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REVIEW ARTICLE

Microfiber and GHG Emission Analysis Across the Textile Value Chain: Shifting from End-of-Pipe Solution to Circularity

Elias Wagari Gabisa[1*]

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Abstract

The rising global demand for synthetic textiles, which accounted for nearly 64% of the market in 2021, has led to a critical accumulation of persistent microfibers and increased greenhouse gas (GHG) emissions. This study assesses the textile value chain to identify critical hotspots, revealing that while printing and dyeing are primary contributors to microfiber pollution, the dyeing and finishing stages are also major GHG drivers, projected to generate 1.8 Gt CO_2-eq by 2030. Current "end-of-pipe" mitigation, such as tertiary wastewater treatment, can remove over 99% of microfibers; however, the cumulative remaining fraction and the transfer of microplastics to sludge present ongoing environmental risks. To move beyond these isolated, reactive measures, this study proposes a shift toward circularity by integrating LCA-informed design and sustainable manufacturing. Key circular strategies identified include raw material substitution toward non-persistent fibers, mechanical process modifications to increase yarn twist and stitch density, and the adoption of bio-based finishing modifiers like chitosan and pectin to reduce shedding. By addressing both the methane-intensive agricultural stage and fossil-heavy chemical synthesis, these findings underscore that a holistic circular economy approach is essential to decouple textile production from systemic environmental degradation.

Keywords Microfibers · Textile · Synthetic Fiber · Value Chain · Holistic Approach

1. Introduction

Microfibers are secondary microplastics derived primarily from synthetic textiles across various life cycle stages such as production, washing, and disposal with a maximum length of 15mm and a length-to-diameter ratio greater than (Gago et al., 2018). The amount of microfibers in the environment has been increasing over time as textile production and consumption grow at an exponential rate. After Covid-19, global fiber production reached a record of approximately 113 million tons in 2021. Global fiber production has doubled in the last 20 years and it is expected to reach 149 million tons by 2030. The increase in fiber is almost entirely due to an increase in synthetic fiber production, which accounts for 64% of global fiber production in 2021(Figure 1).

[*] Corresponding author: elias.wagari86@gmail.com
[1] Department of Water Supply and Environmental Engineering, Institute of Technology, Werabe University, Werabe, Ethiopia

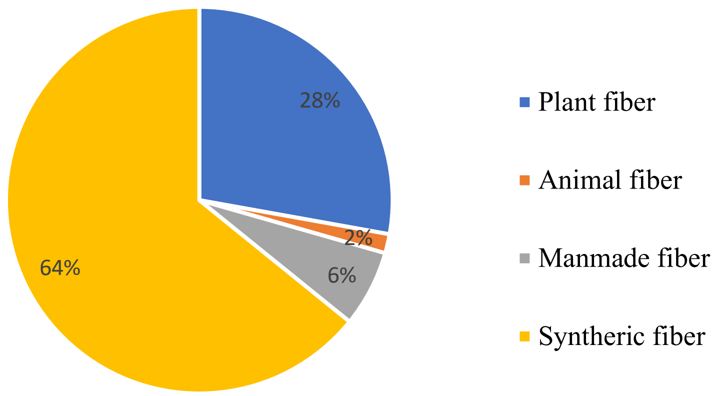

Figure 1. Market share analysis of fiber production by type in 2021 (Data modified from Global fiber market 2021)

Among microplastics entering the ocean, synthetic textiles contribute 35%, which shows Microfibers have a higher contribution (Boucher & Friot, 2017). It is estimated that a population of 100,000 is responsible for a release of 50.6 to 1,180 kg of Microfibers a year (Y. Q. Zhang et al., 2021). As a result of increased global production of synthetic fibers and rising market demand, there is concern that Microfibers derived from textiles will pose a future major threat to the environment, particularly the oceans (Henry et al., 2019).

Nowadays Microfibers are abundant in wastewater treatment plants (WWTP), both sanitary wastewater and textile industry wastewater (Kay et al., 2018; Murphy et al., 2016). Textile Microfibers are found not only in WWTPs, but also in freshwaters, according to recent research(Kawecki & Nowack, 2019). Atmospheric fallouts have also been found to contribute to Microfibers in various parts of the world (Allen et al., 2019; Dehghani et al., 2017; Dris et al., 2015; Roblin et al., 2020; Wright et al., 2020). Every year, three to ten tons of Microfibers are deposited as a result of atmospheric fallout, with synthetic Microfibers accounting for 29% of the total(Dris et al., 2016). This implies that Microfibers are present in the food we eat, the air we breathe and the water we drink, and eventually in our blood (Leslie et al., 2017, 2022). Studies on seafood, salt, honey, and milk revealed the presence of Microfibers in them (Kim et al., 2018; Kosuth et al., 2018; Rhodes, 2018; Seltenrich, 2015; Yang et al., 2021). This is clear evidence that we are consuming Microfibers through a single or multiple environmental pathways (Cox et al., 2020; Hantoro et al., 2019; Peixoto et al., 2019). For example, the amount of Microfibers/microplastics we ingest through various pathways is estimated to be 39,000 to 52,000 per individual per year (Cox et al., 2020). According to a study conducted to estimate the amount of Microfibers, we could consume about 13,731 – 68,415 Microfibers during dinner per year (Catarino et al., 2018).

In this study, we aim to investigate microfibers emission from various stages of textile value chain, viz., production–(knitting, printing, and finishing), wastewater treatment plants (WWTP), and laundry washing. Other studies have been conducted in such a way that they focus on a single stage, such as washing or WWTP, which we believe falls short of providing a comprehensive picture of the problem. Therefore, this study fills this gap by providing a comprehensive analysis along textile value chain. Future perspectives on what needs to be done at various stages along the value chain to support ongoing research projects around the world have also been discussed.

2. Sources of microfibers in textile production process (manufacturing)

This section investigates the sources of microfibers along the textile production unit operations. All unit operations were thoroughly investigated to determine whether they contribute to microfibers emissions or not. This will help to inform the selection of appropriate mitigation measures and to fully understand which textile manufacturing unit operations contribute to the release of microfibers most. There are two types of fibers: natural and synthetic or man-made. Although the raw materials are completely different, the two types have nearly identical major process unit operations. Natural fibers are made from natural resources such as plants, animals, and minerals. Synthetic fibers are made from natural polymers, synthetic polymers, and refractory materials. The production of synthetic textiles begins with preparation of monomers as a raw material (Figure 2).

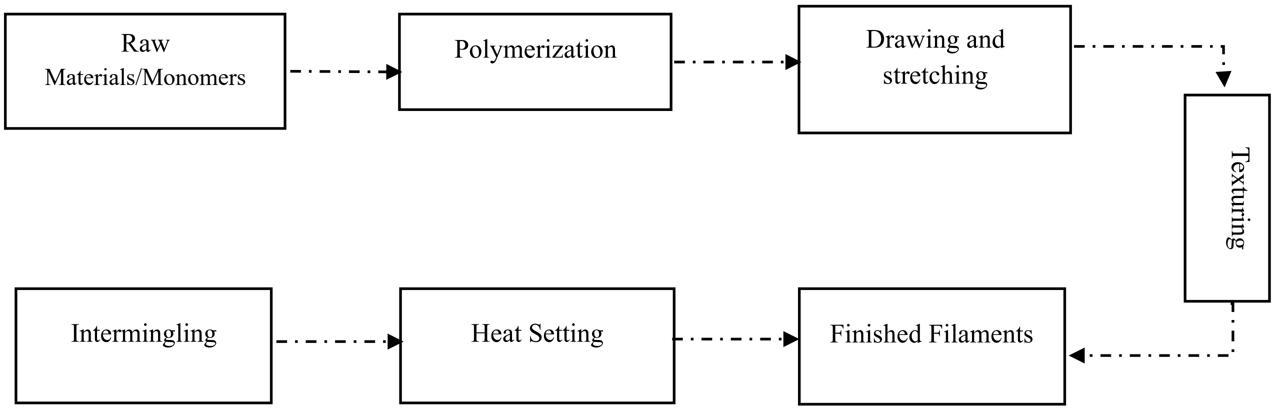

Figure 2. Simple process flow chart of textile filament production

The finished filaments are reduced in size to short fibers before being cut into slivers. The slivers are then spun into yarns, which are then woven/knitted into textiles/fabrics. Finally, the finishing process is carried out to improve the final product's appearance, feel, and strength. Emission of microfibers to the environment occurs at various stages of the product's value chain, including production, transportation, recycling, and disposal. It is critical to identify the sources of microfibers in order to track them and devise appropriate mitigation measures, since it is almost impossible to remove these pollutants from the environment(Cai et al., 2020). For example, if the number of microfibers at the finishing unit operation is increased, finishing agents may need to be changed or modified. However, the presence of microfibers throughout the textile production stages may necessitate changes to the involved unit operations and so on. To that end, researchers are looking into the sources of microfibers as a way to reduce their concentration in the environment (de Oliveira et al., 2023).

There are very limited studies on microfibers analysis from textile mills. For instance, the study conducted in one of the largest China’s textile industrial parks shows there is a significant emission of microfibers from printing and dyeing unit operations. The studied mills (two mills) effluent had exhibited microfibers ranging from 1000 to 2000 microfibers/L of effluent (Zhou et al., 2020). This study did not just look at the mill's effluent, but also at the WWTPs in the textile industrial park, and Microfibers concentrations in the WWTP effluent ranged from 300 to 600 Microfibers per litter of effluent. The concentration of Microfibers in the nearby surface water has also increased to 600 MF/L. This suggests that textile mills, both dyeing and printing, are the primary source of Microfibers in surface water, which requires further investigation (Belzagui et al., 2019; Belzagui & Gutiérrez-Bouzán, 2022). Mechanical processes such as knitting and weaving also have a significant impact on MF emission. This is due to the fact that they influence how the textile fabric is structured, which influences how easily and severely microfibers can be detached from the fabric. According to De Falco et al.’s research, woven polyester fabric emits more microfibers than knitted polyester fabric (De Falco et al., 2018, 2019; Weis & De Falco, 2022). In general, woven fabrics have a more rigid structure than knitted fabrics, which increases surface rupture. This is also an example of how knitting will give the fabric elasticity. Another finding indicates that highly twisted yarns are less vulnerable in terms of detaching Microfibers (Carney Almroth et al., 2018). The treatment used during the manufacturing process has a significant impact on the detachability of Microfibers later. Fabrics with higher abrasion resistance and friction coefficient, for example, demonstrated less MF detachment (Zambrano et al., 2019, 2021). According to a study conducted in China, textile printing and dyeing are significant sources of Microfibers, amounting to half a million tonne per year.

A study which focused on a textile industrial park's advanced central WWTP, discovered that the textile dyeing unit operations were a significant source of microfibers. They concluded that capacity and variation in the manufacturing process had a significant impact on the amount of MF emission (Xu et al., 2018). Screen painting is another unit operation that generates a lot of Microfibers. It has been reported that the use of adhesives and edge cut contributes significantly to the emission of Microfibers during screen painting (Rathinamoorthy & Raja Balasaraswathi, 2023). Despite the fact that no water was used during the printing process, fibers were found in the wastewater. It is most likely the result of cleaning water used to clean the screen table to which the fabrics were adhered, and as a result, some fibers attached to the screen table are washed to join the wastewater. The applied pressure during screen printing and the cut edge may both play a role in the adherence of microfibers to the table. Painting frequency could also play a role in the release of Microfibers. As the use of different colors increases, so does the frequency of applying pressure to adhere the different colors, increasing the number of Microfibers on the printing table. Other reported sources of Microfibers in the environment are those caused by weathering during or after disposal. For example, fishing equipment, sanitary materials, and agricultural textiles. According to reports, almost all fishing materials use systematic fabrics such as nylon and polyolefin (Andrady, 2011; Liu et al., 2021). In the case of sanitary materials, it has been reported that synthetic textiles account for approximately 70% of materials trapped in sewage filters (Le Hyaric et al., 2009).

3. Evaluation of Textile fibers and their carbon emission

Global fiber production is expected to reach about 150 million tons by 2030 and it is not without putting burden on the environment (Textile Exchange, 2021). The amount consumed in apparel production reaches 129 million tons (Figure 3a). The textile sector is roughly emitting 1.2 billion tons of CO_2eq, which is 10% of the global GHG emissions in the year 2019(Leal Filho et al., 2022) and the fiber production takes the big share of it (Figure 3b). For instance, in EU alone textile purchases emitted around 270kgCO_2eq per person in the year 2020, which means textile products consumed in EU generated 121 million tons of GHG (EUC, 2020; Nikolina, n.d.).

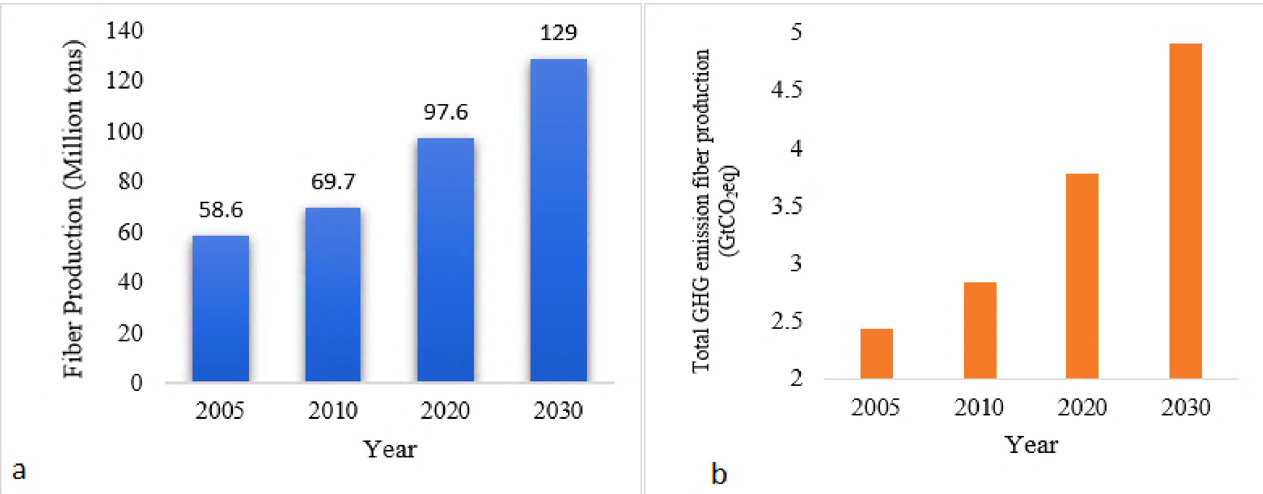

Figure 3. Global fiber production(a) and total GHG emission from fiber production (b)

The carbon emission of different fibers production varies based on the type of fibers and involved production processes. When compared to other fiber types, wool fiber production has a higher carbon footprint followed by polyester fiber and acrylic fiber (Figure 4). This is because wool production involves the raising of sheep, which emit methane via intestinal fermentation. According to International Wool Textile Organization (IWTO) methane emissions account for roughly 80% of wool production's greenhouse gas emissions. It also requires land use for production of their feeds and raising, which also has a significant contribution to the higher carbon footprint.

Dyeing and finishing processes are the higher contributors of life cycle GHG emissions followed by yarn preparation and fiber production (Figure 5). This is because dyeing and finishing processes are energy intensive for water heating, steam generation and drying purpose and fossil fuels are the main energy sources. The life cycle GHG emission for fiber production shows an increasing trend which is because of the demand for fiber materials is increasing globally hence the GHG emission as well increases. And recent days fiber is in produced from polyester, which is produced from fossil fuel (Hertwich, 2021).

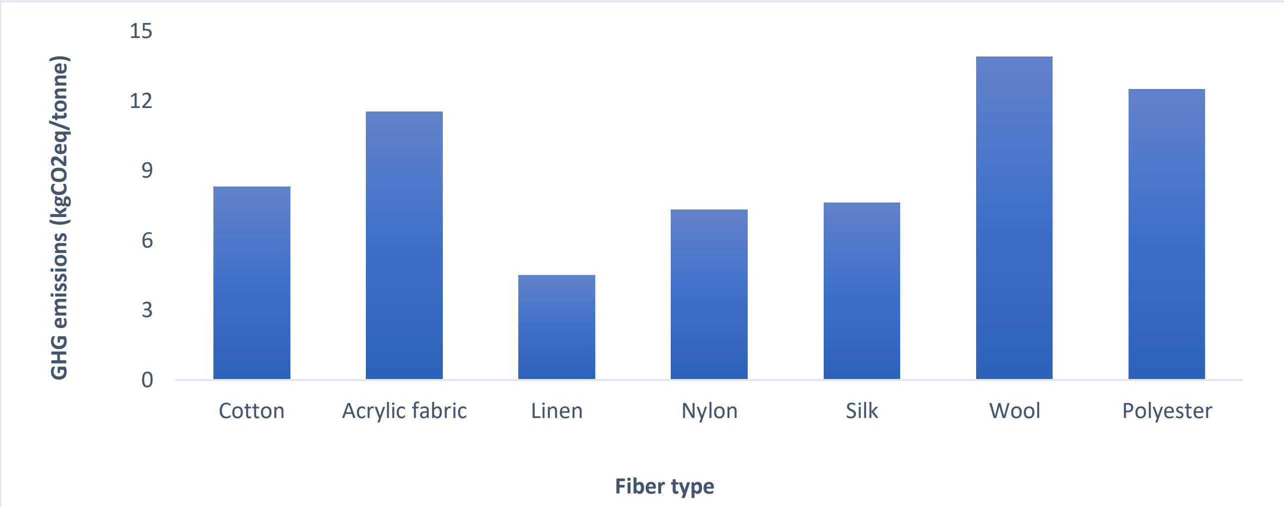

Figure 4. Life cycle GHG emission to produce different kinds of fibers in 2016 (authors own calculation from the data extracted from textile exchange (Textile Exchange, 2021).

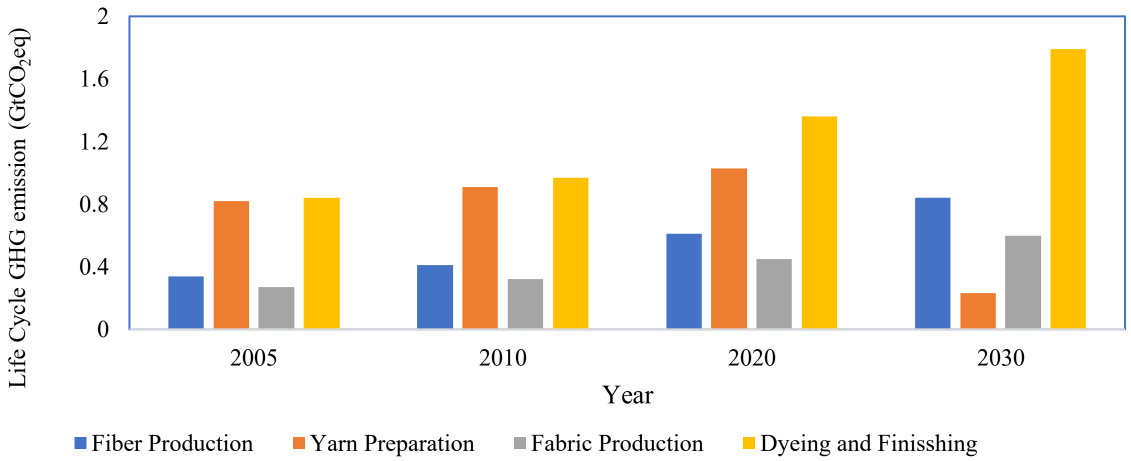

Figure 5. Life cycle GHG emission at the different life cycle stages involved in textile and apparel production projected to 2030 (The data source from Groz-Beckert (GROZ- BECKERT, 2017)

While natural fibers like wool are associated with significant biogenic greenhouse gas emissions—primarily enteric methane from livestock which possesses a high global warming potential—synthetic fibers such as polyester and acrylic present a distinct and substantial carbon burden rooted in fossil fuel extraction and chemical processing. These synthetic fibers are derived from non-renewable petroleum feedstocks, specifically paraxylene and acrylonitrile, whose extraction and refining processes release significant volumes of CO_2. The manufacturing phase is particularly energy-intensive; the polymerization of these precursors requires high-pressure and high-temperature environments, typically powered by fossil fuels. Furthermore, the extrusion and spinning of synthetic filaments—where polymers are melted or chemically dissolved and forced through spinnerets—account for a large portion of the "factory-gate" emissions that are absent in the mechanical processing of most natural fibers.

Consequently, while wool's carbon footprint is "front-loaded" at the agricultural stage, the footprint of polyester and acrylic is sustained throughout the chemical manufacturing chain. By articulating these two different emission profiles, this study underscores that a transition to circularity must simultaneously address the methane-heavy animal agriculture sector and the fossil-heavy chemical synthesis sector to effectively reduce the textile industry's total atmospheric impact.

4. Abundance and occurrence of microfibers in textile and sanitary wastewater influent and effluent

A study conducted on a 30,000-tonne-per-day wastewater treatment plant (WWTP) revealed that microfibers are more prevalent in influents (334.1 items/liter) than in effluents (16.3 items/litter), indicating a removal efficiency of greater than 95%. However, this does not imply that the remaining 5% entering the environment has no effect on the environment or that the treatment facility is sufficient for Microfibers removal, since the cumulative amount of microfibers entering the environment is high. The investigated WWTP receives effluents from 33 printing and dyeing enterprises. The higher concentration of microfibers in the influent suggests that printing and dyeing unit operations are a significant source of microfibers in the textile mill value chain. Other important findings from this study include the proportional removal of other pollutants at the same treatment stages as the microfibers. This may be an indication as there might be a correlation between other pollutants and microfibers requires additional research. Because of their capacity to absorb other pollutants, including heavy metals, microfibers are criticized (M. Zhao et al., 2022).

A similar study was conducted in another textile industry's WWTP with a completely different treatment plant technology than the previous one. They used physicochemical treatment technology, and the MF concentration in the influent ranged from 893 to 4,450 microfibers/liter, while it was reduced to between 310 and 2,404 Microfibers/liter in the effluent. The variation is due to the various locations and times at which the samples were collected. The removal efficiency of the plant reached up to 65% (Akyildiz et al., 2022). This implies that the employed technology needs a significant modification or upgrading to tertiary treatment for effective removal of the microfibers. Otherwise, with this technology above 30% of microfibers will reach the environment, which is a huge amount. Depending on the employed technology and volume of waste generated, the abundance of microfibers ranges between 0 to 27 microfibers/liter for most of the sewage treatment plants(Lares et al., 2018; Mintenig et al., 2017; Talvitie et al., 2015, 2017).

The concentration of rayon-type microfibers in textile wastewater effluents reached 54,100 microfibers/liter. Typically, rayon fabrics are subjected to high-temperature, high-pressure steaming, followed by surfactant soaping and thorough rinsing, which indicates that the type and method of fabric treatment affects microfibers detachment (Patel & Kanade, 2019). Because these treatments have the ability to stretch, shrink, swell, and abrade the fabrics, a higher concentration of Microfibers may result [57]. Aside from the structural distortion caused by high temperature and pressure steaming, additives such as acids, alkalis, and oxidants may have a significant impact on MF detachability [58].

Other studies on different WWTPs found that advanced tertiary treatment technologies are more effective at removing microfibers. They were able to remove more than 90% of the during the secondary treatment stage and 95% during the tertiary treatment stage (Kang et al., 2018). Reverse Osmosis (RO), for example, has been shown to eliminate almost all microfibers. Another study discovered that effluents after RO contained up to 5 microfibers/liter and 0.21 microfibers/liter. However, the total amount appears to be large in both studies, therefore it must be addressed (Ziajahromi et al., 2017).

Microplastics concentrations ranged from 380 to 7900 microplastics/liter in samples collected from 14 locations along China's surface water, with microfibers accounting for more than 80% of the microplastics (Lin et al., 2018). Another similar study discovered microplastics/microfibers concentrations ranging from 100 to 4100 microplastics/liter in non-industrial areas (S. Zhao et al., 2015). However, the area was becoming overcrowded and economically thriving. As a result, Microfibers concentrations in freshwater bodies can be attributed to human activities if no transboundary rivers enter the system. It is critical to remember that there are currently no standardized procedures for comparing study outcomes (Koelmans et al., 2019). As a result, for the quantification and identification of microfibers, careful consideration must be given to the various production technologies, treatment pathways, wastewater composition, and sample collection mechanisms.

Despite the presence of advanced wastewater treatment technologies, the concentration of microfibers from textile industries will still necessitate mitigating measures when compared to municipal wastewater treatment, according to all the studies. According to reports, the concentration of Microfibers in textile wastewater effluents is 10 to 10,000 times higher than in domestic wastewater effluents (Pensupa et al., 2017). Thus, textile factories emit significantly more microfibers than other anthropogenic activities and sanitary wastewater treatment plants (STPs).

The microfibers concentration in sanitary wastewater treatment plants is lower than in textile WWTP. However, this does not imply that the concentration is insignificant. According to some global studies, STP are an important source of Microfibers (Gündoğdu et al., 2018). It was discovered that a Turkish STP contained up to 35,000 microplastics/liter. However, the amount of sanitary wastewater entering the environment is less than in other countries. This is because only a small amount of effluent enters the environment. The influent of the STP in Denmark was reported to contain 10,044 microplastics/liter, while the effluent contained only 447 microplastics/liter. Among the identified microplastics, more than 70% were Microfibers (Cheung et al., 2016; C. Zhang et al., 2019).

A similar study on two STPs in China discovered that both the influent and effluent of the treatment plant contain high concentrations of microplastics. The abundance of microplastics in the influent ranges between 23.3 and 80.8 microplastics/liter, according to their findings (Tang et al., 2020). This report demonstrates that there are substantial differences between studies. The removal efficiency of the two plants was 66.3% and 62.7%, respectively, meaning that over 30% of the microplastics in the influent will be released into the surrounding environment. Although they did not deduce the cause of the significant difference between the two treatment plants, it could be attributed to the different anthropogenic activities at various locations.

Abundance and occurrence of Microfibers vary among the different WWTP facilities. According to the reviewed studies, there is very limited research on WWTP facilities as a point source of microplastics/Microfibers. Textile WWTP are efficient at removing Microfibers much better than that of STPs. The advanced technologies like RO helped to reduce Microfibers significantly. However, the remaining small percentages still have a cumulative large amount when it enters the environment. Therefore, textile WWTP remains and should have to be investigated as a point source of Microfibers. Similarly, even if the amount of microfibers in STP effluent is not as large as that of textile WWTP, improving the technologies will have a significant effect to reduce the microplastics. To this end, treatment plants, whether industrial or municipal, need a great attention for the reduction of micro-pollutants joining the environment. It is clearly seen that the removal efficiency of WWTP varies for different types of microfibers (Figure 6). Removing rayon fiber is difficult with the existing WWTP technologies while polyester (PES) and natural fibers can be removed relatively easily. It may be attributed to the relative lower molecular weight of rayon, which is one-fifth of the cotton.

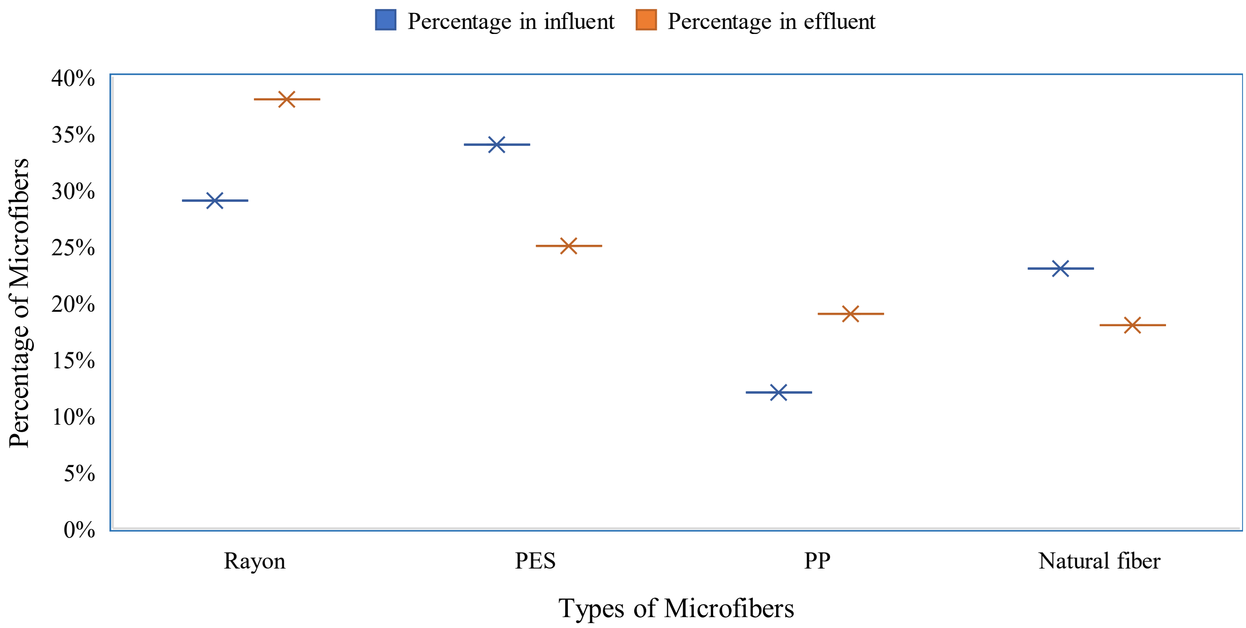

Figure 6. Percentage abundance of Microfibers in WWTP influents and effluents by type

5. Current and emerging textile wastewater treatment technologies and microfiber removal

Even though textile manufacturing contributes to the world's booming economy, particularly in developing countries, the associated massive amount of water consumption and, eventually, wastewater, calls for research. Because of its low biodegradability index, textile wastewater poses a significant threat to existing water treatment systems (Faghihinezhad et al., 2022). Textile manufacturing is thought to use the most water in any manufacturing sector. Water consumption in the medium-capacity textile industry can reach 200 liters per kg of fabric manufactured (Zhou et al., 2020). According to the World Bank, textile industry processes such as finishing processes contribute 17-29% of global industrial wastewater generation (Holkar et al., 2016). Microfibers are among the emerging pollutants that are abundant in wastewater treatment facilities, both influents and effluents. In the United States, for example, tertiary WWTPs emit no Microfibers, whereas secondary treatments emit some (1440 microplastics/liter) (Carr et al., 2016). However, a tertiary treatment in Finland was discovered to release a small amount of microplastics (0.7-3.5 microplastics/liter). As a result, treating this massive amount of wastewater is critical for both pollution reduction and water resource conservation (Memon et al., 2016).

There are wastewater treatment technologies that have been found to be effective. For example, advanced oxidation is a new technology that has recently been used in conjunction with other treatments (Kaur et al., 2018). Photocatalytic degradation is one of the advanced oxidation processes used to treat textile wastewater, and it has been shown to degrade from 50 to 80% of micropollutants in the wastewater (Jamil et al., 2019). Oxidation by UV/H_2O_2 reduced polyester fabric Microfibers by 52.7% (Easton et al., 2023). Another similar study conducted in China using TiO_2/graphite granules revealed that PVC microplastics can be degraded up to 75% (Mermaids, 2012). The summary of the removal efficiency of different technologies is shown in the following Table 1.

Table 1. Comparison of microfiber removal efficiencies of different emerging wastewater treatment technologies

Technology	Microfibers/microplastics removal efficiency (%)	Waste Type	Reference
Membrane Bioreactor	99.9	Municipal STP	(Talvitie et al., 2017)
Membrane Ultrafiltration	96.7	Synthetic textile wastewater	(Tadsuwan & Babel, 2022)
Reverse Osmosis	50-99	Textile wastewater	(Ziajahromi et al., 2017)
Electrocoagulation	97.3	Synthetic textile wastewater	(Shen et al., 2022)
Adsorption by activated carbon	92.8	Textile wastewater	(Kim et al., 2018)
Fe_3O_4-LIGPs adsorbents	92-98	Municipal wastewater	(S. Zhao et al., 2015)
Advanced Oxidation (Photo-Fenton)	97	Textile wastewater	(Hamd et al., 2022)
Advanced Oxidation (Peroxymonosulfate)	92.4	Synthetic textile wastewater	(Wang et al., 2023)

To address the issue of Microfibers in textile wastewater, green technologies, also known as eco-friendly or sustainable technologies, have been developed. Adsorption is one of the technologies, which involves the use of solid biomass materials to adsorb and retain Microfibers from wastewater. For example, activated carbon made from bamboo had a higher MF adsorption capacity than activated carbon made from other biomasses such as rice husk. Other similar studies for MF removal include zeolite, chitosan, and graphene. The study using zeolite and bentonite as sorbents revealed a significant removal of Microfibers from wastewater of more than 90% (Spacilova et al., 2023).

Biodegradation is another environmentally friendly method for removing microplastics/Microfibers from textile wastewater. A fungal strain called *Aspergillus fulvous* was used to test the degradation efficiency and was discovered to effectively degrade microplastics. The significant reduction in mass as well as particle surface morphology confirmed the degradation. A similar study using two bacteria consortia from the gut of Tenebrio mirliton larvae revealed a significant reduction in polyethylene mass of up to 18% in 30 days (Chai et al., 2020). This is relatively fast degradation as compared to other isolates from soil and gut of insects (Chamas et al., 2020).

Another study discovered that chitosan pretreatment significantly reduced Microfibers emission. Pretreating polyester clothes with chitosan, for example, reduced Microfibers emissions by 95%. Whereas applying the same chitosan to other types of fabrics reduced Microfibers emissions by less than half [59]. Photocatalytic degradation is also effective at degrading HDPE microplastics. A green N-TO_2 derived from the extrapallial fluid of saltwater mussels showed an excellent promoting mass loss of HDPE microplastics/Microfibers over 8 hours experiment.

6. Microfibers from textile laundry/washing effluent

This section discusses and summarizes the emission of Microfibers from household washing machines as well as the impact of various operating parameters, washing machine orientations, and washing detergents. The magnitude of Microfibers emissions in comparison to emissions from activities such as finishing and printing. It was recently discovered that laundry washing processes account for 35% of primary Microfibers.

6.1. Effect of detergent

The use of detergent reduces Microfibers emissions significantly, though the magnitude varies depending on the fabric material. Except for 100% pure cotton fabric, other fabrics that are washed with detergent reduce emissions by more than half (Marei et al., 2021). This is largely due to the detergent acting as a lubricant, which reduces friction between the fabrics and the machine. Cotton has a low friction coefficient because of its high detergent absorption capacity (Lim et al., 2022). In contrast to the previous study, a powder detergent study showed the opposite result. It was discovered that using detergent resulted in 2.7 times more Microfibers emission than not using detergent (Mahbub & Shams, 2022). The findings were justified by claiming that the retention of detergent contents such as zeolite and silica may contribute to an increase in mechanical friction between the fabrics, resulting in higher MF detachment during washing. Another study using liquid detergent found that washing with detergent significantly increases the emission of Microfibers from PET fabrics. Washing with bio-detergent revealed similar results, indicating that it increased MF detachment.

The study was carried out to see if different detergent types have a different effect on Microfibers detachment from polyester T-shirts, and they discovered that there is no significant difference when using different detergents as well as washing with water only (Volgare et al., 2021). The detergent was found to increase Microfibers detachment from synthetic fibers by 1.22-5.62-fold depending on the fabric type (Li et al., 2020). Both liquid and powder detergent were found to have similar effects, increasing the release of Microfibers during laundry by up to four times that of water-only washed fabrics (Orona-Návar et al., 2022). The other study on accelerated laundering found that using detergent significantly increases microfibers' release regardless of washing temperature (Zambrano et al., 2021).

6.2. Effects of textile characteristics

The study compared three different types of synthetic fabric. Polyamide fabric released the most microfibers, followed by acetate fabric and polyester fabric (Li et al., 2020). This could be attributed to the fabric's weight per unit area as well as density. The greater the yarn count of the fiber per cross section, the greater the release of microfibers. However, as the structure tightens, the higher the yarn count per unit length, the lower the Microfibers release. The geometry of the textile may also have an impact on the release of Microfibers. For example, fabrics made of short fibers emit more microfibers than fabrics made of continuous filaments. This could explain why polyamide and acetate fabrics released more microfibers than polyester fabrics.

Knitting and weaving are two textile unit operations that are thought to contribute to microfibers emissions to the environment to varying degrees. Polyester/cotton (PES/COT) knit staple, for example, released a high amount of microfibers per kilogram of fabric (1054), whereas PES-woven fabrics released as few as 128. The high number of microfibers emitted by PES/COT-knit staple may be attributed to the hydrophobicity of cellulosic fiber, which influences wettability and thus increases MF release, and cotton wet abrasion is high (McQueen et al., 2017). The study on interlock structure and single jersey found that after washing, a higher number of microfibers were released (Raja Balasaraswathi & Rathinamoorthy, 2022). This could be attributed to the fabrics' stitch density and tightness factor. Because increasing the stitch density and tightness factor shortens the loop length, resulting in more thread binding and less floating. Another significant finding is that the upstream processes during manufacturing, such as loading and unloading, vibration and oscillation using the spinning process, have the greatest impact on the subsequent processes, aggravating the release of Microfibers. Because during such activities, the fibers may be damaged, resulting in fragmented fibers and short fibers (Palacios-Marín et al., 2022). These short fibers will be attached to the yarn up a spinning and may migrate to the surface of the yarn (Özkan & Gündoğdu, 2021). Finally, due to the different mechanical forces applied, there is a greater chance of detachment and release to the environment during laundry washing (Kelly et al., 2019).

The orientation of the washing machine was also discovered to influence the release of Microfibers during washing. The two types of washing machines available are top load and front load. For example, a study comparing the two orientation effects discovered that top load machines emit approximately 10% more Microfibers than front load machines (Arutchelvi et al., 2008). This may be due to the increased likelihood of water fabric contact time and agitation level for the top load. A study on the effect of temperature found that increasing the temperature increased Microfibers emissions (Periyasamy, n.d.). This is due to the surface hydrolysis properties of polyester in alkaline media at high temperatures.

7. Proposed solution and future perspectives

Microfibers can be found in water, soil, and the atmosphere. That is, we are exposed to it in some way, and the effects are beginning to manifest in the human system as well as other living organisms. There have been numerous studies conducted to address this emerging pollutant. However, most studies have been focused on identifying their sources, emission factors, and how much they are in their various forms and sizes. These are important studies that will help us get one step closer to the solution. Despite these studies, Microfibers continue to increase in the environment year after year due to the exponential growth in global textile demand. As a result, it is critical to address the issue. For example, addressing source identification across the value chain/life cycle is critical to identifying hotspots and taking actions to reduce emissions to the environment. The conducted studies are very limited and must be considered as soon as possible. Otherwise, end-of-pipe solutions such as changing a washing machine filter will not suffice. Rather, it is possible that Microfibers will be transferred from one environmental compartment (water) to another (soil) during disposal.

Textile manufacturing must place a strong emphasis on how to produce less detachable fabrics and longer-lasting garments. This can only be determined by using life cycle assessment and/or circular economy approach (holistic approach) to improve the production system at a low cost and in a short period of time. Because locating the hotspot is the first step toward resolving the issue. The microplastics/microfibers impact assessment method has been integrated into the life cycle assessment. However, it should be accompanied by policy guidelines aimed at standardization and application before it is too late.

As is well known, the textile industry is the most polluting industry on the planet. According to a United Nations Environment Programme (UNEP) study, the recent introduction of synthetic fiber emission stands tall in polluting the environment (United Nations Environment Programme), 2021). The study emphasizes not only the emission of microfibers, but also the use of non-renewable resources in the production of these synthetic fibers. As a result, the problem must be addressed holistically, such as through life cycle assessment and circularity analysis. Only by approaching the problem holistically can the complexity and hotspots of microfibers be understood (Figure 7).

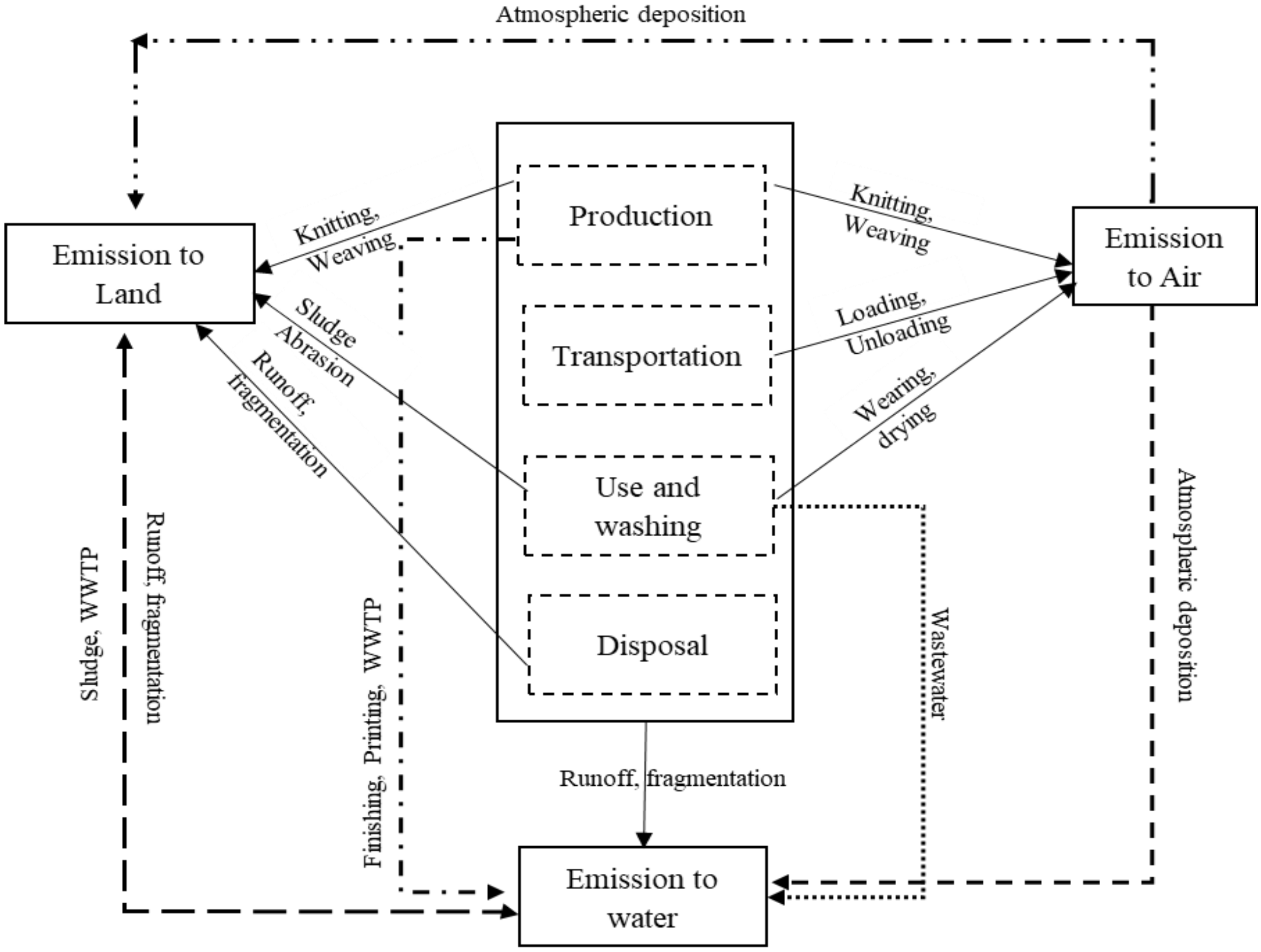

Figure 7. Proposed Emission pathways of microfibers from different life cycle stages of textile manufacturing

We can clearly comprehend the complexity of the paths of microfibers emission at different life cycle stages from the above (Figure 6). For example, removing Microfibers at the production stage alone will not fix the problem because the emissions will reach the water and land via atmospheric deposition. Therefore, it is critical to understand the problem holistically and address it using life cycle assessment technique or by adopting circularity concepts. A study on pre-consumer microfibers pollution suggested similar approaches, which they tested on all manufacturing steps (Berber, 2020). They proposed the following changes at each stage of the textile value chain: a) a better understanding of the relative emissions of microfibers at each manufacturing step; b) developing microfiber control technologies and codifying best practices; c) scaling up the proposed solution by supporting it with policies and regulations; and d) raising stakeholder awareness of the issue. They believe that doing so will solve 90% of the problem. While suggesting improvements to wastewater treatment technologies, care must be taken to avoid problem shifting (from water to soil and vice versa). Most microfibers are trapped in wastewater treatment plant sludge, which is then used for soil amendment or other purposes in another environmental compartment. As a result, sludge management from the WWTP must receive special attention. According to studies, microfibers are becoming a threat to land as well as the water environment. Improvements in textile parameters, washing machine filters and washing machine filters, water temperature, and detergents are another option.

Preparing fewer emitting materials is another improvement opportunity to reduce microfibers emissions. Super-hydrophobic and super-oleophilic polyester materials, for example, have been developed and are thought to reduce Microfibers emissions (J. Zhang & Seeger, 2011). Non-woven materials, such as wipes and melt-blown non-woven, can be used less because they produce more Microfibers in general than textile fabrics (Athey et al., 2020). The following solution is proposed following the sustainable waste management strategy (Figure 8).

In summary, the following measures have the potential to significantly reduce MF emissions into the environment:

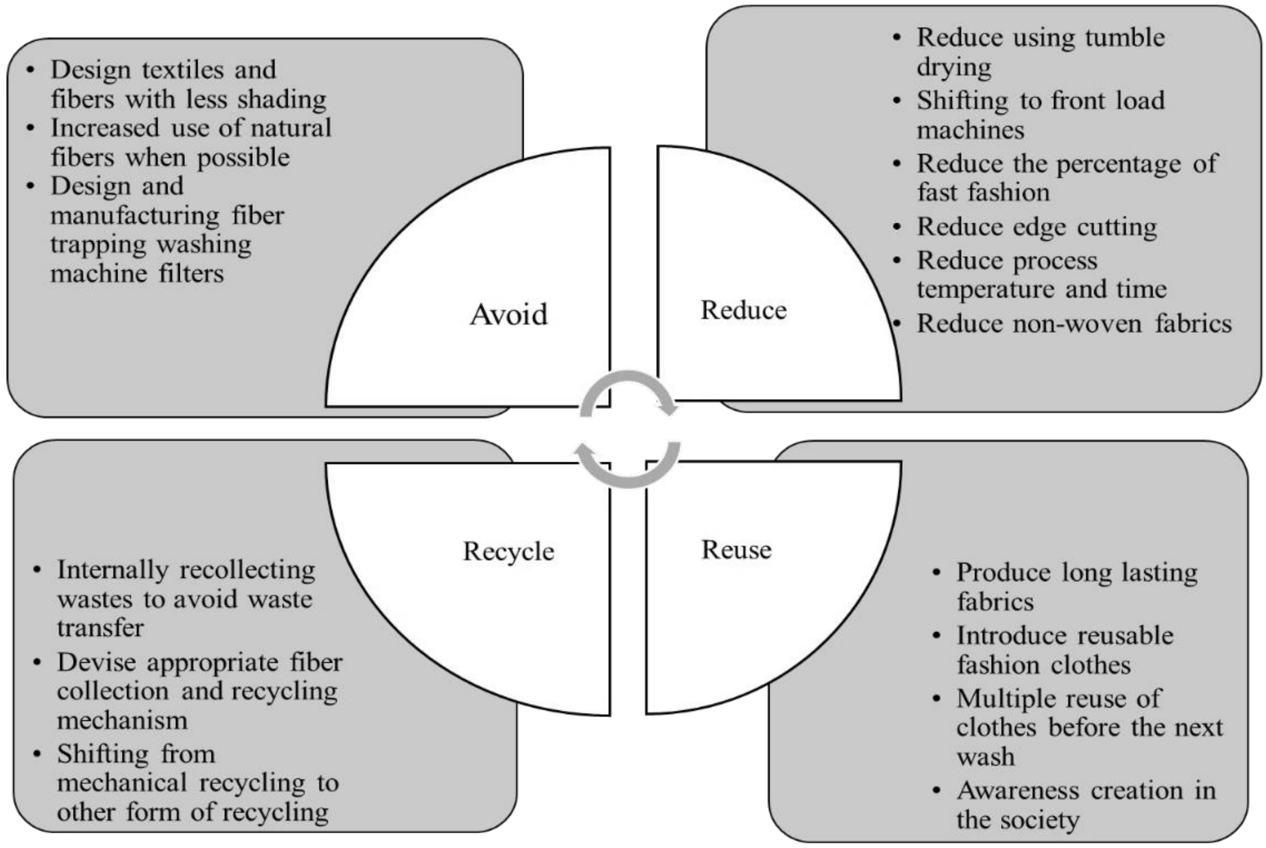

Figure 8. Proposed solutions according to the sustainable waste management principles customized to microfibers from textile

7.1. Raw material selection

Shifting away from petroleum-based raw materials and toward natural materials such as cotton will help to reduce the concentrations of harmful Microfibers- in the environment [6]. However, this does not imply that natural MFs have no environmental impact; rather, their impact is less than that of synthetic Microfibers because they do not persist in the environment.

7.2. Textile process modification

MF emissions are primarily caused by finishing processes such as dyeing and printing. As a result, optimizing this process will significantly reduce microfibers in the manufacturing process (Figure 9). Not only the finishing process, but also mechanical processes such as knitting and weaving, are responsible for Microfibers emissions into the atmosphere, which are later deposited in water bodies and on land. Avoiding woven fabrics can also help to reduce emissions significantly. The use of abrasive friction during manufacturing is an a crucial factor in the formation of microplastics. Because synthetic fabrics tend to release the most microplastics during the first 5-10 washes, pre-washing at production facilities could capture a significant portion of the microfibers (Roos et al., n.d.). In industrial plants, microfibers are more likely to be captured since the plants are generally connected to wastewater treatment.

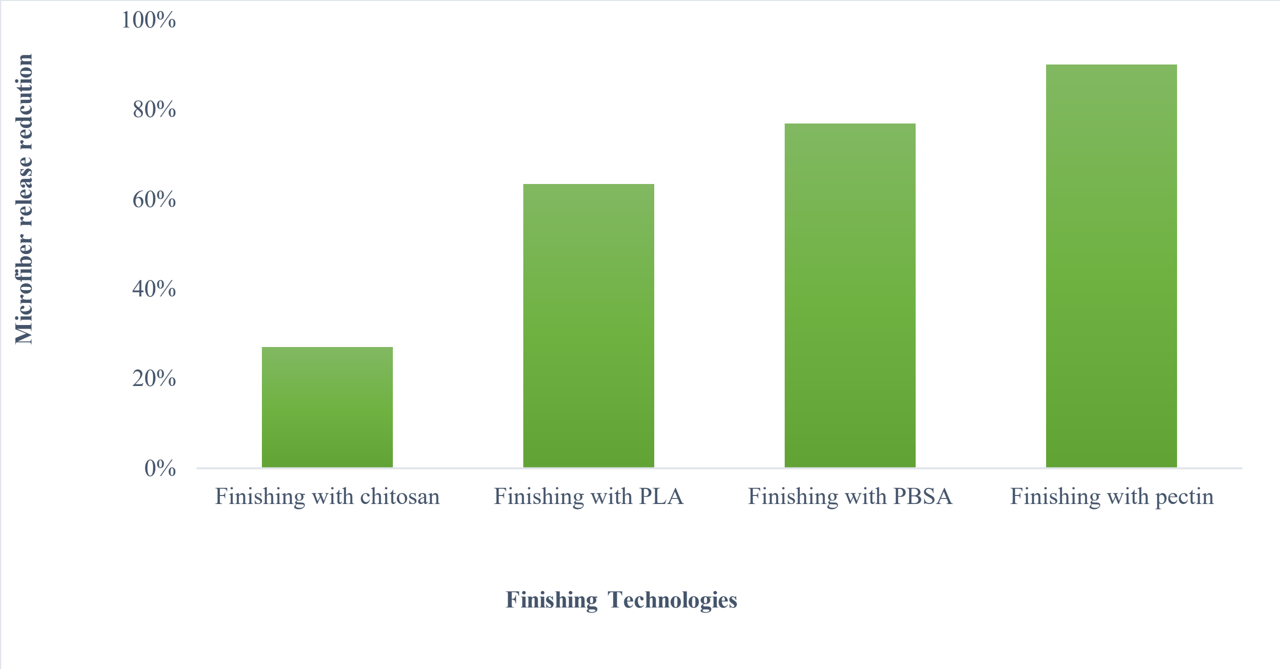

Figure 9. Microfiber release rate reduction percentage for different finishing technologies using different modifiers like poly lactic acid (PLA), Poly (butylene succinate-co- butylene adipate (PBSA), pectin and chitosan (The data was extracted from Periyasamy, n.d. and modified accordingly for our case)

7.3. Wastewater treatment technologies improvement

Even though some existing technologies trap a significant amount of microfibers, the remaining percentage is higher when the total number of microfibers entering the water environment is considered. As a result, it is critical to reduce microfibers to zero by upgrading technologies. However, the problem of shifting from water to other environmental compartments such as soil via sludge must be avoided to the greatest extent possible. Because industrial plants are typically linked to wastewater treatment facilities, microfibers are more likely to be captured.

7.4. Selection of washing machines and washing parameters

Top load and front load washing machines are the two most common types. Front load washing machines emit seven times less Microfibers than top load washing machines (Hartline et al., 2016). Reduced water volume and a shorter washing cycle may also help to reduce microfibers emissions as well as using cold water (Kalnasa et al., 2019). Avoiding the use of tumble dryers, softeners, and mild or biobased detergents will also help to reduce microfibers emissions (O'Brien et al., 2020). The use of effective filters in washing machines can also assist in the integration of Microfibers into the local sewage system and, ultimately, the water body (Quantis, n.d.). However, as with sludge, a discarding mechanism must be in place to avoid problem shifting.

7.5. Putting policies and regulations in place

The above mitigation options will be effective only if supporting policies and regulations are in place. To be fruitful, any development must be supported by policy and regulations. Another critical point that must be considered in policy development is the inclusion of community participation and awareness creation mechanisms.

7.6. The Microfiber-Carbon Nexus: Synergies in Mitigation

A critical challenge in textile sustainability is the potential trade-off between microfiber retention and greenhouse gas (GHG) emissions. Current "end-of-pipe" interventions, such as the installation of advanced tertiary treatment stages (e.g., Membrane Bioreactors or Ultrafiltration) in wastewater treatment plants, are highly effective at capturing up to 99% of microfibers. However, these technologies are energy-intensive, leading to an increase in operational GHG emissions if the energy grid is not decarbonized.

The synergy between these two pollutants becomes most apparent when shifting from end-of-pipe solutions to circularity-based interventions:

- **Material Efficiency and Longevity:** By extending the life of garments through improved fabric construction, the shedding rate per wash cycle decreases. Simultaneously, this reduces the "replacement rate" of the garment, avoiding the high GHG emissions associated with the production, dyeing, and finishing of new textiles—stages identified earlier in this study as major carbon contributors (projected at 1.8 Gt CO_2-eq by 2030).
- **Integrated Process Design:** Moving toward "low-shedding" and "low-carbon" textile designs requires a unified strategy. For instance, the transition from conventional energy-intensive dyeing processes to digital printing not only reduces the carbon footprint but also minimizes the mechanical and chemical stress on fibers, which in turn reduces subsequent shedding during consumer use.
- **Circular Feedback Loops:** Implementing a circular economy framework ensures that when a garment reaches its end-of-life, the fiber recovery process is optimized for both low energy consumption and the prevention of secondary microfiber release during recycling.

Therefore, addressing microfiber release in isolation risks a "carbon penalty"; however, by adopting a holistic circularity model, the textile industry can achieve a dual-benefit: reducing the biological impact of microplastic pollution while meeting global climate targets for GHG reduction.

8. Conclusion

Textile manufacturing is found to be more polluting when it comes to microfibers as it is emitting large amount of microfibers into the wastewater. Microfibers are emitted at all stages of textile value chain. Finishing, knitting, and weaving are among the major hotspots for microfiber emission at the production stage. More importantly, dyeing and printing are emitting large number of microfibers to the wastewater treatment plant (WWTP). The existing WWTP are not primarily designed in way to remove microfibers. However, they are reducing up to 90% from wastewater. This did not prevent WWTP from being considered as a point source of microfibers, since the cumulative number of emitted microfibers is very high. Textile laundry washing is also a major emitter of microfibers. The triggering factors for the microfiber emission during washing are mainly detergent usage, fabric properties, washing machine type and water temperature to some extent. Therefore, it is very important to approach the problem holistically rather than trying to solve it at the end of pipe.

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Author contributions E.W. G: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing

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Declarations

Competing Interests The authors declare no competing interests.

References

Akyildiz, S. H., Bellopede, R., Sezgin, H., Yalcin-Enis, I., Yalcin, B., & Fiore, S. (2022). Detection and Analysis of Microfibers and Microplastics in Wastewater from a Textile Company. *Microplastics*, *1*(4), 572–586. https://doi.org/10.3390/microplastics1040040

Allen, S., Allen, D., Phoenix, V. R., Le Roux, G., Durántez Jiménez, P., Simonneau, A., Binet, S., & Galop, D. (2019). Atmospheric transport and deposition of microplastics in a remote mountain catchment. *Nature Geoscience*, *12*(5), 339–344. https://doi.org/10.1038/s41561-019-0335-5

Andrady, A. L. (2011). Microplastics in the marine environment. *Marine Pollution Bulletin*, *62*(8), 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030

Arutchelvi, J., Sudhakar, M., Arkatkar, A., Doble, M., Bhaduri, S., & Uppara, P. V. (2008). Biodegradation of polyethylene and polypropylene. *Indian Journal of Biotechnology*, *7*(1), 9–22.

Athey, S. N., Albotra, S. D., Gordon, C. A., Monteleone, B., Seaton, P., Andrady, A. L., Taylor, A. R., & Brander, S. M. (2020). Trophic transfer of microplastics in an estuarine food chain and the effects of a sorbed legacy pollutant. *Limnology And Oceanography Letters*, *5*(1), 154–162. https://doi.org/10.1002/lol2.10130

Belzagui, F., Crespi, M., Álvarez, A., Gutiérrez-Bouzán, C., & Vilaseca, M. (2019). Microplastics' emissions: Microfibers' detachment from textile garments. *Environmental Pollution*, *248*, 1028–1035. https://doi.org/10.1016/j.envpol.2019.02.059

Belzagui, F., & Gutiérrez-Bouzán, C. (2022). Review on alternatives for the reduction of textile microfibers emission to water. In *Journal of Environmental Management* (Vol. 317). Academic Press. https://doi.org/10.1016/j.jenvman.2022.115347

Berber, M. R. (2020). Current Advances of Polymer Composites for Water Treatment and Desalination. In *Journal of Chemistry* (Vol. 2020). Hindawi Limited. https://doi.org/10.1155/2020/7608423

Boucher, J., & Friot, D. (2017). Primary microplastics in the oceans: A global evaluation of sources. In *Primary microplastics in the oceans: A global evaluation of sources*. https://doi.org/10.2305/iucn.ch.2017.01.en

Cai, Y., Mitrano, D. M., Heuberger, M., Hufenus, R., & Nowack, B. (2020). The origin of microplastic fiber in polyester textiles: The textile production process matters. *Journal of Cleaner Production*, *267*. https://doi.org/10.1016/j.jclepro.2020.121970

Carney Almroth, B. M., Åström, L., Roslund, S., Petersson, H., Johansson, M., & Persson, N. K. (2018). Quantifying shedding of synthetic fibers from textiles; a source of microplastics released into the environment. *Environmental Science and Pollution Research*, *25*(2), 1191–1199. https://doi.org/10.1007/s11356-017-0528-7

Carr, S. A., Liu, J., & Tesoro, A. G. (2016). Transport and fate of microplastic particles in wastewater treatment plants. *Water Research*, *91*, 174–182. https://doi.org/10.1016/j.watres.2016.01.002

Catarino, A. I., Macchia, V., Sanderson, W. G., Thompson, R. C., & Henry, T. B. (2018). Low levels of microplastics (MP) in wild mussels indicate that MP ingestion by humans is minimal compared to exposure via household fibres fallout during a meal. *Environmental Pollution*, *237*, 675–684. https://doi.org/10.1016/j.envpol.2018.02.069

Chai, B., Wei, Q., She, Y., Lu, G., Dang, Z., & Yin, H. (2020). Soil microplastic pollution in an e-waste dismantling zone of China. *Waste Management*, *118*, 291–301. https://doi.org/10.1016/j.wasman.2020.08.048

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J. H., Abu-Omar, M., Scott, S. L., & Suh, S. (2020). Degradation Rates of Plastics in the Environment. *ACS Sustainable Chemistry and Engineering*, *8*(9), 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635

Cheung, P. K., Cheung, L. T. O., & Fok, L. (2016). Seasonal variation in the abundance of marine plastic debris in the estuary of a subtropical macro-scale drainage basin in South China. *Science of the Total Environment*, *562*, 658–665. https://doi.org/10.1016/j.scitotenv.2016.04.048

Cox, K. D., Covernton, G. A., Davies, H. L., Dower, J. F., Juanes, F., & Dudas, S. E. (2020). Erratum: Human consumption of microplastics (Environmental Science & Technology (2019) 53:12 (7068−7074) DOI: 10.1021/acs.est.9b01517). *Environmental Science and Technology*, *54*(17), 10974. https://doi.org/10.1021/acs.est.0c04032

De Falco, F., Di Pace, E., Cocca, M., & Avella, M. (2019). The contribution of washing processes of synthetic clothes to microplastic pollution. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-019-43023-x

De Falco, F., Gullo, M. P., Gentile, G., Di Pace, E., Cocca, M., Gelabert, L., Brouta-Agnésa, M., Rovira, A., Escudero, R., Villalba, R., Mossotti, R., Montarsolo, A., Gavignano, S., Tonin, C., & Avella, M. (2018). Evaluation of microplastic release caused by textile washing processes of synthetic fabrics. *Environmental Pollution*, *236*, 916–925. https://doi.org/10.1016/j.envpol.2017.10.057

de Oliveira, C. R. S., da Silva Júnior, A. H., Mulinari, J., Ferreira, A. J. S., & da Silva, A. (2023). Fibrous microplastics released from textiles: Occurrence, fate, and remediation strategies. *Journal of Contaminant Hydrology*, *256*, 104169. https://doi.org/10.1016/j.jconhyd.2023.104169

Dehghani, S., Moore, F., & Akhbarizadeh, R. (2017). Microplastic pollution in deposited urban dust, Tehran metropolis, Iran. *Environmental Science and Pollution Research*, *24*(25), 20360–20371. https://doi.org/10.1007/s11356-017-9674-1

Dris, R., Gasperi, J., Rocher, V., Saad, M., Renault, N., Tassin, B., Microplastic, al, Johnny Gasperi, C., Vincent Rocher, A., Mohamed Saad, B., Nicolas Renault, A. A., & Tassin, B. A. (2015). Microplastic contamination in an urban area: a case study in Greater Paris. *Environmental Chemistry*. https://doi.org/10.1071/EN14167ï

Dris, R., Gasperi, J., Saad, M., Mirande, C., & Tassin, B. (2016). Synthetic fibers in atmospheric fallout: A source of microplastics in the environment? *Marine Pollution Bulletin*, *104*(1–2), 290–293. https://doi.org/10.1016/j.marpolbul.2016.01.006

Easton, T., Koutsos, V., & Chatzisymeon, E. (2023). Removal of polyester fibre microplastics from wastewater using a UV/H2O2oxidation process. *Journal of Environmental Chemical Engineering*, *11*(1). https://doi.org/10.1016/j.jece.2022.109057

EUC. (2020). Circular Economy Action Plan:For a cleaner and more competitive Europe. In *EU*.

Faghihinezhad, M., Baghdadi, M., Shahin, M. S., & Torabian, A. (2022). Catalytic ozonation of real textile wastewater by magnetic oxidized g-C3N4 modified with Al2O3 nanoparticles as a novel catalyst. *Separation and Purification Technology*, *283*. https://doi.org/10.1016/j.seppur.2021.120208

Gago, J., Carretero, O., Filgueiras, A. V., & Viñas, L. (2018). Synthetic microfibers in the marine environment: A review on their occurrence in seawater and sediments. In *Marine Pollution Bulletin* (Vol. 127, pp. 365–376). Elsevier Ltd. https://doi.org/10.1016/j.marpolbul.2017.11.070

GROZ-BECKERT. (2017). *The fabric year 2017*.

Gündoğdu, S., Çevik, C., Güzel, E., & Kilercioğlu, S. (2018). Microplastics in municipal wastewater treatment plants in Turkey: a comparison of the influent and secondary effluent concentrations. *Environmental Monitoring and Assessment*, *190*(11). https://doi.org/10.1007/s10661-018-7010-y

Hamd, W., Daher, E. A., Tofa, T. S., & Dutta, J. (2022). Recent Advances in Photocatalytic Removal of Microplastics: Mechanisms, Kinetic Degradation, and Reactor Design. In *Frontiers in Marine Science* (Vol. 9). Frontiers Media S.A. https://doi.org/10.3389/fmars.2022.885614

Hantoro, I., Löhr, A. J., Van Belleghem, F. G. A. J., Widianarko, B., & Ragas, A. M. J. (2019). Microplastics in coastal areas and seafood: implications for food safety. In *Food Additives and Contaminants - Part A Chemistry, Analysis, Control, Exposure and Risk Assessment* (Vol. 36, Issue 5, pp. 674–711). Taylor and Francis Ltd. https://doi.org/10.1080/19440049.2019.1585581

Hartline, N. L., Bruce, N. J., Karba, S. N., Ruff, E. O., Sonar, S. U., & Holden, P. A. (2016). Microfiber Masses Recovered from Conventional Machine Washing of New or Aged Garments. *Environmental Science and Technology*, *50*(21), 11532–11538. https://doi.org/10.1021/acs.est.6b03045

Henry, B., Laitala, K., & Klepp, I. G. (2019). Microfibres from apparel and home textiles: Prospects for including microplastics in environmental sustainability assessment. *Science of the Total Environment*, *652*, 483–494. https://doi.org/10.1016/j.scitotenv.2018.10.166

Hertwich, E. G. (2021). Increased carbon footprint of materials production driven by rise in investments. *Nature Geoscience*, *14*(3), 151–155. https://doi.org/10.1038/s41561-021-00690-8

Holkar, C. R., Jadhav, A. J., Pinjari, D. V., Mahamuni, N. M., & Pandit, A. B. (2016). A critical review on textile wastewater treatments: Possible approaches. In *Journal of Environmental Management* (Vol. 182, pp. 351–366). Academic Press. https://doi.org/10.1016/j.jenvman.2016.07.090

Jamil, S., Loganathan, P., Listowski, A., Kandasamy, J., Khourshed, C., & Vigneswaran, S. (2019). Simultaneous removal of natural organic matter and micro-organic pollutants from reverse osmosis concentrate using granular activated carbon. *Water Research*, *155*, 106–114. https://doi.org/10.1016/j.watres.2019.02.016

Kalnasa, M. L., Lantaca, S. M. O., Boter, L. C., Flores, G. J. T., & Galarpe, V. R. K. R. (2019). Occurrence of surface sand microplastic and litter in Macajalar Bay, Philippines. *Marine Pollution Bulletin*, *149*. https://doi.org/10.1016/j.marpolbul.2019.110521

Kang, H.-J., Park, H.-J., Kwon, O.-K., Lee, W.-S., Jeong, D.-H., Ju, B.-K., & Kwon, J.-H. (2018). Occurrence of microplastics in municipal sewage treatment plants: a review. *Environmental Health and Toxicology*, *33*(3), e2018013. https://doi.org/10.5620/eht.e2018013

Kaur, P., Kushwaha, J. P., & Sangal, V. K. (2018). Electrocatalytic oxidative treatment of real textile wastewater in continuous reactor: Degradation pathway and disposability study. *Journal of Hazardous Materials*, *346*, 242–252. https://doi.org/10.1016/j.jhazmat.2017.12.044

Kawecki, D., & Nowack, B. (2019). Polymer-Specific Modeling of the Environmental Emissions of Seven Commodity Plastics As Macro- and Microplastics. *Environmental Science and Technology*, *53*(16), 9664–9676. https://doi.org/10.1021/acs.est.9b02900

Kay, P., Hiscoe, R., Moberley, I., Bajic, L., & McKenna, N. (2018). Wastewater treatment plants as a source of microplastics in river catchments. *Environmental Science and Pollution Research*, *25*(20), 20264–20267. https://doi.org/10.1007/s11356-018-2070-7

Kelly, M. R., Lant, N. J., Kurr, M., & Burgess, J. G. (2019). Importance of Water-Volume on the Release of Microplastic Fibers from Laundry. *Environmental Science and Technology*, *53*(20), 11735–11744. https://doi.org/10.1021/acs.est.9b03022

Kim, J. S., Lee, H. J., Kim, S. K., & Kim, H. J. (2018). Global Pattern of Microplastics (MPs) in Commercial Food-Grade Salts: Sea Salt as an Indicator of Seawater MP Pollution. *Environmental Science and Technology*, *52*(21), 12819–12828. https://doi.org/10.1021/acs.est.8b04180

Koelmans, A. A., Mohamed Nor, N. H., Hermsen, E., Kooi, M., Mintenig, S. M., & De France, J. (2019). Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. In *Water Research* (Vol. 155, pp. 410–422). Elsevier Ltd. https://doi.org/10.1016/j.watres.2019.02.054

Kosuth, M., Mason, S. A., & Wattenberg, E. V. (2018). Anthropogenic contamination of tap water, beer, and sea salt. *PLoS ONE*, *13*(4). https://doi.org/10.1371/journal.pone.0194970

Lares, M., Ncibi, M. C., Sillanpää, M., & Sillanpää, M. (2018). Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology. *Water Research*, *133*, 236–246. https://doi.org/10.1016/j.watres.2018.01.049

Le Hyaric, R., Canler, J. P., Barillon, B., Naquin, P., & Gourdon, R. (2009). Characterization of screenings from three municipal wastewater treatment plants in the Region Rhône-Alpes. *Water Science and Technology*, *60*(2), 525–531. https://doi.org/10.2166/wst.2009.391

Leal Filho, W., Perry, P., Heim, H., Dinis, M. A. P., Moda, H., Ebhuoma, E., & Paço, A. (2022). An overview of the contribution of the textiles sector to climate change. In *Frontiers in Environmental Science* (Vol. 10). Frontiers Media S.A. https://doi.org/10.3389/fenvs.2022.973102

Leslie, H. A., Brandsma, S. H., van Velzen, M. J. M., & Vethaak, A. D. (2017). Microplastics en route: Field measurements in the Dutch river delta and Amsterdam canals, wastewater treatment plants, North Sea sediments and biota. *Environment International*, *101*, 133–142. https://doi.org/10.1016/j.envint.2017.01.018

Leslie, H. A., van Velzen, M. J. M., Brandsma, S. H., Vethaak, A. D., Garcia-Vallejo, J. J., & Lamoree, M. H. (2022). Discovery and quantification of plastic particle pollution in human blood. *Environment International*, *163*. https://doi.org/10.1016/j.envint.2022.107199

Li, Y., Lu, Z., Zheng, H., Wang, J., & Chen, C. (2020). Microplastics in surface water and sediments of Chongming Island in the Yangtze Estuary, China. *Environmental Sciences Europe*, *32*(1). https://doi.org/10.1186/s12302-020-0297-7

Lim, J., Choi, J., Won, A., Kim, M., Kim, S., & Yun, C. (2022). Cause of microfibers found in the domestic washing process of clothing; focusing on the manufacturing, wearing, and washing processes. *Fashion and Textiles*, *9*(1). https://doi.org/10.1186/s40691-022-00306-8

Lin, L., Zuo, L. Z., Peng, J. P., Cai, L. Q., Fok, L., Yan, Y., Li, H. X., & Xu, X. R. (2018). Occurrence and distribution of microplastics in an urban river: A case study in the Pearl River along Guangzhou City, China. *Science of the Total Environment*, *644*, 375–381. https://doi.org/10.1016/j.scitotenv.2018.06.327

Liu, J., Liang, J., Ding, J., Zhang, G., Zeng, X., Yang, Q., Zhu, B., & Gao, W. (2021). Microfiber pollution: an ongoing major environmental issue related to the sustainable development of textile and clothing industry. In *Environment, Development and Sustainability* (Vol. 23, Issue 8, pp. 11240–11256). Springer Science and Business Media B.V. https://doi.org/10.1007/s10668-020-01173-3

Mahbub, M. S., & Shams, M. (2022). Acrylic fabrics as a source of microplastics from portable washer and dryer: Impact of washing and drying parameters. *Science of the Total Environment*, *834*. https://doi.org/10.1016/j.scitotenv.2022.155429

Marei, I. C. A., Saleh, F. I. E., Manullang, C. Y., Soamole, A., & Rehalat, I. (2021). Occurrence and distribution of microplastics in the beach sediment of Anday Beach, West Papua (Indonesia). *IOP Conference Series: Earth and Environmental Science*, *944*(1). https://doi.org/10.1088/1755-1315/944/1/012070

McQueen, R. H., Batcheller, J. C., Moran, L. J., Zhang, H., & Hooper, P. M. (2017). Reducing laundering frequency to prolong the life of denim jeans. *International Journal of Consumer Studies*, *41*(1), 36–45. https://doi.org/10.1111/ijcs.12311

Memon, H., Khatri, A., Ali, N., & Memon, S. (2016). Dyeing Recipe Optimization for Eco-Friendly Dyeing and Mechanical Property Analysis of Eco-Friendly Dyed Cotton Fabric: Better Fixation, Strength, and Color Yield by Biodegradable Salts. *Journal of Natural Fibers*, *13*(6), 749–758. https://doi.org/10.1080/15440478.2015.1137527

Mermaids. (2012). *Handbook for zero microplastics from textiles and laundry*.

Mintenig, S. M., Int-Veen, I., Löder, M. G. J., Primpke, S., & Gerdts, G. (2017). Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-Fourier-transform infrared imaging. *Water Research*, *108*, 365–372. https://doi.org/10.1016/j.watres.2016.11.015

Murphy, F., Ewins, C., Carbonnier, F., & Quinn, B. (2016). Wastewater Treatment Works (WwTW) as a Source of Microplastics in the Aquatic Environment. *Environmental Science and Technology*, *50*(11), 5800–5808. https://doi.org/10.1021/acs.est.5b05416

Nikolina, S. (n.d.). *Environmental impact of textile and clothes industry*.

O'Brien, S., Okoffo, E. D., O'Brien, J. W., Ribeiro, F., Wang, X., Wright, S. L., Samanipour, S., Rauert, C., Toapanta, T. Y. A., Albarracin, R., & Thomas, K. V. (2020). Airborne emissions of microplastic fibres from domestic laundry dryers. *Science of the Total Environment*, *747*. https://doi.org/10.1016/j.scitotenv.2020.141175

Orona-Návar, C., García-Morales, R., Loge, F. J., Mahlknecht, J., Aguilar-Hernández, I., & Ornelas-Soto, N. (2022). Microplastics in Latin America and the Caribbean: A review on current status and perspectives. *Journal of Environmental Management*, *309*. https://doi.org/10.1016/j.jenvman.2022.114698

Özkan, İ., & Gündoğdu, S. (2021). Investigation on the microfiber release under controlled washings from the knitted fabrics produced by recycled and virgin polyester yarns. *Journal of the Textile Institute*, *112*(2), 264–272. https://doi.org/10.1080/00405000.2020.1741760

Palacios-Marín, A. V., Jabbar, A., & Tausif, M. (2022). Fragmented fiber pollution from common textile materials and structures during laundry. *Textile Research Journal*, *92*(13–14), 2265–2275. https://doi.org/10.1177/00405175221090971

Patel, B., & Kanade, P. (2019). Sustainable dyeing and printing with natural colours vis-à-vis preparation of hygienic viscose rayon fabric. *Sustainable Materials and Technologies*, *22*. https://doi.org/10.1016/j.susmat.2019.e00116

Peixoto, D., Pinheiro, C., Amorim, J., Oliva-Teles, L., Guilhermino, L., & Vieira, M. N. (2019). Microplastic pollution in commercial salt for human consumption: A review. In *Estuarine, Coastal and Shelf Science* (Vol. 219, pp. 161–168). Academic Press. https://doi.org/10.1016/j.ecss.2019.02.018

Pensupa, N., Leu, S. Y., Hu, Y., Du, C., Liu, H., Jing, H., Wang, H., & Lin, C. S. K. (2017). Recent Trends in Sustainable Textile Waste Recycling Methods: Current Situation and Future Prospects. In *Topics in Current Chemistry* (Vol. 375, Issue 5). Springer International Publishing. https://doi.org/10.1007/s41061-017-0165-0

Periyasamy, A. P. (n.d.). *Evaluation of microfiber release from jeans: the impact of different washing conditions*. https://doi.org/10.1007/s11356-021-14761-1/Published

Quantis. (n.d.). *MEASURING FASHION 2018 Environmental Impact of the Global Apparel and Footwear Industries Study*.

Raja Balasaraswathi, S., & Rathinamoorthy, R. (2022). Effect of fabric properties on microfiber shedding from synthetic textiles. *Journal of the Textile Institute*, *113*(5), 789–809. https://doi.org/10.1080/00405000.2021.1906038

Rathinamoorthy, R., & Raja Balasaraswathi, S. (2023). Characterization of microfibers originated from the textile screen printing industry. *Science of the Total Environment*, *874*. https://doi.org/10.1016/j.scitotenv.2023.162550

Rhodes, C. J. (2018). Plastic pollution and potential solutions. *Science Progress*, *101*(3), 207–260. https://doi.org/10.3184/003685018X15294876706211

Roblin, B., Ryan, M., Vreugdenhil, A., & Aherne, J. (2020). Ambient Atmospheric Deposition of Anthropogenic Microfibers and Microplastics on the Western Periphery of Europe (Ireland). *Environmental Science and Technology*, *54*(18), 11100–11108. https://doi.org/10.1021/acs.est.0c04000

Roos, S., Arturin, O. L., & Hanning, A.-C. (n.d.). *microplastics shedding from polyester fabrics*. www.mistrafuturefashion.com

Seltenrich, N. (2015). New link in the food chain? Marine plastic pollution and seafood safety. In *Environmental Health Perspectives* (Vol. 123, Issue 2, pp. A34–A41). Public Health Services, US Dept of Health and Human Services. https://doi.org/10.1289/ehp.123-A34

Shen, M., Zhang, Y., Almatrafi, E., Hu, T., Zhou, C., Song, B., Zeng, Z., & Zeng, G. (2022). Efficient removal of microplastics from wastewater by an electrocoagulation process. *Chemical Engineering Journal*, *428*. https://doi.org/10.1016/j.cej.2021.131161

Spacilova, M., Dytrych, P., Lexa, M., Wimmerova, L., Masin, P., Kvacek, R., & Solcova, O. (2023). An Innovative Sorption Technology for Removing Microplastics from Wastewater. *Water (Switzerland)*, *15*(5). https://doi.org/10.3390/w15050892

Tadsuwan, K., & Babel, S. (2022). Microplastic abundance and removal via an ultrafiltration system coupled to a conventional municipal wastewater treatment plant in Thailand. *Journal of Environmental Chemical Engineering*, *10*(2). https://doi.org/10.1016/j.jece.2022.107142

Talvitie, J., Heinonen, M., Pääkkönen, J. P., Vahtera, E., Mikola, A., Setälä, O., & Vahala, R. (2015). Do wastewater treatment plants act as a potential point source of microplastics? Preliminary study in the coastal Gulf of Finland, Baltic Sea. *Water Science and Technology*, *72*(9), 1495–1504. https://doi.org/10.2166/wst.2015.360

Talvitie, J., Mikola, A., Koistinen, A., & Setälä, O. (2017). Solutions to microplastic pollution – Removal of microplastics from wastewater effluent with advanced wastewater treatment technologies. *Water Research*, *123*, 401–407. https://doi.org/10.1016/j.watres.2017.07.005

Tang, N., Liu, X., & Xing, W. (2020). Microplastics in wastewater treatment plants of Wuhan, Central China: Abundance, removal, and potential source in household wastewater. *Science of the Total Environment*, *745*. https://doi.org/10.1016/j.scitotenv.2020.141026

Textile Exchange. (2021). *Preferred Fiber & Materials Market Report 2021*.

UNEP (United Nations Environment Programme). (2021). From pollution to solution: a global assessment of marine litter and plastic pollution. In *New Scientist* (Vol. 237, Issue 3169). https://www.unep.org/resources/pollution-solution-global-assessment-marine-litter-and-plastic-pollution

Volgare, M., Castaldo, R., Errico, M. E., Gentile, G., Avolio, R., Ambrogi, V., & Cocca, M. (2021). "The effect of the detergent on microfibre release during the washing process of polyester textiles." *2021 IEEE International Workshop on Metrology for the Sea: Learning to Measure Sea Health Parameters, MetroSea 2021 - Proceedings*, 444–448. https://doi.org/10.1109/MetroSea52177.2021.9611615

Wang, G., Hambly, A. C., Zhao, D., Wang, G., Tang, K., & Andersen, H. R. (2023). Peroxymonosulfate activation by suspended biogenic manganese oxides for polishing micropollutants in wastewater effluent. *Separation and Purification Technology*, *306*. https://doi.org/10.1016/j.seppur.2022.122501

Weis, J. S., & De Falco, F. (2022). Microfibers: Environmental Problems and Textile Solutions. *Microplastics*, *1*(4), 626–639. https://doi.org/10.3390/microplastics1040043

Wright, S. L., Ulke, J., Font, A., Chan, K. L. A., & Kelly, F. J. (2020). Atmospheric microplastic deposition in an urban environment and an evaluation of transport. *Environment International*, *136*. https://doi.org/10.1016/j.envint.2019.105411

Xu, X., Hou, Q., Xue, Y., Jian, Y., & Wang, L. P. (2018). Pollution characteristics and fate of microfibers in the wastewater from textile dyeing wastewater treatment plant. *Water Science and Technology*, *78*(10), 2046–2054. https://doi.org/10.2166/wst.2018.476

Yang, H., Chen, G., & Wang, J. (2021). Microplastics in the marine environment: Sources, fates, impacts and microbial degradation. *Toxics*, *9*(2), 1–19. https://doi.org/10.3390/toxics9020041

Zambrano, M. C., Pawlak, J. J., Daystar, J., Ankeny, M., Cheng, J. J., & Venditti, R. A. (2019). Microfibers generated from the laundering of cotton, rayon and polyester based fabrics and their aquatic biodegradation. *Marine Pollution Bulletin*, *142*, 394–407. https://doi.org/10.1016/j.marpolbul.2019.02.062

Zambrano, M. C., Pawlak, J. J., Daystar, J., Ankeny, M., & Venditti, R. A. (2021). Impact of dyes and finishes on the microfibers released on the laundering of cotton knitted fabrics. *Environmental Pollution*, *272*. https://doi.org/10.1016/j.envpol.2020.115998

Zhang, C., Zhou, H., Cui, Y., Wang, C., Li, Y., & Zhang, D. (2019). Microplastics in offshore sediment in the Yellow Sea and East China Sea, China. *Environmental Pollution*, *244*, 827–833. https://doi.org/10.1016/j.envpol.2018.10.102

Zhang, J., & Seeger, S. (2011). Polyester materials with superwetting silicone nanofilaments for oil/water separation and selective oil absorption. *Advanced Functional Materials*, *21*(24), 4699–4704. https://doi.org/10.1002/adfm.201101090

Zhang, Y. Q., Lykaki, M., Alrajoula, M. T., Markiewicz, M., Kraas, C., Kolbe, S., Klinkhammer, K., Rabe, M., Klauer, R., Bendt, E., & Stolte, S. (2021). Microplastics from textile origin-emission and reduction measures. In *Green Chemistry* (Vol. 23, Issue 15, pp. 5247–5271). Royal Society of Chemistry. https://doi.org/10.1039/d1gc01589c

Zhao, M., Huang, L., Babu Arulmani, S. R., Yan, J., Wu, L., Wu, T., Zhang, H., & Xiao, T. (2022). Adsorption of Different Pollutants by Using Microplastic with Different Influencing Factors and Mechanisms in Wastewater: A Review. In *Nanomaterials* (Vol. 12, Issue 13). MDPI. https://doi.org/10.3390/nano12132256

Zhao, S., Zhu, L., & Li, D. (2015). Microplastic in three urban estuaries, China. *Environmental Pollution*, *206*, 597–604. https://doi.org/10.1016/j.envpol.2015.08.027

Zhou, H., Zhou, L., & Ma, K. (2020). Microfiber from textile dyeing and printing wastewater of a typical industrial park in China: Occurrence, removal and release. *Science of the Total Environment*, *739*. https://doi.org/10.1016/j.scitotenv.2020.140329

Ziajahromi, S., Neale, P. A., Rintoul, L., & Leusch, F. D. L. (2017). Wastewater treatment plants as a pathway for microplastics: Development of a new approach to sample wastewater-based microplastics. *Water Research*, *112*, 93–99. https://doi.org/10.1016/j.watres.2017.01.042