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Critical review of microfiber release from textiles: Results, comparative challenges, mitigation strategies, and legislative perspectives

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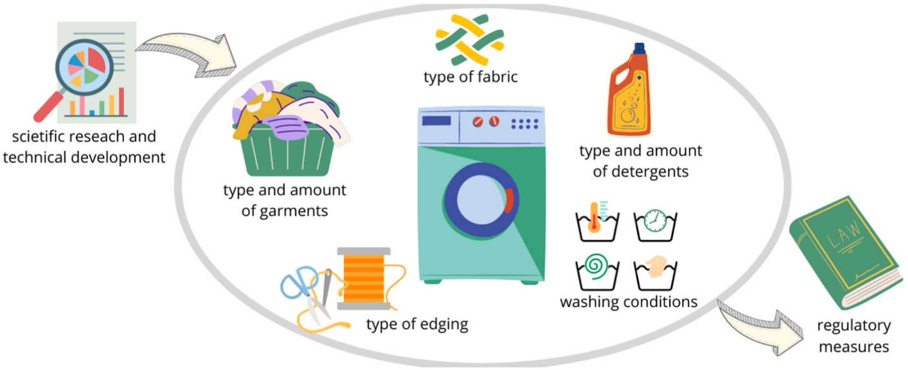
HIGHLIGHTS

- MFs release from synthetic laundry is a growing environmental concern.
- Inconsistent methods for measuring MFs release hinder data comparison across studies.
- Factors like washing machine type, program, and detergent affect MFs release.
- MF retention devices show promise, but efficiency is low and requires manual upkeep.

GRAPHICAL ABSTRACT



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ABSTRACT

The release of microfibers (MFs) from laundry has emerged as a significant environmental concern, drawing extensive attention from the scientific community. This review aims to provide a comprehensive overview of the current state of research on MFs release during washing, focusing on the factors influencing this phenomenon and the methods used to assess it. The results highlighted that, despite the proliferation of studies, a standardized protocol for measuring MFs release remains absent, leading to inconsistencies and challenges in data comparison. Direct and indirect methods have been used, both presenting different disadvantages that make the comparison quite challenging, with the first being more operator-dependent and likely giving lower magnitude value and the second being more prone to the error induced by the presence of other substances (like the detergent used during the washing). Moreover, the lack of a unified measurement unit further complicates cross-study comparisons. Factors such as the type of washing machine, washing program, detergent, and softener significantly impact the quantity of MFs released. While internal and external devices directly developed for MFs retention show promise in lowering the release, their current efficiency is low. Additionally, this review examines legislative efforts to address MFs' pollution, emphasizing the critical need for a thorough investigation within the scientific

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community. The results presented are intended to benefit both (i) the scientific community by identifying current gaps in the literature and offering guidance for future research, and (ii) technical stakeholders, such as washing machine manufacturers and developers of MFs mitigation systems, by providing insights into reducing microfiber release during laundry activities.

1. Introduction

Since 1950, plastic production has intensified every year due to its widespread and extensive use in nearly every aspect of life (Ahmed et al., 2021). Indeed, almost 400 million tons of plastic were produced worldwide in 2022 (PlasticsEurope, 2023). Plastics are ubiquitous pollutants, as they have been found even in the most remote areas of the world, from lakes to rivers, from the sea to the atmosphere (Browne et al., 2011). This pollutant can be categorized into macro-, meso-, and microplastics (MPs) depending on the size of the particles. Generally, MPs (ranging from 5 mm to 1 μm) are divided into primary MPs, which are directly produced at this size by industries (such as spheres in cosmetics and fibers in the textile industry), and secondary MPs, which originate from the degradation of larger plastic debris due to environmental factors such as photo-oxidation, wind, and water erosion (Wagner and Lambert, 2018; Young and Elliott, 2016; Browne et al., 2011). MPs represent a substantial problem due to their difficulty in being detected and removed from the environment. Among MPs, microfibers (MFs) represent a dominant fraction found in the environment, largely due to their release from textiles during domestic laundering (Acharya et al., 2021; Mathalon and Hill, 2014; Remy et al., 2015). While synthetic MFs, primarily derived from polyester (PES) and polyamide (PA), have been a focal point of concern, it is increasingly recognized that natural fibers (such as cotton and wool) also persist in ecosystems due to the treatments and dyes used in the textile processing (Acharya et al., 2021). MFs can enter the environment through different pathways: (i) directly, from washing machine effluent, particularly in regions where wastewater (WW) remains untreated, or (ii) indirectly, as they are small enough to bypass wastewater treatment plants (WWTPs) (Carnevale Miino et al., 2024). It has been estimated that a single laundry load can release thousands to millions of MFs in a single wash (Erdle et al., 2021). Indeed, the production and use of synthetic materials in the textile industry have been steadily increasing since 1950, rising from 2.1 million tons of fibers to over 87 million tons in 2022 (Statista, 2024). Given that synthetic fiber production has increased from 2.1 million tons in 1950 to over 87 million tons in 2022, accounting for approximately 65 % of global fiber production (Statista, 2024).

The scientific literature on plastic pollution has seen an exponential increase in publications in recent years. Numerous reviews have attempted to draw conclusions to outline new directions for future research. However, this has not yet occurred in the field of MFs, were the significant variations in the methodologies used to quantify the release during laundering hinders a precise understanding of the true environmental impact of MFs. These inconsistencies limit the ability to design effective mitigation strategies. Recent reviews on this topic have primarily focused on compiling results on various aspects without providing a clear and precise picture of the difficulties in comparing the currently available data (Allen et al., 2024; De Oliveira et al., 2023; Liu et al., 2023; Periyasamy, 2023; Sheikhi et al., 2024). Thus, this review aims to address these challenges by: (i) provide a comprehensive analysis of the experimental conditions and measurement techniques employed in studies assessing MFs release from washing machines; (ii) highlight the inconsistencies in current methodologies and their implications for understanding the real impact of microfiber pollution, and (iii) discuss ongoing legislative efforts to address this issue and emphasize the importance of standardization for future research and policy development. The lack of uniformity in measurement protocols directly impedes the ability to compare and consolidate findings, which in turn prevents the development of universally applicable mitigation strategies. Establishing consistent methodologies would not only improve the comparability of data across studies but also enhance the reliability of results, facilitating more informed decision-making by researchers, policymakers, and industry stakeholders.

By identifying gaps in current methodologies, this review intends to serve both the scientific community, outlining best practices and areas requiring further investigation, and technical stakeholders, including washing machine manufacturers and textile industries, who play a crucial role in mitigating MFs pollution.

2. Methodological approach of the review

2.1. Aims and literature search

This study aims to discuss four main aspects:

- What are the methodologies currently available for the detection and quantification of MFs release in laundry WW;
- How many MFs are produced during laundry activities and what are the factors that can influence their release;
- What are the main mitigation strategies that can be adopted to prevent the MFs' release into the water;
- What are the current regulatory measures for the prevention of MFs release and the installation of containment devices.

Given the aims of the work, the literature was searched using the keywords “microplastic*” AND “microfib*” were used in combination with “release" “washing machine", “laundry", “washing condition*", “removal", “filter" depending on the specific topic that was discussed. Scopus®, Google Scholar, and Web of Science® databases were used to select original articles, reviews, books, editorials and conference proceedings. Only studies investigating MFs release and written in English were selected. To focus the work on the most recent findings, documents published before 2011 were excluded. Additionally, grey literature has been considered to provide deeper insights into topics such as (i) the technologies currently available on the market for mitigating MFs release in the laundry sector, and (ii) the relevant legislative framework.

2.2. Meta analysis

A meta-analysis has been carried out to evaluate the impact of different washing conditions (spin speed, washing time, and temperature) on MFs release during laundry activities in washing machines. Data from other types of devices (e.g., Gyrowash and portable washer) has not been considered with the meta-analysis. Similarly, the use of detergents has not been investigated in the meta-analysis due to the limited amount of data available that could lead to misrepresenting the relation with the release of fibers.

MFs lost during laundry activities have been expressed as MFs/kg of textile washed. Considering that various units of measurement were used to express the MFs release in different studies, in the meta-analysis when MFs/wash was used, it was assumed that 4 kg of clothes were tested for each cycle. When other units of measurement were used (e.g. MFs/L), the studies were not considered in the meta-analysis. The studies found in the literature and selected for the meta-analysis are listed in Table S1. The data has been grouped according to the textile: cotton (CO), polyester (PES), and mixture (MIX). Only one study reported the results for acrylic and was excluded from the analysis.

To better understand the combined effect of washing time, spin speed and temperature on the release of MFs from different textiles, an influence factor (IF) has been also calculated as reported in Eq. (1):

$$IF\ (RPM*min*^{\circ}C) = T*SS*t \tag{1}$$

where T, SS, and t represent the temperature (in °C), the spin speed (in rotation per minute – RPM), and the duration of the washing (in min), respectively. Due to the very strict amount of data given by the limited number of studies and by the difficulties in comparing results about MFs released, given the different units of measure used in the previous studies, the meta-analysis has been limited to investigate the linear correlation between MFs and the different variables using Excel software (Microsoft Corporation, Redmond, WA, USA).

3. Detection and quantification of microfiber release

Although MFs are widely studied nowadays, there is currently no standardized protocol for their assessment. However, Fig. 1 illustrates the general steps of such studies: first, one or more fabric types are selected, followed by washing either in a conventional washing machine or with a Gyrowash, a laboratory-scale washing device. WW is then collected and filtered, often with a sieve or a vacuum pump. MFs are subsequently collected on a paper filter and examined under a microscope to assess their length, quantity, and other properties. Given the limitations of microscopic detection, spectroscopy (usually FTIR or Raman) is employed to verify whether the fibers originate from the selected fabric type or not.

The emission of MFs from washing machines is calculated using both direct and indirect methods. Direct methods involve counting MFs using a microscope, while indirect methods calculate the MF's weight to determine the release rate. Some studies employing indirect methods use the mean length of MFs to estimate the number of MFs released, although this is typically done on a limited number of samples. (Galvão et al., 2020). For example, Pirc et al. (2016) proposed a weight-based quantification method, wherein MFs are collected on filter paper and then weighed. Napper and Thompson (2016) also assessed the weight of the released MFs and used it to calculate the number of MFs released, based on the length, radius and density of MFs (Belzagui et al., 2019). However, these methods may not be entirely representative, as they also include the weight of other external contaminants (Rathinamoorthy and Raja Balasaraswathi, 2023). Anyway, both methods are strongly dependent on the researcher performing such procedure, but usually, direct methods report a lower order of magnitude (Galvão et al., 2020).

In the chemical identification of MFs, pyrolysis-gas chromatography spectrometry has been widely utilized, but it is an invasive technique that does not provide information on the shape or size of the particles (Schirinzi et al., 2019). Non-invasive techniques, such as optical microscopy, scanning electron microscopy (SEM) and fluorescence microscopy using Nile Red dye, have also been employed (Belzagui et al., 2019; Carney Almroth et al., 2018; De Falco et al., 2019; Napper and Thompson, 2016; Pirc et al., 2016; Yang et al., 2019; Zarfl, 2019). However, these methods do not offer information about the polymer composition, and false positives may occur with Nile Red, as this dye can bind to both lipids and synthetic polymers (Corami et al., 2020). The most commonly used technique nowadays involves performing microscope analysis, followed by analysis with FTIR (Fourier Transform Infrared Spectroscopy) or Raman spectroscopy, which allows the identification of polymer composition (Corami et al., 2020; De Falco et al., 2018; Napper and Thompson, 2016; Pirc et al., 2016). Typically, these techniques are employed to identify MPs, but they can also identify natural fibers such as cotton and rayon (Remy et al., 2015). Recently, Corami et al. (2020) used the micro-FTIR technique, in which optical microscopy is combined with spectroscopy, allowing for simultaneous quantification and identification. This method is non-destructive and therefore reproducible, but fiber counting is still manual and is only performed on a portion of the sample, risking either overestimation or underestimation of the actual number of MFs present in the sample.

The lack of standardized measurement techniques remains a major challenge in assessing MFs release from washing machines. Furthermore, different measurement approaches can lead to significant discrepancies in reported values, as direct counting methods often yield lower estimates compared to weight-based calculations, which may include external contaminants. The reliance on researcher-dependent techniques further exacerbates the issue, introducing subjectivity and reducing reproducibility.

Similarly, fiber identification methods vary in accuracy. While FTIR and Raman spectroscopy reliably characterize polymer composition, the need for manual fiber counting remains a major limitation, often leading to inaccurate quantification. Moreover, optical methods, though useful for morphology, cannot distinguish synthetic from natural fibers, potentially inflating synthetic MFs estimates. Utilization of micro-FTIR and micro-Raman improves precision by combining identification and quantification, but the lack of accurate automated recognition and counting programs reliable for fibrous objects remains a limitation.

4. Microfibers released in laundry wastewater

Focusing on the amount of MFs released in laundry WW, some authors have reported their results in terms of the number of MFs released (Table 1). Among them, some presented their findings as the number of MFs per wash, while other preferred to express them in relation to the mass of textile wash (gram o kilogram). Additionally, some studies reported their results as MFs per unit area of textile (square meter) or per volume of filtered water (liter).

Browne et al. (2011) conducted the first study investigating MFs release from domestic laundry, washing various polyester garments without detergent. They found that a single garment can release up to 1 900 MFs per wash. Sillanpää and Sainio (2017), examining polyester and cotton, reported much higher values (223 000 MFs/wash and 978 000 MFs/wash, respectively). Later, Carney Almroth et al. (2018) investigated releases from polyester, polyamide, and polyacrylic garments, reporting higher releases compared to other studies, with up to 110 000 MFs/(garment-wash) for polyester textiles and a lower release for the other two, around 900 MFs/(garment-wash). Additionally, De

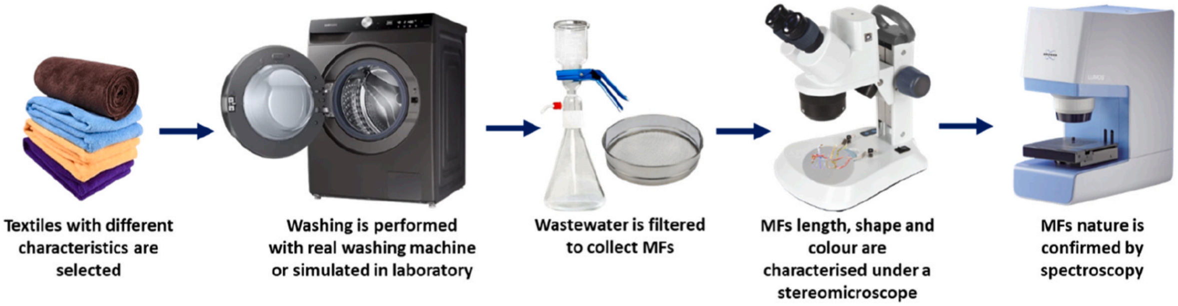


Fig. 1. General steps of the analysis of MFs generated by laundry.

Table 1
Literature results about MFs release in different washing conditions. *NM*: not mentioned; PES: *polyester;* PA: *polyamide;* PC: *polyacrylic;* CO: *cotton;* PAN: *polyacrylonitrile;* AC: *acetate;* TC: *tetron cotton;* LY: *lycra;* EA: *elastane;* MD: *modal;* NY: *nylon;* RY: *rayon.*

Reference	Device	Textile material	Temperature (°C)	Washing time (min)	Centrifugation (RPM)	Main results
Browne et al. (2011)	Washing machine	PES	40	NM	600	1900 MFs/wash
Hartline et al. (2016)	Washing machine	PES	29	24	1200	1174 mg/wash
Napper &Thompson (2016)	Washing machine	PES-CO, PES, PC	30–40	75	1400	PES-CO: 137,951 MFs/6 kg washing load PES: 496,030 MFs/6 kg washing load PC: 728,789 MFs/6 kg washing load
Pirc et al. (2016)	Washing machine	PES	30	15	600	11,300 MFs/500g of fabrics or 6 mg/500g of fabric
Sillanpää and Sainio (2017)	Washing machine	PES, CO	40	75	1200	PES: 223,000 MFs/wash or 340 mg/wash CO: 978,000 MFs/wash or 809 mg/wash
Carney Almroth et al. (2018)	Gyrowash	PES, NY, PC	60	30	NM	PES: 110,000 MFs/(garment-wash) NY: 900 MFs/(garment-wash) PC: 900 MFs/(garment-wash)
De Falco et al. (2018)	Gyrowash	Woven PES, knitted PES, woven PP	40–60	45–75 - 90	NM	Woven PES: 162–3538 MF/g of textile Knitted PES: 143–2907 MF/g of textile Woven PP: 226–1925 MF/g of textile
Belzagui et al. (2019)	Washing machine	PES-EA, PA-EA	Room temperature	15	100	PES-EA: 175 MFs/(g-wash) or 30 000 MFs/(m^2-wash) PA-EA: 560 MFs/(g- wash) or 465 000 MFs/(m^2-wash)
De Falco et al. (2019)	Washing machine	PES, PES-CO-MD	40	107	1200	PES: 640 000–1 100 000 MFs/(garment-wash) PES-CO-MD: 1 500 000 MFs/(garment-wash)
Kelly et al. (2019)	Washing machine; Gyrowash	PES	30–15	30 - 59 - 85	600 - 1600	Washing machine: 266 798 – 1 474 793 MF/kg or 37.35–206.49 mg/kg of textile Gyrowash: 370 317–855 884 MF/kg or 51.85–119.83 mg/kg of textile
Yang et al. (2019)	Washing machine	PA, AC, PES	30-40-60	15	NM	PA: 49 619 MFs/(m^2-wash) AC: 74 816 MFs/(m^2- wash) PES: NM
Zambrano et al. (2019)	Gyrowash	PES-CO, RY, CO, PES	25–44	16	NM	Cellulose-based fabric: 0.2–4 mg/g of textile PES fabric: 0.1–1 mg/g of textile
Dalla Fontana et al. (2020)	Washing machine	PES	40–30	90–3	1400-600	33.86–40.19 mg/kg of textile
De Falco et al. (2020)	Washing machine	PES-CO, PES	40	107	1200	PES-CO: 3898 MFs/(g-wash) PES: 709–1 747 MFs/(g-wash)
Choi et al. (2021)	Washing machine	PES	40	80	NM	51.6 mg/kg – 107.7 mg/kg of textile
Kärkkäinen and Sillanpää (2021)	Washing machine	PES, PA, PAN	40	75	1200	PES: 1.8×10^5 to 6.3×10^6 MF/kg of textile PA: 5.2×10^5 MF/kg of textile PAN: 1.0×10^5 MF/kg of textile
Periyasamy (2021)	Washing machine	PES, PES-CO PET-LY-CO	30-45-60	60-75-90	1200-1400	PES: 2 300 000–4 900 000 MF/kg of textile PET-CO: 620 000 MF/kg of textile PET-LY-CO: 560 000 MF/kg of textile
Dreillard et al. (2022)	Washing machine	PES, PES-PA, CO, PC	30	NM	1200	PES: 690 000–1 570 000 MF/kg of textile PES-PA: NM PC: 1 390 000 MF/kg of textile CO: NM
Mahbub and Shams (2022)	Portable washer	PAN	20–40	30-45-60	NM	60.22–162.49 mg/kg of textile
Julapong et al. (2024)	Washing machine	PES, TC, chief value CO, CO	NM	28	NM	PES: 2 382 MF/L TC: 2 844 MF/L Chief value CO: 4 022 MF/L CO: 2 279 MF/L

Falco et al. (2019), studying MFs release from polyester and polyester-cotton-modal blend, showed a release of 640 000 to 1 100 000 MFs/(garment-wash) for the former and 1 500 000 MFs/(garment-wash) for the latter.

Pirc et al. (2016), instead, revealed a MFs release of 11 300 MFs/500 g of fabric. De Falco et al. (2018), using lab-scale devices, tested woven polyester, knitted polyester and woven polypropylene and found up to 3 538 MF/g of textile, 2 907 MF/g of textile and 1 925 MF/g textile respectively. This study also estimated a real release, with conventional washing machine, of 17 million MFs/5 kg of washing load. Conversely, Belzagui et al. (2019) examined MFs release from polyester-elastane blend and polyamide-elastane blend. The study showed a release of 175 MFs/(g-wash) for polyester-elastane blend and 560 MFs/(g-wash) for polyamide-elastane blend. Later, De Falco et al. (2020) observed a release of 3898 MFs/(g-wash) for polyester-cotton blend and up to 1747 MFs/(g-wash) for 100 % polyester. Kelly et al. (2019) investigated various washing programs using polyester textiles and texting different devices. This study demonstrated that, using a Gyrowash, MFs release is lower (from 370 317 to 855 884 MF/kg of fabric) than when using a real washing machine (from 266 798 to 1 474 793 MF/kg). Periyasamy (2021) reported significantly higher values, exceeding 4 million MFs/kg of washing load. Similarly, Dreillard et al. (2022) observed a release of almost 3 million MFs/kg of textile. Kärkkäinen and Sillanpää (2021) documented an even greater release rate, reaching up to 6.3×10^6 MF/kg. Napper and Thompson (2016) examined the release from different textiles (polyester-cotton blend, polyester and polyacrylic), revealing that polyacrylic textiles can shed up to 728 000 MFs/6 kg wash load, while the polyester-cotton blend and polyester textiles showed a lower release (respectively 137 951 MFs/6 kg and 496 030 MFs/6 kg wash load). Yang et al. (2019), instead, reported a release of 74 816 MFs/(m^2-wash) for acetate and 49 619 MFs/(m^2-wash) for polyamide.

Finally, Julapong et al. (2024) analysed different types of textiles (polyester, tetron cotton, chief value cotton, cotton) and found that chief value cotton released the highest number of MFs (4 022 MF/L of water), followed by tetron cotton (2 844 MF/L of water), PES (2 382 MF/L of water), and cotton (2 279 MF/L of water).

On the other hand, some authors presented their results in terms of the weight of MFs. For example, Hartline et al. (2016) reported an average loss of 1174 mg of MFs/wash. Zambrano et al. (2019) obtained up to 4 mg of MFs/g of cellulose-based fabric (Rayon, cotton, PES-cotton blend textile) and 1 mg of MFs/g of PES fabric. Dalla Fontana et al. (2020) documented a release of up to 40.19 mg/kg of PES textile washed, while Choi et al. (2021) reported a maximum release of 107.7 mg/kg of PES textile. Lastly, Mahbub and Shams (2022) reported a release of polyacrylonitrile (PAN) fabric of up to 60.22 mg/kg when washed without detergent.

Some authors expressed their results in more than one unit measurement. For example, Pirc et al. (2016) showed that the release of 11 300 MFs/500 g of fabric correspond to 6 mg/500 g and Sillanpää and Sainio (2017) reported 340 mg/wash for polyester and 809 mg/wash for cotton corresponding to 223 000 MFs/wash and 978 000 MFs/wash, respectively.

The quantification of MFs release from textiles is, indeed, highly heterogeneous in terms of unit measurements. The absence of a standardized protocol has resulted in the adoption of different methodologies and analytical techniques, each chosen based on the specific objectives of the study.

As a matter of fact, differences in measurement units express distinct aspects of MFs release. For example, MFs/wash and MFs/L of water quantify the total MFs release into the environment, making them useful to estimate environmental impact. In contrast, expressing MFs release per mass of textile (MFs/g or MFs/kg) allows to assess the shedding efficiency of different fabrics. Similarly, measuring MFs loss per unit area (MFs/m^2) helps determine the influence of textile structure. Using mass-based units (g of MFs/wash or g of MFs/kg of textile) is, instead, relevant to estimate both total emissions and potential environmental damage. Also, different analytical techniques are employed to quantify MFs. Optical microscopy or SEM allow direct fiber counting and morphological characterization (i.e. fiber length and diameter), while gravimetric methods (precision balance measurement) only assess the total mass of released MFs. However, converting between these units is not that simple. The transition from count-based to mass-based units, as a matter of fact, requires knowledges about fiber dimension and density (based on the textile material).

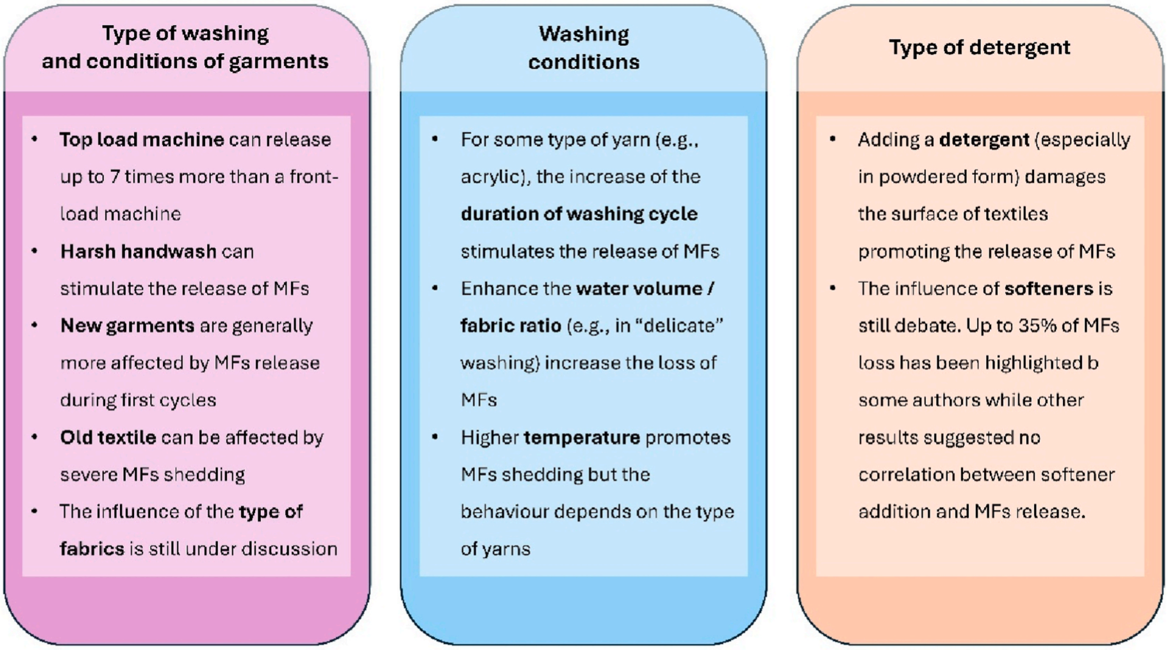
For these reasons, researcher should be encouraged to adopt common units of measurement and, where possible, align their results with the most widely used units across studies. Moreover, the development of reliable conversion factors between the different measurement, for example, through morphometric MFs analysis, could enable more accurate and consistent comparisons and the creation of shared databases from different laboratories using standardized methodologies could improve comparability across studies.

5. Factors influencing microfiber release

Different factors can influence the amount and length of MFs released from washing machine (Fig. 2), such as the (i) the type of washing (front-load or up-load washing machines, handwash) and conditions of garments (new or previously used), (ii) washing conditions (water volume, duration, temperature and centrifugation), and (iii) the use of different types of detergent (liquid, powder) and softener.

5.1. Type of washing and conditions of garments

Top and front-load machines work differently, under diverse agitation levels (Sudheshna et al., 2022). According to the literature, top-load machines can release around 10 % more MFs than front-load ones (De Falco et al., 2018). Hartline et al. (2016) showed that a top-load machine can release up to 7 times more MFs than a front-load machine. Comparing washing machines with handwashing, Rathinamoorthy and Raja Balasaraswathi (2022) highlighted that there is no significant difference since they both shed a similar number of MFs. However, a harsh handwash can release a significantly higher amount of MFs compared to machine washing (Rathinamoorthy and Raja Balasaraswathi, 2022).



Type of washing and conditions of garments

- **Top load machine** can release up to 7 times more than a front-load machine
- **Harsh handwash** can stimulate the release of MFs
- **New garments** are generally more affected by MFs release during first cycles
- **Old textile** can be affected by severe MFs shedding
- The influence of the **type of fabrics** is still under discussion

Washing conditions

- For some type of yarn (e.g., acrylic), the increase of the **duration of washing cycle** stimulates the release of MFs
- Enhance the **water volume / fabric ratio** (e.g., in “delicate” washing) increase the loss of MFs
- Higher **temperature** promotes MFs shedding but the behaviour depends on the type of yarns

Type of detergent

- Adding a **detergent** (especially in powdered form) damages the surface of textiles promoting the release of MFs
- The influence of **softeners** is still debate. Up to 35% of MFs loss has been highlighted b some authors while other results suggested no correlation between softener addition and MFs release.

Fig. 2. Summary the different factors that can influence the amount and length of MFs released from washing machines.

Garments can be affected differently by wash cycles but generally, the release of MFs stabilizes during consecutive washing (Pirc et al., 2016). New garments shed more MFs during the first washing due to the presence of residues from the fabric production process (Belzagui et al., 2019; Dalla Fontana et al., 2021; De Falco et al., 2019; Le et al., 2022). Usually, after the first wash cycles, a steady state is reached but the number of washes necessary to reach this condition can vary depending on the type of yarn (Le et al., 2022; Mahbub and Shams, 2022). However, contradictory results have been presented on this aspect, as Hartline et al. (2016) found that old textiles are generally more affected by MFs shedding. Some types of fabrics are more susceptible to microfiber loss, such as PES than PAN (Kärkkäinen and Sillanpää, 2021). Some studies have highlighted that the shape and type of product can influence the release of MFs during washing. For example, Browne et al. (2011) studied 3 different PES textiles (blankets, fleeces and shirts) and highlighted that fleeces release up to 180 % more MFs than the other fabrics. Furthermore, also the type of thread used and edges can explain differences in the release, with increases that can go up to 43 % and mask other contributions from other textile parameters, as underlined by Dalla Fontana et al. (2021). However, the importance of the type of fabric is still under debate since also other authors have found a lower influence on MFs release (Belzagui et al., 2019).

5.2. Washing conditions

The conditions in which the washing of textiles is carried out can influence the release of MFs. Some studies seem to highlight that the longer the duration of the cleaning cycle, the higher the release of fibers. Mahbub and Shams (2022) pointed out that increasing the duration of washing PAN textiles from 30 min to 60 min led to more than doubling the release of MFs (from 60 mg/kg to 132 mg/kg). These findings seem to be corroborated by the results of the meta-analysis that highlighted a positive linear correlation for natural fibres like cotton ($R^2 = 0.515$) but also for polyester ($R^2 = 0.446$) and mixture of them ($R^2 = 0.516$) (Fig. 3a). However, to define a solid correlation a bigger set of data (which means a higher number of tests) should be available. In fact, the literature is quite conflicting on this aspect and the reason seems to be the behaviour of different types of yarn in releasing MFs depending on the duration of the cycle. For instance, Hernandez et al. (2017) tested knitted PES and increased the wash duration from 1 h to 8 h but no statistical difference has been highlighted in terms of the mass of MFs released during laundry.

Some studies highlighted a direct influence of the spin speed on the loss of MFs from textiles (Periyasamy, 2021). At first glance, the increase in spin speed would appear responsible for a greater quantity of MFs released into the wash water (Fig. 3b). However, recent findings related the enhancement of the shedding mainly to the increase in water volume/fabric ratio rather than spin speed. In delicate water cycles, which

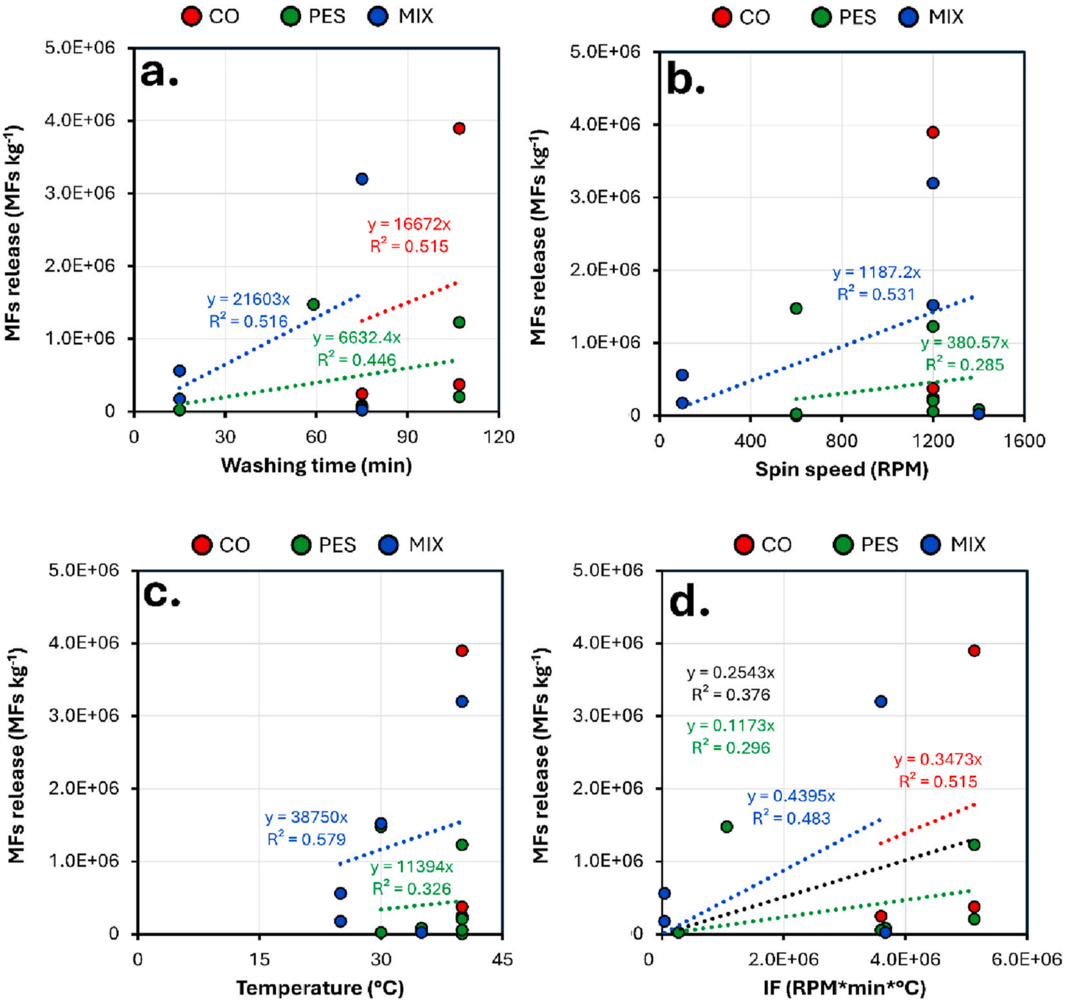


Fig. 3. The release of MFs as a function of (**a**) washing time, (**b**) spin speed, (**c**) temperature, and (d) IF. Black dotted line represents the fitting of data related to all types of MFs. In case of spin speed and temperature, the linear correlation of cotton has not been calculated due to the limited amount of available data. CO: cotton; PES: polyester; MIX: mix of textiles; IF: influence factor.

often use more than twice the amount of water than standard washing, this ratio is very high with a consequent huge loss of MFs. For this reason, ensuring a full-load wash and avoiding delicate wash conditions could be reasonable for limiting MFs release (Kelly et al., 2019). However, as suggested by the meta-analysis, the behaviour could be also dependant by the type of yarns, and this could explain why the linear correlation better explain the data related to mixture of textile ($R^2 = 0.531$) with respect to polyester ($R^2 = 0.285$).

Also, the temperature of the water during the wash can influence the amount of MFs lost from the textiles. Some studies seem to highlight that the higher the temperature, the higher the amount of MFs released. Washing at high temperatures can affect fabric geometry by promoting the expansion of yarns and loosening the bonds between fibers, creating spaces where broken MFs are easily released (Hernandez et al., 2017). For instance, Mahbub and Shams (2022), found that by enhancing the temperature from 20 to 40 °C, the MFs released were 1.8 times higher. Similar results were also reported by De Falco et al. (2018), Hartline et al. (2016), Napper and Thompson (2016), and Pirc et al. (2016). Generally, washing clothes at a low temperature could reduce MFs emissions by up to 50 % (Cotton et al., 2020). However, the behaviour of different yarns is not always the same. For instance, acetate and PES fabrics seem to be more susceptible than PA fabrics (Yang et al., 2019). Generally, this difference is significant when comparing washing conditions at low (20–30 °C) and high temperatures (60 °C). However, in the case of cotton-made fabrics, even washing at 40 °C can cause a significant increase in MFs released into the water (Zambrano et al., 2019).

The meta-analysis of data from previous studies highlighted a positive linear correlation for synthetic fibres (polyester, $R^2 = 0.328$) and mixture of synthetic and natural ones ($R^2 = 0.579$). As for the other variables a bigger set of data can help to define a more solid correlation of temperature with the loss of MFs (Fig. 3c). Moreover, it should be considered that multiple factors (e.g. washing conditions, presence of detergents, type of fabric) on MFs release in washing waters make challenging to compare data obtained in different studies. For this reason, in order to estimate the combined influence of washing time, spin speed and temperature, on MFs released, IF have been evaluated. Considering that a positive linear correlation with the fibres lost seems to have been found for all variables, the aim was to confirm this result studying a fictional IF that took into account all the variables together. The results suggested a positive linear correlation for cotton ($R^2 = 0.515$), polyester ($R^2 = 0.296$) and mixture of textile ($R^2 = 0.483$) and also considering all data not depending by the type of yarn ($R^2 = 0.376$) (Fig. 3d). These results demonstrated that washing time, spin speed, and temperature could play a key role in the release of MFs during washing and fabrics. However, this analysis represents only a first step in the evaluation of the influence of washing conditions on the released MFs, since the data set available in the literature and comparable with each other is still too limited for more in-depth evaluations and more robust results. For this reason, more comprehensive data on MFs released during washing of synthetic and non-synthetic fabrics are necessary before defining in detail the real influence of each of the washing conditions. When the results of further tests will be available, further analyses (e.g. non-linear model) could be carried out evaluating also the influence of other variables such as the volume of washing water and the amount of detergent used.

5.3. *Types of detergent*

The addition of detergent during the wash cycle seems to promote the release of MFs (Mahbub and Shams, 2022). The presence of substances such as zeolite and silica decreases the surface tension, damaging fibres, and encouraging fibre loss (Carney Almroth et al., 2018; Dalla Fontana et al., 2020; De Falco et al., 2019). Moreover, the high alkaline conditions ($pH > 9$) could damage the structure of fabrics through hydrolysis, accelerating the release of MFs (Bishop, 1995). This phenomenon is particularly evident in the case of synthetic textiles due to the hydrophobic properties of these plastic fibres that favour the degradation due to the attachment of organic surfactants (Julapong et al., 2024). Not all detergents have the same effect on fabrics. For instance, comparing liquid detergents and powder detergents, the latter determines a higher release of MFs probably due to the presence of zeolite that might cause friction on the textile surfaces but also because of other insoluble particles that increase the abrasion of the fabrics (De Falco et al., 2018; Le et al., 2022). The lower loss of MFs using liquid detergents instead of powder ones has also been highlighted by Issac and Kandasubramanian (2021) and Periyasamy (2021).

However, the results on this aspect are still conflicting. For instance, Pirc et al. (2016) highlighted that the impact of detergent on the loss of fibres is relatively negligible, while Hernandez et al. (2017) showed that the difference in using powder or liquid detergent in increasing the dose of detergent is not significant. Volgare et al. (2021) tested different types of liquid detergents and found that the type and the quantity of these substances were not responsible for an increase in the release of MFs during the wash cycles. Some authors also focused on the effect of the addition of softener with contrasting results. For instance, De Falco et al. (2018) highlighted that up to 35 % of MFs loss can be prevented using softeners. On the contrary, Rathinamoorthy and Raja Balasaraswathi (2022) pointed out that adding 0.5 g/L and 2.5 g/L of detergent induces a reduction of shedding up to 77.6 % and 72.5 %, but the correlation between softener concentration and the reduction is weak.

6. Mitigation of microfiber release

Two different approaches can be followed for removing MFs released during domestic laundry activities: (i) the use of an internal device to prevent microplastics from leaving the drum or (ii) the use of an external device that collects MFs released preventing their dispersion into the sewer system (Fig. 4).

6.1. *Internal devices*

Several examples of internal devices are presented in the literature. For instance, Cora Ball® is the result of the nonprofit Rozalia Project (CORA, 2024). It consists of a plastic ball with many small protruding “structures” that help capture MFs released during laundry washing. Napper et al. (2020) studied the effectiveness of this device by testing three different synthetic fabrics (100 % PES, 100 % PAN, and 60 % PES + 40 % cotton) to simulate a common washing machine load. Their results highlighted that Cora Ball® can remove up to 31 % of MFs released in the drum during laundry activities. In another study, McIlwraith et al. (2019) studied the efficiency of Cora Ball® in trapping synthetic MFs released during the washing of a 100 % PES fleece blanket. They showed that the device reduced the content of MFs by almost 26 % but only a 5 % reduction has been evidenced considering the weight of fibres.

Kärkkäinen and Sillanpää (2021) tested the release of PES MFs from five different types of textiles and the consequent removal by Cora Ball®. They found that only 10 % of MFs were captured and they suggested that the effectiveness of this device could depend on the dimension of the fibres: a higher length of MFs reflects in a higher trapping efficiency of Cora Ball® (Kärkkäinen and Sillanpää, 2021). Despite this type of device does not require to be cleaned after every wash, this operation could be difficult, and it is also reported by the same Founders that this type of device should be avoided in the case of delicate clothes due to possible damage (CORA, 2024; Napper et al., 2020; Ramasamy and Subramanian, 2021).

On the market, there are also other devices for preventing MFs release that can be categorized as laundry bags. For instance, the GUPPYFRIEND® Washing Bag is one of them and as reported by the Producers, it consists of a bag made of monofilaments in PES that helps to prevent the loss of MFs at the source, protecting the fabrics during

Fig. 4. Type of devices suitable for MFs retention currently available in the market.

washing treatment (GUPPYFRIEND, 2024). Napper et al. (2020) found that, among those studied, this was the most effective internal device that allowed to reduce the shedding of MFs from the textiles during the washing cycle by almost 54 %.

A similar bag is produced by Fourth Element with a similar concept and specifically designed for Fourth Element clothes. In this case, probably due to the different pore sizes, lower effectiveness has been reported (almost 21 %) (Napper et al., 2020).

In general, the main disadvantages of laundry bags are: (i) the potential shedding and release of MFs considering they are mainly in plastic, and (ii) in dryers, the uncontrolled release of trapped MFs (Ramasamy and Subramanian, 2021). It should be specified that none of these devices can be considered resolutive for tackling MFs release during domestic laundry activities, given the low effectiveness in trapping low-length fibres (Le et al., 2022).

6.2. *External devices*

External devices consist of filters located outside the drum of the washing machine that separate MFs from the water flux before their release into the sewer system. It must be specified that this approach is not helpful in preventing MFs release from the textiles in the drum, as with the laundry bag, but it acts on the fibres already released during the washing cycles.

Several filtration systems have already been tested and different products are available on the market. For instance, PlanetCare® consists of a washing machine filter equipped with reusable cartridges that can be replaced once they are full of MFs and sent back to the company for a complete refurbishment (PlanetCare, 2024). De Falco et al. (2021) evaluated two different prototypes of the PlanetCare® filter in order to optimize its performance. Textiles made by 100 % PES has been used as source of MFs during washing cycles. Their results highlighted that, in optimal conditions, the filter was able to remove more than 60 % of PES fibres (De Falco et al., 2021). Napper et al. (2020) tested the PlanetCare® filter for limiting the release of MFs produced during the washing of a common load of clothes, highlighting that 5–45 % of these MFs were trapped.

Filtrol® is another example in which the water flows into a 100 μm PES filter bag located outside the washing machine. After 8–10 washing cycles, the filters should be cleaned and MFs disposed of as urban solid waste (Filtrol, 2024). Le et al. (2022) reported that the performance of this device was higher than 85 %; however no further studies have been found in the literature with this same technology.

The LINT LUV-R filter (pore size: 150 μm) is designed to be placed outside the washing machine in a similar way to the other filters and needs to be periodically cleaned (every 2 to 3 loads of laundry) to remove the trapped MPs. The producer said the action of the filter is dynamic, becoming more efficient as it traps fibres (Environmental Enhancements, 2024). The device seemed to be effective in removing the 87 % of MFs larger than 100 μm from water by count (McIlwraith et al., 2019). Lower efficiency has been found by Napper et al. (2020) (14–44 %) probably because smaller MFs (size 1–100 μm) were also considered. However, it has been estimated that the release of 20–31 trillion of MFs each year can be prevented if all households in Toronto adopt this type of device (McIlwraith et al., 2019).

XFiltra® is a filter designed to be integrated directly into washing machines during the manufacturing process. Two different versions are currently available, covering both domestic and industrial machines (Xeros, 2024). Results suggested that the performance of this filter can vary from 78 % to more than 90 % (Napper et al., 2020; Ramasamy and Subramanian, 2021). Based on literature, the effectiveness of this device is high, probably due to the smaller size of the pores (60 μm) and the presence of a centrifugal separator to facilitate the flow of the water through the filter (Napper et al., 2020).

Other non-commercial filters have been tested for MFs in water discharged from washing machines. For instance, Sheraz et al. (2024) developed a “barbed” filter made of PET monofilaments to effectively capture PE MFs. Based on their results, up to 91 % of MFs larger than 100 μm were retained by the filtration unit (Sheraz et al., 2024). Choi et al. (2023) developed and tested a Janus branch filter (JBF) specifically for washing machines, consisting of two components: a hydrophilic filter and a hydrophobic filter. First of all, silicone oil is added to the WW coming out of the washing machine. This causes hydrophobic MPs and surfactants to migrate into the oily phase, separating the solution into two distinct phases: one composed of silicone oil and the other of water, which contains instead hydrophilic MPs and surfactants. Next, the water layer passes through the hydrophilic filter membrane, which captures hydrophilic MPs and surfactants. Similarly, the oily phase passes through the hydrophobic filter, which retains hydrophobic MPs and surfactants. This technique has a high recovery rate, with 99.7 % and 78.2 % of hydrophobic and hydrophilic MPs, respectively, effectively separated from WW.

Internal devices show a lower retention rate of MFs (ranging from 10 % for the Cora Ball® to 54 % for the GUPPYFRIEND® washing bag) compared to external devices (from 5 to 45 % for the PlanetCare® filter up to 90 % for XFiltra®). This difference could be due to their diverse positions and mechanisms. MFs released during washing are dispersed into the water, and internal devices passively collect them, while external filters actively force water through their filtration systems, ensuring direct contact. Additionally, design differences may influence their effectiveness. For instance, external filters often have finer mesh sizes capable of trapping smaller MFs, whereas devices like the Cora Ball® are only capable of capturing longer fibers. Anyway, despite their lower efficiency, internal devices are easy to use, cost-effective and require no installation, while external devices are more complex to install, typically more expensive and often require more difficult maintenance.

However, comparing these devices remains challenging due to variability in the studies, which use different textiles and washing conditions. Both types of devices are less effective at retaining smaller MFs, which poses an environmental concern since these fibers are harder to remove and more likely to persist in the environment. A combined use of internal and external devices may be a more effective strategy to minimize MFs release during domestic laundry, but these systems must be improved in terms of both performance and ease of use to ensure widespread adoption.

7. Regulatory measures for microfiber release containment

Since the problem of MFs release came to public attention, several initiatives have emerged to limit its extent. However, unlike the situation with microbeads intentionally added to personal care products (that have been strictly banned in European countries under the EU Regulation, 2023/2025 and in the United States under the Microbead-Free Waters Act of 2015), legislative interventions for MFs are still significantly less impactful and heterogeneous depending on the country.

However, some efforts have been made by governments, organizations, and companies. In March 2022, the European Union released the “EU Strategy for Sustainable and Circular Textiles," aiming to create a greener textile sector. This document states that “fast fashion is out of fashion" and that every textile placed on the EU market must be durable, repairable, and recyclable (EU Strategy for Sustainable and Circular Textiles, 2022). In California, since 2020, all clothing made of fabric containing more than 50 % polyester are mandatory marked with a label that warns of plastic MFs shedding during regular washing (California Assembly Bill 2379, 2017–2018). Furthermore, from 2029, all new washing machines sold or offered for sale in California will contain a microfiber filtration system with a mesh size not greater than 100 μm, as stated in a bill recently approved (California Assembly Bill 1628, 2023–2024). Similarly, France has decided to require the installation of MP filters in washing machines starting in 2025, introduced through an amendment to Article 79 of Law No. 2020-105 of February 10, 2020, relating to the fight against waste and the circular economy. These steps are crucial as they promote a paradigm shift in managing MFs, shifting from the approach of removing these pollutants at WWTPs to encouraging their retention at the source, before their release into the sewer system.

Progress is also being made in the standardization of quantification methods. A standardized test for measuring fiber loss from textiles during simulated domestic laundering was developed in 2021 through a collaboration between the University of Leeds, the European Outdoor Group, and The Microfibre Consortium. The TMC Test TMC Method (2025) is based on ISO 105-C06 and employs standardized laboratory equipment to ensure comparability across different textile manufacturers and research institutions. This allows for globally consistent results, supporting industry-wide sustainability initiatives. Additionally, the American Association of Textile Chemists and Colorists (AATCC) introduced the TM212-2021 test method to assess fiber shedding from fabrics during laundering, further contributing to the standardization of microfiber emission analysis. More recently, in 2023, the International Organization for Standardization (ISO) introduced three complementary methods: UNI EN ISO 4484–1:2023, which provides a systematic approach for collecting material losses from textiles under washing conditions; ISO 4484–2:2023, which establishes guidelines for reducing microplastic fiber release from textile products; and ISO 4484–3:2023, which focuses on measuring fiber fragmentation during laundering. These efforts mark significant progress in developing reliable and standardized methodologies for assessing and mitigating microfiber pollution.

Another initiative involves textile manufacturers investing in the development of fabrics that shed fewer microfibers through tighter weaves and advanced finishing techniques. Similarly, significant efforts are being directed toward creating filtration systems that combine high efficiency with ease of management. This goal is shared not only by washing machine manufacturers, as discussed in the referenced literature, but also across numerous experimental projects. Researchers are making significant strides in developing biodegradable materials suitable for their use in the textile industry and in finding natural fibers that inherently shed fewer MFs. Additionally, advanced fabric treatments and innovative coatings are being engineered to further minimize shedding, representing a critical frontier in reducing MFs pollution at the source. Additionally, certifications such as those from the OEKO-TEX® Association now include criteria aimed at reducing MFs release, setting industry benchmarks for environmental sustainability.

Overall, while progress has been made in understanding and mitigating MFs pollution, challenges remain in implementing comprehensive and globally harmonized solutions. The combination of legislative actions, industry-driven innovations, and standardized testing methods represents a crucial step forward. However, further efforts should also focus on consumer awareness and behavioral changes, as well as fostering international collaboration to establish consistent regulatory frameworks. By integrating scientific advancements with policy measures and sustainable textile production, it will be possible to create a more effective strategy to minimize MFs release and its ecological consequences.

8. Conclusions and future perspectives

Although the release of MFs is widely studied, significant gaps remain in our understanding of their generation, measurement and mitigation. One major challenge is the lack of a standardised protocol for assessing MFs release, which limits comparability across studies and impedes the development of regulatory guidelines. Current methods are divided into direct methods (counting MFs under a microscope) and indirect ones (estimating MFs weight) each with critical limitations. Indirect methods are more prone to errors due to the inclusion of external contaminants, while direct methods are more dependent on the operator and often report lower magnitudes than indirect methods. Additionally, there is no standardized unit of measurement for assessing MFs release, with some studies expressing MFs per mass of garment or wash, others per volume of water used, or per fabric surface area.

Further complicating the issue, there is no consensus on the primary factors influencing MFs shredding. While washing machine type, cycle parameters, and the type of detergent and softener used are acknowledge as key contributors, results vary significantly. Some studies highlight that top-load washing machines tend to release more MFs compared to front-load machines, possibly due to the higher agitation levels. However, the impact of washing conditions, such as water temperature or detergent type, remains more contested. Some studies suggest that higher wash temperatures lead to increased microfiber shedding due to the weakening of fabric bonds, while others find no clear correlation. This variability suggests that the relationship between washing conditions and microfiber release may depend on the type of fabric, which is a critical area for future research. The meta-analysis seems to confirm this outcome for washing time, spin speed, and temperature but the data set available in literature is too limited for solid results. Further tests in standardized conditions should be carried out in order to increase the data set, evaluate also the influence of the volume of washing water and the amount of detergent used, and carry out further analyses (e.g. non-linear model). The limited availability of large-scale, standardized datasets prevents the development of robust, predictive models, further hindering our ability to derive clear recommendations.

The efficacy of MFs retention device also remains an open question. While internal and external filtration systems have been proposed, their efficiency is still low, and their cost-effectiveness and long-term maintenance requirements are often overlooked. Further research is essential to optimize these technologies, ensuring they are both practical and scalable.

To address these critical gaps, future studies should focus on (i) standardization of MFs measurement protocols, to establish unified methodologies for quantifying MFs release, including agreed-upon measurement units, improved contamination controls, and standardized test conditions; (ii) long-term and real-world testing, with the investigation on how aged garments and repeated washing cycles impact MFs shedding, as most current studies rely on new fabrics and a limited number of washes; (iii) developing more effective retention systems, enhancing the efficiency, affordability, and scalability of MFs filtration and capture technologies to ensure wider adoption; (iv) investigating environmental and policy implications of all human-made MFs, to assess also the impact of natural and regenerated fibers, which may carry harmful chemical treatments; and (v) strengthening legislative efforts, promoting the implementation of globally consistent regulations that encourage industry accountability, enforce sustainable production practices, and mandate the adoption of effective mitigation strategies.

The lack of standardization and inconsistencies across studies remain key obstacles to progress in understanding and mitigating MFs pollution. Without a unified approach, scientific findings risk being fragmented and impractical for policy implementation. Addressing these gaps will be essential for translating research into tangible environmental and regulatory actions, ensuring that both industry and consumers can contribute to meaningful solutions.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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