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From production to pollution: a review of microfiber release mechanisms and mitigation strategies in the textile industry

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ABSTRACT

Microfiber pollution, a subset of microplastics, has arisen as a serious environmental and health issue, driven by the widespread use of textiles and the worldwide extent of microplastic contamination. Microfibers, which come from primary sources such as textile manufacturing and secondary processes such as garment fragmentation, are ubiquitous contaminants with far-reaching environmental and human health consequences. This review examines the origins, pathways and impacts of microfiber pollution, with a focus on the textile industry's role and potential solutions. Bibliometric analysis reveals a sustained research interest in microfiber-related challenges and solutions, with publications peaking in 2022. Advancements in textile manufacturing methods, the use of biodegradable fibers, the integration of filtration systems in washing machines, advanced wastewater treatment technologies and the implementation of legislative frameworks such as the European Union (EU) Green Deal are all important strategies for addressing microfiber pollution. Collaboration among industry, governments, R&D institutions and consumers is critical to reducing microfiber release and promoting sustainable practices.

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Microfiber pollution; microplastics; textile industry; laundry emissions; environmental pollution

1. Introduction

The definition of microplastics (MPs) remains a topic of ongoing discussion. ISO/TR 21960 (2020) classifies plastic particles based on size, categorizing those over 5 mm as macroplastics, 1–5 mm as large microplastics, particles between 1 mm and 1 μ m as microplastics, and those under 1 μ m as nanoplastics. According to ISO 4484-2 (2023), microplastics are defined as solid polymer materials containing additives or other substances, where at least 1% by weight consists of particles with sizes between 100 nm and 5 mm. For fibers, this includes particles with lengths between 300 nm and 15 mm and a length-to-diameter ratio greater than 3.

Microplastics are typically classified by shape into microbeads, nurdles, fibers, foam and fragments (Lehmann et al., 2021). A specific and prevalent form of microplastic, particularly relevant to the textile industry, is fibrous microplastics. For precise terminology within this review, it is important to distinguish between the textile term and the pollutant term. Conventionally, a microfiber is defined in the textile industry as a synthetic fiber finer than one denier or

decitex per thread, typically having a diameter of <10 μ m. These fibers offer unique properties such as lightweight, exceptional softness, excellent drapability, high water absorbency, breathability and quick drying. Due to these characteristics, they are widely used in various applications including fashion apparel, sportswear, home furnishings, cleaning textiles, high-performance filters, synthetic leather and medical products (Othman et al., 2024). However, in the context of environmental pollution, the term 'microfiber' (MF) is broadly used to refer to any fibrous particle shed from textiles into the environment, regardless of composition (e.g. natural, regenerated or synthetic) or specific textile fineness. It is therefore crucial to differentiate this general usage from 'fibrous microplastics', which specifically refer to fibers composed of synthetic polymers or those chemically modified to become environmentally persistent. According to European Union Commission Regulation (EU) 2023/2055, any fiber \leq 5 mm in length is classified as a microplastic if it contains \geq 1% synthetic polymer by weight or is fully coated with such a material. Regenerated fibers such as rayon or lyocell are

derived from natural polymers (typically cellulose) and, while chemically processed, are not automatically classified as microplastics under this regulation unless they are blended with or coated by synthetic polymers. Notably, rayon remains biodegradable under environmental conditions, which distinguishes it from conventional synthetic microplastics in terms of persistence and ecological impact (Zambrano et al., 2019).

A subset of microplastics, synthetic microfibers, originates from both primary sources (fibers released during textile production and use) and secondary sources (fragmentation of discarded textiles) (Henry et al., 2019). Microfibers released into the environment may originate from natural fibers (e.g. cotton, wool), regenerated fibers (e.g. rayon, lyocell) or synthetic polymers (e.g. polyester, nylon). However, only synthetic microfibers—or those containing or coated with synthetic polymers—are classified as microplastics under current regulatory definitions, due to their persistence and plastic-based composition (Alberts et al., 2024; Cintron et al., 2024; Dos Santos et al., 2024). Several studies showed the presence of these pollutants in habitats and species, such as in fish, in which fibers were the most prevalent (82%), followed by fragments (13%) and films (3%) (Xia et al., 2021).

Microfibers, whether natural, regenerated or synthetic fibers shed from textiles, significantly contribute to pollution in ecosystems like marine environments, rivers and groundwater (Athey et al., 2020; Balestra et al., 2024; Chen et al., 2024; Kumar et al., 2024; Li et al., 2023; Samal et al., 2024; Suaria et al., 2020; Sustainable Investment Institute, 2022; Tyagi, 2024; Yan et al., 2024). Synthetic microfibers are the most common microplastics in the environment (Acharya et al. 2021), with about 1.4 trillion in the oceans, impacting biodiversity (Kang et al., 2021). Microfibers enter ecosystems through laundry, wastewater discharge and garment wear, affecting marine and freshwater life (Athey et al., 2020; Chen et al., 2024; De Falco, 2019; Kapp & Miller, 2020; Lant et al., 2020; Pedrotti et al., 2021; Salahuddin & Lee, 2022). They persist in environments, traveling via atmospheric deposition and accumulating in marine sediments, surface waters, deep seas and freshwater bodies (Balestra et al., 2023; Martynova et al., 2024; Priyadarshini et al., 2024). Microplastics have also been found in high-altitude clouds, potentially affecting cloud formation and climate (Wang et al., 2023). Synthetic microfibers are a significant source of microplastic pollution in the air, while natural fibers also contribute pollutants transported by wind and rain (Kannankai & Devipriya, 2024; Sandin & Peters, 2018; Sun et al., 2018).

Cox et al. (2019) estimate annual microplastic ingestion in the USA ranges from 74,000 to 113,000 particles per capita, affecting health through immune stress, growth inhibition and oxidative damage (Zhang et al., 2020). Microfibers release harmful additives like phthalates and Bisphenol A (BPA), which can damage DNA, proteins and reproductive hormones, while also acting as carriers for dyes, flame retardants and plasticizers that leach into aquatic environments, posing ecological and toxicological risks to marine organisms and ecosystems (Hartline et al., 2016; Meeker et al., 2009; Samal et al., 2024). Microplastic has been found in human stool, placenta and meconium, raising health concerns (Liu et al., 2023; Ó Briain et al., 2020; Sharma et al., 2024; Shruti et al., 2021). Microplastics may carry pathogens and disrupt the gut microbiome, impacting immune function and metabolism (Hirt & Body-Malapel, 2020). Yang et al. (2023) detected microplastics in cardiac surgery patients' tissues and blood, indicating potential health risks.

As shown in Figure 1, scientific interest in microfiber and microplastic pollution has grown steadily since 2015, with publications peaking in 2022 and citations reaching their highest in 2024. This trend highlights the increasing academic focus on the environmental and health impacts of microfiber release. To explore the extent of research on microfiber-related pollution, a bibliometric analysis was conducted using the Web of Science Core Collection database. The search was executed on 16 July 2025, and limited to publications between 2015 and 2025. The following Boolean query was applied in the 'Topic (TS)' field to ensure comprehensive coverage of relevant literature: TS=((microfiber* OR 'microplastic fiber*' OR 'textile washing' OR 'microfiber pollution' OR microplastic* OR 'plastic pollution') AND (pollution OR environment* OR impact* OR release*)). This query was designed to capture research focused on microfiber and microplastic contamination, particularly from textile sources, and their environmental impacts. A total of 1006 articles were retrieved and analyzed for publication trends, citation dynamics and thematic clustering using VOSviewer software (v1.6.20). To understand the thematic landscape of microfiber pollution research, a keyword co-occurrence network was generated using VOSviewer (Figure 2). Although clustering is algorithmically generated, the resulting groups align well with the conceptual framework of this review. Specifically, four major research domains emerge:

- *Sources and emissions*: focusing on microfiber shedding during textile production, laundering and

2. The textile industry and microfiber pollution

The primary structural components of textile products are derived from both natural and manufactured (man-made) fibers (Figure 3). Plants, animals or minerals are the sources from which natural fibers are classified (Ahmed & Mondal, 2021; Cherif, 2016). Manufactured fibers can be categorized into organic and inorganic fibers. Organic fibers are classified into two primary categories based on their sources: regenerated and synthetic fibers. Regenerated fibers originate from natural raw materials, primarily cellulose, which undergo chemical processing to produce fibers such as rayon and viscose (Cherif, 2016). Synthetic fibers, including polyester and polyamide, are fully manufactured from petrochemicals, providing significant strength, durability and resistance to environmental influences (Karthik & Rathinamoorthy, 2017).

The textile industry has embraced ‘fast fashion’, which prioritizes cheap, disposable clothing, leads to environmental harm from resource-intensive production to disposal. In 2020, the typical EU individual’s consumption led to the utilization of 391 kg of raw materials, 400 m² of land and 9 m³ of water, with a carbon footprint of approximately 270 kg. The majority of resource consumption and emissions occurred outside of Europe (European Environment Agency, 2022a).

Global textile fiber production reached 124 million tonnes in 2023, up from 116 million tonnes in 2022, and is projected to grow to 160 million tonnes by 2030 if current trends continue. Synthetic fibers dominated the market, accounting for approximately 67% of global production at around 84 million tonnes. Polyester led the sector with a 57% market share and 71 million tonnes produced (Figure 4). Other synthetic fibers, including polyamide, polypropylene, acrylic and elastane, collectively constituted 10% of the market in 2023 (Textile Exchange, 2024).

Approximately 80% of the environmental impact of textiles occurs during the manufacturing process. An additional 3% occurs during distribution and retail, 14% during usage (washing, drying and ironing), and 3% during the end-of-life phase (collection, sorting, recycling, incineration and disposal) (European Environment Agency, 2022b). Synthetic textiles contribute to 8% of microplastics in European oceans, with global estimates ranging from 16% to 35% (De Falco et al., 2019; European Environment Agency, 2022a). The Ellen MacArthur Foundation (2017) projects over 160 million tons of clothing sales by 2050, releasing 22 million tons of microfibers into

oceans between 2015 and 2050. Microfiber release occurs during textile production (49%), laundering (28%) and usage (23%) stages (Lim et al., 2022; Salvador Cesa et al., 2017). Research shows synthetic fiber pollution is widespread globally (Balestra & Bellopede, 2022; Panno et al., 2019). In a study by Browne et al. (2011), synthetic microfiber concentrations varied across 18 coastlines, with polyester (56%) being the most common, followed by acrylic (23%), polypropylene (7%), polyethylene (6%) and polyamide (3%), and their abundance correlated with population density, particularly in wastewater. While attention has focused on synthetic microfibers, studies assert natural fibers like cotton and wool also contribute significantly to microfiber pollution (Athey et al., 2020; Liu et al., 2021; Pedrotti et al., 2022; Santini et al., 2022). Chemical treatments during manufacturing can impact the environment, with natural microfibers showing persistence and potential harm to ecosystems (Athey et al., 2020; Siddiqui et al., 2023). Understanding the environmental impact of both synthetic and natural fibers is crucial, as they contribute to carbon emissions and persist in the environment (Karim et al., 2021).

3. Factors influencing microfiber release in textiles

Microfiber shedding can occur at various stages of textile manufacturing, including spinning, weaving, dyeing, cutting and sewing (Liu et al., 2022). The extent of microfiber shedding from different types of textiles depends on fabric properties and production methods (Jönsson et al., 2018; Salvador Cesa et al., 2017).

3.1. Fiber properties

The physical and chemical characteristics of fibers significantly influence their propensity to release microfibers during use and laundering. Factors such as surface structure, tensile strength and hydrophobicity directly impact the shedding behavior (Rathinamoorthy & Raja Balasaraswathi, 2022). Natural fabrics, such as wool and cotton, release more microfibers due to their physical properties. These fibers feature crimped and irregular structures, shorter staple lengths and rougher surfaces, all of which increase surface area and make them more likely to shed during washing (Athey & Erdle, 2022; Lim et al., 2022; Liu et al., 2021; Periyasamy, 2021). Furthermore, natural fibers have amorphous regions in their structure that are more prone to breakage than the

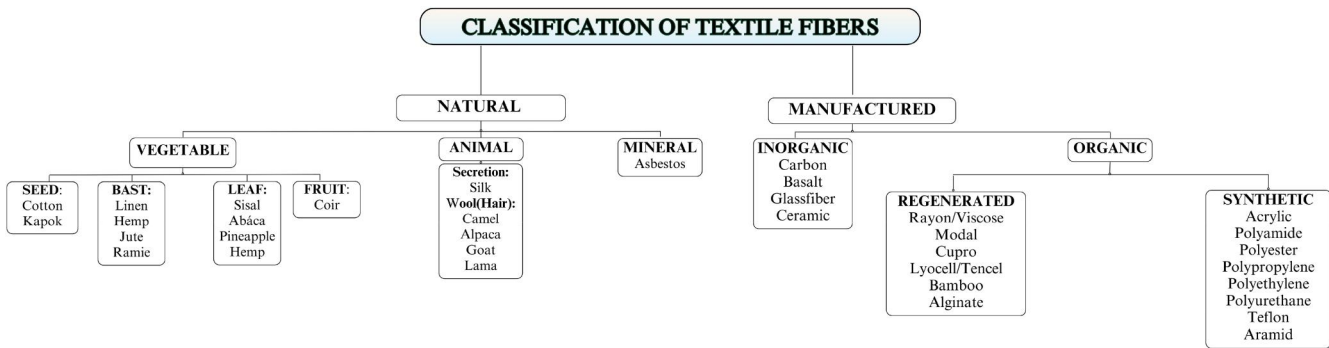


Figure 3. Classification of textile fibers based on their origin.

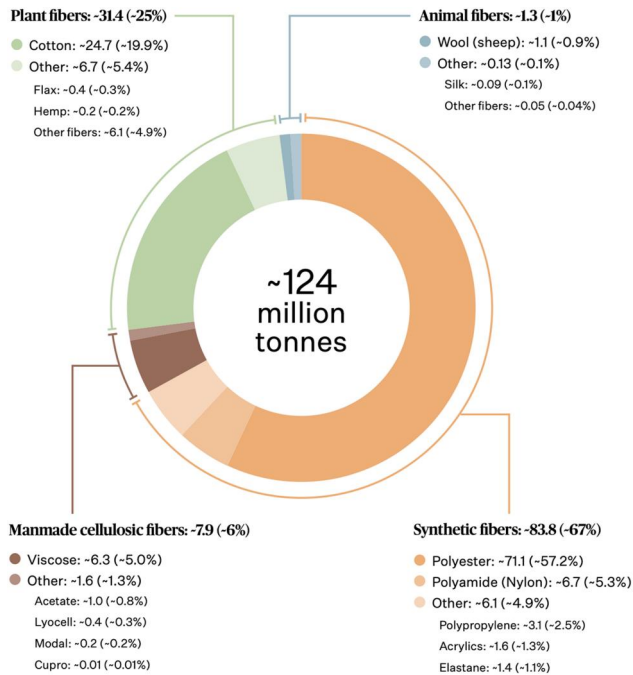


Figure 4. Global fiber production percentages in 2023 based on their origin. (Retrieved from Textile Exchange (2024). Materials Market Report 2024).

highly crystalline regions seen in synthetic fibers like polyester. The high crystallinity of synthetic fibers increases molecular alignment, making them more resistant to fragmentation and shedding (De Falco et al., 2018; Napper & Thompson, 2016). Natural fibers tend to shed due to surface defects and irregularities, while synthetic fibers like polyester have smoother surfaces, uniform cross-sections and engineered finishes that improve abrasion resistance (Özkan & Gündoğdu, 2021; Zambrano et al., 2019). Polyester and polyamide, for example, have higher tensile strength, making them less prone to mechanical damage and shedding than weaker fibers such as cotton (Napper & Thompson, 2016). Another significant factor is water absorption: hydrophilic natural fibers like cotton absorb substantial amount of water, causing fiber swelling. This swelling

disrupts the fiber matrix, making it more susceptible to mechanical stress during washing. In contrast, hydrophobic synthetic fibers such as polyester resist water absorption, maintain structural integrity and shed less fiber under wet conditions (Yang et al., 2019).

On the other hand, acrylic fibers shed the greatest quantity of microfibers during laundering compared to other synthetic fibers (Akyildiz et al., 2024; Vassilenko et al., 2021). This higher shedding is largely due to their reduced elongation properties, which make acrylic fibers more prone to fragmentation under mechanical stress during washing (Frost et al., 2020). The physical properties of polyamide, such as its rougher surface and lower tensile strength in comparison to polyester, are responsible for its longer length of microfiber release (Nyssanbek et al., 2022). Polyester fabric sheds fewer fibers during the laundry than polyamide fabric (Xu et al., 2021).

The impact of recycling on polyester fibers remains debated. Recycled polyester fibers (r-PET) have been reported to shed more microfibers than virgin polyester fibers due to structural changes during the recycling process (Akyildiz et al., 2024; Križmančić, 2023; Özkan & Gündoğdu, 2021). These changes result from exposure to high temperatures and shear forces, leading to a decrease in the average molecular weight, molecule chain length and crystallinity of the fiber (Julienne et al., 2019). Consequently, the mechanical properties of recycled polyester, such as elongation and breaking strength, are reduced compared to virgin polyester (Özkan & Gündoğdu, 2021). However, contradictory findings exist in the literature. Several studies, including Frost et al. (2020) and Gao et al. (2024), found no statistically significant difference in microfiber release between recycled and virgin polyester fabrics. Gao et al. (2024) suggested that factors such as fabric structure and surface treatments may play a more significant role in microfiber shedding than the origin of the polyester fibers.

Fiber blends, like polyester–cotton and polyester–viscose, generally release more microfibers after laundering than single-fiber textiles due to various variables. Blended textiles frequently comprise threads of differing lengths, potentially leading to increased shedding (Allen et al., 2024; Palacios-Marín et al., 2022). Microfiber release is also increased by surface interactions between fibers that have different properties, such as hydrophobicity (Dimitrov et al., 2022; Julapong et al., 2024; Wang et al., 2023). Mechanical stress and abrasion during laundering accelerate fiber damage and fragmentation in blended textiles, resulting in increased microfiber shedding (Jabbar & Tausif, 2023; Palacios-Marín et al., 2022). The interactions of diverse fiber lengths, surface interactions and the tendency of synthetic fibers to fragment explain the increased microfiber shedding noted in fiber blends relative to single-fiber textiles.

3.2. Yarn properties

The structure and characteristics of yarn, including its composition and manufacturing process, significantly influence microfiber shedding. Variations in yarn type, twist and density contribute to differences in durability and fiber loss (Rathinamoorthy & Raja Balasaraswathi, 2022). Staple yarns shed more microfibers than filaments due to shorter fiber length, increased hairiness, and exposed fiber ends that break during abrasion, use and laundering (Allen et al., 2024; Hazlehurst et al., 2023; Palacios-Marín et al., 2022; Palacios-Mateo et al., 2021). Staple yarns have a looser structure and more hairiness than filament yarns, which contributes to higher microfiber release. Continuous filaments, particularly those with higher twist, have lower shedding due to better fiber cohesion and restricted fiber movement (Salahuddin & Lee, 2022; Han et al. 2024).

Multifilament yarns shed more due to increased surface area and exposed filaments. Monofilament yarns, with their single continuous strand, exhibit higher resistance to fiber dislodgment (Choi et al., 2021). Coarser yarns with higher linear density shed more due to the greater number of fibers per unit area. Finer yarns reduce shedding as fewer fibers are exposed per unit area (Özkan & Gündoğdu, 2021). Higher twist levels in yarns reduce shedding by enhancing fiber cohesion and reducing protruding fibers. Yarns with low twist or no twist have greater fiber mobility, leading to increased shedding (De Falco et al., 2018). Hairiness directly correlates with microfiber release; lower hairiness reduces the

number of exposed fibers ends and the potential for shedding (Allen et al., 2024; Periyasamy, 2021). Moreover, fabrics with high thread counts have better cohesiveness, which reduces fiber loss (Choi et al., 2021).

Rotor-spun yarns shed more microfibers than ring and air-jet spun yarns due to mechanical damage caused by the rotor spinning process, which twists fibers in the yarn core while integrating wrapper and bellyband fibers on the surface. This results in a more open and hairy yarn structure, making rotor-spun yarns more prone to fiber breakage and microfiber release during abrasion and laundering. Compact yarns manufactured using improved spinning processes, such as compact, siro and air-jet spinning, have lower microfiber release due to increased inter-fiber cohesiveness. The compact spinning procedure compresses the fiber bundle before twisting, minimizing the spinning triangle and resulting in a tighter, less hairy yarn structure. This improved fiber-to-fiber cohesion reduces fiber breaking and microfiber shedding while in usage and laundering. Ring-spun yarns have a more open and hairy structure than compact yarns, which contributes to more microfiber shedding (Allen et al., 2024; Jabbar et al., 2023; Palacios-Marín et al., 2022; Salahuddin & Lee, 2022).

3.3. Fabric properties

The structural design and mechanical integrity of fabrics, defined by parameters such as weave or knit type, thread density and fabric weight, are key determinants of their susceptibility to microfiber release. Variations in these properties influence how fabrics respond to friction, tension and abrasion (Han et al., 2024). Knitted structures generally release more microfibers than woven fabrics due to their open-loop design, which increases fiber mobility, slippage and breakage compared to the more constrained and stable structure of woven fabrics (Almroth et al., 2018; Cai et al., 2020; Yang, et al., 2020; Frost et al., 2020; A. Periyasamy, 2021; Rathinamoorthy & Subramanian, 2023). The inherent openness of knitted fabrics provides less resistance to fiber movement, leading to greater microfiber shedding. However, some studies have observed that knitted fabric structures release fewer fibers than woven fabrics (Akyildiz et al., 2024; De Falco et al., 2018). For woven fabric construction, plain weaves exhibit reduced shedding compared to satin weaves owing to a greater number of interlacement points. Weaves with reduced intersections facilitate enhanced fiber movement, thereby

augmenting shedding potential (Choi et al., 2021). Nonwoven fabrics release significantly more fibers due to the lack of yarn structure and the random orientation of fibers. Nonwovens are particularly susceptible to shedding during abrasion and washing (Zambrano et al., 2019).

Fabrics with higher abrasion resistance are predicted to have a lower tendency to release microfibers due to the mechanical action of the washing process (Zambrano et al., 2021). Tighter fabric structures reduce shed due to better fiber holding (Choi et al., 2021). Thicker fabrics with higher basis weights shed more microfibers due to the larger abrasion surface. Studies have indicated that materials with greater basis weights and larger surface areas, such as fleece and pile fabrics, release significantly more microfibers during laundering compared to thinner, densely woven fabrics. This is attributed to their larger abrasion surfaces and looser fiber structures, which make them more susceptible to fiber detachment under mechanical stress (Almroth et al., 2018; Vassilenko et al., 2021).

Fleece fabrics, with their brushed surfaces, release significant amounts of microfibers compared to other textile fabrics. Studies have found that fleece fabrics can release up to 1210 ± 96 fibers per 100 cm^2 of fabric during laundering, which is significantly higher compared to other knitted fabrics made from polyester, polyamide and acrylic (Almroth et al., 2018).

3.4. Pretreatment, textile coloration (dyeing and/or printing), finishing processes

Pretreatment, finishing and coloration processes alter the chemical and physical attributes of textiles, often enhancing their functionality and appearance. However, these processes can also weaken fiber structures or modify surface properties, making fabrics more or less prone to microfiber shedding during their lifecycle (First Sentier MUFSG Sustainability Institute, 2022). The release of microfibers can be minimized by mechanical finishes such as calendaring or singeing. Calendaring is the process of compressing fabric by running it between two or more rollers under carefully regulated pressure, temperature and duration parameters. Singeing is the technique of eliminating loose, hairy fibers that are extending from the fabric surface using a controlled open flame (Hossain et al., 2021).

Shearing, brushing and raising are mechanical finishing processes aimed at enhancing the softness and bulk of textiles. Shearing evenly trims protruding

surface fibers to a specific length, while brushing removes fibers from the yarn structure, both of which significantly modify the fabric's surface and increase microfiber release. Similarly, the raising process creates a soft, fluffy texture, as seen in fleece, by loosening fiber connections, which further contributes to increased shedding due to the generation of loose fibers (Cai et al., 2020).

Scouring eliminates natural impurities from fibers, including waxes, oils and pectin, which can weaken the fiber surface and enhance microfiber shedding (Periyasamy, 2023). While scouring stabilizes the fabric structure by removing impurities and embedding fibers, it may temporarily weaken certain fiber types, such as cotton, resulting in higher shedding in the early phases of fabric use (Rathinamoorthy & Raja Balasaraswathi, 2021). Bleaching, though effective for whitening textiles, can weaken fibers due to chemical exposure, leading to increased shedding during washing (Periyasamy, 2023).

Microfiber shedding may be impacted by water-repellent treatments, which are used to prevent fabric wetting. Although they initially stabilize the surface to reduce shedding, these finishes can deteriorate with frequent washing, increasing shedding (Rathinamoorthy & Raja Balasaraswathi, 2021). Durable press finishes, commonly applied to cellulosic fabrics using formaldehyde-based resins, enhance shrinkage resistance and wrinkle recovery but increase microfiber shedding. This is due to crosslinking, which restricts cellulose chain movement, leading to brittleness, reduced tensile and tearing strength, and lower abrasion resistance, all of which contribute to greater fiber release (Zambrano et al., 2021).

High temperatures, mechanical agitation and chemical treatments during the dyeing process can all contribute to shedding. The influence is dependent on the dyeing procedure (Cai et al., 2020; Zambrano et al., 2019). Post-dyeing treatments like fixation minimize further shedding by stabilizing the fabric. However, improper rinsing after dyeing can leave residues that exacerbate shedding (De Falco et al., 2018). Polyester dyeing increases microfiber release due to the mechanical, thermal and chemical stresses involved, with high-temperature processes exacerbating shedding compared to normal or carrier dyeing. Darker shades further intensify microfiber release. Shedding during dyeing far exceeds that of domestic washing, highlighting its significant role in microplastic pollution (Mondal & Takebira, 2023). The reactive dyeing process involves the formation of covalent bonds between the dye molecules and the cellulose

fibers. This chemical reaction can cause structural changes and damage to the fiber, weakening the fiber structure (Kwon et al., 2022; Lant et al., 2020). The degradation of the fiber structure can make the fibers more susceptible to shedding and the release of microfibers during subsequent washing and wear (Özkan & Gündoğdu, 2021; A. Periyasamy, 2021). Textile printing processes, particularly manual screen printing, have been identified as significant yet under-recognized contributors to microfiber release. Rathinamoorthy and Balasaraswathi (2023) reported effluent containing an average of $1,394,205 \pm 426,262$ microfibers/L, attributed to direct collection, minimal water usage and mechanical stress. Contributing factors include adhesive table gum, squeegee pressure and fabric handling. Lab simulations show that adhesive processes alone emit 1156.63 ± 21.74 microfibers/cm², exceeding household laundry emissions (320.31 ± 49.74 microfibers/cm²). Though daily wastewater from printing is limited, high fiber density leads to 41.8 million microfibers/day, making it imperative to incorporate printing processes into microfiber pollution frameworks.

In addition to mechanical and chemical influences on microfiber release, it is important to recognize that fibers can act as carriers for hazardous substances introduced during agricultural or manufacturing processes. For instance, cotton fibers may retain pesticide residues used during cultivation, while synthetic or regenerated fibers may carry surfactants, dyes or finishing agents such as plasticizers and flame retardants. When these fibers are shed as microfibers, they can leach these substances into aquatic environments, contributing to combined chemical–microplastic pollution. (Acharya et al., 2021; Gelbke et al., 2009; KEMI, 2016; Pesticide Action Network, 2017).

3.5. Clothing production processes

The methods employed during garment production, including cutting, sewing and edge finishing, directly affect the structural stability of textiles. Inefficient production techniques or insufficient edge sealing can lead to increased fiber detachment and higher rates of microfiber release during use and laundering (Han et al., 2024). Scissor-cut edges release more fibers, including longer fibers, due to the disruption of yarn structure, while laser or ultrasonic cutting methods produce fewer fibers by sealing edges or minimizing damage (Cai, Yang et al., 2020).

Edge-sewing techniques, like overlock sewing, do not reduce microfiber discharge; overlock-sewn

samples emit more microfibers than those with unfinished edges. About 84% of microfibers are released from the fabric's edge, highlighting its importance in microfiber emission (Cai et al., 2020).

4. Microfiber release during domestic washing and drying

Domestic washing and drying are among the most significant contributors to microfiber release into the environment (Rathinamoorthy & Raja Balasaraswathi, 2022). According to research estimates, the global ocean floor contains more than 14 million tonnes of microplastics. Between 200,000 and 500,000 tonnes of microplastics from textiles are introduced into the global marine environment annually (European Environment Agency, 2022a). It is important to note that the washing process can cause up to 90% more damage to clothes than the actual wear and tear, making the lifespan of garments often dependent on their ability to endure repeated washes. Both mechanical and chemical factors play crucial roles in microfiber shedding (Rathinamoorthy & Raja Balasaraswathi, 2021).

ISO 4484-1:2023 presents a standardized method for laboratories to assess the shedding behavior of different fabrics during laundering, providing manufacturers with valuable data to make informed decisions on fabric selection and manufacturing processes that minimize material loss. The standard outlines a systematic approach, involving accelerated laundering conditions and gravimetric assessment, to achieve comparable and accurate results. ISO 4484-3:2023 provides a technique for measuring the collected material mass released from the output hose of a standard washing machine, as specified in ISO 6330 and ISO 3758. ISO 6330 outlines a test method for collecting and analyzing fibers discharged from domestic washing machines during the washing of textile end products. Utilizing specified conditions and equipment, including care labels according to ISO 3758, this method aims to provide valuable information for the textile industry to develop products that reduce shedding materials through the washing process.

The initial laundering of textiles is where the highest amount of microfibers are released (European Environment Agency, 2022a). Microfiber release during laundering is a significant environmental concern, with different textile materials showing varying levels of release. Cotton-based textiles released approximately 165 mg of microfibers per kg (Vassilenko

et al., 2021). Polyester-based textiles are also significant contributors, releasing between 124 and 308 mg of microfibers per wash (De Falco et al., 2019). For instance, a study estimated that a 5 kg laundry load of only polyester fabrics could discharge over 6 million microfibers (Kapp & Miller, 2020). These findings illustrate the wide variation in microfiber loss, ranging from 9.6 to 1240 mg per kilogram of textile per wash (Vassilenko et al., 2021). The cumulative effect of these discoveries is significant. For instance, annual emissions from household laundry machines have been estimated at 154,000 kg for polyester and 411,000 kg for cotton microfibers (Sillanpää & Sainio, 2017). Additionally, materials like denim emit approximately 56,000 microfibers per laundry (Athey et al., 2020). Acrylic fabrics, for example, are prolific microfiber emitters, with 6 kg laundry load discharging between 140,000 and 730,000 microfibers (Li et al., 2023).

4.1. Washing parameters

Washing parameters, such as machine type, wash cycle intensity, water temperature and load size, introduce varying levels of stress to textiles (Napper & Thompson, 2016). Studies have compared the effects of front-loading and top-loading washing machines on fiber shedding, with the latter producing significantly more microfibers. Top-loading machines produced seven times as many microfibers as front-loading machines (Kelly et al., 2019).

The number of wash cycles affects microfiber shedding, with shedding decreasing over successive washes. Hernandez et al. (2017) investigated the release of microplastic fibers from polyester textiles during washing. In the first four washes, there is a significant decrease in the amount of fiber released, regardless of the fiber type used. However, the reduction percentage decreases after the fourth wash.

The laundry temperature has a significant impact on microfiber discharge from synthetic fabrics. Significant microfiber emissions were observed at 60 °C compared to lower temperatures (30 °C or 40 °C) (Cai et al., 2020; L. Yang et al., 2019). In contrast, Hernandez et al. (2017) found no major differences in fiber release at different temperatures ranging from 25 °C to 80 °C.

In laboratory-scale experiments, the effect of water quantity in relation to drum rotation speed and cycle duration pauses was studied. Statistically significant differences were observed in various water quantities, with greater water volume resulting in more

microfiber release. Similar results were obtained when these experiments were conducted with a standard washing machine. Milder cycles with higher water volume produced more microfibers than more intense cycles (Rathinamoorthy & Raja Balasaraswathi, 2021).

Longer washing durations increase microfiber release due to prolonged exposure to mechanical stress, water movement and abrasion between fibers and the drum of the washing machine (Rathinamoorthy & Raja Balasaraswathi, 2021). Moreover, hard water led to higher fiber release compared to distilled water (Sheikhi et al., 2024).

4.2. Detergents and softeners

The role of detergents and softeners in the laundering process extends beyond cleaning and fabric conditioning; their chemical properties can alter fiber surface interactions (Rathinamoorthy & Raja Balasaraswathi, 2022). Detergent use can increase microfiber shedding during washing (Almroth et al., 2018; L. Yang et al., 2019; Zambrano et al., 2019). The addition of detergent to the washing process significantly increased fiber shedding by reducing surface tension and increasing fiber wettability. This promotes the detachment of loose fibers from knitted fabrics during laundering (Napper & Thompson, 2016). However, some studies report no significant impact of detergents on microfiber shedding (Kwon et al., 2022; Pirc et al., 2016). In contrast, Cesa et al. (2020) found that the use of detergents may reduce fiber emissions from synthetic garments.

It is worth noting that whether the detergent is in liquid or powder form is less important than its chemical composition. For example, powder detergent results in fiber shedding during home laundry, and the chemical composition of the detergent plays a critical role (Periyasamy & Tehrani-Bagha, 2022). It is also noteworthy that the inclusion of inorganic content in detergents, such as zeolite, may enhance microfiber shedding due to friction with the fabric. Additionally, the pH of the detergent may contribute to chemical damage to polyester and increased fiber release (Rathinamoorthy & Raja Balasaraswathi, 2021).

Using a fabric softener can reduce fiber loss due to its ability to reduce friction (De Falco et al., 2018; Gong & Bhatia, 2009; Napper & Thompson, 2016). Rathinamoorthy and Raja Balasaraswathi (2021) noted that fabric softeners reduced shedding by up to 40% compared to detergent-only washes. However, some studies reported that the use of fabric softeners had

no significant impact on microfiber release (Lant et al., 2020; Volgare et al., 2021).

4.3. Dryers

Drying processes subject textiles to mechanical agitation and thermal stress, making them a significant source of microfiber release. The type of drying method, temperature settings and the effectiveness of lint traps influence the quantity and characteristics of released microfibers (Rathinamoorthy & Raja Balasaraswathi, 2022). Lant et al. (2022) found that microfiber emissions during tumble drying were comparable to those during washing, with anti-wrinkle fabric conditioners and dryer sheets significantly reducing emissions.

Tao et al. (2022) reported that vented dryers emitted 433,128 to 561,810 microfibers in 15 min, with microfibers originating from both polyester and cotton textiles. The quantity of polyester microfibers emitted was directly related to the amount of clothing loaded into the dryer, although such a relationship was not observed for cotton textiles. Almroth et al. (2018) reported that tumble drying can cause up to 60% more fiber loss than line drying due to a combination of heat and mechanical forces. De Falco et al. (2020) observed that lint traps capture a significant portion of released fibers, making proper maintenance of lint traps crucial to reducing microfiber release. Tumble drying, especially at high temperatures, increases microfiber shedding due to friction and heat degradation. Air drying is a better alternative (Kapp & Miller, 2020). On the other hand, Lant et al. (2022) investigated how fabric conditioning products influence microfiber release during tumble drying. Their findings revealed that using a double dose of fabric conditioner significantly reduced microfiber release by 21.6% compared to a control scenario without any fabric conditioner.

5. Solutions and mitigation strategies for reducing microfiber pollution

Effective microfiber pollution reduction requires collaboration among multiple stakeholders, including manufacturers, retailers, consumers and lawmakers. Initiatives like the Microfiber Consortium, which brings together industry experts to share best practices and develop solutions, demonstrate the value of collaboration (Microfiber Consortium, 2021). On the base of previous researches, solution suggestions for microfiber pollution can be listed as follows (Figure 5):

5.1. Improved textile production processes

Microfiber pollution must be addressed throughout the entire textile supply chain, from fibers to consumers. Technological advancements in the textile industry can mitigate the problem at its source (Liu et al., 2021). Figure 6 provides an overview of the key properties and processes that minimize microfiber release from textiles, highlighting factors such as fiber characteristics, yarn structure, fabric design, textile processing methods and garment production techniques. It outlines how higher fiber crystallinity, finer yarn counts, tighter fabric weaves and advanced processing methods (e.g. singeing and ultrasonic cutting) contribute to reduced shedding, while emphasizing the importance of optimizing each stage of textile production to mitigate microfiber emissions. These indicators suggest that eco-friendly design of textile products can significantly reduce shedding, emphasizing the importance of modifying fiber, yarn and fabric qualities during the design and manufacturing phases (Liu et al., 2021).

5.2. Filtration systems in washing machines

Although technologies exist to prevent microfiber reduction during washing, adoption is difficult. Entrepreneurs have developed innovative laundry accessories designed to capture microfibers during the laundering process, either by enclosing garments or by functioning as in-drum devices within washing machines (Ellen MacArthur Foundation, 2017). Filtrol 160 and the Lint LUV-R filters effectively captured 89% and 87% of microfibers, respectively, while the Cora Ball captured 26% (Sheikhi et al., 2024). Filtrol 160 and Lint LUV-R are external filtration systems designed to capture microfibers from wastewater during the laundering process. These filters work by physically trapping fibers as water flows through their fine filtration materials. In contrast, the Cora Ball is an in-drum device placed inside the washing machine. It operates by allowing microfibers to adhere to its unique surface structure as they are released during the wash cycle (Sheikhi et al., 2024). Another effective tool is the Guppyfriend bag, a specially designed microfiber filter bag where garments are placed during washing. This bag reduces microfiber emissions by approximately 54% by preventing fibers from escaping into wastewater and minimizing friction between garments that contributes to fiber shedding (Napper et al., 2020). Moreover, up to 90% of microfibers that are released during the laundry process can be captured by washing machines that are equipped with internal microfiber filters, such as the

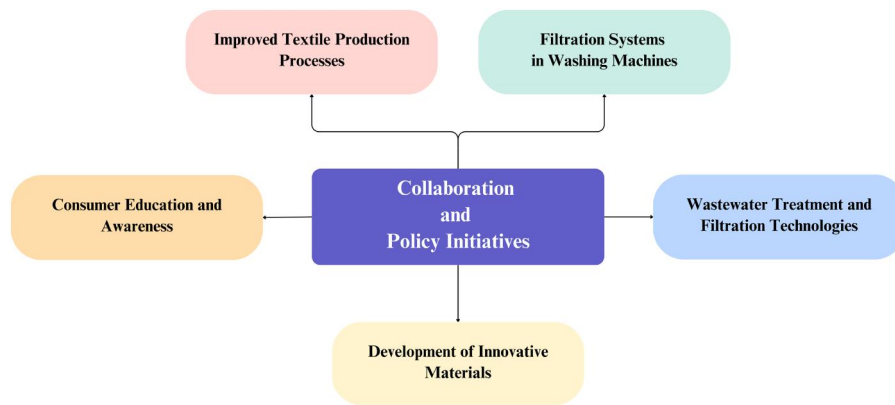


Figure 5. Solutions and mitigation strategies for reducing microfiber pollution.

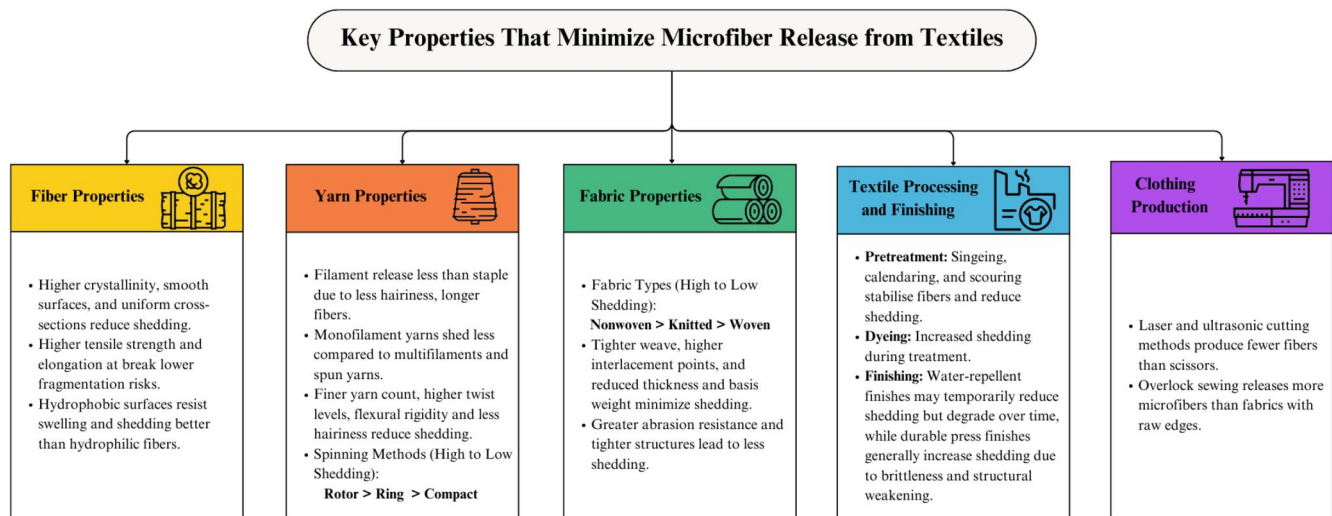


Figure 6. Key factors influencing microfiber release in textile production and use.

'PlanetCare[®]' system. These systems offer a direct and effective solution to the reduction of microfiber pollution (Cedillo-González, 2024). Capturing microfibers is only part of the solution—safe and sustainable disposal remains equally essential to prevent re-entry into the environment (Ellen MacArthur Foundation, 2017).

Currently, microfibers collected by household filters are typically disposed of in general waste, often sealed in containers to prevent re-release. However, this commonly results in their accumulation in landfills, where they may still pose long-term environmental risks (U.S. Environmental Protection Agency, 2021). In municipal wastewater treatment plants, microfibers are primarily retained in sewage sludge, which is either incinerated, landfilled or applied to agricultural land—each presenting potential pathways for environmental re-entry (First Sentier MUFG Sustainability Institute, 2022; Ocean Conservancy, 2024). To address these risks, emerging approaches are focusing on more sustainable disposal and treatment. Companies like PlanetCare have developed

closed-loop return programs where used microfiber filter cartridges and collected fibers are returned for recycling or upcycling into new materials (PlanetCare, 2024). In our recent study, we upcycled microfiber waste sourced from industrial textile effluent into acoustic insulation panels using a hot-pressing process with polyester binder fibers. This method, which can also be applied to microfibers captured from household washing machines, produced panels with strong water resistance and excellent acoustic performance (absorption coefficient up to 0.9 at 3000 Hz). The approach demonstrates the circular economy potential of microfiber waste as a sustainable alternative to synthetic insulation materials like fiberglass and polyurethane (Akyildiz et al., 2025).

5.3. Wastewater treatment and filtration technologies

Wastewater Treatment Plants (WWTPs), which may include both primary and secondary MPs, are a

significant entry point for microplastics into the aquatic environment (Iyare et al., 2020). Preliminary, primary, secondary and tertiary stages are the four main phases of a traditional WWTP. Pretreatment is the process of removing the majority of microplastics from wastewater. The claims state that 35%–59% of the microplastics may be eliminated during the first phase and 50%–98% may be eliminated after the initial phase (Sun et al., 2019). According to Iyare et al. (2020), general tertiary WWTPs recovered 94% (from 82% to 99%) of microplastics from sewage influent.

Membrane bioreactors (MBRs) integrate biological treatment with membrane filtration to improve microfiber removal. Research indicates that MBRs are highly efficient, catching up to 99% of microplastics (Surana et al., 2024).

Sand filtration, microfiltration and ultrafiltration serve as tertiary treatments to remove residual microfibers following primary and secondary treatment processes. Ultrafiltration membranes possess pore sizes sufficiently small to effectively retain fine microfibers. The pore diameters of microfiltration and ultrafiltration membranes are, respectively, 0.1–50 and 0.00–1.1 μm (Surana et al., 2024). The bulk of MPs can be effectively retained by the microfiltration membrane, and almost all MPs appear to be retained by the ultrafiltration membrane due to size selection; when ultrafiltration had a nominal size of 0.2 μm , microplastic removal efficiency approached 100% (Baresel et al., 2019).

While traditional WWTPs effectively capture most microfibers, advanced technologies are being developed to degrade or immobilize fibers more sustainably. The application of photodegradation has been considered a highly efficient and promising technique for the remediation of harmful organic pollutants, such as microplastics, in wastewater (Liu et al., 2019). In this process, a semiconductor material absorbs visible or ultraviolet light, resulting in the production of free radicals, including reactive oxygen species like singlet oxygen and superoxide radicals. These free radicals then break down the microplastics (Zhu et al., 2019).

Electrochemical oxidation is an environmentally friendly and economical method used for wastewater treatment. It involves two approaches: anodic oxidation and indirect cathode oxidation (Du et al., 2021). Studies have demonstrated the successful breakdown of different types of organic pollutants, such as microplastics, antibiotics, antipyretics and dyes, using this method. The process converts them into harmless substances like carbon dioxide and water vapor

without the need for additional chemicals (Du et al., 2021; Ouarda et al., 2018). Advanced Oxidation Processes (AOPs) use extremely reactive radicals to degrade microfibers in wastewater. This method is especially useful for treating wastewater with persistent synthetic fibers and transforming them into less hazardous chemicals (Surana et al., 2024). Electrocoagulation (EC) utilizes an electric current to destabilize and eliminate suspended fibers from wastewater. This method is both cost-effective and scalable for the remediation of microfibers in industrial and domestic effluents (Parida & Dash, 2024). The efficacy of magnetic separation in eliminating microplastics from wastewater has been demonstrated, owing to the enduring magnetic properties of the utilized materials and their substantial capacity for removal (Abdel Maksoud et al., 2020). The removal process involves the use of different materials, referred to as magnetic seeds, such as iron nanoparticles and magnetic carbon nanotubes (H. Han et al., 2021).

5.4. Development of innovative materials

Researchers are exploring the use of alternative materials, such as biodegradable and natural fibers. This could reduce the amount of synthetic microfibers released during the manufacturing, usage and disposal of textiles (Liu et al., 2021). Biodegradable fibers, including polylactic acid and various bio-based polymers, are engineered to decompose naturally in the environment under specific conditions. These fibers are being engineered to substitute conventional synthetic materials such as polyester and nylon, which remain in the environment for extended periods (Surana et al., 2024). The advancement of textiles derived from bacterial cellulose, algae and mycelium is increasingly gaining attention. These fibers provide sustainable solutions; however, they are costly and have restricted production capacity (De Falco et al., 2019). CiCLO[®] is a patented additive technology that makes synthetic fibers, including polyester and nylon, biodegradable by establishing sites within the material for microbial colonization, facilitating the breakdown into natural components such as biomass, carbon dioxide and water. The biodegradation rate is comparable to that of natural fibers, such as wool, while maintaining the functional properties of the fibers, including strength, texture and moisture-wicking capabilities (CiCLO, 2023).

Initiatives like Conservation X Labs' Microfiber Innovation Challenge aim to identify and support potential solutions. A council of professionals in the

apparel industry, materials scientists, conservationists and investors selected the winners from submissions from 19 countries. For example, Mango Materials has developed a production method for obtaining biodegradable biopolyester fibers (polyhydroxyalkanotes (PHAs)) from waste biogas (methane). They use a fermentation technique that entails supplying waste methane gas to non-genetically modified bacteria, which produces a substance that can be melt-spun to create textile fibers. Another American company, Tandem Repeat Technologies, successfully developed a new fiber called Squitex using synthetic biology. They isolated genes found in the proteins of squid tentacles that are capable of synthesizing self-healing fibers, resulting in materials that are 100% biodegradable and recyclable. Two American companies, Natural Fiber Welding and Werewool, have developed alternative methods. The first inventor patented a technique for modifying the hydrogen bonds in natural fibers (e.g. cotton, flax, wool) and achieve comparable performance to synthetic fibers. Werewool designed fibers at the DNA level to achieve specific properties, such as color, elasticity and moisture management. The final victors of this competition, PANGAIA and MTIX, are joining forces to develop a nano-level treatment based on laser surface enhancement technology that could reinforce fabric surfaces to prevent microfiber release (Weis & De Falco, 2022).

In addition to bio-based and biodegradable innovations, advanced material modification techniques are increasingly employed to reduce microfiber shedding. Textile surface treatments, including acrylic resins, siloxanes and bio-based compounds such as chitosan and pectin, effectively decrease microfiber shedding by adhering loose fibers and enhancing the smoothness of the fabric surface (Surana et al., 2024). Siloxane-based coatings provide a flexible and durable coating on fabric surfaces, improving resistance to mechanical stress and minimizing fiber breakage during laundering (Weis & De Falco, 2022). Finishing techniques such as electrospraying biopolymers onto polyamide fabrics have reduced microfiber release by over 80% (De Falco et al., 2019), with some studies reporting up to 90% reduction (Ramasamy & Subramanian, 2021). Synthetic finishes, including silicone-based agents like Polysilk-CTE, have shown considerable efficacy—achieving up to 63.25% microfiber reduction in polyamide fabrics—by creating smooth and cohesive coatings that bind loose fibers and reduce mechanical abrasion during laundering (Rathinamoorthy & Raja Balasaraswathi, 2022).

However, scalability issues and concerns about the ecological footprint of synthetic compounds have prompted the exploration of bio-based alternatives. For instance, Kang et al. (2021) demonstrate that chitosan pretreatment reduces up to 95% microfiber release from synthetic garments during laundering by forming a protective layer on the fiber surface. Complementing these bio-based solutions, oxygen plasma treatment has emerged as a clean, sustainable alternative that reduces microfiber shedding by 43% in mass and 73% in count by increasing fiber surface roughness and inter-fiber friction (Jabbar et al., 2024).

5.5. Consumer education and awareness

Consumer education and awareness are essential to reducing microfiber contamination across the textile lifecycle. While attention has often focused on synthetic microfibers, recent studies indicate that natural fibers such as cotton and wool can also contribute significantly to microfiber pollution (Liu et al., 2021; Pedrotti et al., 2022; Santini et al., 2022). These fibers, particularly when chemically treated, can persist in the environment and pose ecological risks (Athey et al., 2020; Siddiqui et al., 2023). Furthermore, their production may involve intensive water use, pesticide application and energy consumption, contributing to carbon emissions (Karim et al., 2021).

Despite these concerns, biodegradable or organically produced textiles—such as organic cotton, hemp or bamboo—generally degrade more rapidly than synthetic alternatives and may be preferable when produced and managed sustainably (Cedillo-González, 2024). Consumers can play a significant role by choosing such materials, reducing clothing overconsumption and embracing behaviors that extend garment life, such as proper washing, repairing and reusing (Lant et al., 2020; Liu et al., 2021).

Education and awareness efforts should focus on encouraging consumers to adopt laundering practices that minimize microfiber shedding. For instance, using liquid detergents instead of powdered ones can significantly reduce microfiber release, as liquid detergents are gentler on fabrics and do not contain abrasive particles that can increase friction during washing (Lant et al., 2020). Additionally, lower washing temperatures should be emphasized, as they limit fabric degradation and reduce microfiber shedding. Studies show that cool or low-temperature washes generate significantly fewer microfibers compared to high-temperature cycles, as excessive heat damages synthetic fibers (Belzagui & Gutiérrez-Bouzán, 2022).

Consumers should also be informed about the benefits of shorter laundry cycles, which reduce mechanical stress on textiles and, consequently, the number of microfibers shed. Long wash cycles, especially those conducted at high spin speeds, substantially increase fiber breakage and microfiber pollution (Weis & De Falco, 2022). By adopting these practices, individuals can play a crucial role in mitigating the environmental impact of microfiber pollution during the laundering process.

5.6. Collaboration and policy initiatives

Efforts to encourage the rapid adoption of technologies that reduce microfiber discharge must be a priority for policymakers (Ellen MacArthur Foundation, 2017). The EU is addressing the growing concern about microplastic pollution and its potential impact on human health and the environment in its new regulations and communications (Commission Regulation EU—2023/2055). The implementation of new regulations on microplastic release will be gradual in order to give the industry time to adapt to the new requirements. In addition, the regulation requires manufacturers and users to report on microplastic emissions, which may include microfibers. This comprehensive approach aims to reduce the environmental impact of microplastics by controlling their use and promoting the development of biodegradable alternatives (European Union, 2023). By 2025, France will require all washing machines to have microfiber filters, as part of a drive to minimize pollution from household laundry (French Government, 2020).

The EU Green Deal focuses on reducing environmental pollution, including microplastics and microfibers. The EU's Circular Economy Action Plan encourages sustainable textile production and waste management; reduces purposeful microplastic use and targets microfiber release with improved filtration technology and promotes long-lasting, repairable and recyclable textiles to lessen environmental impact (European Commission, 2020).

Reducing the discharge of microfibers requires the involvement of multiple stakeholders. Achieving systemic change demands industry-wide cooperation, involving R&D institutions, waste management companies, washing machine manufacturers, detergent producers, and textile manufacturers. The Mermaids—a European Life + project—study has demonstrated how detergents and washing methods can influence the quantity of microfibers lost during a wash, indicating the potential role of improved

labeling of washing and care instructions in encouraging washing habits that reduce microfiber loss (Ellen MacArthur Foundation, 2017).

6. Conclusion

Microfiber pollution, driven by the rapid growth of the textile industry and fast fashion, presents an escalating environmental and public health challenge. The persistence of synthetic and natural microfibers across aquatic, terrestrial and atmospheric systems calls for urgent action throughout the textile value chain—from raw material production to end-user behavior. This review emphasizes the importance of textile production, usage and user behavior in microfiber generation. While recent innovations such as biodegradable fiber alternatives, functional surface treatments and advanced wastewater filtration technologies show promise, they alone are insufficient. Future efforts must adopt a systemic perspective. Research should not only prioritize the development of environmentally benign materials and scalable mitigation techniques but also focus on the standardization of microfiber measurement protocols, ecotoxicological risk assessment and the fate of microfibers in different ecosystems. Policy will play a crucial role in shaping sustainable practices. Regulatory actions—such as extended producer responsibility, mandatory filtration systems, eco-labeling and incentives for sustainable design—must be globally aligned and science-driven. Equally important is the education and engagement of consumers, whose laundry habits, purchasing decisions and disposal practices significantly influence microfiber emissions. The role of interdisciplinary collaboration—among scientists, governments, industry stakeholders, R&D institutions and civil society—will be essential in achieving transformative change. Tackling microfiber pollution requires more than technical solutions; it demands collective commitment, cultural shifts and international coordination. A circular, transparent and equitable textile system is not only necessary but increasingly possible through sustained cross-sectoral innovation and governance.

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Consent to participate

All the authors consent to participate in this work. Further, this is to confirm that we have not used any animal or human organs/tissues or any other materials that need permission. We also consent that we have not used any private data and information in our study that can be an objectionable issue.

Consent for publication

We declare that this manuscript has not been published previously and is not under consideration for publication elsewhere, that its publication is approved by all the authors, and that, if accepted, it will not be published elsewhere, including electronically in the same form, either in English or in any other language, without the written consent of the copyright holder.

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