Microfibre Emissions from Textile Manufacturing Industries: A Critical Review

Key findings

- Textile manufacturing is an important but underappreciated source of MF pollution.
- Dyeing (wet) and spinning (dry) stages are the dominant source of MFs.
- Wet processing releases 2x more MFs than dry processing.
- Microfibre length from spinning to the final garment manufacturing reduces by 57%.
- Scalable ‘better-by-design’ interventions could reduce MF emissions during production.

Abstract

MF emissions from all types of textiles, natural, synthetic and semi-synthetic, are not well studied with most papers identifying domestic washing as the major cause of MF leakage; however, this ignores large-scale MF shedding during manufacturing. In the last 5 years, only 10 papers have focused on MF release during textile manufacturing, highlighting gaps in knowledge. A review of available literature demonstrated manufacturing as an important but underappreciated source of MF pollution and a potential opportunity for mitigation. Varying methods of analysis, levels of replication, and different data reporting norms pose difficulty in gaining a holistic overview of the data available. The need for more stringent research into this area is evident to fully map MF emissions throughout the supply chain and to ensure adequate process design and remediation methodologies. On average, wet processing releases two times more MFs (~1,300 MF g^{-1} fabric) than dry processing (~700 MF g^{-1}), whilst dyeing (~800 MF g^{-1}) releases most MFs. Wet processes also release 2x more mass of MF compared to dry processes, and MF length in wet processing is 57% shorter compared to dry processing. Wastewater treatment plant capture efficiency for MFs depends on MF size in the influent, which in turn depends on the type of fibres used in production, the manufacturing processes, and material characteristics. Scalable ‘better-by-design’ interventions offer a significant opportunity to reduce MF emissions in production, including selecting yarns with higher twist and packing density, laser cut fabrics, pre-treatment of textiles using plasma treatment, low temperature dope dyeing and in-situ dyeing methods with reduced abrasion, and pre-washing textiles before sending to the consumer to reduce MF emissions.

Keywords: Microfibres, Textiles, Manufacturing, Emissions, Sustainability, Process Design.

1. Introduction

Plastic microfibres (MFs), defined as fibres with a cross-sectional diameter of <10 μm and length ranging from 1 μm to 5 mm, have recently taken the spotlight as one of the most important environmental challenges of our time; they have been found in 90% of surface waters on the planet, at the bottom of oceans, and in human tissues and bodily fluids (Gaylarde et al., 2021; Liu et al., 2019; Wang et al., 2023). According to the European Environment Agency (2022), of the 14 million tonnes (Mt) of MPs on the world's ocean floor, 16-35% originate from synthetic textiles, equating to the annual release of 200,000-500,000 t of MFs into the marine environment (Šaravanja et al., 2022). However, the issue is not exclusive to synthetic textiles: one study reported that 80% of MFs in Southern European seafloor sediments were not plastic but dyed cellulosic fibres (Sanchez-Vidal et al., 2018). In another study, MFs present in the River Trent (UK) were found to be 93.8% natural fibres (Stanton et al., 2019). Therefore, natural fibres, due to the material composition and textile characteristics, dominate marine, freshwater, and airborne textile fibre populations (De Falco et al., 2020).

Natural fibres (e.g. cotton, wool, silk, and hemp) are often considered to be a more sustainable, environmentally benign option to replace their synthetic counterparts – polyethylene (PE), polypropylene (PP), polyester (PET), polyamide (PA), and polyacrylonitrile (PAN) – although this may not be the case (Weis & Falco, 2022). Fibres present in their natural form, unchanged from how they occur in plants, may not be harmful or as persistent as synthetic fibres, but the use of textile auxiliaries, strong alkali/acids, detergents, oxidisers, dyes and finishes, etc., during textile manufacturing alters the chemical and crystal structure of the natural polymer, increasing its longevity in the environment and causing myriad potential environmental and health implications (Zambrano et al., 2021a). Due to the higher rates of degradation of these natural fibres compared to synthetic fibres, such chemical additives (metals, polychlorinated biphenyls, polycyclic aromatic hydrocarbons) are more easily released to the environment (Elfaleh et al., 2023; Henry et al., 2019; Ladewig et al., 2015; Weis & De Falco, 2022). Remy *et al.* (2015) revealed most of the fibres in the Mediterranean coastal zone were industrially dyed viscose, which is a man-made cellulosic fibre (also referred to as a regenerated cellulosic fibre). The viscose process involves dissolution of a source of natural cellulose I (typically from wood pulp), which is then regenerated into cellulose II and extruded into fibre - cellulose II does not occur in nature. Furthermore, studies examining the incidence of non-petroleum based MFs within the environment and biota tend to systematically underestimate these fibres, due to processing with various acids and oxidisers that favour the recovery of petroleum-based (synthetic) fibres (Athey & Erdle, 2022). Research has recently shown that exposure to both synthetic and non-petroleum (modified or unmodified natural)

MFs can induce negative effects within aquatic organisms, demonstrating a general harm from both MF types (Parker et al, 2025).

MFs are released during the entire life cycle of textiles from raw materials extraction, through processing, production, use, wash, and disposal (Harvey et al., 2022). The processing and production of textiles is a complex multi-stage process, and MF shedding varies greatly with the fibre type used, fibre length, construction, and end use of the product. Fibres undergo several dry and wet processes for textile manufacturing. Dry processing of textile fibres or yarns does not use water or liquids, instead abrasion forces are involved in mechanical or physical treatments during fibre production, spinning and winding, knitting, and weaving (WRAP, 2019). Unlike dry processing, wet processing uses water and chemicals to treat fibres, yarns, or fabrics to achieve colouration, texture modification, or other functional properties.

Due to their small size and similarity to items of prey, MFs have enormous potential to be readily consumed by aquatic organisms (Gaylarde et al., 2021). Jemec *et al.* (2016) found that the length of the majority of ingested PET MFs in the gut of freshwater *Daphnia magna* was ~300 μm, followed by large, twisted fibres ~1400 μm in length, which resulted in increased mortality as MFs prevented feeding. Another study found 13 types of natural MFs (cellulose, lignin) and 11 types of synthetic MFs (PE, PP and PET) in the stomachs of fish from European seas (Collard et al., 2015). The results demonstrate that the effects of MFs are nuanced, depending on complex combinations of exposure and organisms, and that the literature is heavily biased towards studies on synthetic fibres (Athey & Erdle, 2022). More recent studies directly comparing exposure to synthetic and non-synthetic MFs have found comparable ecotoxic effects and occasionally enhanced toxicity for non-synthetic MFs (Courtene-Jones et al., 2024; Détrée et al., 2023; Kim et al., 2021), often implicating the presence of other associated chemicals with various toxic modes of action (Zambrano et al., 2021). A recent meta-analysis found negative ecotoxicological effects of both petroleum-based and non-petroleum microfibres on aquatic organisms, however non-petroleum microfibre exposures were underrepresented (Parker et al. 2025). Non-synthetic MFs, therefore, require further study on their relative sustainability and ecotoxicity to address this growing form of environmental pollution (Stanton et al., 2024).

A generalised upstream and downstream process for textile manufacturing is shown in Figure 1, illustrating the complexity of the manufacturing chain and the individual stages at which MFs can be generated. Upstream (dry) processing converts raw material into yarn through cleaning, baling, filament formation, sliver preparation (carding and combing), spinning and winding, with MFs generated by mechanical abrasion from the baling stage onward. The yarn is then knitted or woven into greige fabric (a further dry, abrasive step). Downstream wet processing stages involving chemical treatments and comprises pre-treatment (e.g. scouring and bleaching), dyeing and/or printing, and rinsing, all of which can generate MF release into the aqueous treatment liquor. Subsequent dry stages, notably heat setting and brushing, generate further MFs by abrasion before the finished textile is obtained. Finishing may also involve further wet processing in terms of addition of functional finishes, such as flame retardants and water-repellents.

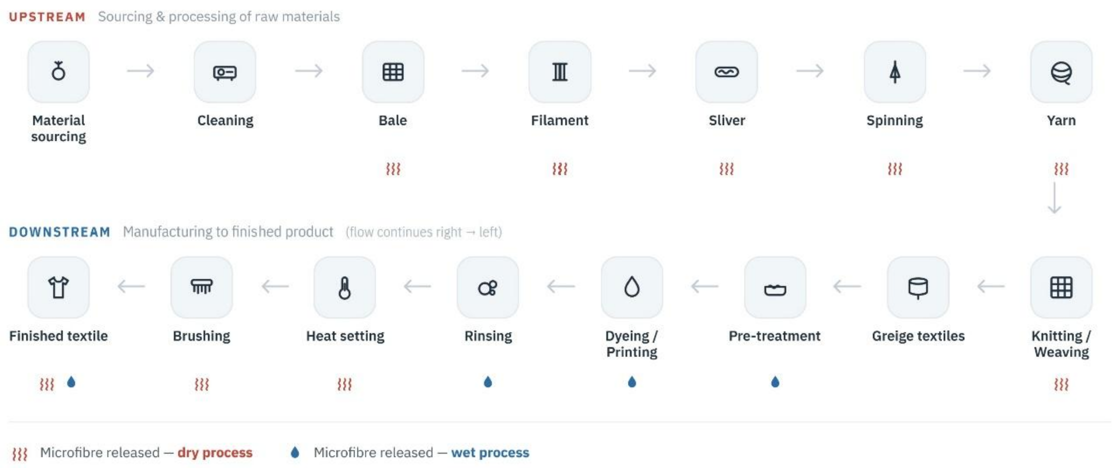

Figure 1. Generalised flowchart of the textile manufacturing process showing stages at which microfibres may be released. The process consists of several dry-processing (red) stages to produce the textile structure and later wet-processing stages (blue) which further modify properties. Note: sliver is loose, untwisted bundles of fibres and is an intermediate stage between raw fibres and the final yarn created through carding or combing (Cai et al., 2020; Pinlova et al., 2022; M. Wang et al., 2023).

The fate of these MFs after release is largely determined by wastewater treatment. Wastewater treatment plants (WWTPs) capture most, but not all, of the MFs generated during manufacturing, and their capture efficiency depends strongly on MF size in the influent: larger, denser fibres (100–1000 μm, >1 g cm^{-3}) settle out through coagulation and sedimentation into the sludge, while secondary biological treatments further reduce fibres >300 μm (Akyildiz et al., 2022; Cai et al., 2020; Zhou et al., 2020). Because this sludge is commonly applied to agricultural land, captured MFs can re-enter the environment *via* precipitation and wind (Haque et al., 2024). Treatment efficiency is therefore governed by influent MF size, which is itself determined by fibre type, manufacturing process, and material characteristics — making MF length a principal factor in both final emissions and mitigation strategy.

Certain additives that are covalently bound to fibres permanently change the chemical and physical properties of fibres and may influence subsequent environmental impacts (Zambrano et al., 2021; Zimmerman et al., 2020). The known range of modifications to natural textile materials and environmental contamination by these fibres has given rise to the term “anthropogenically modified natural” and “semi-synthetic” fibres to describe different forms of cellulose (Athey & Erdle, 2022). Sites downstream of textile manufacturers often experience water pollution from dyes and other chemicals, whose single and combined effects of degradation are largely unknown (Gomez et al. 2008; Madhav et al. 2018; Dutta et al. 2022). Arguably, proactive vs reactive steps are likely to be most effective and targeting upstream manufacturing makes more sense than downstream since there are fewer upstream sources. This study aimed to review the existing data on MF shedding from textile industries to identify which steps release most MFs and suggest potential remediation or preventative measures to reduce MF release into the environment.

2. Systematic literature review

This review used a systematic approach to identify relevant literature (Pickering and Byrne, 2014) and followed the set guidelines by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA; Moher et al., 2010) as shown in Figure 2. Systematic review was done using the Web of Science (Core Collection) database with a single search string that would include both studies using the English “microfibre” and the Americanised “microfiber”: ("Microfibre" OR "Microfiber" OR "Fibre" OR "Fiber") AND ("Textile" OR "Industry" OR "Pollution") AND ("Release" OR "Effluent" OR "Emission"). The search was performed on 11th August 2024, and the date range was restricted to those published/accessible within the last 5 years arbitrarily (2020, 2021, 2022, 2023, and 2024, inclusive to the search date).

From the search string, 1,686 records were identified and the title and abstract screened to exclude those deemed irrelevant to the present study; those not reporting MF emissions from textile manufacturing industries. The raw data from Web of Science extraction to final data selected for study can be seen in Supplementary Data. This initial screening resulted in 7 suitable articles with all exclusion reasons provided in the Supplementary data, the other 1679 lacked the industrial MF emissions in particular, and focused more on industrial wastewater treatment (Bastakoti et al., 2024; Bediako et al., 2024; Panda et al., 2020; Rajhans et al., 2021; Ramirez-Pereda et al., 2020; Roy, 2021; Sontakke et al., 2022; Zou et al., 2021), fibre shedding from laundry emissions (Bektas et al., 2022; Galvão et al., 2020; Manga et al., 2022; O’Brien et al., 2020; Rathinamoorthy & Raja Balasaraswathi, 2020; C. Wang et al., 2023), and alternative dyeing techniques and technology (Khandual et al., 2020; Wang et al., 2020; Wang et al., 2022).

Using the 7 articles as a starting point, a forward (all citing studies) and backward (all cited studies) search was additionally carried out and the title and abstracts of the resulting 1,985 studies were similarly screened, resulting in 28 retained studies (Figure 2). Forward and backwards searches are an efficient way of identifying additional relevant studies and has been used in previously published meta-analyses (Parker et al., 2025). After removing duplicates, 3 additional studies were subject to full text eligibility assessment and included resulting in a final dataset comprising 10 papers.

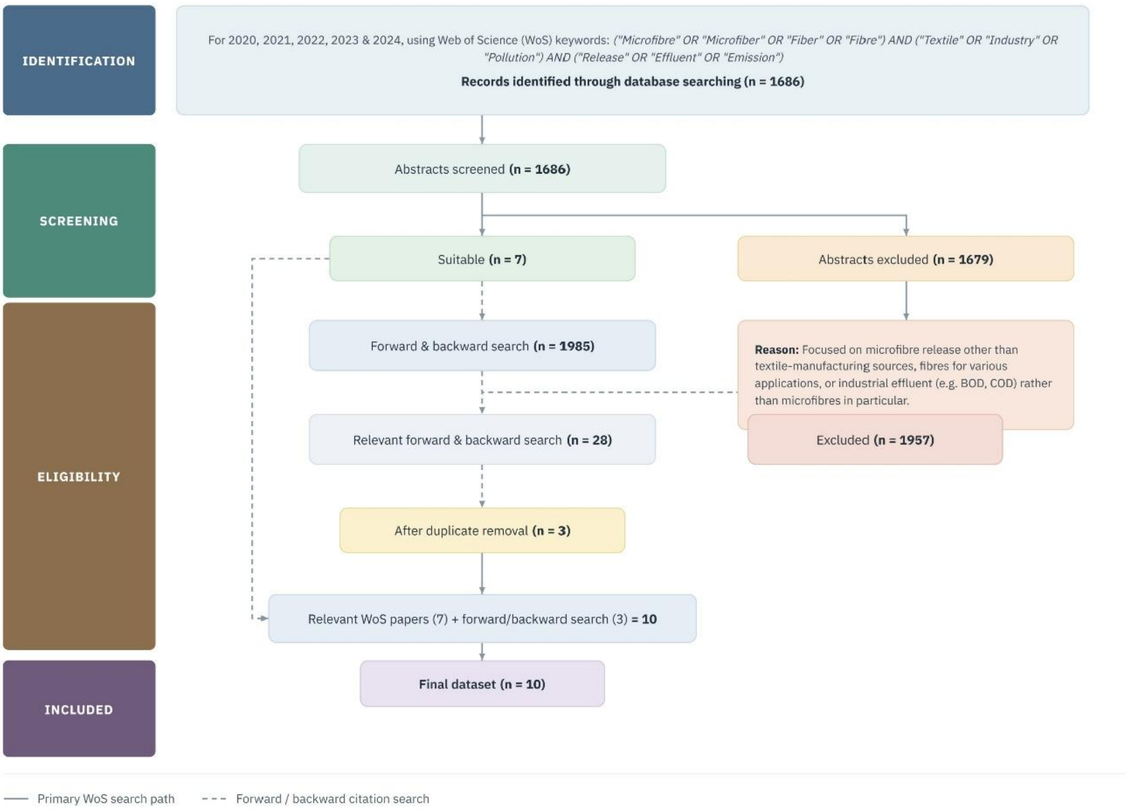

Figure 2. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) diagram of systematic literature review selection process. Records were identified through Web of Science database searching and supplemented by a forward/backward citation search of the retained articles. More information available in Supplementary data.

For the 10 eligible studies (date range of 2020-2024), 7 papers discussed MF release from wet effluents (Akyildiz et al., 2023; Akyildiz et al., 2022; Chan et al., 2021; Deng et al., 2020; Haque et al., 2024; Rathinamoorthy R & Balasaraswathi, 2023; Zhou et al., 2020), 2 papers studied MF from dry effluents (Cai et al., 2020; Pinlova et al., 2022) , and 1 paper studied MF release from both dry and wet process (Wang et al., 2023). For each study, the following information was extracted (where applicable): the geographic location (country) where samples were collected, the year(s) of collection, process used for sample collection, sample collection interval, type of industry (e.g. printing, dyeing, PET production mill, finishing), point of sampling, other fabric technical specifications if available, fibre composition (inflow, outflow), MF recovery and quantification method, MF type (inflow, outflow), MF length distribution (inflow, outflow), MF concentration (inflow, outflow), factors influencing MF release, MF colour (inflow, outflow), type of WWTPs (primary, secondary, tertiary) installed, their removal efficiency and units used. These details are shown in Table 1, which includes mean responses with corresponding standard deviations were extracted from the manuscript data, wherever possible. MF in wet effluents are represented as MF L^{-1} and MF in sludge as MF kg^{-1}. This critical review will analyse the available literature as discussed and will identify discrepancies in methodologies, gaps in knowledge and the potential for future work to accurately represent the limited information available within the scientific literature on MF emission throughout the pre-consumer supply chain.

Table 1. Data extracted from 10 compiled results (Supplementary Information 1) obtained from Web of Science search showing the microfibre (MF) released per litre or kg, MF weight, number of MF released per g material, MF fibre length, fibre type, and number of studies conducted.

Process	**MF L^{-1} (for wet effluent) and MF kg^{-1} (for sludge)** Mean (±std. dev)	**mg MF g^{-1} fabric** Mean (±std. dev)	**MF g^{-1} material** Mean (±std. dev)	**MF length (µm)** Mean (±std. dev)	**Fibre type**	**# studies**	**Ref**
Bale	-	0.020 (±0.007)	99 (±29)	138 (±27)	Black, Dope-Dyed PET Staple Fibers	3	(Pinlova et al., 2022)
Filament	-	0.000 (±0.000)	11 (±3)	285	White Polyester	3	(Cai et al., 2020)
Sliver	-	0.039 (±0.022)	280 (±92)	405	White Polyester	3	
Ring yarn	-	0.066 (±0.021)	131 (±30)	528 (±66)	Black, dope-dyed PET staple fibers	3	(Pinlova et al., 2022)
Compact yarn	-	0.073 (±0.019)	137 (±36)	575 (±115)	Black, dope-dyed PET staple fibers	3	
Rotor yarn	-	0.441 (±0.035)	2244 (±60)	206(±16)	Black, dope-dyed PET staple fibers	3	
Air-jet yarn	-	0.016 (±0.002)	47 (±4)	328 (±39)	Black, dope-dyed PET staple fibers	3	
Ring spin yarn	-	0.039 (±0.022)	117 (±39)	393	Black PET yarn	3	(Cai et al., 2020)
Ring spin yarn	-	0.006 (±0.002)	93 (±360)	393	White PET yarn	3	
Rotor spun	-	0.182 (±0.014)	2136 (±257)	226	White PET yarn	3	
Air-jet yarn	-	0.007 (±0.002)	142 (±26)	393	White PET yarn	3	
Greige	-	0.088 (±0.021)	190 (±21)	104 (±11)	Black PET	3	(Wang et al., 2023)
Pre-treatment	-	0.075 (±0.010)	174 (± 58)	325 (±45)	Black PET	3	
Manual textile screen printing (undiluted)	1,394,205 ± 426,262 MF L^{-1}	-	-	519.1 (136-2810)	Black, 100% cotton interlock knitted fabric	8	(Rathinamoorthy & Balasaraswathi, 2023)
Dyeing	-	0.102 (±0.024)	764 (±211)	129 (±22)	Black PET	3	(Wang et al., 2023)
Rinsing	-	0.031 (±0.009)	191 (±10)	171 (±19)	Black PET	3	
Heat setting	-	0.035 (± 0.003)	183 (± 37)	230 (±11)	Black cotton/polyester fabric, white cotton/ polyester fabric, black cotton fabric, and white cotton fabric	3	
Before brushing	-	0.131 (±0.039)	1750 (±488)	136 (±7)	Black cotton, white cotton, black cotton/polyester, white cotton/ polyester, black polyester, black recycled polyester, and white recycled polyester		
After brushing	-	0.085 (±0.029)	702 (±179)	139 (±6)	Black cotton, white cotton, black cotton/polyester, white cotton/ polyester, black polyester, black recycled polyester, and white recycled polyester	3	
Wet process	-	0.238 (±0.037)	-	0-50 (0-400)	Black cotton, white cotton, black cotton/polyester, white cotton/ polyester, black polyester, black recycled polyester, and white recycled polyester	3	(Wang et al., 2023)
Wet process	893-4452 MF L^{-1}	-	-	10-100 (0-900)	Cotton, wool, acrylic, polyester, polypropylene, polyamide, and viscose (rayon)	5	(S. H. Akyildiz et al., 2022)
Wet process	-	-	-	100-300	Colourless, black, and blue fibres	3	(Zhou et al., 2020)
Wet process (woven, knit and denim)	615 (± 377) MF L^{-1}	-	-	0-100	Nylon, ethylene-vinyl acetate, polyethylene terephthalate, acrylonitrile butadiene, styrene, cellulose acetate, low-density	3	(Haque et al., 2024)

					polyethylene, and high-density polyethylene. Black, brown and blue MFs		
Wet process (polyester fleece dyeing and finishing)	361 (±24) MF L^{-1}	-	-	<1000	Polyester fleece	17,392	(Chan et al., 2021)
Laundry	-	0.090 (±0.007)	-		100% PET	3	(Wang et al., 2023)
Finished fabrics	-	0.058-0.251	-		Cotton and acrylic fabric		(S. Akyildiz et al., 2023)
Finished textiles	-	-	45400	100-200			(Cai et al., 2020)
Finished textiles	-	0.109 (±0.028)	298 (±49)	197 (±33)	Black PET		(Wang et al., 2023)
WWTP effluent	-	-	-	0-900	Cotton, wool, acrylic, polyester, polypropylene, and polyamide,	5	(S. H. Akyildiz et al., 2022)
WWTP effluent	-	-	-	100-300	Black, blue, colourless MFs	3	(Zhou et al., 2020)
WWTP effluent (woven, knit and denim)	212 (± 80) MF L^{-1}	-	-	0-100	Black- nylon, ethylene-vinyl acetate, polyethylene terephthalate, acrylonitrile butadiene styrene, cellulose acetate, low-density polyethylene, and high-density polyethylene	3	(Haque et al., 2024)
WWTP effluent	17.7 (±1.2) MF L^{-1}	-	-	--	Polyester fleece	3	(Chan et al., 2021)
Surface water (synthetic printing and dyeing)	600 (±430) MF L^{-1}	-	-	100-300	Black, blue. colourless MFs	3	(Zhou et al., 2020)
Surface water from PET manufacturer	2.1-71.0 MF L^{-1}	-	-	100-1000	Polyester (blue, red and black)	3	(Deng et al., 2020)
Sludge (knitting industry synthetic)	6800 MF kg^{-1}	-	-	100-500	Black MFs	3	(Haque et al., 2024)
Sludge (Knitting industry)	5600 MF kg^{-1}	-	-	-	-	3	
Sludge (Denim industry)	5400 MF kg^{-1}	-	-	-	-	3	
Sludge (Synthetic printing and dyeing)	17-1323 MF kg^{-1}	-	-	100- 1000	Polyester (black, white or blue)	3	(Deng et al., 2020)

3. Results and Discussion

Most of the publications reporting MF emissions from textile manufacturing were performed in China (3 studies) with others from Türkiye (2), Switzerland (1), Bangladesh (1), India (1), Malaysia (1), and China and Switzerland (1). The total number of studies is extremely limited, even when considering the date range (2020-2024), which exemplifies the lack of data available on MF release during textile production. Furthermore, most studies were conducted within Asia and Europe, with no representation from other continents, and includes countries that are key manufacturers of textiles. This result highlights both a lack of general data and spatial resolution around MF releases during manufacture and requires urgent addressing.

3.1. Microfibre emissions from dry and wet textile production processes

The cumulative number of MFs released from dry and wet processing during textile manufacturing are quoted as ~2000 MFs g^{-1} textile, where wet processing releases 2x more MFs (~1300 MF g^{-1}) than dry processing (~700 MF g^{-1}). As shown in Figure 3, MFs are released from both dry process and wet process, where, on a per-gram basis, dyeing releases the most MFs of any single wet-processing (fabric-stage) step (764±214 MF g^{-1} fabric; n = 3). Figure 3 shows, however, that dry-processing steps at the yarn stage, particularly rotor spinning (up to ~2,244 MF g^{-1} yarn; discussed below), can release more MFs per g than dyeing, so MF release must be interpreted with reference to the production stage and material mass rather than attributed to a single dominant step (M. Wang et al., 2023). When analysing MF shedding during production, Wang *et al.* (2023) reported MFs shedding from all four wet processing steps (pre-treatment, dyeing, heat setting, rinsing) releasing up to 25x more MFs when compared to home laundering whereas dyeing contributed to 95% of total MF emissions because of the intensive use of high temperatures, chemicals and mechanical treatments (Wang et al., 2023).

When considering the dyeing of blended fabrics, black polyester-cotton blends are exposed to two separate dyeing processes, which can result in overall greater damage and increased MF release, compared to monomaterial dyeing. Polyester is dyed at 130 °C, which is not used for 100% cotton dyeing (typically dyed at 60-80 °C), creating a situation where greater thermal energy could cause greater damage to the fibre; similarly, cotton is typically dyed with reactive dyes that involve a fixation step at pH 10.5-11.0, that 100% PET does not encounter during its typical dyeing process – the exposure of PET to these extreme pH values is likely to cause greater damage (Zambrano et al., 2021b). Therefore, limiting the amount of wet processing a textile material is exposed to in pre-consumer stages of production would theoretically lead to reduced MF emissions throughout the textile supply chain. Black thermo-mechanically recycled polyester textiles has been quoted to shed 2.2-2.3x higher MFs than black-dyed virgin polyester textiles (Rathinamoorthy & Balasaraswathi, 2020; Wang et al., 2023) because black recycled polyester fabrics possess high levels of impurities and are exposed to high temperatures during the recycling process, both of which are likely to create greater damage to the polymer and enhance MF release (Wang et al., 2023). Chemical recycling of polyester is likely to eliminate this issue as the polymer properties should be the same as virgin polyester, but these processes are not currently in extensive use in the industry. All these contributing factors are likely to damage the structure of fibres, leading to the liberation of high volumes of MFs into effluent (Zhou et al., 2020).

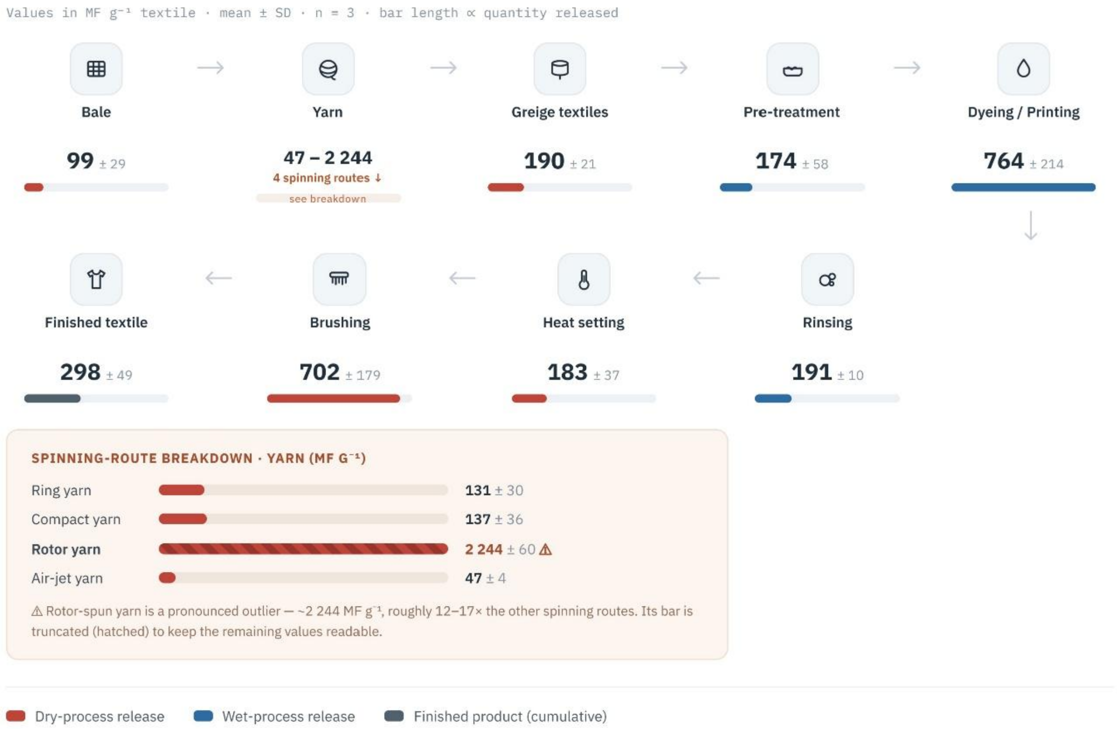

Figure 3. MF released from each individual manufacturing stage for production of a black polyester textile. Greige textiles are output of knitting/weaving processes. Brushing is a finishing process for removal of dust, lint, and other particles from fabric surfaces. Values are provided as MF released per gram of materials (MF g^{-1}), which differs relative to the production stage (fibre, yarn, fabric); each value is ± standard deviation where data are available; sample size n=3.

During dry processes, fibre and yarn characteristics, including yarn twist, fibre type (staple/filament), method of production, fabric structure and specific density, are reported to influence MF release. For black, dope-dyed polyester staple fibers, air-jet (47±4 MF g^{-1} yarn), compact (137±36 MF g^{-1}), and ring (131±30 MF g^{-1}) spinning have been shown to exhibit relatively low MF release due to high yarn twist and tighter structure creating greater tension than rotor-spun yarns (2,244±60 MF g^{-1}) (Pinlova et al., 2022). In another study, fewer MFs were released from air-jet (1,950 MF g^{-1}) and rotor-spun structures (2,250 MF g^{-1}), respectively, as compared to the ring-spun materials (2,700 MF g^{-1}) for polyester staple fibres (Jabbar & Tausif, 2023). In another study, MF formation is higher in ring yarns than compact and rotor yarns (Basu & Gotipamul, 2003). The method for spinning fibres into yarns, and fibre properties such as hairiness index, fineness denier, has a large effect on MF shedding. However, results obtained comparing MF release from various spinning method vary significantly in the level of replication, transparency of methods and reporting, demonstrating the need for both more and more standardised research.

3.2. Length of microfibre emissions from various processes

The length of MFs in the textile influent is influenced by myriad variables, such as the type of fibres used, cutting method (scissor-cut or laser cut), structure (knit and weave), the manufacturing processes, and surface type (processed or unprocessed). Average MF length distribution in various contexts of textiles manufacturing is shown in Figure 4, where it is observed that MF length reduces by 57% from spinning to the final garment manufacturing. In dry textile manufacturing processes, mean MF lengths released are up to 409 μm, whereas in wet textile manufacturing processing, mean MF lengths released are up to 325 μm (Haque et al., 2024; Rathinamoorthy & Balasaraswathi, 2023; Wang et al., 2023; Zhou et al., 2020). Due to the small size of these MFs, they have an elevated chance of ingestion by aquatic organisms, where they entangle as large clots causing blockage within the gut leading to health complication and mortality (Jemec et al., 2016). MFs with the shortest length pose the greatest risk to the environment and are more difficult to detect and remove in comparison with larger MFs. By contrast, from an ecotoxicological perspective, while shorter fibres can be more toxic due to increased internalisation, longer fibres can be more difficult to remove.

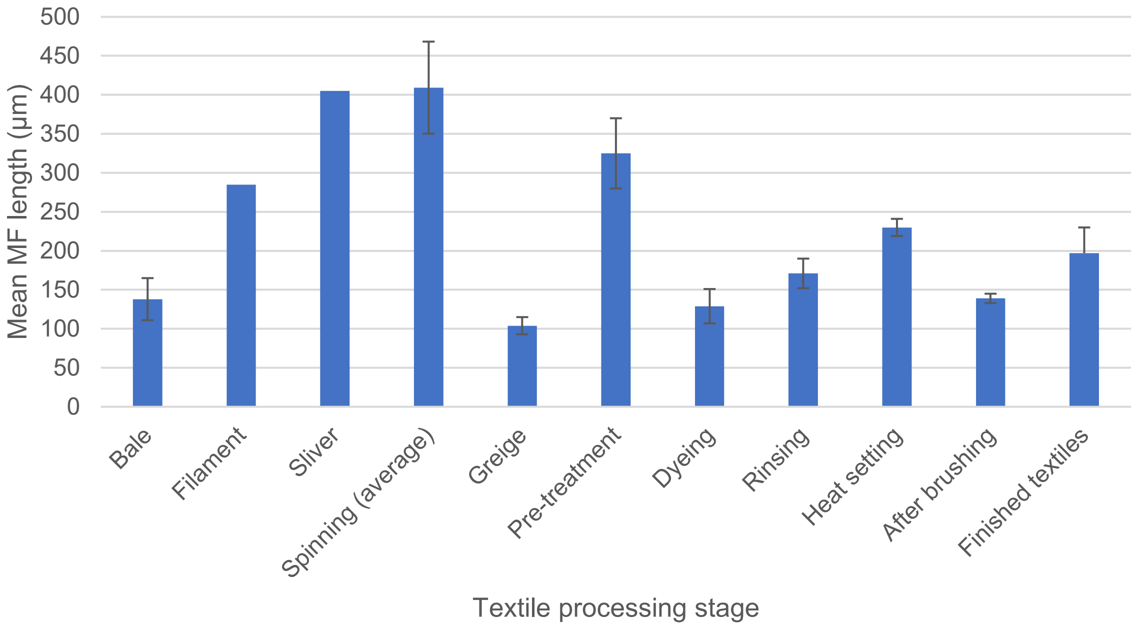

Figure 4. Mean length of MF released from various intermediate of textile manufacturing stages in subsequent order of processing/release stage*Click or tap here to enter text.*. Error bars show ± standard deviation where data available.

Different yarn types will shed MFs of varying length. For black dope dyed polyester, the shortest MF length is achieved for rotor-spun yarn (206±16 μm) as the fibre dust accumulates in rotor grooves causing yarn defects and end breakages as compared to ring-, compact-, and air-jet-spun yarns (300-500 μm) where the ultrashort fibres are already removed (Pinlova et al., 2022). Fibre length is also influenced by the cutting method where scissor-cut samples shed longer MFs than laser cut samples due to surface treatment and the type of knitted/woven structures of textile (Cai et al., 2020). Length of the MFs is also shown to be influenced through surface treatment where processed surfaces such as plain brushed and fleece release shorter length MFs compared to unprocessed textiles surfaces (Cai et al., 2020). For black polyester, greige fabric contains large numbers of unfixed fibres, which results in the release of shorter MFs (104±11 μm) in textile effluents compared to finished fabrics (197±33) (Wang et al., 2023), due to most of the smaller MFs already being emitted during the fabric treatment processes in more heavily processed/dyed fabrics. Textile structure also has an impact on MF length, as knitted textiles have a loop structure which when cut produce long fragments whereas in woven, cutting line can pass at random fibre position forming MFs. These contrasting results mean, therefore, more research is needed to fully understand the effect of textile structures on length distribution of released MFs. However, the fate of these ultrashort fibres is unknown and could potentially lower the attraction of these spinning methods once identified and quantified, once again highlighting the insufficient nature of the currently available literature to obtain a holistic full-process view of MF emissions through textile production.

3.3. Microfibre capture technologies

As shown in Table 2, wastewater treatment technologies include:

- **Preliminary:** for large object removal (screen, grit, pump);
- **Primary:** for suspended organic solid removal (floatation, sedimentation);
- **Secondary:** for soluble organic removal involving biological treatment (membrane bioreactor, biofilms, activated sludge);
- **Advanced treatment technologies:** for suspended solid removal (membrane technology, photocatalytic degradation, electrochemical process, ion exchange).

All these technologies are capable of efficiently capturing MFs from industrial influents. For the knitting and weaving industry, chemical (precipitation, neutralisation, reduction, oxidation, hydrolysis) and biological (microorganism mediated aerobic, anaerobic, and anoxic processes) treatments can capture 45-82% of MFs released, depending on the type of knit or weave (Haque et al., 2024); biochemical treatment processes that combine the benefits of biological and chemical treatment steps provide a more comprehensive approach to wastewater treatment (Rao et al., 2017). For wet processes, advanced treatment plants are highly efficient allowing only 0.5% of MFs to be transferred (Haque et al., 2024). Advanced tertiary treatments using membrane bioreactors and reverse osmosis can reduce dyeing and printing mill effluent concentrations from 1000 MF L^{-1} to 5 MF L^{-1} with 99.5% efficiency (Zhou et al., 2020). However, advanced tertiary treatments are limited by high capex, operational costs, and energy demands. The degree of wastewater treatment varies widely and there is also no effective waste route for collected MFs, therefore, mitigation strategies involving intelligent design and adequate remediation processes should be implemented at every step of textile manufacturing to reduce MF emissions.

Methods for removal of MFs from wastewater can be broken down by their mode of action; physical (e.g. filtration, reverse osmosis), chemical (e.g. flocculation) and biological treatment, with some processes demanding multiple steps within each mode of action, and a combination of different methods to effectively remove MFs. Table 1 also highlights that even companies in the same sector often do not use the same method for MF removal, highlighting the need for critical research into the efficacy and economics of the different methods, so that companies have a clear understanding of best practice. This research would allow the implementation of equipment to effectively capture MFs from textile manufacturing and reduce their entry into the environment.

Collaboration on methodology is essential for this area of research; Table 2 shows 12 different strategies from 12 different industries to tackle the same problem (with varying degrees of success). The efficacy of the processes varies from 23.5% to 99.5%, and MF concentration values vary from 170 to >54,000 MF L^{-1}; however, as the literature available on the methods used by different industries to specifically remove MFs from wastewater is so limited, any conclusions on the efficacy of removal of MFs from wastewater represents huge assumptions for a global industry, particularly given the previously mentioned geographical bias. It is also noteworthy that, in general, if an industry is happy to report on their waste treatment, it is usually because of a perceived economic benefit in letting stakeholders know of ‘good practice’, as such, it may be inferred that many industries that do not report their waste treatment methods perform much worse than those in Table 2. It is unclear as to what design decisions led to each industry adopting the exact waste processing treatments reported, with the likelihood being that each industry developed their method in isolation, with no specific guidelines or collaboration to guide them. This, once again, highlights the need for more clear and defined research into this area, as the development and installation of many of these treatment methods would not be easy or cheap. Having more information and guidance when designing and building them would be of huge economic benefit to the industry in question and would lead to an increased efficacy of MF removal across different industries.

Table 2. Source of MF release, effluent concentration before and after treatment (MF L^{-1}), and treatment efficiency of effluent treatment plant in textile manufacturing obtained from the selected studies represented as % of MFs passed through treatment process (%) in proportion to the influent concentration entering the effluent treatment plant.

Influent Source	Average Influent Concentration (MF L^{-1}) for Sample size 'n'	Primary Effluent Treatment Process	% MFs passed through primary treatment	Secondary Effluent Treatment Process	% MFs passed through secondary treatment	Overall MF transferred (%)	Reference
Dyeing and printing mill (Alkali reduction, dyeing and printing wastewater of synthetic fibres)	1,000 (±560) n=3	Influent → conditioning tank → membrane bioreactor	55.7	Reverse osmosis	55.2	0.5	(Zhou et al., 2020)
Dyeing and printing mill (Rayon printing wastewater)	54,100 (±7000) n=3	Influent → conditioning tank → Anaerobic-oxic process	4	air flotation	1.5	2.5	(Zhou et al., 2020)
Dyeing and printing centralized WWTP	13,600 (±9200) n=3	Influent → primary treatment → oxidation ditch	9.3	air flotation → ozone + activated carbon → fibre rotary disc filter	6.7	2.6	(Zhou et al., 2020)
Wet processing mill (PET fleece)	362 (±25) n=3	Neutralization, Equalisation, Flocculation, Primary Sedimentation, → Biological Oxidation, Secondary Sedimentation, Coagulation → Filtration → common effluent treatment plant	4.9	-	-	4.9	(Chan et al., 2021)
Dyeing and printing centralized WWTP	8,367 (±3720) n=3	Influent → primary treatment → anaerobic-anoxic-oxic process	19	denitrification filter → Fenton oxidation → air flotation	11.9	7.2	(Zhou et al., 2020)
Dyeing and printing mill (Washer wrinkle fabric dyeing wastewater)	12,000 (±7800) n=3	Influent → conditioning tank → membrane bioreactor anaerobic-oxic process	25.6	Reverse osmosis	9.7	15.3	(Zhou et al., 2020)

Influent Source	Average Influent Concentration (MF L^{-1})	Primary Effluent Treatment Process	% MFs passed through primary treatment	Secondary Effluent Treatment Process	% MFs passed through secondary treatment	Overall MF transferred (%)	Reference
Wet processing (Denim industries)	1,460 n=3	Biochemical treatment	17.8	-	-	17.8	(Haque et al., 2024)
Wet processing (Knit industries)	500-860 n=3	Biological treatment	26 - 45	-	-	26- 45	(Haque et al., 2024)
Wet processing (Knit industries)	880 n=3	Chemical treatment (coagulants, and flocculants)	36	-	-	36	(Haque et al., 2024)
Wet processing mill (Natural and synthetic textiles)	893-4452 (n=5)	Multiphase physic-chemical process using lime, iron-sulfate, and anionic polyelectrolyte in stirred reactors → coagulation/settling tank	35 - 62	-	-	35-62	(S. H. Akyildiz et al., 2022)
Wet processing (Knit industries)	330 n=3	Biochemical treatment	48	-	-	48	(Haque et al., 2024)
Wet processing (Woven industries)	170-350 n=3	Biological treatment	55 - 77	-	-	55 - 77	(Haque et al., 2024)

3.4. Potential process for pre-consumer microfibre reduction

MFs in the environment are almost impossible to be removed; their small size means they cannot be captured from air, and therefore potential workplace exposure to MFs would require ventilation and filtration systems. Atmospheric deposition is a greater source of synthetic MFs (46%), than water (38%), indicating both can serve as pathways into the marine environment (Napper et al., 2023). Current information on MF generation during processing and production is inadequate, as it fails to consider all wet and dry processing that textiles go through from fibre generation/harvesting to finished garment and this could lead to potentially huge underestimation of MF generation and release during a textile's lifespan (Hartline et al., 2016; WRAP, 2019). Due to the lack of available data, manufacturing industries are unaware of the specific process steps that are the biggest MF emitters and are unsure of existing technological solutions. The rise of "fast fashion" in which consumers favour higher numbers of lower quality garments that are worn for short periods before disposal brings additional environmental and sustainability challenges (Niinimäki et al., 2020). Pre-consumer MF generation during manufacture is likely to be even more important to consider and remediate, especially if production continues its expected upward trajectory (European Environment Agency, 2022). Garment construction is more important for fibre shed than fibre type and the design and manufacture of the garments are important drivers of global MF pollution and thus mitigation (Stanton et al., 2023). The fate of captured MFs needs to be determined and, if they end up in landfills or incinerators, this will cause the re-release of the adhered toxic dyes/ chemicals.

3.5. Strategies for Better by design interventions

Removal and prevention of MFs entering the environment demonstrates several methodological challenges, and therefore reduction might be more effective upstream. Based on the data extracted through the literature reviewed, the effect of individual stages, the science basis, and effects of these steps in reducing MF emissions is presented.

Pre-treatment of textiles: In one study on MF release in laundry, a 43% decrease in MF mass and 73% decrease in MF count was observed for PET textiles subjected to surface oxygen plasma treatment, suggesting this clean finishing may mitigate MF shedding (Jabbar et al., 2024). Plasma treatment improves the surface of the textile polymer without any noticeable change in the bulk properties of the polymer improving wettability, and dyeability of textile. (Mehmood et al., 2014; Sparavigna, 2008; Wróbel et al., 1978). However, this solution would lead to increased production costs and material usage.

Spinning: Most fibres in air-jet-spun yarn are in a parallel orientation and twisted around the yarn core to exhibit tensile forces, offering a higher effective packing density that potentially results in lower MF release from these structures (Jabbar & Tausif, 2023) than hairier yarns producing more fly, shorter fibres resulting in un-sized yarns (Basu & Gotipamul, 2003; Lawrence & Mohamed, 1996). Continuous filament yarn, which have no twist and low hairiness will shed less MFs compared to short staple fibres, which have a greater number of fibres exposed per unit area due to their hairiness and yarn structure (De Falco et al., 2019). In continuous filament yarn, long, fine and flexible fibres move towards the core, and are not protruding outwards therefore shed less MF whereas in staple yarn, short, coarse and stiffer fibres move away from the core towards the sheath during the spinning process and can easily slip away due to the mechanical actions of wearing and moving. Unprocessed surfaces (such as fleece and plain brushed) will release 5x less MFs than processed PET textile products due to abrasive friction caused by sandpaper or sand blasting to improve the feel and look of the textile during processing (Cai et al., 2020).

Cutting: A major source of MF release is the cutting procedure, where laser cutting (11,300 MF g^{-1}) generates ~25% of the number of MFs compared to scissor cutting (45,400 MF g^{-1}) grey woven microfibre textiles as MF release from laser-cut samples is primarily from the surface; for scissor-cut samples, MF release is from both fabric surface and edges (Cai et al., 2020). Also, the edges of laser-cut samples exhibit a seal of molten polymer, whereas edges of scissor-cut samples have many open ends releasing more MFs. Laser cutting should therefore be favoured wherever possible to increase the accuracy of cutting while subsequently reducing the production of MFs.

Type of construction: Type of fabric is also a crucial factor in determining the amount of MFs released during washing and dyeing. Recycled (0.150±0.020 mg MF g^{-1} textile) and regular PET (0.155±0.015 mg MF g^{-1} textile) shed the most MFs, whereas 100% cotton with an open yarn construction (0.004±0.001 mg MF g^{-1} textile) and 100% cotton with a ring yarn construction (0.015±0.002 mg MF g^{-1} textile) shed the least MFs as the fabrics are tightly twisted, preventing MF shedding easily (Wang et al., 2023). Moreover, open and ring yarn constructions do not contain any synthetic materials or flocculants that can contribute to MF shedding, making these fabrics and constructions an environmentally conscious choice.

Dyeing temperature: Dyeing is one of the most significant contributing processes to MF shedding in textile production. The combination of high temperatures and agitation in water over extended time periods can lead to very high MF liberation into dyeing effluent and represent the highest concentrations of MFs from any wet process (see Table 2). There are scant data on methods to reduce MF release in dyeing processes, but any method that can reduce dyeing temperature and/or agitation could reduce MF emissions. One potential option is the use of reactive dyeing of cotton using cold pad-batch (CPB) dyeing methods, where dye is applied to fabric rolls at room temperature, covered, and left to adsorb and react over many hours. Not only could this method reduce MF release but also reduce energy and water consumption in production representing an environmental and economic “win-win” for industries implementing more sustainable practices. However, while (CPB) dyeing is eco-friendly and economical, it faces several challenges, including slow production rates, difficulty in making shade adjustments, and the need for precise control over processing parameters. The use of alternate coloration methods, such as ‘dope dyeing’ or *in-situ* wet-spun dyeing, where dyes or pigments are incorporated at the time of fibre spinning, could be green and durable methods that reduce water and energy consumption and release fewer MFs during fabric production (Houghton et al., 2024). Dope dyeing and *in-situ* dyeing methods significantly reduce mechanical friction and degradation of the fibre in relation to the coloration step, which could significantly reduce MF emissions (Wang et al., 2023).

During dyeing, for 100% cotton, it is recommended to use a temperature as low as 60 °C as significant numbers of MFs are released with the increase of temperature from 60 °C (0.015±0.002 mg MF g^{-1} textile) to 130 °C (0.028±0.002 mg MF g^{-1} textile), with no significant increase in MF generation from 30 °C (0.014±0.002 mg MF g^{-1} textile) to 60 °C (0.015±0.002 mg MF g^{-1} textile) (Wang et al., 2023). This suggests that lower temperatures have negligible effect on the MF release. As for 80% cotton/20% PET fabrics, which undergo a two-step dyeing process (PET followed by cotton), it is recommended to maintain a temperature of 60 °C throughout the process as increasing MF release occurs with an increase in washing temperature from 60°C (0.022±0.003 mg MF g^{-1} textile) to 130 °C (0.045±0.003 mg MF g^{-1} textile). For 100% regular PET, it is recommended to maintain a temperature of 60 °C for regular (0.11±0.015 mg MF g^{-1} textile) and recycled PET (0.13±0.015 mg MF g^{-1} textile).

Treatment plant: Effluent treatment using a combination of a membrane bioreactor and biological catalysis, or ultrafiltration with crossflow module and reverse osmosis are improved industrial wastewater treatment practices that could be used to prevent the unintended release of MF using 0.1-0.001 μm filter membrane (Forum for the Future, 2023). Acoustic wave technology shows potential for an eco-alternative route to capturing and removing MF greater than 20 μm using ultrasonic technology (HKRITA, 2022). The treated wastewater can be reused for wet processing of textiles. However, effluent treatment is still a remediation method, and efforts should be primarily focused on manufacturing techniques that reduce MF emissions in the first instance.

Pre-washing of textiles: It has been shown that MF release during laundry from garments is greatest in new garments during the first 5-10 washes after purchase, in comparison with used clothing (Roos et al., 2017). Recent studies suggest that these MFs are formed during fibre and yarn production (Wang et al., 2023). Therefore, pre-washing textiles at emission points prior to consumer purchase could enable controlled capture of a substantial proportion of MFs in industrial WWTPs. This would reduce MF emissions in consumer laundry, hence reducing the need for domestic filters for MF capture and allowing relevant wastewater treatment processes to be implemented based on the textile type and process history (see Table 2).

Reusing textile waste/ effluents: There are many opportunities for textile wastes to be recovered and reused, for example de Jesus Conceição *et al.* (2023) discussed a prototype 3D printer that can convert pre-consumer polyamide mesh waste from beachwear into filament for use in various accessories, making use of the 30% of waste generated in the process and preventing its disposal in landfill. In another study, sustainable bio-based composites were manufactured using 100% cotton denim fabric waste strips, reinforced using bio-epoxy (Khan et al., 2025). Forster (2017) manufactured filaments extruded using pellets of PLA sheets laminated between cashmere, wool, and leather pieces for 3D printing. The 3D printable materials for cashmere, and wool were obtained from the waste of knitting machines, looms, unusable scraps, and fluff swept up from under the machinery, and leather was obtained from recycled airplane leather seats. Other than using waste from knitting machines, the wastewater generated during textile manufacturing can also be reused. Mixing freshwater with wastewater at a ratio of 50:50 for the pretreatment (scouring and bleaching process) of cotton knitted fabric reduces freshwater intake by 33%, saving 5 L kg^{-1} freshwater in the process (Panda et al., 2020). In another study, textile effluents with reactive dyes were treated with electrochemical-UV system for reuse in new dyeing processes, saving up to 70% of water and 72% of salt (Buscio et al., 2019).

Implementing better-by-design practices: Overall, employing better-by-design interventions using economically viable and scalable models for industries, along with increasing consumer awareness, will help to tackle MF challenges. Mitigation strategies through co-creation, and prototype development at every step of dry and wet processing of textile manufacturing should be implemented along with advanced effluent treatment methods to reduce MF emissions and incorporate circularity in textile manufacturing. Initiatives such as the Future Fibres Network+ are working to align environmental science with textile manufacturing and design to reduce microfibre shedding and entry into the environment (Cherrington et al. 2025). The proposed model aligns with the 2020 EU circular economy norm focusing on sustainable design and production of synthetic textiles for unintentional MF release into air and water (European Commission, 2020). Production processes that include pre-washing could capture released MF in a controlled way at industrial emission points as the plants are well connected to wastewater treatment, particularly in Europe. From an end-of-life processing perspective, circular business models incorporating advanced wastewater treatment methods for MF removal and wastewater treatment sludge management could prevent release of MF into the environment. However, economic considerations are paramount as set up and running multi-stage water treatment is expensive and generally requires a large amount of water, energy and space, so for an industry with tight margins both capex and operational costs of more effective wastewater treatments (e.g. multi-stage combined chemical, biological and filtration) make such process improvements non-viable. However, the first principle of green chemistry (Anastas & Warner, 2000) is that pollution prevention is preferable to pollution treatment (remediation), so if MF shedding can be reduced/prevented at source through intelligent design and process optimisation, the need for expensive and involved waste treatment processes could potentially be reduced or eliminated.

3.6. Knowledge gaps

Throughout this paper the main theme has been the need for more information, more research, and more collaboration to fully understand and map pre-consumer MF emissions. Of the 3,671 research papers identified herein for this critical review, only 10 gave information on pre-consumer MF generation, starkly highlighting the lack of research in this area. This knowledge gap has the potential to result in a vast underestimation of MF generation throughout a textile's life cycle. It also highlights that the textile industry does not only produce garments. Additionally, control and research into consumer generation of MFs through laundering is inherently difficult: every laundry load is different depending on household, materials involved, detergent choice, wash temperature, washing machine design, etc., leading to a huge number of variables that have to be considered when designing remediation strategies. The mix of fibres produced from laundering creates additional challenges in the recovery and reuse of those MFs compared to in the pre-consumer stages. This also relies on the consumer performing the remediation methodologies by either investing in new equipment, or changing their wash conditions, neither of which are a given. The suggestion for fitted filters also ignores the crucial fact that over 50% of the global population does not have regular access to a washing machine, and these people launder 'off-the-grid', typically by hand, where it is not possible to capture released MFs (Stanton et al. 2023). Stanton et al. (2023) additionally demonstrated that the shedding during hand-washing may approach levels from laundering and the route for MFs into the environment is even shorter. For industry, however, the variables are vastly reduced, as each producer has ultimate control over what goes in and out of their process, and these industries are far easier to control through regulation and legislation to enforce adopting strategies for MF reduction. Even within research performed on the same stage of textile manufacturing, the methods for analysis vary widely even within the limited number of studies focussed on pre-consumer textile processing. Methods of analysis, number of repetitions, different data reporting norms all add to the confusion and difficulty in gaining a holistic overview of the data available. While this is not a facile issue to resolve, a common measuring methodology needs to be adopted so that accurate and easy comparisons can be made, and processes designed to mitigate MF generation or remediate released MFs can be shared across sectors and industries so that the textile sector can collaboratively deal with this issue.

4. Conclusions

Pre-consumer textile production is a critical but understudied source of MF emission. On a whole-fabric basis dyeing is the single largest contributor, accounting for up to ~95% of total emissions in a representative wet-processing study (Wang et al., 2023); however, on a per-g basis individual dry-processing steps, particularly rotor spinning (up to ~2,244 MF g^{-1} yarn), can release comparable or greater numbers of MFs than dyeing (~764 MF g^{-1} fabric), so spinning is also a major source of MF release. Importantly, dry and wet manufacturing stages should not be viewed in isolation. Mechanical damage introduced during dry processes such as spinning, including protruding fibre ends and weakened inter-fibre cohesion, may not release MFs immediately but can act as a latent source that is subsequently mobilised during downstream wet processing, brushing, and garment construction. Dry and wet manufacturing processes therefore exert a cascading effect on overall MF release, and linking upstream spinning conditions to downstream emissions would improve causal understanding and strengthen the design of mitigation strategies.

Because emissions at the pre-consumer stage are far easier to control and regulate than other parts of the production process, the need for more stringent research into this area is evident to fully map MF emissions throughout the supply chain and to ensure adequate process design and remediation methodologies are implemented. It has also been identified through this critical review that there is a severe lack of literature (n = 10 suitable studies within the past 5 years) on MF shedding during textile processing, with the small number of studies limited by inconsistencies in the analysis methodologies used, which does not easily enable comparison of results. A common measuring methodology needs to be adopted, and policies that enforce fibre shedding assessment, mandate capture technologies, and incentivise low shedding manufacturing processes are imperative. This review suggests pre-consumer MF mitigation steps such as laser-cutting, dyeing at lower temperatures and with less water. By attaining a clear and in-depth understanding of MF generation during textile production and adopting some of the discussed methods, textile industries have the opportunity to achieve “win-win” scenarios of meaningful reductions in MF emissions as well as financial savings on water and energy that may encourage implementation and foster future sustainability improvements.

Data availability

Data is available in the supporting information as Supplementary Data.

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