-stage evaluations.
	ROI	The financial benefit relative to technology cost, expressed as a payback period.
Intervention Rating	Technology Readiness Level (TRL)	A standardized scale that rates a technology's maturity from initial successful deployment (TRL 9), reflecting its progress from research to real-world use.
	Land Footprint	The amount of physical space required to install and operate the technology.
	Operational Complexity	Level of skilled labor required to properly operate the technology.
	Risk for Malfunction	Technology's susceptibility to fouling and mechanical malfunction.
	Scalability	Ability to adapt to various textile scales or wastewater complexities while maintaining performance.
	Integration	Technology’s requirements and compatibility for integration with existing systems and processes.

	Limitations	Constraints of the technology.
	Adoption Rate	The degree to which a technology has been implemented across textile manufacturing or wastewater treatment.

2.4. Technology Identification

The central focus of this study is to address microfiber pollution at the pre-consumer stage of the textile industry, specifically during the textile manufacturing process. A thorough literature review and desktop research were conducted in two main intervention classes: manufacturing technologies, aiming to reduce microfiber shedding during textile wet processing, and wastewater treatment technologies, focusing on the capture and removal of microfibers before discharge.

Manufacturing technologies were included if they addressed sustainability challenges, such as reducing water, energy, or chemical use, or if they were at an emerging stage of development or adoption and had been tested for microfiber reduction or demonstrated potential to do so. Wastewater technologies were selected based on their potential for microfiber removal, the low-to-minimum risk for fragmentation/meteorization, innovative or selective separation mechanisms, and promising economic or scalability potential. The final set of 38 technologies was selected based on these criteria, data availability, and input from expert interviews and vendor discussions. Then, technologies were organized into classes (i.e., manufacturing and wastewater technologies) and sub-classes (e.g., waterless dyeing, mechanical filtration) based on core operating principles to enable consistent comparison. The evaluation was conducted at the sub-class level rather than focusing on specific brands.

Manufacturing technologies include a range of approaches that focus on minimizing microfiber shedding, reducing water consumption, improving process efficiency, and promoting sustainable alternatives in textile processing. These solutions were categorized based on their underlying principles into six technology sub-classes: waterless bleaching, waterless dyeing, waterless printing, green chemistry, air-assisted finishing, and waterless finishing (Table 6).

Table 6. Definitions for manufacturing technology sub-classes

Technology Class	**Description**
Waterless Bleaching	Textile bleaching process that significantly reduces the use of water by utilizing alternative bleach application techniques.
Waterless Dyeing	Textile coloration process that eliminates or significantly reduces the use of water by utilizing alternative dye application techniques.
Waterless Printing	Non-aqueous textile printing process that eliminates or significantly reduces water usage by utilizing alternative ink application methods.
Green Chemistry	Design, development, and application of chemical processes & materials to minimize environmental impact, reduce hazards, and enhance efficiency.
Air Assisted Finishing	Technologies that use airflow to enhance finishing processes in manufacturing, aiming for increased product quality and process efficiency.
Waterless Finishing	Textile coating process that eliminates or significantly reduces the use of water by utilizing alternative finishing (coating) application techniques.

The specific technologies considered under each of these sub-classes are listed in Table 7 with definitions that clarify their mechanisms, applications, and contributions to reducing microfiber shedding or improving overall sustainability in textile manufacturing processes.

Table 7. Classification of manufacturing technologies and their definitions

Class	Solutions	Definitions
Waterless Bleaching	Spray Bleaching	Bleaching process that applies chemical bleaching agents in a fine mist or spray onto textiles, eliminating the need for immersion in water-based bleach baths.
Waterless Dyeing	Spray Dyeing	Technique that applies dye as a fine mist directly onto both sides of the fabric, reducing water consumption, and often incorporating heat and steam to facilitate dye migration and fixation.
	Supercritical Fluid Dyeing	Dyeing technique that utilizes supercritical CO_2 as a solvent, to dissolve and transfer of dyestuffs into fibers without the use of water, enhancing dye penetration and reducing processing times.
	Ultrasonic Dyeing	Dyeing method that employs high-frequency sound waves to create cavitation bubbles in the dye bath, enhancing the penetration of the dye into fiber pores and improving color strength and fastness
	Dope Dyeing	Dyeing method where color pigments are mixed into the polymer solution prior to extrusion, resulting in fibers that are uniformly colored throughout.
	Pigment Dyeing	Dyeing method that uses binders to fix insoluble pigments to fabric surfaces, with heat curing to activate adhesion without fabric penetration.
	Non-water Solvent Dyeing	Dyeing method that utilizes organic solvents instead of water to dissolve and apply dyes to fabrics.
	Digital Dyeing (Fabric)	Textile coloring process that uses digital technology to apply dyes directly onto fabric.
	Digital Dyeing (Yarn)	Yarn coloring process that employs digital technology to apply dyes directly onto yarn fibers.
	Biological Dyeing	Dyeing method that uses natural, biobased pigments and dyes derived from living organisms, such as bacteria, fungi, or plants, to color textiles.
	Chemically-engineered dyeing	Dyeing method is formulated with wetting, emulsifying, and dispersing agents that allow simultaneous pretreatment and dyeing in a single bath.
	Supercritical-assisted dyeing	Process that pre-coats textiles with conventional dyes, then subjects them to supercritical CO_2 conditions, where the CO_2 penetrates the fabric, dissolves the dye, and embeds it into the fibers.
Waterless Printing	Direct Digital Printing	Method for printing designs directly onto fabric or other materials using digital technology, without the need for screens or plates.
	Transfer Digital Printing	Printing method where a design is printed onto a transfer paper using digital technology, then transferred onto fabric or another material using heat and pressure.
	Hybrid Digital Printing	Printing method that supports both direct digital printing and transfer digital printing.
Green Chemistry	Natural Dyes	Natural dyes are colorants derived from plant-based or biological sources, eliminating synthetic dye pollutants.
	Catalytic Scouring	Chemical process that uses catalysts to accelerate or modify chemical reactions while minimizing energy consumption, waste generation, and harmful byproducts in the scouring process

Air Assisted Finishing	Microfiber Air Removal	Technology that utilizes airflow to remove microfibers from textiles, enhancing product cleanliness and reducing environmental impact.
Waterless Finishing	Spray Finishing	Finishing process that applies finishing agents in a fine mist or spray onto textiles, eliminating the need for immersion in water-based finishing baths.

Most of these technologies can help reduce microfiber shedding during the manufacturing process by modifying the factors that contribute to shedding, except for microfiber air removal systems, which are specifically designed to capture and remove microfibers after manufacturing but before they reach the consumer.

The wastewater treatment category involves a range of technologies designed to remove microfibers and improve water quality for safe discharge or reuse. These technologies were broadly categorized based on their fundamental principles and mechanisms into five technology sub-classes: mechanical filtration, membrane filtration, separation technologies, biological treatment, and electrochemical systems (Table 8).

Table 8. Definitions for wastewater treatment technology sub-classes

Technology Class	Definitions
Mechanical Filtration	Physical separation process to remove solid particles and debris from wastewater using barriers such as screens, meshes, or porous media.
Membrane Filtration	Pressure-driven separation process that uses semi-permeable membranes with varying pore sizes to selectively remove particles, microorganisms, and dissolved substances from wastewater.
Separation Technologies	Physicochemical processes that isolate, remove, or recover specific contaminants by exploiting differences in particle size, density, solubility, or chemical affinity.
Biological Treatment	Biochemical processes that utilize microorganisms such as bacteria, fungi, and algae to degrade or metabolize organic pollutants, nutrients, and hazardous contaminants in wastewater.
Electrochemical Treatment	Processes that utilize electrical energy to drive oxidation, reduction, or precipitation reactions for contaminant removal or purification.

The specific technologies considered under each of these broader sub-classes are listed in Table 9 along with concise definitions that highlight their operational principles and relevance for microfiber removal in textile manufacturing wastewater.

Table 9. Classification of wastewater treatment technologies and their definitions.

Class	Technologies	Definitions
Mechanical Filtration	Cartridge Filtration	Cylindrical filtration device containing a roll or pleated filter media inside, for removing suspended solids by trapping them on or within the filter media.
	Disc Filtration	Multiple stacked plastic discs with grooved surfaces, creating a three-dimensional filtration matrix to remove suspended solids and particulate matter.
	Bar Screens	Parallel metal bars or rods aligned vertically or at an angle to remove large debris and solid waste. It can be static or moving.

	Drum Screens	Rotating cylindrical drum with a fine mesh or perforated surface allowing water to pass through while capturing solids.
	Basket Strainers	Filtration devices with a mesh screen, typically made of stainless steel, designed to remove debris and large contaminants from horizontal pipelines.
	Microstrainers	Rotating drum filtration devices with fine mesh screens that remove suspended solids and algae by trapping them on the mesh and washing them into a hopper.
	Microfiber Filter	Filtration system designed to capture microfibers and particulate matter as wastewater flows through it.
Membrane Filtration	Microfiltration	Low-pressure driven (0.1-2 bar) membrane separation process (0.1-1 µm pore size) commonly used for the separation of macromolecules, bacteria, and suspended solids from a water solution.
	Ultrafiltration	Low-pressure driven (2-5 bar) membrane separation process (0.01-0.1 µm pore size) commonly used for the separation of macromolecules, colloids, suspended solids, and viruses from a water solution.
	Nanofiltration	Pressure driven (5-35 bar) membrane filtration (0.001-0.01 µm pore size) commonly used for the separator of divalent ions, viruses, bacteria, protozoa, and suspended solids from a water solution.
	Reverse Osmosis	Pressure-driven (15-70 bar) membrane technology for size exclusion (<0.001 µm pore size) for the concentration of seawater, brackish water or wastewater, and pure water recovery.
Separation Technologies	Alkoxy-silyl binders	Organosilane compounds used to chemically bond microplastics, enhancing adhesion and facilitating their agglomeration, followed by separation through flotation or filtration processes.
	Coagulation	Chemical process where coagulants (e.g., alum, ferric chloride) are added to destabilize particles, forming flocs that can be removed by sedimentation or filtration.
	Foam Fractionation	Method of separation that removes surfactants, proteins, and hydrophobic contaminants by generating foam, allowing pollutants to attach to bubble surfaces and be skimmed from the liquid phase.
	Dissolved Air Flotation	Separation process that clarifies water by releasing dissolved air, forming fine bubbles that lift suspended solids, oils, and other pollutants, to the surface for removal.
	Suspended Air Flotation	Physical separation process that uses pressurized, surfactant-coated air bubbles to lift particles to the surface for removal, targeting suspended solids, oils, and other pollutants.
	Ballasted Flocculation	High-rate clarification process that enhances sedimentation by adding ballast materials to coagulant-treated water, increasing the settling velocity of flocs and improving solids removal efficiency.
Biological Treatment	Membrane Bioreactor	Compact treatment method that combines a biodegradation process with membrane filtration, remove organics, suspended solids and pathogens.
Electro-chemical Systems	Electro-coagulation	Treatment method uses direct current applied to metal electrodes to release coagulant ions, which destabilize and aggregate contaminants for removal through sedimentation or flotation.

2.5. Technology Evaluation

The technology evaluation included 1) the development of the scoring system and 2) the application of the scoring system to each of the technology sub-classes. Note that, due to scarce data on microfiber reduction, i.e., where direct data was lacking, this evaluation uses the best available evidence and conservative estimates to ensure realistic, reliable scoring. First, a semi-quantitative scoring approach was developed, using both qualitative and quantitative criteria on technical performance, sustainability impact, and integration feasibility. A traffic light scoring system—Red (1), Yellow (2), and Green (3) with higher scores indicating better performance —was used to facilitate comparison across both qualitative and quantitative measures (see Table 10).

The traffic light categories were defined based on expert judgment. where red indicates poor performance, yellow represents a moderate or acceptable performance range, and green reflects high or best-in-class efficiency. The microfiber criteria were assigned a weighting factor given the framework's intention to elevate technology solutions to address microfiber emissions. Solution criteria were meant to provide a general high-level overview of the technology solutions and therefore were not scored. All other criteria across the remaining three categories (Sustainability, Cost, and Intervention) were weighted equally.

Table 10. Scoring Framework for Microfiber Mitigation Solutions

Criteria	**WF**	**Traffic Light**		
Microfiber Rating		**Red (1)**	**Yellow (2)**	**Green (3)**
Control Efficiency	3	< 50%	50 – 70%	> 70%
Downstream Effect	3	No	Probable	Yes
Overall Reduction (%)	3	< 10%	10% < X < 20%	> 20%
Control Mechanism	2	-	Capture/Removal	Shedding Reduction
Fate	2	Sludge; Effluent	Filtration Media; Backwash/Retentate	Destroyed; Foamate; Not Produced; Fabric attached/air
Microfiber Composition	2	-	Blend; Natural; Regenerated; Synthetic	All or a combination of 2 or more types
Particle Size Range	2	-	Control over ≤50 µm OR 50–100 µm OR ≥100 µm	Control over ≤50 µm AND 50–100 µm AND ≥100 µm
Sustainability Rating		**Red (1)**	**Yellow (2)**	**Green (3)**
By-Product Management Routes	1	High	Medium	Low
Energy Consumption	1	MT: Above baseline WW: Above baseline	MT: Similar to baseline WW: Slightly above baseline	MT: Below baseline WW: At or below baseline
Energy Savings	1	<50%	50 - 80%	> 80%
Water Savings	1	<49% / Not Applicable	50 - 80%	> 80%
Water Savings Mechanism	1	Not Applicable	Recycling	Reduction
Chemical Usage	1	-	Yes (Mention which chemicals)	No chemical usage
Chemical Savings	1	No savings	<50%	>50%
Other Benefits	1	Little to no benefits	Mild benefits	Excellent benefits
Cost Rating		**Red (1)**	**Yellow (2)**	**Green (3)**
CAPEX	1	MT: Above baseline WW: Above baseline	MT: Similar to baseline WW: Slightly above baseline	MT: Below baseline WW: At or below baseline

OPEX	1	MT: Above baseline WW: Above baseline	MT: Similar to baseline WW: Slightly above baseline	MT: Below baseline WW: At or below baseline
ROI	1	Long-term (>5y)	Medium-term (2-4 y)	Short-term (<2 y)
Intervention Rating		**Red (1)**	**Yellow (2)**	**Green (3)**
TRL	1	<7	7-8	9
Operational Complexity	1	Highly skilled Labor	Skilled Labor	Non-skilled labor
Land Footprint	1	Above baseline	Similar to baseline	Below baseline
Risk for Malfunction	1	Above baseline	Similar to baseline	Below baseline
Scalability	1	Limited	Moderate	High
Integration	1	Challenging	Moderate	Seamless
Limitations	1	Significant	Moderate	Minor
Adoption Rate	1	Demonstration (≤5 facilities)	Early Adopters (6 – 50 facilities)	Early & Late Majority (>50 facilities)

WF: Weighting Factor; MT: Manufacturing Technologies; WW: Wastewater Treatment Technologies.

Secondly, the scoring criteria were applied to each of the technology sub-classes. We evaluated technologies at the sub-class level to provide a representative assessment, however, there may be variation in performance across individual technology manufacturers within each sub-class. To ensure a thorough and balanced assessment, detailed information was compiled for each technology sub-class, including technical specifications, operational requirements, and performance parameters using peer-reviewed studies and industry reports. This was complemented by insights gathered through interviews with vendors and customers, which provided real-world perspectives on technology features, benefits, and limitations.

Using the best available information, each technology sub-class was scored against the criteria presented in Table 7. In cases where specific performance data—particularly for less commonly reported parameters such as microfiber rating parameters—was not publicly available, informed estimates were applied based on available data for the technology sub-class in question and observed trends across comparable technologies. For microfiber reduction, this included assessing factors known to influence shedding—such as abrasion and chemical use (Figure 3). All estimates were made conservatively to avoid overstating performance, ensuring alignment with tested capabilities and maintaining analytical consistency and rigor.

Finally, to validate the reliability of the information and assess practical feasibility, consultations were held with domain experts, including technology developers, industry practitioners, and academic researchers. While every effort has been made to ensure the reliability of the findings, the completeness and accuracy of certain estimates cannot be fully guaranteed. Decision-makers are encouraged to validate key data points, particularly those based on informed estimates, before relying on them for critical decisions.

2.6. Microfiber Release Through Textile Manufacturing

Total microfiber shedding from textile wet processing was estimated using data collected for baseline conditions on microfiber shedding and wastewater production and the total volume of fiber production. For each wet process, microfiber concentrations in wastewater were calculated by dividing the mass of microfibers per unit of fabric by the corresponding wastewater volume per unit of fabric (Table 11).To determine the average concentration of microfibers in the combined wastewater stream, a weighted average was applied, reflecting each process's relative contribution to total wastewater volume (Equation 1): $C_{MF,av}$ is calculated as the sum of the product of each process's wastewater volume $Q_{WW,i}$ and its microfiber concentration $C_{MF,i}$, divided by the total wastewater volume across all processes:

Equation 1. Formula for estimating weighted average microfiber concentration in combined textile effluent.

$$C_{MF,av} = \frac{\sum_{i=1}^{n} Q_{WW,i} \cdot C_{MF,i}}{\sum_{i=1}^{n} Q_{WW,i}} = \frac{Q_{WW,1} \cdot C_{MF,1} + Q_{WW,2} \cdot C_{MF,n} + \cdots Q_{WW,n} \cdot C_{MF,n}}{Q_{WW,1} + Q_{WW,2} + \cdots Q_{WW,n}}$$

Here, i refers to each individual wet processing stage (e.g., washing, bleaching, dyeing), and n is the total number of such stages considered in the analysis.

Table 11. Microfiber concentration (milligrams per liter) from textile wet processing calculated from the wastewater production (liters per kilogram of fabric) and the associated microfiber shedding (grams per kilogram of fabric).

Process	Wastewater Production (L/kg)[a]	Microfiber Shedding (g/ kg)	Microfiber concentration (mg/L)[a]
Desizing	7	0.34870	49.81
Scouring	6	0.34870	58.12
Bleaching	6	0.34870	58.12
Mercerizing	8	0.34870	43.59
Washing	14	0.58462	41.76
Bio-polishing	8	0.39276	49.10
Dyeing	30	0.53594	17.86
Printing	20	0.50089	25.04
Finishing	5	0.52500	105.00
Rinsing	6	0.16487	27.48

a) Wastewater production and microfiber concentration are equivalent to $Q_{WW,i}$ and $C_{MF,i}$ in Equation 1, respectively.

In 2023, global fiber production in the textile industry reached 124 million metric tons (MMT) per year (Textile Exchange, 2024). The total volume of wastewater for each wet processing stage and the associated microfiber concentration was estimated based on the production of 124 MMT of textiles and the process-specific wastewater production and microfiber concentration estimates (Table 11). Wastewater production and microfiber concentration were summed across all wet processing stages to provide the total wastewater production and microfiber emissions from textile manufacturing.

3. Results

3.1. Baseline Conditions

Textile Manufacturing Process

Textile manufacturing consists of four key stages, each encompassing a set of mechanical and/or chemical processes that contribute to the final product for the consumer:

1. **Raw Material Obtention:** Involves the cultivation, harvesting, and processing of natural fibers, the chemical transformation of raw materials into regenerated fibers, and the synthesis of polymers for synthetic fibers.
2. **Thread Manufacturing:** Thorough cleansing of the fiber for subsequent fiber separation, spinning, and twisting to produce a strong yarn.

3. **Fabric Manufacturing:** Interlacing yarns for further pretreatment to improve dye fixation to produce colored fabric.
4. **Textile Manufacturing:** Printing, cutting, sewing, marking, and final details to produce garments and textiles to be sold to the final consumer.

These stages contain dry and wet unit operations that transform raw materials into high-quality finished fabrics or garments. Figure 6 outlines the complete sequence of processes, both dry and wet, involved in textile manufacturing for the assumed baseline scenario. The production process begins with fiber preparation, followed by yarn formation, fabric production, and wet processing techniques that enhance fabric properties and aesthetics, ultimately leading to distribution and branding for consumer use. Dry processes, such as fiber preparation, spinning, weaving/knitting, and finishing steps, i.e., drying, heat setting, cutting, and sewing, do not involve water-based treatments. In contrast, wet processes (highlighted in blue), rely on water and chemicals to modify the textile's physical and chemical properties. Wet processes are particularly relevant to microfiber pollution due to their water-intensive nature and associated wastewater discharges; hence, they were assessed for their contribution to microfiber shedding (Table 12).

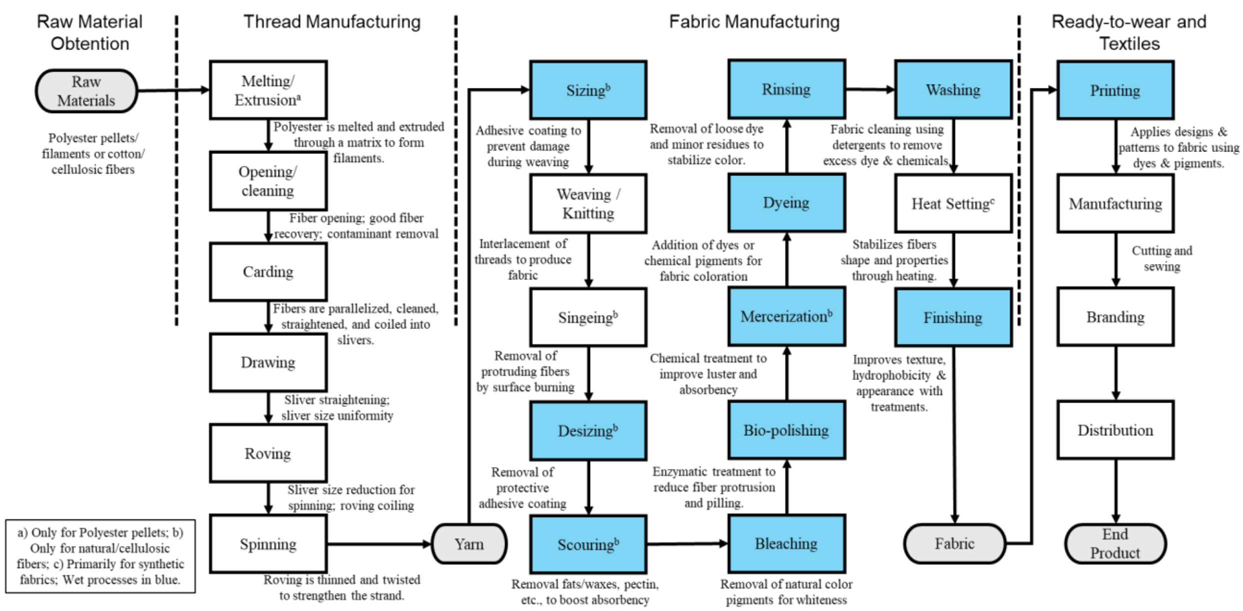

Figure 6. Flow diagram of the textile manufacturing process used in the baseline scenario. a) Process limited for polyester pellets; b) Process restricted to natural and cellulosic fibers; c) Process mainly applied in synthetic fabrics; Blue-colored boxes indicate wet processing stages.

Table 12. Common wet processing steps included in the baseline textile manufacturing scenario.

Wet Process	Definition
Sizing*	The application of a protective coating, typically starch-based or synthetic polymers, to warp yarns before weaving to strengthen them and reduce breakage.
Desizing*	The process of removing sizing agents from the fabric after weaving to prepare it for subsequent treatments like scouring and bleaching.
Scouring*	Cleaning raw textiles by removing natural impurities (oils, waxes, pectins, dirt) with alkaline solutions to make the fabric hydrophilic.
Bleaching	The removal of natural pigments or colorants from fabrics using oxidizing agents to produce a uniform white appearance.

Mercerizing*	Treating cotton or cellulose-based textiles with concentrated caustic soda under tension to enhance luster, strength, dye uptake, and stability.
Bio-Polishing	Using enzymes (e.g., cellulases) to remove microfibrils or loose fibers from fabric surfaces to prevent pilling and enhance smoothness.
Dyeing	Adding color to textile materials (fibers, yarns, or fabrics) using dyes in aqueous solutions or other media at various stages of production.
Rinsing	The process of removing excess chemicals, dyes, and impurities from textiles after chemical treatments or dyeing to ensure clean, ready-to-process fabrics.
Washing	The thorough cleaning of textiles using water and detergents or soaps to remove soils, impurities, and residual chemicals from the fabric to ensure it meets quality and hygiene standards.
Printing	Applying patterns or designs onto textiles using dyes or pigments through methods like screen, digital, or roller printing.
Finishing	Final treatments to textiles that enhance performance, appearance, or functionality, such as water repellency, wrinkle resistance, or flame retardancy.

* These processes are primarily used for treating cellulosic fibers.

Baseline Operating Conditions

Baseline operating conditions were established for each stage of wet processing including microfiber shedding, water use, wastewater generation, energy consumption (Table 13), and chemical use (Table A 4). These conditions provide the quantitative foundation used to compare the impact of new technology interventions on microfiber shedding and overall sustainability (water efficiency, wastewater pollution, energy efficiency, and chemical use). Referenced results for each parameter's baseline conditions are included in Appendix A.

Table 13. Baseline operating conditions for microfiber shedding (grams per kilogram of fabric), water consumption (liters per kilogram of fabric), waster production (liters per kilogram of fabric), and specific energy consumption (SEC, kilowatt-hours per kilogram of fabric) in each stage of textile wet processing.

Process	Microfiber Shedding (g/kg)	Particle Size Range (µm)	Water Consumption (L/kg)	Wastewater Production (L/kg)	SEC (kWh/kg)
Sizing	--	--	2	--	0.032
Desizing	0.34870	50 – 400 µm	10	7	0.6
Scouring	0.34870	50 – 400 µm	8	6	1.0
Bleaching	0.34870	50 – 400 µm	20	14	1.5
Mercerizing	0.34870	50 – 400 µm	10	8	0.3
Washing	0.58462	50 – 400 µm	8	6	0.5
Bio-polishing	0.39276	50 – 250 µm	10	8	0.25
Dyeing	0.53594	50 – 400 µm	40	30	5.0
Printing	0.50089	100 – 1000 µm	25	20	3.5
Finishing	0.52500	150 – 800 µm	8	5	2.0
Rinsing	0.16487	50 – 400 µm	10	6	0.15

3.2. Technology Evaluation

Manufacturing based solutions

A total of 19 textile manufacturing innovations were evaluated for the microfiber shedding reduction in textile production using the framework (see Table 14). The technology sub-classes were scored, following the criteria set out in Table 10, with higher scores indicating higher performance in each rating, while the total score (TS) represents the sum of all individual ratings. Each technology sub-class was classified based on the production stage at which the technology is applied and assessed on all criteria included in the microfiber, sustainability, cost, and intervention ratings.

Table 14. Comparative assessment of textile manufacturing innovations. Individual metrics use a green-to-red scale—green for strong, yellow for moderate, and red for poor performance—based on a linear ranking of values. The Total Score column uses a blue-to-red gradient, where blue indicates the highest overall scores, red is the lowest, and white represents mid-range values. Both gradients follow a percentile-based range, with darker colors showing extremes and lighter shades indicating intermediate performance levels.

Technology Sub-class	Stage	Microfiber Rating	Sustainability Rating	Cost Rating	Intervention Rating	Total Score
Chemically-engineered dyeing	Scouring	44	17	7	22	90
Pigment Dyeing	Dyeing	36	21	8	22	87
Dope Dyeing	Dyeing	35	21	7	23	86
Spray Finishing	Dyeing	37	19	7	21	84
Direct Digital Printing	Printing	41	22	5	15	83
Spray Dyeing	Dyeing	34	22	8	18	82
Supercritical Fluid Dyeing	Finishing	38	22	4	17	81
Ultrasonic Dyeing	Bleaching	36	19	5	20	80
Biological Dyeing	Finishing	36	21	8	15	80
Digital Dyeing (Fabric)	Dyeing	36	21	7	15	79
Microfiber Air Removal	Dyeing	38	16	7	17	78
Digital Dyeing (Yarn)	Dyeing	35	17	6	20	78
Transfer Digital Printing	Printing	35	21	5	17	78
Hybrid Digital Printing	Printing	35	21	5	16	77
Supercritical-assisted dyeing	Dyeing	33	20	4	16	73
Spray Bleaching	Dyeing	29	19	5	17	70
Non-water Solvent Dyeing	Dyeing	29	17	5	17	68
Catalytic Scouring	Scouring	26	18	7	16	67
Natural Dyes	Dyeing	28	13	5	18	64

The highest-ranking solution, Chemically-engineered Dyeing (TS 90) is a single-bath process that combines pretreatment and dyeing using multifunctional chemicals, saving 60% water, 50% energy, and up to 90% chemicals. Combining these processes cuts microfiber shedding by an overall 50% across pretreatment, dyeing, washing, and rinsing, and even in consumer-phase washes through optimized liquor-to-fabric ratios and shorter processing times. With no new equipment needed, it's ideal for water-stressed, high-tariff, or regulated mills, and brands addressing microfiber pollution. Operating at TRL 9 with no CAPEX but higher OPEX, it offers a practical sustainability upgrade, though it is suited for batch processes, and performance varies by fiber, color, and chemical dosing.

Pigment Dyeing (TS 87) is a waterless process that applies insoluble pigments to fabric surfaces and fixes them with heat, avoiding chemical fixation, washing, and rinsing. With a TRL of 9, it is estimated to reduce microfiber shedding by 20%, save 95–99% water, and eliminate salt use. Ideal for cotton and blends, it offers a fast setup, simple operation, and no CAPEX, though it’s limited to light shades and woven fabrics and has a slightly higher OPEX, offering a variable to immediate ROI. Therefore, it is best suited for mills in water-stressed areas with controlled drying systems.

Dope Dyeing (TS 86), is a waterless dyeing method where pigment chips are incorporated directly into the polymer solution before fiber extrusion, creating uniformly colored synthetic fibers. This dry process reduces microfiber shedding by 13% across textile wet processing. It achieves 30–40% energy savings and 100% water savings, with no need for post-dyeing chemicals. Pigment chip use cuts chemical inputs by 90%, and GHG emissions are lowered by up to 40% due to reduced processing energy. While CAPEX and OPEX are similar to baseline systems offering a variable to immediate ROI. It requires minimal operator skill but depends on continuous pigment chip supply and suitable extrusion conditions. With high scalability and low malfunction risk, Dope Dyeing is ideal for mills producing synthetic textiles in fewer color variations and seeking a robust, sustainable alternative to traditional wet dyeing.

Spray Finishing (TS 84) is a closed-chamber spray technology sub-class, that delivers uniform application of low-viscosity finishing agents via precision-controlled valve systems. It reduces overall microfiber shedding by an estimated 10%, achieves 50–90% water savings, 99% energy savings, and 40–50% chemical savings. With a TRL of 9 and a compact 10 m^2 footprint, it supports modular scalability for high-throughput production and requires skilled labor for accurate formulation and spray consistency. While its effectiveness depends on maintaining agent viscosity below 8 CPS and managing batch-specific cleaning, it has similar CAPEX and OPEX to baseline systems and a short ROI (0.5–1.8 years). This makes it ideal for mills in water-stressed or high-tariff regions and those facing discharge or water reuse pressures.

Direct Digital Printing (TS 83) is a market-ready, waterless technology sub-class using ink heads to print directly onto the fabric, reducing overall microfiber shedding by 10%, and saving over 90% water and over 70% energy Fully electric with a compact 100 m^2 footprint (TRL 9), it enables plug-and-play use but requires precise calibration and leveling, and printhead clogging, fabric jams, and dust pose moderate risks. While automation lowers risks, skilled labor is still needed for alignment and maintenance. High CAPEX and slower throughput make this sub-class unsuitable for large-scale use. It fits best in greenfield mills with small-batch or shifting production needs—especially in regions with water stress, high energy costs, or strict discharge limits.

Spray Dyeing (TS 82) is a closed-chamber, spray-based dyeing system that eliminates padders and uses precision nozzles to apply low-viscosity dyes efficiently. It achieves an estimated 20% overall reduction in microfiber shedding, 90% water and energy savings, and 10% less dyestuff use, zero salt discharge. With a TRL of 9 and a compact 36 m² footprint, it operates in batch mode with modular scalability. Though dye fixation takes 4–20 hours, it offers similar CAPEX, lower OPEX, and a short ROI (1.4–3 years). Hence, it is ideal for mills in hot, water-stressed regions with high energy costs or strict discharge limits.

Supercritical Fluid Dyeing (TS 81) is a waterless dyeing technology sub-class that uses supercritical CO_2 to dye polyester fabrics, influencing both dyeing and industrial washing/rinsing processes. It reduces microfiber shedding by an estimated 20% through interventions such as reducing the liquor-to-fabric ratio, chemical use, and process duration. The system achieves 100% water savings, 60% energy savings, and 50% dyestuff reduction with no wastewater production. With a TRL of 9 and a compact 150 m² footprint, it is fully automated but requires skilled operators due to high-pressure operation. Despite strong sustainability and microfiber performance, adoption is hindered by high CAPEX which commonly results in a long-term ROI. Hence, it is best suited for greenfield textile mills with capacities above 10 tons/d.

Ultrasonic Dyeing (TS 80) is a waterless textile dyeing technique that uses high-frequency sound waves to generate cavitation bubbles in the dye bath, enhancing dye penetration into fiber pores. Operating at TRL 9 with a compact 10–15 m² footprint, it is a batch process that reduces microfiber shedding by 16%. The system claims a 60% energy saving, 80% water reduction, full dye fixation, and eliminates all pre- and post-dyeing chemical steps and steam use. While CAPEX is similar to conventional systems, OPEX may be higher due to energy use, though a short-term ROI is reported. Integration is straightforward, but skilled labor is needed to monitor parameters like frequency and temperature. With low mechanical failure risk and medium scalability, it suits mills seeking to reduce effluent discharge and improve operational efficiency in batch-mode processing.

Biological dyeing (TS 80) uses engineered microbes and renewable feedstocks to produce dyes, eliminating hazardous chemicals and enabling easy integration with existing equipment. It reduces microfiber shedding by 20% due to lower liquor ratios, reduced chemical use, and shorter processing times in dyeing, washing, and rising. The process offers 70–80% water savings, 20–35% energy savings, and fully replaces conventional dye chemicals with onsite dye production. With a TRL of 9, it has moderate CAPEX and low OPEX, making it suitable for regions with strict water regulations. Key limitations include a limited color range, sensitivity to bioreactor failures, and slower dye production, requiring skilled oversight and careful supply chain management.

Digital Fabric Dyeing (TS 79) uses precision dyeing with in-line drying and fixation and is estimated to reduce microfiber shedding by 25%. It targets shedding during dyeing, washing, and rising by reducing liquor-to-fabric ratios and dye overuse. The system significantly reduces wastewater production and delivers 90–95% water savings, 60–85% energy savings, and 30% chemical savings. Scalability is high, though skilled labor is required, and nozzle clogging remains a manageable risk. With a TRL of 8, it is best suited for greenfield setups due to high CAPEX but offers 50% lower OPEX and fast ROI (1–1.5 years).

The following technology sub-class is worth highlighting for its potential in microfiber control; however, it scored lower in this assessment due to its early stage of development. Microfiber Air Removal (TS 78) is a dry, pre-distribution microfiber control device that captures loose fibers through controlled air suction and surface filtration. It enables a reduction in the consumption phase, equivalent to a 14% reduction in microfiber release during the wet processing stages. While its adoption introduces an additional process that increases energy use at the mill—raising operational costs and potentially offsetting some sustainability gains—it offers a compact footprint (3–5 m²), plug-and-play design, and operability by non-skilled labor. Despite limited capacity and some clogging risk, its low OPEX and moderate CAPEX make it appealing for early adopters focused on sustainability. The technology sub-class is currently at TRL 7.

In summary, Chemically-engineered Dyeing ranks highest for sustainability and microfiber reduction, achieving up to 50% shedding reduction across all wet processing stages and delivering strong water, energy, and chemical savings without requiring new equipment. Pigment Dyeing and Dope Dyeing follow closely, offering near-total water savings and strong reductions in chemicals and energy, with Dope Dyeing also lowering GHG emissions by 40%. Spray Finishing and Direct Digital Printing provide modular, waterless finishing and printing options with additional shedding control, ideal for mills facing water stress or discharge restrictions. Spray Dyeing and Supercritical Fluid Dyeing offer robust performance in polyester or batch applications but face trade-offs in dye fixation time or CAPEX. Biological and Digital Fabric Dyeing show promising performance with growing scalability, while Microfiber Air Removal offers future potential despite its early development stage.

Wastewater treatment technologies

A total of 19 wastewater treatment technologies were evaluated for the capture and removal of microfibers in textile effluents using the framework (see Table 15). The technologies sub-classes were scored, following the criteria set out in Table 10, with higher scores indicating higher performance in each rating, while the total score (TS) represents the sum of all individual ratings. Each technology sub-class was classified based on the treatment stage at which the equipment is applied and assessed on all criteria included in the microfiber, sustainability, cost, and intervention ratings.

Table 15. Comparative assessment of wastewater treatment technologies. Individual metrics use a green-to-red scale—green for strong, yellow for moderate, and red for poor performance—based on a linear ranking of values. The Total Score column uses a blue-to-red gradient, where blue indicates the highest overall scores, red is the lowest, and white represents mid-range values. Both gradients follow a percentile-based range, with darker colors showing extremes and lighter shades indicating intermediate performance levels.

Technology Sub-Class	Stage	Microfiber Rating	Sustainability Rating	Cost Rating	Intervention Rating	Total Score
Microfiltration	Tertiary	29	17	6	21	73
Ultrafiltration	Tertiary	29	17	6	21	73
Membrane Bioreactor	Secondary	29	18	7	18	72
Cartridge Filtration	Tertiary	26	17	8	20	71
Disc Filtration	Tertiary	26	16	9	20	71
Basket Strainers	Tertiary	26	16	8	20	70
Microstrainers	Tertiary	26	16	8	20	70
Dissolved Air Flotation	Primary	27	14	8	20	69
Suspended Air Flotation	Primary	27	15	8	19	69
Electrocoagulation	Primary	27	16	7	18	68
Bar Screens	Pretreatment	21	15	9	22	67
Coagulation	Primary	21	15	9	21	66
Drum Screens	Pretreatment	21	15	9	20	65
Microfiber Filter	Tertiary	26	15	6	14	61

Nanofiltration	Tertiary	27	14	3	16	60
Reverse Osmosis	Tertiary	27	14	3	16	60
Ballasted Flocculation	Primary	24	14	5	16	59
Foam Fractionation	Tertiary	25	13	4	15	57
Alkoxy-silyl binders	Primary	22	14	6	11	53

Ultrafiltration (UF; TS 73) and microfiltration (MF; TS 73) are membranes-based technologies with pore sizes of 0.01–0.10 µm and 0.1–1.0 µm, respectively, and are effective for complete (or near complete) microfiber removal in tertiary treatment or direct filtration. They offer 85–95% water recovery, strong filtration performance, and easy scalability by adjusting membrane modules. Though energy-intensive (0.2–0.3 kWh/m^3) and requiring skilled operation, both systems include automated monitoring but generally require pre-filtration to limit fouling. Regular cleaning is needed, but their compact footprint (2–3 m^2), moderate costs, and medium-term ROI make them suitable for advanced reuse applications.

Membrane Bioreactor (MBR; TS 72) combines biological treatment with membrane filtration (MF or UF) to biodegrade organics and remove microfibers and textile dyes, achieving high COD removal, near-complete BOD removal (≈2 g/m^3) and complete TSS removal. By eliminating secondary clarifiers and separate filtration, it reduces land footprint and simplifies layouts. Its modular design enables >80% water recovery through effluent recycling, lowering freshwater use and sludge production. Fouling is managed via aeration, backflushing, or cleaning agents. Though energy intensive (1–1.3 kWh/ m^3) and requiring skilled labor, MBRs are scalable and well-suited for microfiber control and water reuse, with short-term ROI and moderate CAPEX and OPEX.

Among other notable alternatives, Cartridge filtration (TS 71) stands out as a compact, modular solution for microfiber control in tertiary wastewater treatment. It removes suspended solids and microfibers among other pollutants, through mechanical surface or depth filtration, with 70–99% efficiency for microfibers sized 1–100 µm. Using media like polypropylene, PTFE, or stainless steel, it offers moderate CAPEX, a small footprint (2–3 m^2), and easy operation. While energy use is low (0.04–0.06 kWh/m^3), frequent cartridge replacement under high solids loads adds to OPEX. The technology sub-class integrates easily as a polishing filter, offers quick ROI, and is scalable via modular cartridges, though performance may drop with microfiber buildup, especially finer ones.

Disc filtration (TS 71) is a polymeric disc-based surface filtration technology sub-class designed for solids and microfiber control in wastewater pretreatment and tertiary stages. It achieves 40–98% removal efficiency for suspended solids, microfibers, and other pollutants, safeguarding downstream systems and enhancing effluent quality. Automated backwashing enables continuous operation with limited manual intervention, though skilled labor is needed to monitor performance and cleaning cycles. The system has a compact footprint (0.8–1.2 m^2) and is scalable to different flow rates, making it suitable for retrofit and new textile facility installations. Energy use is moderate (0.03–0.08 kWh/m3), but frequent maintenance is needed under high solids conditions, and filtered microfibers must be managed via sludge disposal. Although initial CAPEX is high, OPEX remains low, and short-term ROI is possible in high-load or precision filtration applications.

Finally, Basket strainers (TS 70) and Microstrainers (TS 70) are surface filtration systems used in the pretreatment and tertiary stages of wastewater treatment to remove large particulates and microfibers through mechanical screening. Operating with 70–95% removal efficiency across a particle size range of 50–1000 µm, they are typically implemented upstream of pumps and valves to safeguard downstream systems. Strainers require skilled labor for regular monitoring, cleaning, and maintenance due to the risk of clogging, especially when fine mesh screens are used. Though energy consumption is low (0.02–0.04 kWh/m³) and CAPEX/OPEX are minimal. Their footprint (1.5–2 m²) and modular mesh configurations enable adaptability to different flow and particle loads, but mechanical removal requires additional waste handling and disposal. Despite limitations, strainers provide short-term ROI and low operational complexity, making them a practical, low-cost option for basic solids removal in textile and industrial wastewater systems.

Suspended Air Flotation (SAF; TS 69) and Dissolved Air Flotation (DAF; TS 69) are primary physicochemical treatment processes that use microbubbles (10–120 µm)—with SAF also using surfactants—to float suspended solids, microfibers, dyes, and fats for removal. With proper chemical dosing, they can achieve over 90% solids removal and over 70% dye removal. Designed for high-strength effluents, both systems are modular and scalable, typically including air-saturation tanks, chemical dosing units, and surface skimmers. While relatively energy-intensive (0.06–0.08 kWh/m³) and dependent on skilled operation, they offer a compact footprint (13–16 m²), quick ROI, and reliable performance across textile wastewater types. A key consideration is sludge generation—often rich in microfibers—which adds to OPEX due to dewatering and disposal needs. Still, these systems markedly improve effluent clarity, especially in textile wastewater.

Finally, Electrocoagulation (TS 68) offers contaminant removal performance comparable to air flotation systems without requiring external chemical dosing, as it produces coagulants directly onsite. This can result in a shorter return on investment under certain conditions. However, the process is both energy intensive, with consumption ranging from 1 to 1.7 kWh/m³, and capital intensive, which may limit its practicality for smaller facilities. It also requires frequent replacement of sacrificial anodes, typically every two to four months. Additional challenges include electrode fouling and reduced effectiveness when treating low-conductivity wastewater, which can impact overall operational reliability. However, Electrocoagulation offers a clear improvement over traditional coagulation and flocculation for removing microfibers, colloids, and dye-related compounds.

In summary, Microfiltration and Ultrafiltration emerge as the most robust solutions for comprehensive fiber and TSS removal, offering a strong balance of performance, scalability, and suitability for reuse applications. Membrane Bioreactors are also highly effective, particularly where integrated biological treatment is beneficial. Moreover, advanced treatment like MF, UF, and MBR produce high-quality effluent suitable for indirect reuse, making them an attractive solution especially in water-stressed regions with strong reuse regulations. Cartridge and disc filtration systems provide accessible, moderate removal capabilities, while flotation-based systems and electrocoagulation serve as specialized options for more complex wastewater matrices. For simpler applications, strainers remain viable, though their limitations must be carefully weighed.

4. Discussion

In 2023, global fiber production in the textile industry reached 124 MMT per year (Textile Exchange, 2024) resulting in an estimated 13.64 billion cubic meters (B m³/y) of wastewater and 508,260 metric tons (MT/y) of microfiber emissions into the environment (Table A 5). Addressing the scale of microfiber pollution in the textile industry requires a holistic approach. This is because no single action or technology class can provide a comprehensive solution in all contexts. While outside of the scope of this report, low or no-cost steps to optimize existing operations can be an important first step to reduce microfiber pollution and may provide additional reductions when combined with technology solutions evaluated here. A combination of technologies, tailored to the specific regional and operational conditions of each textile mill may offer a more comprehensive approach to addressing pollution than any singular technology. This integrated strategy can optimize environmental performance, cost-effectiveness, and resource efficiency. In this regard, by reducing microfiber shedding at the source and capturing residual fibers in wastewater, textile mills can significantly lower fiber pollution while also conserving water, energy, and chemicals, and achieving co-benefits such as reduced greenhouse gas emissions.

However, there are various challenges regarding microfiber pollution in the textile industry. First, it is necessary to understand microfiber shedding in both liquid and dry processes. This is highlighted by the fact that research in this area remains limited, as most have focused on the textile consumer phase (Rathinamoorthy & Raja Balasaraswathi, 2020). Likewise, textile producers and brands must agree on a standardized method to facilitate peer comparison (The Microfiber Consortium & Fashion For Good, 2025). Similarly, wastewater treatment for microfibers faces challenges, as most systems are designed for solids, organics, and dye removal among others rather than for microfiber removal. Hence, counting methods need to be in place to measure and compare microfiber control performance across technologies. Establishing these benchmarks is vital for tracking microfiber contamination, driving innovation in the sector, and assisting in decision-making.

Second, only two wet processing manufacturing technologies have been evaluated based on microfiber shedding reduction. Microfiber Air Removal is designed to remove microfibers adhered to garments before distribution, aiming to reduce shedding in the consumption phase. Chemically-engineered Dyeing was designed based on water, energy, and chemical conservation, which are complemented by its microfiber shedding reduction during pre-treatment, dyeing, washing, and even in consumer use. For other manufacturing technologies, microfiber reduction was estimated on process fundamentals and their effect on shedding influencing factors, i.e., reduced abrasion, chemical use, etc. (Figure 3), rather than direct technology-specific testing. Consequently, technology developers are encouraged to validate these estimates through targeted testing.

Treatment technologies may offer versatility in removing a range of microfiber types across variable wastewater production and pollutant loading, they require research on the final destination of the microfibers either on the effluent or in the byproducts such as the sludge to prevent the reinsertion of the captured microfibers (Alibekov et al., 2025). Therefore, it is worthwhile for technology developers, producers, and brands to work together to evaluate microfiber reduction within textile processes as well as in the industry's wastewater. Existing life cycle assessment (LCA) frameworks can likely be augmented to accomplish this by including microfiber reduction alongside existing environmental impact categories, such as eutrophication potential, acidification potential, global warming potential, ozone depletion, abiotic resource depletion, freshwater use, and cumulative energy demand, among others, (Bates & Townsend, 2025; Henry et al., 2019b). Although LCAs in wastewater treatment are less common, their implementation is growing, and they could also be extended to evaluate the end-of-life of microfibers (Alibekov et al., 2025).

Third, the adoption of these technologies will not be uniform, as regional conditions vary based on economic development, regulations, and market pressures. Some textile mills may benefit from client-driven sustainability incentives along with progressive regulation, while others face barriers due to infrastructure limitations and the high upfront cost of technologies. Nevertheless, while these solutions may require significant initial investment, they often provide long-term economic value and immediate sustainability gains that must be accounted for in the ROI. For example, reductions in microfiber shedding, energy use, and water consumption contribute not only to environmental performance but also to brand reputation and compliance with emerging regulatory standards (Yu et al., 2023).

Fourth, microfiber contamination should not be seen as an isolated phenomenon, as it is fundamentally part of one of the dimensions of water risk in the textile industry. Water is central to every stage of textile production, from the procurement of raw materials (from the production of cotton or other cellulosic materials, as well as synthetic fiber filaments), to the production processes, intervening indirectly in some dry processes and directly in wet processes during which microfibers are often released. Therefore, microfiber contamination is interrelated with broader water sustainability challenges such as climate change, and pollution, which is exacerbated due to microfibers' capacity to transport chemical additives and toxicants degrading water quality and affecting the surrounding biota, and rising demand for clothing.

Consequently, addressing microfiber pollution requires focusing on interventions within a broader framework of environmental stewardship in the textile industry. However, major textile production hubs such as countries in South Asia and Southeast Asia, Western Europe, and Southern Europe, as well as Türkiye, Central Mexico, and South Brazil, known as hotspots for water vulnerability must be prioritized (Planet Tracker, 2024; WWF & OSH, 2022). In this regard, microfiber control strategies must align with local hydrometeorological stressors such as extreme weather, flooding, water scarcity, and related phenomena, to guarantee that the mitigation efforts are both effective and sustainable.

Ultimately, microfiber control is a strategic opportunity for the textile sector to align sustainability pillars, i.e., environmental protection, social equity, and economic efficiency together with innovation. Nevertheless, the latter requires coordinated investment, harmonized regulation, and collective action across the value chain, especially among lower-tier suppliers in developing countries where enforcement and financing are weak. This is where brands must step in, leading pilots and programs along with public-private partnerships that embed microfiber control into sourcing criteria and providing incentives to drive technological adoption across supply chains.

These challenges – in particular insufficient microfiber shedding data, a lack of standardized measurement methods, and regional disparities, among others – highlight the complexity of effectively addressing microfiber pollution and emphasize the need for a structured and adaptable approach that can address this variability. While scarce data together with the complexity of the framework and the comparisons made, the framework presented here has been designed with versatility in mind, guided by the rationale that when facility-specific data is applied, it allows for tailored assessments that identify the most appropriate and impactful technology combinations to ensure that decision-making is not only technically sound but also contextually relevant.

In summary, microfiber control is not just a technical necessity, it is a strategic opportunity to link sustainability and innovation. By focusing on regions with high textile production, and therefore the greatest risk of microfiber pollution, and by aligning control technologies with local infrastructure and manufacturing practices, the textile sector has an opportunity to lead in addressing this growing environmental challenge. Fortunately, the framework presented here provides a clear roadmap for the assessment of solutions to cope with microfiber pollution across textile manufacturing and supports a broader industry paradigm shift, enabling the textile industry to adopt innovative, technically sound, and environmentally friendly solutions that protect ecosystems and public health from microfibers.

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6. Appendix A

Table A 1. Microfiber shedding in textile wet processes in grams (g) of microfibers per kilogram (kg) of fabric.

Process	Microfiber Shedding (g/ kg)	Particle Size Range [a]	Reference
Desizing	0.34870	50 – 400 μm	(M. Wang et al., 2023)
Scouring	0.34870	50 – 400 μm	(M. Wang et al., 2023)
Bleaching	0.34870	50 – 400 μm	(M. Wang et al., 2023)
Mercerizing	0.34870	50 – 400 μm	(M. Wang et al., 2023)
Washing	0.58462	50 – 400 μm	(M. Wang et al., 2023)
Bio-polishing	0.39276	50 – 250 μm	(Grillo et al., 2023)
Dyeing	0.53594	50 – 400 μm	(M. Wang et al., 2023)
Printing	0.50089	100 – 1000 μm	(Rathinamoorthy & Raja Balasaraswathi, 2023a)
Finishing	0.52500	150 – 800 μm	(Zambrano et al., 2021)
Rinsing	0.16487	50 – 400 μm	(M. Wang et al., 2023)

a) Estimated based on particle size distribution reported in the table references.

Table A 2. Water use and wastewater production in textile wet processes in liters (L) per kilogram (kg) of fabric.

Process	Water Consumption (L/kg)	Wastewater Production (L/ kg)	Reference
Sizing	2	-	-
Desizing	10	7	(Roth et al., 2023)
Scouring	8	6	(Roth et al., 2023)
Washing	20	14	(Roth et al., 2023)
Bio-polishing	10	8	(Marzoug & Cheriaa, 2023)
Bleaching	8	6	(Kumar & Pavithra, 2019)
Mercerizing	10	8	(Kumar & Pavithra, 2019)
Dyeing	40	30	(Roth et al., 2023)
Printing	25	20	(Roth et al., 2023)
Finishing	8	5	(Roth et al., 2023)
Rinsing	10	6	(Roth et al., 2023)
Total	151	110	

Table A 3. Specific energy consumption (SEC) in textile wet processes in kilowatt-hours (kWh) per kilogram (kg) of fabric.

Process	SEC (kWh/kg)	Reference
Sizing	0.032	(Koç & Çinçik, 2010)
Desizing	0.6	(Roth et al., 2023)
Scouring	1	(Roth et al., 2023)
Washing	1.5	(Roth et al., 2023)
Bio-polishing [a]	0.3	-
Bleaching	0.5	(Roth et al., 2023)
Mercerizing	0.25	(Roth et al., 2023)
Dyeing	5.0	(Roth et al., 2023)
Printing	3.5	(Roth et al., 2023)
Finishing	2	(Roth et al., 2023)
Rinsing[b]	0.15	-
Total	14.83	

a) Estimated at 50% of desizing SEC due to lower temperature and shorter process duration.
b) Estimated at 10% of washing SEC due to shorter process duration.

Table A 4. Types of chemicals commonly used in the wet processing stages of textile manufacturing.

Process	Chemicals used	Reference

Sizing	Lubricants: Tallow-based wax (synthetic tallow like polyethylene glycol and polypropylene glycol can be used). Film formers: Starch, modified starch (ethers or esters), carboxymethyl cellulose (CMC), polyvinyl alcohol (PVA), polyacrylate, polyacrylamide, and polymethyl acrylate	(H. Wang & Memon, 2020)
Desizing	Hydrolytic methods: diluted sulfuric acid (H_2SO_4) or hydrochloric acid (HCl) for acid steeping, amylase (enzyme steeping). Oxidative methods: Chlorine gas* (Cl_2), sodium chlorite* ($NaClO_2$), sodium bromite* ($BrNaO_2$), hydrogen peroxide (H_2O_2), sodium persulfate ($Na_2S_2O_8$), ammonium persulfate [$(NH_4)_2S_2O_8$], potassium persulfate ($K_2S_2O_8$).	(H. Wang & Memon, 2020)
Scouring	Sodium hydroxide (NaOH), trichloroethylene cyclohexanol, methylhexanol, chelating agents, sodium carbonate,	(H. Wang & Memon, 2020)
Bleaching	H_2O_2, sodium silicate (buffer), NaOH	(H. Wang & Memon, 2020)
Bio-polishing	Cellulases	(H. Wang & Memon, 2020)
Mercerization	NaOH, Liquid ammonia (NH_3)	(Choudhury, 2017)
Dyeing	Sodium chloride (NaCl), reactive dyes (Mono-fluoro-triazynylamino, Dichloro-triazynilamino, Mono-chlorotriazynylamino, Bis–Triazinyl, Vinyl sulfone), sodium sulfide, sulfur dyes, Azo dye, diazonium salt, aromatic amines, basic dyes, thiox, sodium hydrosulfite, zinc, NaOH, Indigo dye, Vat dye, Direct dye, sodium sulfate (Na_2SO_4), Natural dyes, Disperse Dye, Acid Dye, Vat Dye.	(H. Wang & Memon, 2020)
Washing	Detergent & Softeners	(De Falco et al., 2018)
Finishing	Starch, Fillers (Kaolin, Talc, Calcium Sulphate), Softeners (Anionic, Cationic, Amphoteric, Nonionic, Reactive, Silicone), Antiseptics (zinc & magnesium chloride, etc.), Synthetic Polymers (PVA, PVME, etc.), Water-proof agents (Metal Salts, Paraffin, PFHA), Flame retardants (Aluminium trihydroxide, THPC), Stability Agents (Urea-formaldehyde, Chitosan), Antibacterial agents [Phenolic compounds, quaternary ammonium salts organometallic Compounds (Mercury; Hg)]	(Choudhury, 2017)
Printing	Thickeners (starch, plant gum (Arabic, Tragacanth, Sodium alginate, etc.), Cellulose derivatives (CMC, Methyl Cellulose, Glycol Cellulose), Hygroscopic Agents (thiourea, urea, thiodiethylene glycol), Dye (Disperse, Vat, Direct, Acid, Metal Complex, Azo, Reactive, Pigment, etc.), NaOH, potassium hydroxide (KOH), Defoamers (pine oil, TBP, silicone-based & non-silicone-based), Reducing agents (sodium, zinc or calcium formaldehyde sulphoxylate, thiourea dioxide), Oxidizing agents (Potassium chlorate, Sodium chlorate), Dispersing agents (Dibutyl Carbitol, Diethyl Carbitol), Wetting agents (Turkey Red Oil), Swelling agents (phenol, resorcinol, benzoic acid, DEGDA)	(Kolanjikombil, 2025)

	Binders (Styrene, Vinyl acetate), Resist agents (acetic acid, citric acid, ammonium chloride, ammonium sulphate)

*not eco-friendly so its use in desizing has been reduced/restricted.

Table A 5. Total wastewater production (billions of cubic meters) and associated microfiber release (thousands of metric tons) from the production of 124 million metric tons of fibers in 2023.

Process	**Wastewater (B m3/y)**	**Total microfiber release (1000 MT/y)**
Desizing	0.868	43.24
Scouring	0.744	43.24
Bleaching	0.744	43.24
Mercerizing	0.992	43.24
Washing	1.736	72.49
Bio-polishing	0.992	48.70
Dyeing	3.72	66.46
Printing	2.48	62.11
Finishing	0.62	65.10
Rinsing	0.744	20.44
Total	13.64	508.26