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Review

Microfibres Release from Textile Industry Wastewater Effluents Are Underestimated: Mitigation Actions That Need to Be Prioritised

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Abstract: The release of microfibres (MFs) from textiles has been observed in various environments, pointing towards the impact of human activities on natural systems. Synthetic textile microfibres, a subset of microplastic fibres (MPFs), are reported to be the primary contributor to microplastic pollution. With the forecasted growth in textile production, the problem of MF pollution is expected to worsen and become more challenging to address. Wastewater treatment plants (WWTPs) are crucial in managing microfibre pollution as they can act as a sink and source of these pollutants. Studies have shown that textile industrial effluent can contain MFs at a rate of up to a thousand times higher than municipal wastewater. As more garments are made than sold and worn, the impact of industrial MF release could be higher than predicted. The detection and quantification of microfibres released in industrial wastewater effluents do not have a standard test method, and legislation to address this issue is not yet feasible. To tackle this issue, it is crucial to raise awareness in the industry and tackle it using a more holistic approach. With its urgency, but still being an underdeveloped research area, priorities for mitigation actions are examined where efforts are needed to accelerate. These include the need to raise awareness and encourage more investigations from industry and academia. A consistent protocol will help us to compare studies and find solutions of high impact and measure MFs in WWTPs, which can help define the maximum limit for MF releases and support legislation implementation.

Keywords: microfibres; microplastic fibres; textile industrial effluent; textile wastewater treatment

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1. Introduction

There has been growing concern about microfibres (MFs) in textile wastewater as they are a major source and sink of microplastic pollution in the world [1–3]. Among the world's biggest water-consuming industries, the textile industry is one of the most water-intensive industries [4]. According to Iowe [5], it is estimated to represent 4% of the global freshwater withdrawal. Textile wastewater effluents contain MFs, which are released in the process of producing and using textile materials.

Recently, microfibre (MF) has become a common term that refers to "microfiber pollution". Japan produced the first MFs for the textile industry in the 1970s, with an exceptionally fine diameter. An older industrial definition defines MF as fibres with a linear density of less than 1 decitex, a linear density unit being a gram per 10,000 m or diameter <10 µm [6]. They are typically made from synthetic fibres. In response to the emergence of concerns about fibre fragmentation, it is now generally defined to include natural and man-made cellulosic fibres with lengths shorter than 5 mm [7] and a length/diameter ratio larger than 3 [8]. Therefore, in the following content of this paper, MF refers to fibres smaller than 5 mm from all types of textile materials. Microplastics (MPs) are synthetic polymers often defined as plastic particles smaller than 5 mm [9–11], which include particles in the nano-size range (1 nm) [12], whereas microplastic fibres (MPFs) are derived from petrochemicals originating from synthetic-based textiles and are considered a subset of MPs [13,14]. MPFs are also defined as fibrous or threadlike pieces of plastic with a length between 100 μm and 5 mm and a width of at least 1.5 orders of magnitude shorter [15–17]. Therefore, MPF refers exclusively to MF from synthetic origin.

To attain the aesthetic and performance requirements, such as sizing, desizing, bleaching, mercerisation, dyeing, printing, finishing, and washing [18], textiles are wet processed with water. Abrasion between fibres, yarns, and fabric surfaces causes fibre fragmentation in these processes. Additionally, adding chemicals and additives may weaken larger molecules, causing them to naturally decompose into smaller ones. Due to the chemical reaction, molecular breakdown occurs, causing the fibre to physically break down and release chemical compounds into various bodies of water through the discharge of wastewater effluents. This has led to concerns regarding the effects of these effluents on the environment, marine life, and humans.

MFs are widely distributed and found in diverse environments such as marine, freshwater, and air environments. Browne [19] first estimated that the accumulation of MPs was associated with shoreline population density worldwide, showing that 85% of the MPs were MPFs. According to Boucher and Friot [20], 35% of MPs released into the ocean are from synthetic textiles, with 25% originating from wastewater. By combining the releases of MPFs shown by the existing domestic washing studies, Iowe [5] predicted that an additional 22 million tonnes of MPFs would be discharged into the ocean between 2015 and 2050, assuming that the demand continues to follow the current pattern. With the rapid growth in textile production, the issue of MF pollution will become more prominent and more difficult to resolve.

There is increasing evidence that the number of MFs released by industrial sources is underestimated, and a significant amount of pollution originates from them [14,21,22]. This makes addressing MF pollution and fibre fragmentation in wet processing units and wastewater treatment plants (WWTPs) crucial. This paper aims to provide a comprehensive overview of MFs from industrial sources and their pathways. Research gaps are analysed in relation to the contribution of pollution from these sources to MF pollution. The measurement of MFs in wastewater effluents is also discussed, along with methods for detecting and quantifying it. In addition, potential controls and mitigation strategies will be examined with a focus on their prioritisation as a result of the lack of legal requirements pertinent to MF releases in the textile and clothing industry.

2. Literature Review

Despite MFs being the most abundant source of MP pollution, most research continues to focus on MPs [23]. Thousands of papers related to MP have been published. Yet, when the subject is narrowed down to MFs, only a limited number of peer-reviewed publications are available.

There was a total of 92 peer-reviewed papers published on the Web of Science used in this paper, which, based on the search criteria, applied "Textile (Topic) and microplastic* fibre* or microplastic* fiber* or microfibre* or microfiber* (Abstract) and effluent* or wastewater* or wastewater treatment or effluent treatment (Abstract)" as of 18 June 2023. In Figure 1a, they are divided into six major categories: aquatic, terrestrial, atmospheric, wastewater effluent, domestic laundry, ecological, and others that are not classified. Domestic laundry has gained the most attention since its first publication in 2011 and is growing steadily. There have been the fewest publications in terrestrial and atmospheric since its publication began in 2018, the most recent date. Concerns have been raised that this pathway may overshoot aquatic.

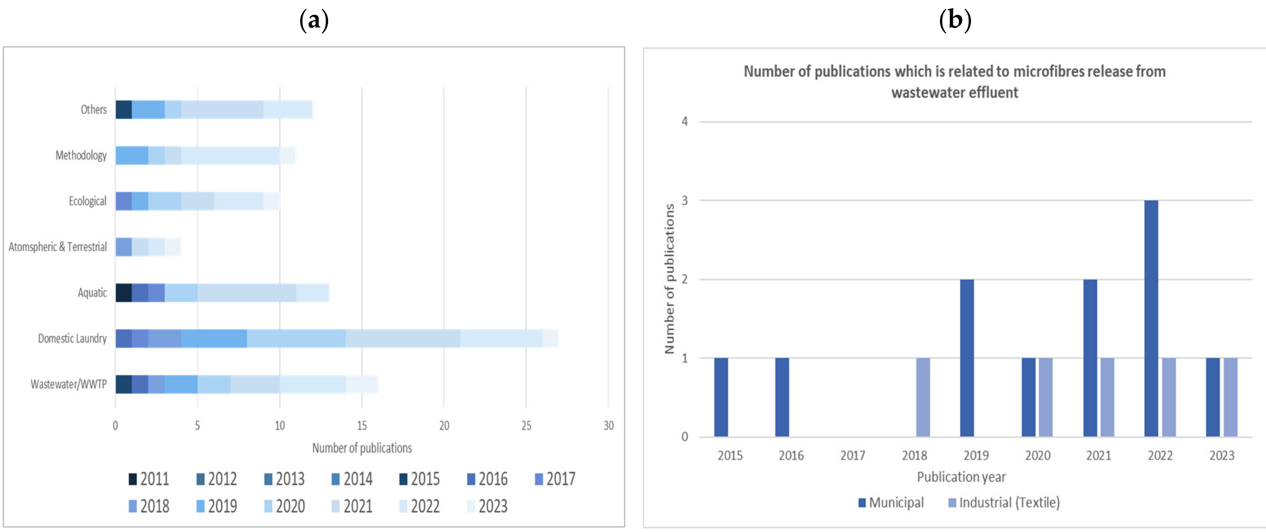

Figure 1. Number of publications. (**a**) Publications grouped into 6 major categories from specific search criteria "Textile (Topic) and microplastic* fibre* or microplastic* fiber* or microfibre* or microfiber* (Abstract) and effluent* or wastewater* or wastewater treatment or effluent treatment (Abstract)" on Web of Science. (One publication covering atmospheric and wastewater is counted in both scopes.); (**b**) Publications related to microfibre release from municipal and industrial (textile) wastewater effluent.

By limiting the research to wastewater effluent, only 16 articles have been identified. In Figure 1b, only five focus on industrial textile sources out of the total count. Notably, there was a considerable research gap in understanding the microfibre releases from wastewater effluents from this source, irrespective that their emissions were reported significantly higher than from municipal, and a lot of the projected figure formulas on MFs calculations were underestimated as they were only based on domestic laundry [20,24–26] and missed out industrial data sources.

2.1. Industrial Textile Effluents as a Source of Microfibre Pollution

Different textile wet processing will eventually generate industrial textile effluents or sludges containing MFs because wastewater treatment is not 100% efficient in retaining them [27]. Like MPs, MPFs are nondegradable and take hundreds of years to decompose, thus inevitably accumulating in the environment. MPFs are emerging as the most prevalent type of secondary MP debris in the aquatic environment [1,17,19,28–30].

Even though WWTPs are reported to be 95–99% effective, these plants are not explicitly designed for MF retention as they can bypass the WWTPs [30–33]. Therefore, due to the enormous discharge volumes, there is strong evidence that WWTPs are significant sinks for MP pollution [27,33–35]. Other than discharge wastewater, solid waste or sludge is generated for disposal from WWTPs. Sludge is a by-product of WWTPs commonly applied to agricultural land as fertilisers. Several studies have reported long MFs found in soil, including Zubris and Richards [36] and more recent studies [37,38].

The earliest extensive study was conducted by Browne et al. [19], who stated that the accumulation of MPs has links to population density at shoreline sites around the globe and that MPFs contribute to 85% of the MPs identified from washing clothes. As a result, domestic laundry was considered the most common source of MF pollution and is widely researched as fibres shed from textiles during domestic washing. Textiles also release fibres into the environment during production, where there is a wider gap in understanding the loss of MFs in this pathway and their relationship. Nevertheless, Roos et al. [39] claimed that removing MPFs from the fabric production stage will reduce the risk of microfibre shedding from garments. Zhou et al. [21] and Chan et al. [22] claimed that

MFs released from industrial sources could be as significant and make no less impact than domestic laundry.

Fibres and fabrics are subjected to mechanical and chemical stresses during their use and production, resulting in their fragmentation and release into the environment. To make raised fabrics softer and more attractive, abrasive processes are applied to create raised fabrics, like fleece fabrics. During domestic washing or industrial wet processing, these loose fragmented fibres will be released and washed off into effluents [40]. Wastewater effluents from wet processing mills are typically treated in WWTPs before being discharged into the environment. Due to the inability of MFs to be captured, they will be released into the atmosphere, effluents, and sludge. Because these processes are not designed to contain MFs, they are unavoidably released into the atmosphere.

Figure 2 demonstrates different wet processing operations that can be potential sources of MF release during production. Wet textile processing is the most renowned source of MF release as these processes use water and discharge effluent into water bodies directly or indirectly via mill WWTPs or Centralised Effluent Treatment Plants (CETP). Wet processing can be divided into three major groups depending on the material and operation types. Textile refers to fabric materials made of synthetic, semi-synthetic, and natural fibres. Most natural plant fibres, like cotton, are cellulosic and require extra pre-treatment. Broadly speaking, the rest of the fibre types, including semi-synthetics or synthetics, commonly go through bleaching, dyeing, printing, and finishing. Synthetic leather is a popular material used in the textile industry to simulate real leather. The wet method of production uses polyurethane (PU). Synthetic textile fabric is used as backing. The textile base is made wet by dipping it into water and coating it with PU fluid. This is followed by solidifying in a N, N-Dimethylformamide (DMF) sink and washing off before drying. Sometimes, products such as garments are finished after being sewn in their final state. This route explicitly applies to garment-dye and washed products, such as denim. MFs fragmented from this route can be released in wastewater at the industrial wet processing units, becoming the primary sources of industrial effluents.

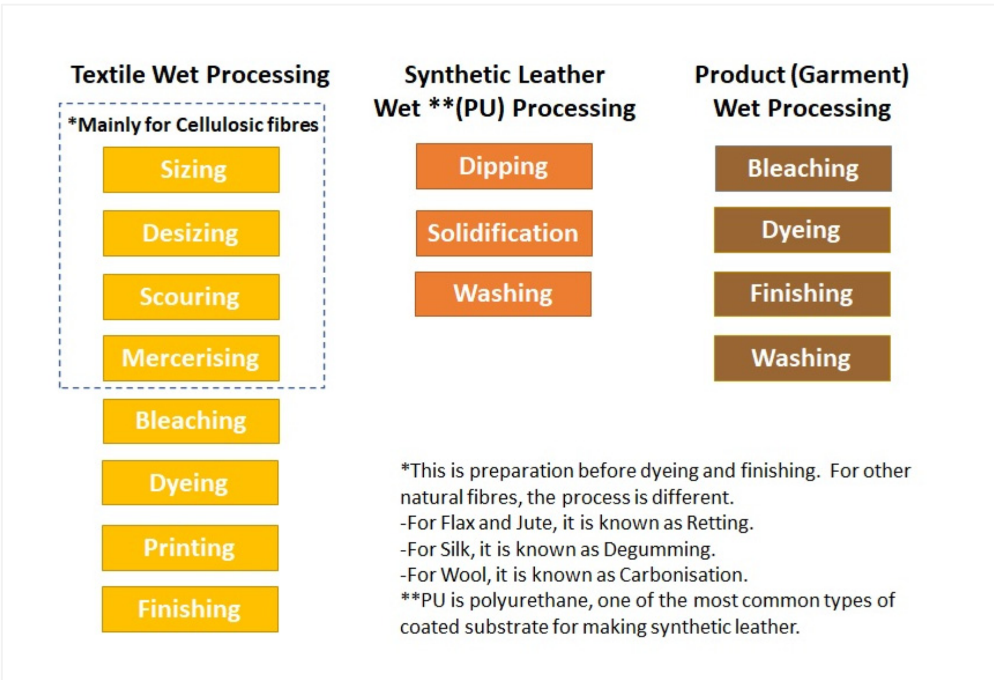

Figure 2. Common textile, synthetic leather, and product wet processing. Reproduced with permission from Ref. [41], CRC Press, 2024. Note: Sizing, Desizing, Scouring and Mercerising are pretreatment processes for cellulosic fabric preparation. Bleaching, Dyeing, Printing and Finishing are processes to enhance the performance or visual appearance of the fabrics.

2.2. Textile Wet Processing Mill Effluents

Although limited MF studies have focused on their release from textile industrial effluents, those identified in the Web of Science are summarised in Table 1. Textile mill effluents refer to wastewater discharge directly from textile mills. The first study was from Swerea IVF [42]; effluents were collected from five mills in Sweden, and the number of MFs released was projected at 100–1450 MFs per litre. However, a coarse mesh size of 100 µm and a comparatively small volume of 0.85 mL were used. There was a potential for underestimation, as much later research claimed that the filter pore size at 100 µm ignored a significant proportion of MF [21,43], and even the most considerable number of the identified MFs were below this length [22]. Despite whether these mills are indirect or direct discharge types, the high end of 1450 MFs/L identified was about three times more than the average of later studies.

The number of MFs/L of wastewater from three distinctive types of mills in China was analysed [21], and a significant difference was found. In addition to the fibre type, the treatment methods of these mills also varied. The best-performing mill had just 5 MFs/L in its effluent because it is a tertiary treatment plant with a membrane bioreactor (MBR) and reverse osmosis (RO). Compared to other mills, the low levels of MFs in this mill are probably the result of tertiary treatment. This result was echoed by Lares et al. [33], who found that MBR was about 2.5 times more efficient than conventional active sludge (CAS) technology.

The China mill reported by Chan et al. [22] has a homogenous production of polyester fleece fabrics all year round. With the data provided, it is possible to benchmark the MF release from this type of fabrication at 361.6 MFs/L compared with a typical wet processing mill with a secondary treatment plant. Compared with Akyildiz et al. [43], who collected wastewater samples over five months in Turkey, the MF releases varied considerably on different production days. This could be attributed to the variety of processed materials during this period. A comparison was not conducted on the percentage of incoming fibre materials for processing and their relationship to release. It was difficult to conclude whether it was solely owing to the difference in the material type being processed, and hence their textile (fibre, yarn and fabric) parameters, which are reported in domestic laundry studies and have a significant impact on MF release [44,45].

According to Chan et al. [22], almost all of the textile mills' discharge mainly showed fibre lengths smaller than 500 µm. The shortest length group, of less than 100 µm, was the most dominant, implying that earlier studies using a 300 µm filter pore size potentially underestimated the MF release. The study was the first to propose 5L as the optimal sampling volume, giving a more consistent result. Although it is essential to balance the time used for filtration, the reliability of using different sampling volumes must be further validated [22].

Table 1. Summary of textile industrial effluents. Reproduced with permission from Ref. [41], CRC Press, 2024.

Reference Source/Type	No of Mills/(No of Receiving Mills)	Discharge Type	Major Fibre Type	Treatment Processes	MP Retention/Removal Efficiency	Sample Region	Adjusted Discharged as Effluent to the Aquatic Environment	Effluent MF Length	The First Filtration Mesh Size (µm)	Finest Filter Size (µm)	Sample Volume (L)	Major Character-Isation Method	MF/L from Direct Effluent
Textile Mill Effluents													
[42]	5	Direct	Polyester, Polyamide, Cotton, Viscose	n.a.	n.a.	Sweden	100–1450 MFs/L	50–500 µm (75%)	n.a.	100	0.85	FTIR	
[21]	3	Indirect	Viscose, cotton, synthetics	Primary, Secondary, and Tertiary	84.7–99.5% (Secondary removal 44.3–96%)	China (Hang-zhou)	0.05–90 * MFs/L	<1000 µm (>90%) 100–300 µm highest%	n.a.	0.45	0.75	Stereo microscopy	5–1800 MFs/L
[22]	1	Indirect	Polyester	Primary, Secondary	n.a.	China (Chang-zhou)	18.1 * MPFs/L	451 µm (<1000 µm 92%) <100 µm highest%	10	1.5	5	Raman	361.6 MFs/L
[43]	1	Indirect	Wool, Cotton, Acrylic, Polyamide, Polyester, Polypropy-lene, Viscose	Primary	54%	Turkey	15.5–120.2 * MFs/L	<1000 µm (82%) 100–500 µm highest%	n.a.	0.7	1	FTIR	310–2404 MFs/L
Laundries Textile Effluents													
[46]	5 laundries (x3 WWTPs)	Indirect (Without WWTP)/Direct)	Polyester, Cotton, Polycotton, Nylon, Rubber	Primary Primary, Secondary	Chemical x2 (65%–96%) Biological x1 97%	Sweden	15–78 MFs/L (worst scenario estimate) 1–5.2 MFs/L (best scenario estimate)	<400 µm are dominant	n.a.	0.65	0.078–0.5	FTIR/SEM-EDS	500–375,000 (MPFs/L only)
[47]	2	Direct	Acrylic, Polyester	Nil	n.a.	Iran	48–81 MPFs/L	<500 (81.6–85.6%)	37	25	10	Stereo microscopy	

Table 1. *Cont.*

Reference Source/ Type	No of Mills/(No of Receiving Mills)	Discharge Type	Major Fibre Type	Treatment Processes	MP Reten-tion/Removal Efficiency	Sample Region	Adjusted Discharged as Effluent to the Aquatic Environment	Effluent MF Length	The First Filtration Mesh Size (µm)	Finest Filter Size (µm)	Sample Volume (L)	Major Character-Isation Method	MF/L from Direct Effluent
Industrial Wastewater Treatment Effluents (mainly received from textile mills)													
[14]	1 (33)	Direct	Polyester, Viscose, Natural fibres (Cotton, Linen, Wool), Polypropy-lene	Primary, Secondary	95.1% (Primary 76%, Secondary 83.7%, Tertiary 95.1%)	China	16.3 MFs/L	30–1000 µm (76.7%)	10	5	12	FTIR	
[48]	5 (unknown)	Direct	Polyester, Viscose, Polyethylene, Polystyrene,	n.a.	89.17–97.15%	China	7.7–9.48 MPs/L	<1000 µm (>70%)	25	5	15	FTIR	
[49]	2 (unknown)	Direct	Polyester, Polyamide, Polypropy-lene, Polystyrene	Primary, Secondary	unknown	China (Chang-zhou)	8–23 MPFs/L	<500 µm (89%)	13	0.45	1	Raman	
[21]	2 (130)	Direct	n.a.	Primary, Secondary, and Tertiary	92.8–97.4%	China (Hang-zhou)	537.5 MFs/L	<3000 µm (>70%) <1000 µm (100%)	n.a.	0.45	0.75	Stereo microscopy	

FTIR (Fourier Transfer Infrared Spectroscopy), SEM (Scanning Electron Microscope), EDS (Energy Dispersive X-ray Spectroscopy). * 95% efficiency is used for the next wastewater treatment before discharge to the waterbodies. n.a. means data not available.

Despite searching for papers on microfibres specifically coming from synthetic leather and garment washing mills, none have been identified. As a few studies [50–52] reinforced the fact that most of the MFs are released from the first wash, the MFs released per unit from industrial garment washing mills are possibly of a higher magnitude than those released by domestic washing because it is theoretically the first wash before they are sold.

2.3. Commercial Textile Laundry Effluents

Regarding commercial textile laundries, only two studies were categorised as being relevant. Post-consumer textiles are washed in commercial laundries on a smaller scale than in industrial textile mills, so this area may go unnoticed. Commercial laundries may also require mitigation measures like those used for domestic washing, but their dominance should not be ignored, given the volume of water used and effluent discharged. Their rate of MPFs released were as high as textile mills or industrial effluents, as illustrated in Table 1.

Five commercial laundries were selected with different sources of products, from workwear, hotels, mats, and hospitals, by Brodin et al. [46]. These products were made from varied materials: cotton, polyester, polycotton, nylon, and rubber. Detecting MFs was more challenging, as they also contained other MPs. Approximately 27–46% of the total MP samples were MFs, making them the most abundant type. Substantial amounts of debris may be exposed to these products, and an extra separation procedure may be needed for analysis.

Beyond the release of MFs in effluent from textile production facilities, the laundries are expected to release MFs and microparticles in the environment [46]. As the laundry removes loose particles (such as dirt), the treatment of the textiles can be harsh. Many other factors can also influence the severity of MF shedding, including if the fabric is entirely new in production versus aged textiles [53]. Studies by Cesa et al. [54] and Vassilenko et al. [55] demonstrated that MFs are released more in the first few washes and are likely to be similar when washed at the laundries. Small particles, between 5 and 15 μm, were dominant in the Brodin et al. [46] study, regardless of the types of textiles washed or whether the laundry had a wastewater treatment facility. From the microscopic, FTIR, and SEM analysis, it could be concluded that microplastics were not dominant in this size range. Most of the particles (in the 5 to 15 μm range) were of other materials (for example, minerals, metal fragments, silica, aluminum silicate, yeast, and starch). There was a significant difference in the amount of MP particles released between the laundries. The wastewater treatment type has a large impact on reducing the number of particles.

According to the results obtained from the treatment of the mats (chemical) and two kinds of workwear (chemical and biological) laundries, the amount of fibre-shaped particles released from the treated effluent decreased by 65%, 96%, and 97%, respectively. Thus, it shows that wastewater treatment at the laundries can efficiently reduce the levels of particles released to the WWTPs. A specific study of carpet laundries by Alipour et al. [47] reported Iran's fast-growing carpet cleaning services, which pointed to the MPF release from commercial laundries in Ahwaz and Sari. Laundries in both areas directly discharge their effluents to the Karun River and absorption wells with relatively high emissions. The amount of wastewater generated by washing one square metre of carpet in Ahwaz and Sari was 81 and 48 MFs/L, respectively. Sari WWTP received water and was found to contain 4.9 and 12 MPFs/L microfibres during the spring and winter. Consequently, carpet-washing workshops released high concentrations of MPFs. Further findings showed that short fibres (37–300 μm) were found to be the most dominant group, at approximately 57%; for <500 μm, it was above 80%. As a result of the severe erosion of the high-speed spinning and drying actions in these laundries, the quantity of potential MFs entering the environment was further amplified. Immediate action is needed to introduce control measures as the concentration is not less than other pathways.

2.4. Industrial Wastewater Treatment Effluents

Xu et al. [14] first reported MFs in textile industrial WWTP effluents. The plant, with a daily capacity of 30,000 tonnes, receives wastewater from 33 textile printing and dyeing mills in a China textile industry park. The average abundance was reduced from 334.1 MFs/L to 16.3 MFs/L after 95.1% efficiency treatment, with synthetics and non-synthetics being incorporated. Also, the MF abundance was observed to be correlated with suspended solids but not with COD, pH, or nitrogen levels.

Another study by Xu et al. [48] reviewed five textiles out of eleven industrial WWTPs in China and found that the average abundance was 7.7–9.48 MPFs/L, with a 89.17–97.15% retention efficiency. The most frequent length identified was 100–500 µm. Wang et al. [50] investigated another five industrial WWTPs, but only two were linked to the textile industries. These WWTPs contributed to 8–23 MPs/L; the removal efficiency was 92.8–97.4%. This finding was comparable to the earlier studies that focused on MPFs. Nevertheless, the outcome concluded that MPs from domestic, industrial, agricultural, and aquacultural sources were insignificant. Polymer types were not examined from each WWTP, making it difficult to correlate MPs and MFs.

A study conducted by Zhou et al. [21] examined MFs from industrial WWTPs receiving influents from 130 textile mills in China. In these WWTPs, the removal rates ranged from 92.8–97.4%, and the MF pollution levels were 537.5 MFs/L, a level comparable to the surface water pollution at 600 MFs/L in nearby communities, as these WWTPs discharge effluent directly onto the surface. According to these studies, industrial WWTPs achieve relatively high removal efficiencies for MFs, but significant amounts of MFs are still discharged to the aquatic environment.

3. Pathways of Microfibres from Textile Industrial Effluents

The majority of discussions on pathways have so far focused on municipal WWTPs. In their first quantitative assessment of the world's ocean, Boucher and Friot [20] calculated the immediate release of primary MPs of 1.5 Mt/year, regionally exceeding the weight of secondary MPs from mismanaged waste. In this study, the main pathways of MPs from the source to the ocean were road runoff (66%), wastewater (25%), and wind transfer (7%). It was estimated that 34.8% of the release was from domestic laundry of synthetic textiles, followed by 28.3% from erosion of tyres while driving. The domestic laundry pathway is the most significant, which explains why it receives the most attention [56]. Industrial effluent is seldom studied, rarely discussed, and rarely estimated.

Figure 3 shows a flow diagram created to show the potential pathways and releases of MFs from industrial sources. The blue arrows indicate pathways through which MFs can enter the aquatic environment. The sources are classified into pre- and post-consumer origins. Industrial wet processing mills are typically produced for pre-consumer use. There are many mills with advanced wastewater treatment systems; however, some mills discharge their wastewater directly into the natural environment. Direct discharge refers to wastewater effluent generated in the first place, released directly without further treatment. Some mills and laundries do not have treatment facilities or effluent quality that meet the direct discharge standards required by local laws and will be directed to CETPs before being discharged to the aquatic environment. These are indirect discharge pathways. It is worth noting that sometimes, effluents will be recycled to reduce water use.

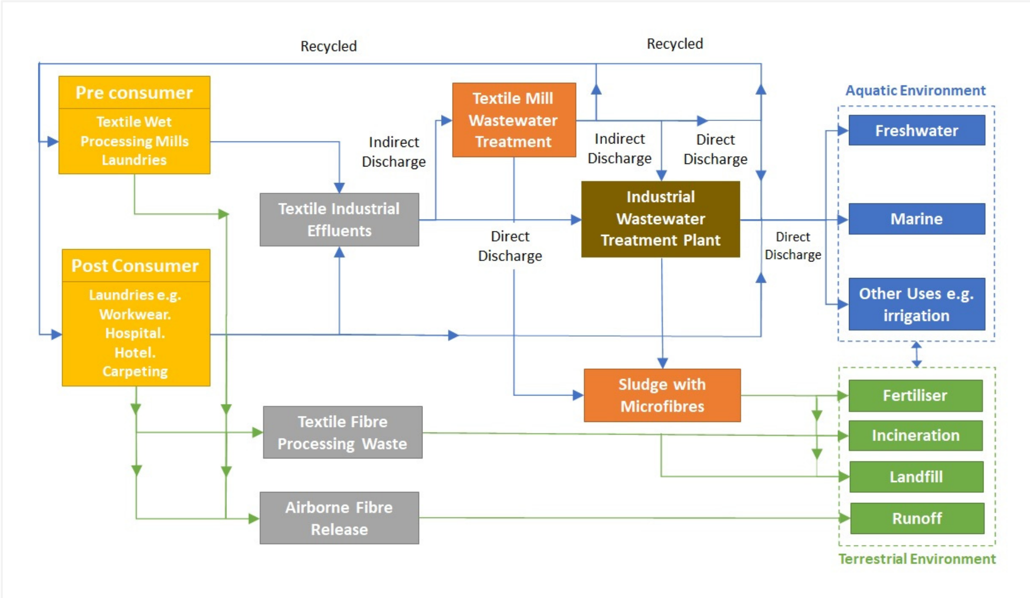

Figure 3. Sources and pathways of microfibres from industrial wet processing of textiles. Reproduced with permission from Ref. [41], CRC Press, 2024.

The green arrows in Figure 3 indicate the terrestrial pathway. WWTPs produce sludge as a byproduct, some of which can still be used as fertiliser. Practically, most of them are incinerated, which is more appropriate for industrial sludge because of the prominent level of toxicity. While airborne MFs are released into the atmosphere during production, textile MF waste intentionally disposed of for incineration or landfill follow the green arrow paths. MFs that cannot be captured might blow via wind current as runoff. Aquatic and terrestrial pathways can interact through storms and wind [57–59].

4. Effectiveness of Wastewater Treatment in Reducing Microfibre Pollution

Mintenig et al. [27] proposed that WWTPs serve not only as sinks but also as sources of MPs, and are thus critically indispensable in MP pollution. WWTPs as pathways for MP release have drawn more attention recently, with an exponentially growing number of related publications in the last few years [59]. There is sound evidence that MPs, MPFs, and MFs can easily bypass WWTP filtration and other solid separation processes, as they are not designed for such a purpose [31,32,60].

Magnusson and Norén [30] and Talvitie et al. [61] demonstrated that the supply of MPs from WWTP effluents to the aquatic environment might be substantial because of the enormous daily discharge volumes. Still, their relative importance concerning other sources/entrance routes is difficult to estimate due to the lack of quantitative studies. The reviewer found that there is still a lack of research in this area, and it is poorly understood [62,63].

4.1. General Performance

In the Conley et al. [60] study, the MPF removal efficiency was reported to be 80.2–97.2%, which was relatively high, but still significantly less than the total MPs. Talvitie et al. [61] suggested that advanced wastewater treatment (e.g., a membrane bioreactor) is needed to improve the removal efficiency of small-sized MPs (<100 µm). This efficiency level was echoed by Ziajahromi et al. [32], who reported that fibres were the dominant type of MPs detected in most effluent samples and were not completely removed even after some advanced treatment processes. A UNEP [25] report estimated the MPF retention efficiencies from four main types of wastewater treatment options, as shown in Table 2.

Table 2. The microplastic fibre removal efficiency for different wastewater treatment options. Modified from [25].

Wastewater Treatment Options	Microplastic Fibre Removal Efficiency
Preliminary	58.0%
Primary	87.0%
Secondary	92.2%
Tertiary	96.5%

Note: Preliminary treatment: is the removal of such wastewater constituents that may cause maintenance or operational problems in the treatment operations, processes, and ancillary systems. It consists solely of separating the floating materials and the heavy settleable inorganic solids. This treatment reduces the BOD of the wastewater, by about 15 to 30% [64]. Primary treatment: treatment of (urban) wastewater by a physical and/or chemical process involving settlement of suspended solids, or other process in which the BOD_5 of the incoming wastewater are reduced by at least 20% before discharge and the total suspended solids of the incoming wastewater are reduced by at least 50%. Secondary treatment: treatment of (urban) wastewater by a process generally involving biological treatment with a secondary settlement or other process, resulting in a BOD removal of at least 70% and a COD removal of at least 75%. Tertiary treatment: treatment (additional to secondary treatment) of nitrogen and/or phosphorous and/or any other pollutant affecting the quality or a specific use of water (microbiological pollution, colour etc.).

WWTPs in developed countries are generally believed to be more efficient. For example, Mintenig et al. [27] discovered that a German WWTP removed 98% of MFs after advanced filtration. In new economies, WWTPs are usually of a lower standard because of inadequate sewage infrastructure. In 2014, China alone accounted for 69% of all polyester fibre production globally, with the combined output of China, India, and Southeast Asia representing over 80% of the global total [13]. Nevertheless, developing countries produce and consume more synthetic textile materials, at 62.7%, compared to 48.2% in developed countries [20]. These regions are still developing and will tend not to have a common tertiary treatment standard, as illustrated in Table 3, which is of more desperate concern.

According to Sun et al. [59], the estimated microplastic flow in wastewater treatment plants with primary at the sedimentation is most effective at up to 50% efficiency and secondary at up to 14%, whereas tertiary treatment processes are up to 2%; this may be assumed to equally apply to MPFs. As for non-synthetic MFs, there has been no independent study focusing on MF retention alone for this group. Most of the data are aggregated because MPs are chemically similar to MPFs, while MPFs are like non-synthetic MFs in their fibrous structure. Therefore, the assumption must be made until there is more data available.

Pre-treatment or primary treatment has an immense impact on the size distribution and removal of sizable MPs via skimming on primary clarifiers and settling heavy MPs trapped in solid flocs during drift removal and gravity separation. The efficiency at this stage was reported to be 35–59%. Sun et al. [59] concluded that secondary treatment, typically comprising biological and clarification, could increase retention by an additional 0.2–14%. At this stage, suspended matter aggregates together, forming a floc that will consequently be removed at the settling stage [65]. However, there were more fragment particles removed relative to the fibres, despite an absence of a larger than 500 μm size that was believed to be effectively removed in this secondary treatment process [27,60,65–67].

Sun et al. [59] illustrated that the overall MP reduction in the tertiary treatment was estimated to decrease further, by 0.2–2%. Talvitie et al. [61] suggested that advanced wastewater treatment could improve the removal efficiency of small-sized MPs (<100 μm). Different tertiary technologies were compared. MBR was considered the most effective at 99.9%, followed by rapid sand filtration (RSF) at 97%, and dissolved air flotation (DAF) at 95%. Disc filter (DF) tended to vary between 40–98.5%.

Table 3. The distribution of wastewater treatment options in Wastewater Treatment Plants of different regions. Source from [25].

	NAFTA (incl. Rest of North America)	Western Europe	Japan	Central Europe and CIS	Middle East	Latin America and Caribbean	Oceania	India	China	Asia (excl. Japan, India, and China)	Africa
Share of population covered in (OECD stat. 2017)	100%	93%	100%	9%	2%	14%	12%	0%	0%	4%	0%
Share going to Preliminary treatment	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Share going to Primary treatment	17%	8%	13%	5%	30%	53%	18%	65%	3%	30%	65%
Share going to Secondary treatment	46%	21%	57%	20%	39%	28%	32%	35%	97%	39%	35%
Share going to Tertiary treatment	37%	72%	30%	75%	31%	18%	50%	0%	0%	31%	0%
Reference	← OCED stat. (2017) →							[68]	[69]	Due to a lack of better data, the treatment share was assumed to be the same as in India.	

4.2. Performance Specific to Industrial Textile Effluents

Referring to Table 1, the Industrial WWTPs have a better MF retention performance, at 90% or above, from all of the reported sources [14,21]. The textile mill has a lower retention rate, at 84.7%, even though it uses MBR tertiary treatment processes, whereas it was at just 54% for the Turkish mill, which only used primary treatment [43]. These textile mills will discharge their effluent to industrial WWTPs. This pathway, with the additional treatment process, should have significantly lowered the rate of MF release and become less risky than those mills or laundries that discharge directly to the aquatic environment. However, even after advanced treatment, most effluent samples were not completely removed [32]. In contrast to other shapes, the fibres retained were more effective, and a higher reduction was found after pre-treatment [28,32].

Xu et al. [14] found that most textile fibres attached to the gravel and flocs were removed in the initial primary sedimentation stage at 76%, and then 83.7% after secondary treatment. Therefore, the additional treatment as a second procedure in CETP potentially contributed to the higher efficiency of the overall MF removal. MFs larger than 1000 µm were most effectively removed at preliminary treatment than those between 500 and 1000 µm. There was no selectivity in smaller MFs.

Only a handful of research has investigated industrial textile wastewater. Indeed, the reported figures between studies were relatively difficult to compare, as there were large variations in the sampling methodologies conducted across various dimensions. For example, the finest filter sizes vary by as much as 153 times (i.e., from as small as 0.65 µm to as big as 100 µm). Furthermore, according to the industrial textile effluent described in Swerea IVF [42], the production parameters, such as the capacity and materials processed, were not captured. This missing detail made analysis difficult, as these parameters might have a significant role in understanding the true scenario of MF fragmentation. For instance, some textile processes might use smaller volumes of water, which could cause higher concentrations of MFs in their effluent, and potentially misrepresent the result. Nonetheless, industrial effluents likely have a dramatically higher concentration of MFs than municipal. For example, a comparison of the results from Xu et al. [14] with the municipal effluents from Yang et al. [70] and Lv et al. [35] in China revealed that there was 28–1310 times more concentrated effluent of MFs discharged directly to aquatic environments from industrial sources than from municipal WWTPs.

5. Detection and Quantification of Microfibres in Textile Effluents

Although there have recently been some achievements in standardising the test method for MFs from domestic laundry effluents—AATCC TM212-2021 [6], BS EN ISO 4484-1:2023 [7], and TMC method-2019 [71]—the methodologies are similar as they each use a percentage weight of the MFs collected compared to the original weight of the fabric as the MF fragmented. These are summarised in Table 4; it is worth noting that the estimations provided for the MF fragments lost during the laundry process do not factor in the quantification or length distribution of MFs in the textile effluents. Additionally, contamination from the fabric is not considered, which can have a significant impact on the weight. Although these commercial methods are economically scalable, unfortunately, without more specific information on the MF fragments, it becomes challenging to find viable solutions to address this issue effectively.

Table 4. Comparison of Commercialise Standard Methods. Consolidated from TMC Method-2019 [71], AATCC TM212-2021 [6] and BS EN ISO 4484-1:2023 [7] standards.

Standard	TMC Method-2019 [71]	AATCC TM212-2021 [6]	BS EN ISO 4484-1:2023 [7]
Description	Quantification of fibre release from fabrics due to domestic laundering	Test Method for Fibre Fragment Release During Home Laundering	Microplastics from Textile Source—Determination of material loss from fabrics during washing
Scope	All textile materials	All textile materials	Synthetic and natural fibres
Sample Specimens	8	4	4
Resultant Dimensions	100 mm × 240 mm	100 ± 10 mm × 240 ± 10 mm	100 ± 10 mm × 240 ± 10 mm
Pre-treatment	Dry at 50 °C 4 h	Option A: 21 ± 2 °C, 65 ± 5% RH 4 h Option B: 70 ± 2 °C 4 h (desiccator 30 min)	50 ± 3 °C dry to constant mass, cool in a desiccator
Liquor	360 mL, grade 3 water, 50 steel balls	360 mL, grade 3 water, 50 steel balls	360 mL, grade 3, 50 steel balls
Detergent	Nil	Option A: 0.25% Option B: Water only	Nil
Wash Conditions	40 °C for 45 min, with a rotation speed of 40 ± 2/min	Wash temperature as the label for 45 min, rotation speed of 40 ± 2/min	40 ± 3 °C for 45 ± 1 min, rotation speed of 40 ± 2/min
Blank Test	Not Required	Required, every 4 specimens	Required, every 4 specimens
Filter	1.6 µm pore size, 47 mm diameter Dry at 50 °C 4 h	1.6 µm pore size, 47 mm diameter, rinse and dry as Pre-treatment	1.6 µm pore size, 47 mm diameter, Dry at 50 ± 3 °C 4 h
Balance Precision	0.0001 g	0.0001 g	0.1 mg
Calculation	Fibre release (%) = 100 × (W2 − W1)/S	Fibre fragment release (g) = W2 − W1 Fibre fragment release (%) = 100 × (W2 − W1)/S	Fibre fragment release (g) = M2 − M1 Fibre fragment release (%) = 100 × (M2 − M1)/S
Reporting	Average mass of fibre fragment release (significant digits 3) Average% of fibre fragment release	The average mass of fibre fragment release and standard deviation Average% fibre fragment release and standard deviation	Mean of mass loss Mass loss% of the original specimen

5.1. Sampling

Hann et al. [72] stated that, potentially, the best methods currently devised for wastewater effluent MP measurement use large sample volumes ($\geq$1 m^3), a small mesh size for filtration (<10 µm), and automated material analyses. However, examining the studies conducted to date, the use of large sample volumes reaching 1 m^3 has rarely been found. Four out of the ten studies shown in Table 1 used larger volumes. A larger volume can have higher accuracy; however, it requires a longer time to complete, as well as using more resources, which might not be justified economically. Some studies also tried taking a sample over different days of production to report an average. These results may not be easy to analyse without understanding the relationship between processed effluents and the production parameters, as the composition was expected to be highly heterogeneous. Collecting samples a few times on a commercial scale is not cost-effective. Chan et al. [22] collected their samples over six hours, covering three production cycles, referencing the wastewater guidelines from the ZDHC Foundation [73], which are more feasible to analyse as production over a shorter period within a day stabilises the test and the results are more conclusive. However, for factories with smaller volumes and higher variations in their production lines, sampling will also become challenging to address. The design of sampling points and volumes requires more comprehensive studies to cover a broader type of textile production processes. Indeed, other researchers have used finer mesh sizes with a positive relationship to potentially retain finer and shorter MFs [32]. In Table 1, three out of ten used a mesh size of over 10 µm—namely, 13, 25, and 35 µm—which might lead to underestimation as textile MFs are between 10–30 µm in diameters [14,74,75].

5.2. Pre-Treatment

Most organic matter in a sample can be destroyed by active digestion using 30% (*v*/*v*) H_2O_2 [75], and this step can significantly reduce major interferences in the subsequent spectroscopic analysis [76]. Alternatively, other chemicals, such as Fenton reagents or enzymes, are sometimes used for other advantages, such as their reaction time and temperature and more rapid organic removal; however, H_2O_2 remains the most popular option for removing organic matter in the sample [60,77]. H_2O_2 is relatively expensive, and its main drawback is that it is less economically viable for treating a larger sample volume [78]. However, this may not be an appropriate method for distinguishing natural and cellulosic-based MFs, as it can destroy them, like organic matter. Alternative methods may need to be explored unless the wastewater has a very low organic content. The density separation is more suitable and effective for sludge. Several studies have used sodium chloride (NaCl), which has a density of about 1.0–1.2 g/cm^3, for sediment samples because of its low costs and low toxicity. It applies to lighter polymer types, such as polypropylene (PP) with 0.8 g/cm^3 and polyamide (PA) with 1.13 g/cm^3 density, respectively. However, NaCl is inappropriate for polyester fibres, as it is denser, at 1.38–1.41 g/cm^3. Zinc chloride ($ZnCl_2$) solution with a density of 1.6–1.8 g/cm^3 is utilised for separating all kinds of plastic, which is more effective and less expensive than sodium iodide (NaI) [77].

Indeed, other researchers have used finer mesh sizes with a positive relationship to potentially retaining finer and shorter MFs [32]. In Table 1, three out of ten have used a mesh size of over 10 µm—namely, 13, 25, and 35 µm—which might cause underestimation as textile MFs are between 10–30 µm in diameter [14,74,75]. Some wastewater studies go directly to purification and extracting MFs using a filtration device with a fine mesh filter below 5 µm. Glass fibre, paper, and nylon filters were mostly used [79].

5.3. Characterisation

For many years, the characterisation of polymers has relied on optical spectroscopy methods to provide information on polymeric materials' identity and chemical compositions. One significant finding was the inaccurate ability to identify MP or MF solely through microscopic visual inspection. Instead, each particle must be verified as plastic using a spectroscopic technique that can handle tiny particle sizes, such as micro-Fourier-transform infrared microscopy (μ-FTIR) or micro-Raman spectroscopy [76]. These techniques are the most common and are highly recommended by [80] for characterising MFs with a similar performance. Raman spectroscopy is a laser-based method that provides better resolution than infrared spectroscopy. It is well suited when the process requires focusing on small regions of a sample. It can also address the identification of MFs as small as 1 μm. The Raman spectrum yields similar but complementary information to that found with FTIR. Optical microscopy can be used with both instruments to establish a standardised method for the qualitative analysis and characterisation of MFs [81]. FTIR was considered the most popular method in general MP and MF studies. A Scanning Electronic Microscope (SEM) was used only by one study in Table 1; it is more commonly available in commercial laboratories, which can be considered as an acceptable option.

ISO 4484-2:2023 [82] was released in September this year, which may be a solution to standardising the test methodology approach to wastewater effluents. However, the test is limited to MPFs only and the maximum test volume is ≤900 mL. The use of micro-FTIR and micro-Raman in this test remains a challenge. A lower concentration of 15% (v/v) H_2O_2 is used instead, and a longer time of 7 days is allowed for organic matter digestion. The determination of the test sample volume depends on the total suspended solids (TSS) level of the samples. It is relatively different to the research studies published in journals. Therefore, there are no relevant published data and it does not relate to the previous studies. Overcoming these problems will rely on this test being adopted both by the industry and academia, with new data for evaluation, which may defer its adoption.

6. Priorities to Mitigate Microfibres from Industrial Effluents

Notably, industrial effluents carry a significantly higher concentration of MFs than municipal effluents when discharged into the environment [14,21,22]. In addition, pathways such as commercial laundries [48] were not treated by standard WWTPs before they were discharged into the environment. The higher concentration of MFs in industrial effluent was alarming, as few data are available. Therefore, identifying these sources and finding the best options to divert these effluents are crucial. Likewise, some direct discharge industrial WWTPs may also deliver a higher concentration of MFs, as sedimentation is the most effective process [14,59]; those pathways that include a second treatment in CETP should also lower the MF concentration in the second process.

Hann et al. [72] and Brodin et al. [83] proposed that there were more loose fibres in the first wash of a garment, as high as three times that of subsequent washes. Therefore, the MFs shed during the manufacturing process are incompletely washed off. As a result, reducing MF loss in production may be a more effective means to tackle the problem than actions during the usage phase.

6.1. Understand the Complete Picture and Urgency to Address Microfibre Pollution

Research from the Ellen MacArthur Foundation et al. [5] and Rudenko [84] revealed that 30% of garments produced are unsold, and 25% of those sold are never worn. Therefore, if we compare industrial to domestic laundry, the impact of MF pollution should be adjusted to reflect the true scenario when considering these factors, where the production volume is higher than those sold and used. Furthermore, as most environmental pollution estimates are derived from previous domestic laundry studies, it has persistently demystified the significance of industrial effluent as a source of MF emissions and thus underestimated the total MF release from all textiles produced and not used.

The existing estimates calculate the MFs shed or lost from domestic laundry related to different textile compositions, fabric types, wash conditions, and methodologies [85–88]. These figures vary widely and were difficult to compare by significant orders of magnitude. Only limited studies estimate global MF loss based on domestic laundry [26]. In addition, these figures have not been updated according to the latest findings, with most of the lengths being <1000 μm and with a finer linear density; therefore, previous studies using larger mesh sizes of up to 300 μm have underestimated the abundance. Therefore, a recalculation must be conducted to compare the earlier estimations meaningfully.

MFs are tiny and can be characterised by various densities, resulting in their dispersal through different layers in the water column [89]. Consequently, removing all MFs that have accumulated and scattered in the oceans is less feasible. In addition, the rate at which MPs enter the environment exceeds the removal rate [90]. Although a few studies identified several bacteria species capable of degrading plastic polymers in soil [91], including polyester, such microbes were not used for mass cleanup. They potentially pose risks not yet fully identified concerning bacteria released into the environment. Even though there is a solution to cleaning plastic debris in the ocean [92], the size is significantly longer than 1000 μm, which is still a long way to go for MFs to be effectively cleaned up, with the majority found to be shorter than this [14,22]. Therefore, a precautionary approach is more viable to tackle the problem, being more realistic for reducing the number of MFs generated and preventing them from entering the aquatic environment.

6.2. Raising Industrial Stakeholder Awareness and Taking Immediate Actions

Raising awareness among all stakeholders in the supply chain of MF release is vital to develop mitigation measures. There is a strong need for a collective effort to accelerate progress. The report by Changing Market [93] found 25 out of the 55 global brands researched have no evident microfibre policies or little available information. Every stakeholder should understand the issue properly in order to play a role in and be part of the solution. For the textile industry value chain, mitigation measures that utilise low-hanging fruit should be used in order to start with known variables that can reduce the severity of MF release, including varying the choice of materials and finishing techniques in the design, production, and usage phases to encourage stakeholders to take immediate actions, from sourcing policies, setting production requirements, and guidance.

In addition, consumers can communicate their concerns about fibre fragmentation from domestic laundry to retailers and manufacturers so that they can improve the fabric performance. Like domestic washing studies, consumer awareness campaigns are more popular than industry stakeholders. Therefore, awareness should extend to the industrial value chain, with each stakeholder having a role in developing, monitoring, and implementing new solutions to reduce fibre fragmentation. As a result, this will facilitate the development of long-term and sustainable solutions to the problem of MF pollution.

6.3. Establishing a Standard Test Method for Measurement and Reporting

Controlling and monitoring the MF release from WWTPs is impractical as the measurements are not comparable due to the absence of a standardised test to evaluate their emission. The analysis methods employed in identifying MPFs and MFs vary considerably, hindering accurate comparison between studies. The lack of a standardised sampling approach poses a significant challenge in researching MFs and wider MPs, making it difficult to compare findings across research groups. Therefore, future studies are expected to refine these methodologies for improved outcomes.

The test procedures must be suitable in order to be employed across the broader industry. The need to utilise expensive micro-FTIR or micro-Raman spectroscopes to verify the characteristics of MFs may represent an economic and logistic barrier to implementation. Academia or the industry alone cannot bridge this knowledge gap. There is a need to collaborate and develop diversified and innovative solutions. For example, the Microfibre Consortium [94] plays a key role in pulling together industry expertise, academia, and government to develop solutions.

At present, preliminary control guideline on MFs in wastewater has been released by TMC [95]. Thus, establishing a standard testing method and reporting is still a recognised priority; the newly published ISO 4484-2:2023 [82] can be a solution if both the industry and academia can widely adapt it in parallel. TMC aims to address the MFs issue for the wider industry, including both natural and synthetic sources, whereas the ISO 4484-2:2023 method only applies to microplastic fibres. Although there is a need to broaden the scope and understand their impacts, the industry should not lose sight of starting with microplastic fibres without delay. Ultimately, a consistent and standardised methodology is most essential, as the results will be reliable for estimating the abundance of MFs and identifying their mitigation pathways.

6.4. Better Product Design and Manufacturing Processes

Product design improvement is recommended through adopting critical parameters that substantially impact the MFs released during washing [96]. These parameters include a longer fibre length, higher yarn twist, coarser yarn count, higher fabric density, and fewer textile auxiliaries, which can reduce MF shedding. Transparent production parameters imply significant steps that must be taken during the design phase to create an impact. Concurrently, further support is necessary for decision-makers to motivate designers and manufacturers to materialise these parameters. It will be critical to enable the capability to measure the effectiveness of these parameters through unbiased testing.

The recommended specifications of the manufacturing processes are yet to be explored. Future studies can encompass an extensive scope for evaluating different production parameters, including the fibre type, fabric constructions, machine settings, chemical agents, and wastewater treatment technologies. These parameters are building blocks for standard implementations, making the improvements in performance scalable.

Shedding reduction may also be implemented by strengthening the cohesive bonds between fibres. However, the research in this area is insufficient, and the gathered data are inconclusive regarding its effectiveness. Alternatively, there are suggestions on the efficiency of pre-wash, air filtration, and exhaustion at sites [97]. However, as industrial facilities have more efficient controls over releases than domestic laundries, these proposals must be applied cautiously, and there must be appropriate disposals without transferring it from the aquatic environment to other means.

6.5. Technology Advancement

Advanced treatment technologies, such as the Membrane Bioreactor (MBR) and Zero Liquid Discharge (ZLD), are available in the industry to reduce water stress and MF pollution, which have proven to be effective in lowering MP discharge by 97% [27]. The MBR may be the most efficient method among the common wastewater treatment technologies to eliminate MFs from wastewater. However, the appropriateness of selecting technology that fits MFs requires further study as the efficiency depends on the material, morphology, size, and density of the input MPs [63]. Zhou et al. [21] suggested that dissolved air floatation (DAF) is preferred for separating MFs, as they are of comparatively lower densities than effluent. In addition, DAF can be a more economical option than reverse osmosis and ZLD. A disadvantage of advanced technology is the relatively high investment costs and, sometimes, the high energy demand, which may negatively impact climate change. This limits their use in industrial WWTPs. Moreover, membrane technology does not play a specific role in MF removal [98]. Therefore, a more affordable and effective means of keeping MFs out of the environment is needed.

Moving to more effective tertiary wastewater treatment or increasing recycled water within WWTPs may seem like a quicker fix for MF pollution. Industry transformation is hampered by a lack of knowledge and test methodology, an inability to include MF requirements in retail sourcing policies, and limited financial incentives for investment. MF pollution and wider sustainability issues will also be addressed as more sustainable technologies are available and green production becomes more prevalent. These benefits can be multiplied when combined to speed up investment decisions.

It is important to note, however, that advanced technology comes with a flip side, unless MF pollution is factored in. As ozone dyeing is a waterless process, it can contribute to cleaner production by eliminating the need to discharge wastewater containing MFs. It is possible that laser printing on fabrics may create more loose fibre fragments as a result of the cutting action on the fabric surface. While this is inconclusive without further research, it is crucial to consider total fibre fragmentation across the entire product life cycle when considering these solution options.

6.6. Robust Sludge Management

As WWTPs are the major source and sink of MFs, a higher retention rate using advanced treatment technology should considerably influence reducing the release of MFs as effluents to water pathways. However, proper sludge handling must occur in parallel to ensure that the problem is not being transferred from aquatic to terrestrial environments. Precautions are required to ensure that the higher concentrations of MFs in sludge do not pose a problem in terrestrial environments. It is expected that as the retention rate of WWTPs continues to improve, the MFs found in terrestrial environments have the potential to overshoot aquatic emissions. In that case, the concentration of MFs in sludge will increase and pollute the terrestrial ecosystem, and with airborne MFs, it was suggested it might overshoot aquatic [99].

Therefore, improving the technology in WWTPs is not a complete solution to stop MF pollution. In order not to transfer the issue to the soil ecosystem, a robust sludge management system must be established. Textile sludge using the incineration technique at 800 °C was reported by Iqbal et al. [100] as an effective method of removing heavy metals and reducing their volume. This temperature is much higher than the melting point of all fibres, so it should decompose all textile fibres. The ash can also be used for block preparation in the construction industry. This can completely prevent MF transfer to terrestrial.

6.7. Legislation and Policy

Although legislation is commonly known as the most powerful tool to accelerate investment and actions, achieving change in the systems without harmonised international action is impossible. Plastic policy will shift significantly when national and international measures are aligned and coordinated across value chains. Monitoring and reporting must be global to enable harmonised knowledge bases that can be used for taking informed action, measuring progress, and refining regulatory interventions. In practice, countries will approach market transformation differently, and the policy mix appropriate for a certain country will need to consider the trade-offs built into the policy options [101].

In particular, the EU has a Microplastics Proposal, a proposed legislative initiative under the REACH regulation to control the release of microplastics in the environment. If it is put in place, the legislation does not directly affect textile products because it only addresses the intentional use of microplastics. The release of microplastics refer to MPFs from textile products, mainly originating from the washing of synthetic textiles during production; garment wash and wear and end-of-life disposal are categorised as unintentional release, and thus fall out of the scope of this proposal [102]. Several countries have started putting legislative measures in place as forerunners. For example, France has introduced the French Decree 2022-748 AGEC (Anti-Waste for a Circular Economy Law), in which the regulation discourages synthetic fibres greater than 50% from using environmental claims. According to the EU strategy for sustainable and circular textiles, the European Commission intends to eliminate unintentional releases of microplastics from synthetic materials. The California Microfibre Pollution Bill—Assembly Bill No. 129 is another example of an attempt to start addressing the issue from a legislative perspective.

Above all, legislation normally takes a long time. In order to move faster, voluntary actions must be taken using a collaborative approach with various stakeholders. Similar to other initiatives, such as CanopyStyle in deforestation, the ZDHC Foundation in the elimination of hazardous chemicals and Textile Exchange in responsible material sourcing standards (such as recycled materials, responsible wool, etc.) have proven to be effective voluntary commitments to be taken and to drive significant impact where the textile industry can take the ownership of it. Stakeholders should start developing their own policies related to control and reduction in MF. At present, the TMC targets the reduction in the MF impact on the environment through a 2030 roadmap; hopefully, they can drive change before legislation is fully in place.

6.8. Responsible Consumption

In addition to the textile industry, several changes must also be made at the consumer level. A few of these include reducing consumption, extending garment life, and ensuring that they are disposed of properly to promote circularity. Consumers must be recognised as part of the solution. Reducing consumption and manufacturing would undoubtedly reduce MF release into the environment.

A significant challenge lies in changing consumer behaviour, multi-stakeholder efforts, and government policies simultaneously and systematically. The Ellen Macarthur Foundation [5] reports that less than 1% of clothing is recycled; therefore, slowing down overall resource consumption and supporting circularity with innovative business models would be a more sustainable approach.

7. Conclusions

The release of MFs from industrial wastewater treatment plants is as substantial as that from domestic laundry. According to the existing research, the impact of MF release from this source may even be more severe. This is because MFs in industrial effluents are more abundant in wastewater treatment plants, while some pathways, such as direct, are still understudied. Additionally, as a large volume is discharged daily into aquatic environments, the impact may be more significant than previously imagined.

Brodin et al. [83] emphasised that MFs shed from the initial wash are three times greater than those from subsequent washes of the same garment. The evidence strongly suggests that the creation of loose fibres occurs during production. Therefore, further opportunities exist to address this issue during the early stages before products are marketed and to prevent MFs from being dispersed into the environment. As more garments are made than there are sold and worn, we can estimate that the impact of industrial MF release could be much higher than previously predicted. Therefore, common sense dictates that addressing this issue upstream would be more effective.

Studies focusing on MF release during production are still in their infancy; many unanswered questions exist. Adopting a consistent protocol will allow for comparisons across studies, which are crucial when identifying areas of high impact. It is necessary to raise awareness and encourage industry and academia to conduct further investigations. The ability to measure MFs in WWTPs can support industry and regulatory bodies in defining the maximum threshold for the release of MFs, thus enabling the evaluation of mitigation measures and improving industrial wastewater treatment practices.

Once MFs can be quantified consistently, it will be feasible to implement control policies in the value chain. Subsequently, this will drive additional efforts to take further upstream remedial measures from designing and developing materials in fibre, yarn, or fabric form. In general, the most effective way of addressing any production issue is to fix it as early as possible before it is too late or too costly to fix later. Although the advancement in WWTP technologies can effectively stop MFs being released as effluents, it should still be considered equally important unless dry processes in production can replace these conventional wet processes. As we know, addressing MF pollution is a pressing issue; a systematic approach should be used to embrace alternative solutions which involve wider stakeholders; this will allow progress to be accelerated.

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