

Updated Literature Review on Microplastics from Household Washing Machines (2020-2024)

Purpose and Objectives: The literature review, conducted by RISE Research Institutes of Sweden, aims to update previous research (2020) on microplastic emissions from textile laundry, with a focus on microfibre release from polyester fabrics in household washing machines. It covers studies from 2020 to 2024 to evaluate trends in microplastic emissions, particularly from polyester garments, which are widely studied due to their prevalence.

In recent years, concerns over microplastic pollution have intensified, particularly with respect to microfibres released during household laundry. To address this issue, APPLiA asked [RISE Research Institutes of Sweden](#) to conduct an updated literature review covering research from 2020 to 2024, focusing on the release of microplastics, specifically from polyester garments, during washing cycles in domestic washing machines.

This review builds upon [previous work completed in 2020](#), and aims to assess the most recent data on microplastic emissions from textiles. Polyester, a common synthetic fibre, is a key focus due to its widespread use in clothing and is also at the centre of research literature. The report meticulously screened 55 studies, but only **three met the strict criteria required for comparison**. These criteria included washing polyester garments at least five times in European domestic washing machines and presenting fibre release data in mg/kg. They ensure that the research is relevant to practice.

The findings highlighted the variability in microfibre emissions. The release of fibres ranged from 6.5 to 55 mg/kg for new fabrics washed up to five times, while emissions from older garments, some in use for up to 15 years, spanned a much broader range, from 0 to 366 mg/kg. This is consistent with earlier findings, which reported fibre releases of 20 to 500 mg/kg.

One key insight from the review is that fibre release tends to stabilise after several washes. In one of the reviewed studies, fibre emissions plateaued after around eight washes, suggesting that once a certain level of wear is reached, the rate of microfibre release becomes relatively constant. This plateau effect was observed in studies using both new and older garments, indicating that initial washes may produce the most substantial fibre loss.

However, despite the useful data collected, comparing these studies was not straightforward due to differing methodologies. For instance, the pore sizes of the filters used to capture microfibres varied widely across studies—from as fine as 1 µm to as large as 40 µm. Smaller pore sizes naturally captured more fibres, while larger ones allowed



smaller fragments to escape. This inconsistency complicates attempts to directly compare results, and highlights the need for standardization in the way microplastic emissions are measured.

Moreover, the review noted that washing conditions significantly influence fibre release. For example, higher washing temperatures and detergent use were found to increase fibre shedding, while larger washing loads tended to reduce it.

In conclusion, while the review offers valuable insights into microplastic pollution from textile laundering, it also highlights the complexities involved in measuring and comparing fibre release. **The variability in research methods suggests a pressing need for more standardised testing protocols.** This will be essential for creating reliable guidelines to mitigate microplastic pollution in the future.

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Updated literature review on microplastics from household front load/top load washing machines and other reference household washing machines (e.g. used for EN and ISO testing) (literature from 2020-2024)

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Summary

The primary objective of this review has been to update the previous review with the newest literature, “Literature review - Microplastic emissions from textile laundry including emission scenarios for EU” [1] produced by RISE in 2020 for APPLiA, with literature published since then. The main literature search was conducted in May and June 2024, covering papers from 2020 to 2024. This includes publications from 2020 that were not available during the writing of the previous report. The selected publications were assessed against the same criteria used in the earlier review to ensure relevance. These criteria focused on presenting results for microfibre release in mg/kg for polyester materials washed five times or more, including pre-wash, in domestic washing machines.

Out of an initial screening of 55 published studies, three met the criteria for this review, focusing on polyester fibre release in European domestic washing machines. The range of release varied significantly, with aged garments showing values between 0-366 mg/kg and new fabrics between 6.5-55 mg/kg, aligned with previous findings.

In addition to the challenge of finding studies that meet specific criteria, certain variations in methodologies complicate direct comparisons among the studies. One of the three studies that met the criteria used old clothes and reported the highest fibre release levels. The pore size of the filter seems to have a large impact on the result when using a gravimetric method for assessing fibre release.

Overall, the findings underscore the complexities of understanding fibre release in polyester textiles, highlighting the need for further research to establish clearer guidelines for testing and contribute to effective strategies for mitigating microfibre pollution.

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1 Aim and objective

The aim of this review has been to update previous review “Literature review-Microplastic emissions from textile laundry including emission scenarios for EU” [1] made by RISE 2020 for APPLiA with literature that have been published since that was published. It will focus on the current literature in the field of microplastic (MP)/microfiber (MF) emissions/shedding/fragmentation/release from textiles during laundry in domestic full-scale washing machines with horizontal axis configuration.

More specifically this review has the following objectives:

- Screening of literature and collection of technical data. The review does not include studies on MPs in natural environments and also does not include any information on toxicology/risks with MPs or MFs. Furthermore, the review has focused on comparison of data only for polyester as this is the most investigated type of synthetic polymer.
- Comparison and evaluation of sample selection, different conditions and parameters during washing and evaluation methods.

2 Method

This report is a continuation and extension of the previous report made by RISE for APPLiA [1], with papers published after the release of the previous report. Papers from 2020 to 2024, and that were not published when writing the previous report, are included. Papers that are accepted, but not yet published and preprints where also included in the search. Papers were primarily found via the search engine Scopus, owned by Elsevier, which covers a broad range of research topics from journals, books, conference proceedings, and patents. Advanced search functions allow for the combination of various criteria and the use of logical operators to refine search results. Other search engines used include SciFinder-n (licensed software provided by the American Chemical Society), PubMed (National Center for Biotechnology Information (NCBI) at the U.S. National Library of Medicine (NLM)), and Google. References cited in the selected literature were also included, as well as searches on names known for previous publications within the field.

The software Mendeley Reference manager (version 2.117.0) was used as a reference library. The main literature search was conducted during May and June 2024.

The initial screening of search results involved reading the titles and abstracts. If a publication seemed interesting at first glance, it was added to a list in Excel. After a more thorough review of the publications, they were colour-coded: green for interesting, yellow for maybe, and red for off-topic. This process was iterated by comparing the publications against the same criteria set by previous review to provide relevant results for the purpose of this review. That is, focus on studies made by using European domestic full-scale washing machines i.e. household front load/top load washing machines with horizontal axis configuration, and other reference household washing machines or studies investigation professional and industrial laundry. The fibre of focus will be on polyester (PES) washed at least 5 cycles, just as previous report.

2.1 Definitions

2.1.1 Fibre fragment

Short piece of a textile fibre, typically less than 5 mm long, released from the main textile structure. These fragments, synthetic or of natural origin, can be released during, and be influenced by, all phases of the product life cycle. These small fragments pollute the environment and are regarded as a risk although more research is needed to fully understand the impact. Diameter of the fibre fragments can vary, e.g., the typical diameter range regarding polyester for textile clothing applications is 10 µm to 40 µm. [2]

2.1.2 Microfibre

Fibre with linear density less than 1 decitex or a diameter less than 10 µm. NOTE: Polyester microfibres typically have a diameter smaller than 10^{-5} m. This is a frequently referenced dimension in the textile sector which originates from the use of fabric made of these fibres commonly used as cleaning cloths but also in other applications.

The formal definition of a microfibre which in accordance with SI form would equal 1×10^{-6} . [2]

2.1.3 Microplastic

According to European Commission [3] and ECHA [4] microplastics include solid, non-soluble fragments of any geographic form between 1 nm to 5 mm at its largest dimension. Synthetic fibres with a length between 3 nm and 15 mm and a length /diameter ratio >3 is also included in ECHAs description.

The following definition of MPs has also been suggested in many of the publications: “MPs are any synthetic solid particle or polymeric matrix, with regular or irregular shape and with size ranging from 1 µm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water”. [5]

3 Result and discussion

3.1 Sample selections

Our criteria for selecting papers for this review are the same as for the first report, meaning that the papers must involve fibre release from polyester, washed at least five times, and present results in mg/kg. Keywords used in the searches to find papers meeting these criteria included terms such as domestic, laundering, microplastic, microfibre, microfiber, washing machines, fragmentation, household, fibre shedding, fibre release, filters, ISO 4484-3, and more. Papers that seemed potentially relevant were added to the list for more detailed examination. Targeted searches were also conducted for authors who had previously published in the field, as well as further searches among the references of papers already on the interest list.

3.1.1 Fibre type

Of the 55 papers that made it onto the list of interest for this updated review, twenty-four [6-28] included polyester fibres, which indicates a significant interest in polyester. Excluding the review papers (9 papers) on this list, papers with polyester focus accounts for more than half of the papers. Some of these papers did not exclusively focus on polyester; they often included other synthetic fibres in the study as well, and/or natural fibre such as cotton, and frequently, a blend of cotton and polyester, known as polycotton. Only two papers [30-31] included investigation of wool.

3.1.2 Textiles and fabrics

In many of the studies, T-shirts and other clothing, both new and used (the latter especially for studies involving household washing), were used. Blankets are also commonly used as a test sample. These pieces are always coloured to make them easier to see for the analysis and to distinguish any potential contaminants. Out of 33 papers, where the type of test material was clearly stated, 25 involved garments and 8 involved fabrics. For the fabrics there were often better specifications on how the fabric was manufactured. Fabrics was mostly used for the papers using lab-scale washing.

3.1.3 Sample size or weight of the textile

Of the 24 polyester papers mentioned above in 3.1.1, 10 involved studies with laundering machines fitting the criteria for the review [6-11], [13-16]. Domestic household machines were used, and many of the authors tried to follow the recommendations of washing machine manufacturers regarding the suggested load weight (see **Table 1**). However, Volgare [6], investigated the impact of different polyester load weights on fibre release and found that the release is reduced (**Table 2**) when the machine is more fully loaded, compared to washing a single garment. Although this study was conducted on new polyester materials after only one wash and without any prewash, it still provides an indication, even if the exact level of fibre release may be influenced by the manufacturing process. Lant also [9] looked at the correlation of microfibre release from soiled consumer wash loads against load mass. The wash loads (n = 79) were collected from U.K. households and where a mixture of washable apparel and household textiles, so not exclusively to polyester fibres. The textiles were pre-sorted by the consumers into loads as they would for laundering at home. The authors made the assumptions that “microfiber release decreased with increasing wash load size”. Therefore, with these two studies in mind, to reduce fibre release during washing, it is recommended to avoid washing single garments and instead fill the machine to the recommended load. One reason for this, also addressed in Lant’s paper may be due to the increased ratio between the water volume and the (very) low load. Modern washing machines can adjust the ratio to a lower load – but in Volgare’s case, the load consists of only one garment. An enhanced water volume when

rinsing leads to more fibre fragments getting released into the wastewater instead of being left in the garment and released later when using the garment.

Table 1 Polyester wash load used in domestic full-scale front-load/top-load washing machine

Specific parameter	Author
0.15 kg	[6]
0.16-0.45 kg	[8]
0.88 kg	[6]
1 kg	[7]
1.64 kg	[6]
1.75 kg	[9]
2 kg	[10]
2.50 kg	[6]
3 kg	[13]
5 kg	[15]
5.6 kg	[14]
Not mentioned	[11]

Table 2 Different wash loads of one type of polyester T-shirt and its corresponding fibre fragmentation presented in mg/kg with different wash loads.

Textile	Machine type	Pre-wash	Number of washes	Released fibres (mg/kg)	Released fibres - first wash (mg/kg)	Author
One T-shirt, Commercial, knit, low twist, blue, filament, 100% polyester, 0.15 kg wash load	Front-load	yes, 1 wash	1	401	401	Volgare [6]
Six T-shirts, Commercial, knit, low twist, blue, filament, 100% polyester, 0.88 kg wash load	Front-load	yes, 1 wash	1	187	187	Volgare [6]
Eleven T-shirts, Commercial, knit, low twist, blue, filament, 100% polyester, 1.64 kg wash load	Front-load	yes, 1 wash	1	104	104	Volgare [6]
Seventeen T-shirts, Commercial, knit, low twist, blue, filament, 100% polyester, 2.50 kg wash load	Front-load	yes, 1 wash	1	76	76	Volgare [6]

3.2 Wash studies

Some papers were excluded because they did not have the horizontal axis drum configuration in top-load machines or any information of the washing procedure at all [9], [12], [17], [19], [33] and some papers [12], [19], [20], [23] were looking at the effect of hand-wash on fibre release. It appears to be an increasing interest in comparing how hand washing measures up against machine washing and laboratory washing since many are washing their clothes by hand. However, this report has a focus on the European conditions and domestic full-scale washing machines, i.e. hand washing will not be addressed further.

Another reason why only 10 papers with the appropriate type of washing machine (**Table 3**) were ultimately selected is that several papers included studies involving garments from private households [8-9], [12], [32-37]. This is a highly interesting and relevant area, but the specific washing machine used was not always specified. Additionally, it is rare for only one type of fibre to be washed at a time; instead, the laundry typically consisted of whatever needed washing at the time and often included blended materials, which falls outside the scope of this review. However, some papers that did involve private garment from households did meet the criteria specifying the fibre content in each sample were Fernandes [8] and Lant [9]. In Lant's case, the paper discussed both household laundry and new polyester garments, with the latter fitting the scope of this review. In Fernandes' study, each garment was washed individually, ensuring the right fibre content.

Table 3 summarizes what is known about the 10 papers in the context of machine used, if there was any information about the wash program and if detergent and softener was included in the study. Lant's paper included washing in both front-load and top-load but since the top-load machine used was of the vertical axis configuration for the American market that part did not fit withing the criteria for this review.

Table 3 Type of washing machine, machine wash program and use of detergent and softener

Specific parameter	Author
Front-Load machine	[6], [7], [8], [10], [11], [13], [14], [16]
Top-load machine	[15]
Both top and front-load machine	[9]
Information about a chosen program	[6], [7], [8], [9], [10], [11], [14], [15]
Detergent	[6], [7], [8], [9], [10], [11], [13], [14], [16]
Softener	[6], [7], [9]

3.2.1 Fibre release - all criteria met

In the end, three papers had all the criteria needed for comparison with each other; the right type of washing machine was used to wash polyester containing fabric and garments and was washed five times or more with results in mg/kg or easily converted to mg/kg, (see **Table 4**). The other papers that could not be converted to mg/kg or was washed less than 5 times is listed in **Table 2** and **Table 5**.

Table 4 Estimated amounts of released micro fibre presented in mg/kg for polyester (PES) materials washed 5 times or more including pre-wash and in domestic washing machines.

Textile	Machine type/wash load/detergent	Pre-wash	Number of washes	Released fibres (mg/kg)	Released fibres - first wash (mg/kg)	Author
Sport shirt (01), interlock knit, 5 years old, used regularly, orange, 100% PES	Front-load/ 160 to 450 g/ 2 mL of liquid detergent	Yes, old clothes	3	-	147	Fernandes [8]
T-Shirt (02), Interlock knit, 5 years old, used rarely, white, 100% PES	Front-load/ 160 to 450 g/ 2 mL of liquid detergent	Yes, old clothes	3	-	0 (no release occurred)	Fernandes [8]
Sport shirt (03), rib stitch knit, 10 years old, used regularly, yellow, 100% PES	Front-load/ 160 to 450 g/ 2 mL of liquid detergent	Yes, old clothes	3	-	255	Fernandes [8]
Polo (04), pique knit, 10 years old, used occasionally, white, 100% PES	Front-load/ 160 to 450 g/ 2 mL of liquid detergent	Yes, old clothes	3	-	49	Fernandes [8]
Sport shirt (05), interlock knit, 15 years old, used regularly, blue, 100% PES	Front-load/ 160 to 450 g/ 2 mL of liquid detergent	Yes, old clothes	3	-	366	Fernandes [8]
Full zip fleeces red, Fruit of the Loom, 100% pill-resistant, polyester	Front-load/1.75 kg/ no detergent	no	1 4 8	70 39 25 (*)	70 (*)	Lant [9]

Textile	Machine type/wash load/detergent	Pre-wash	Number of washes	Released fibres (mg/kg)	Released fibres - first wash (mg/kg)	Author
Full zip fleeces red, Fruit of the Loom, 100% pill-resistant, polyester	Front-load/1.76 kg/detergent pod	no	1 4 8	70 48 28 (*)	70 (*)	Lant [9]
T-shirts black, Fruit of the Loom performance, 100% textured polyester	Front-load/1.78 kg/detergent pod	no	1 4 8 16 32 48	83 59 37 27 23 27 (*)	83 (*)	Lant [9]
T-shirts black, Fruit of the Loom performance, 100% textured polyester	Front-load/1.78 kg/detergent pod & softener	no	1 4 8 16 32 48	79 45 26 31 35 19 (*)	79 (*)	Lant [9]
100% polyester fabric , knitted, ringspun, staple fibres	Front-load/2 kg/45 mL of liquid detergent	Scoured 3 min in washing basket at 35/40C with neutral soap, then tumble dried	5	7.7-6.5 (average of 5 washes)) (*)	6.6-6.3 (*)	Dalla Fontana [10]

(*) average of 4 washing loads

Fernandes' study [8] on old clothes is well-constructed, as it collected garments of various ages, with different levels of use, and varying polyester/cotton content to observe how these aged textiles behave. A total of 38 garments were collected, ranging from 1 to 31 years old, of which five materials were 100% polyester and fit within the scope of this review. Most studies typically use newly purchased clothes that are then prewashed to obtain representative results, but in this case, the materials were washed under real-life conditions and used between washes, contributing to fibre fragmentation beyond the washing process itself. The study did not include a specific prewash, but it could be argued that real-life conditions serve as sufficient prewashing. The materials were washed three times, but only the results from the first wash are presented. The overall conclusion in Fernandes paper is that old garments released nearly twice as many fibres as the newer ones, but a principal component analysis(PCA) indicates that age does not play a crucial factor for garments with a high level of polyester content.

The authors observe that the fibre release of the old garments decreases from the first wash to the subsequent two washes, reaching a plateau. The authors suggest that this is

because the garments were not used between washes, and that if they had been used, there would have been an increase in fibre release due to wear. Therefore, they believe that the first wash provides a truer measure of release from aged garments, as it includes a contribution from usage, not just from the effect caused by the machine. Lant also observe, in his publication [9], a plateau when they reach eight washes. This has been noted in other publications too, while others again indicate that fibre release continues to occur. Lant is also of the same believe as Fernandes and mentions that the garments are not used between washes, so the observed effects are solely due to washing.

Lant compared eight washes without a detergent pod to eight washes with a detergent pod and found no significant difference. Then, they compared 48 washes with a detergent pod against 48 washes with both a detergent pod and fabric softener, and again, there was no significant difference. Previous published data [39] aligns with Lant's findings, but other studies have reported opposite results [40], [41]. According to Lant, the difference between these other two studies is likely due to them being conducted on small lab-scale washing equipment, which may not replicate the physical processes involved in domestic washing, whereas Lant's and Pirc's studies were carried out using full-scale washing machines.

Dalla Fontana examined the differences between various washing conditions. For example, over five washes, they observed that fibre release of fabric washed with a cotton-program wash cycle generated slightly higher and more asymmetric range of values compared to the same material washed with the delicate/silk cycle, which produced lower and more narrowly ranged values. When stain remover was added to five washes using the delicate/silk cycle, the average values over the five washes appeared to decrease compared to without stain remover, but this difference was not statistically significant.

Three studies met the criteria of the original selected 55 published studies. The range of fibre release from polyester was found to be between 0-366 mg/kg for real-life aged garments and 6.5-55 mg/kg for new fabric washed 4-5 times. This value range falls within the same range as the previous review [1] that also ended up with three papers [39], [42], [43] when all criteria were met. The range then was between 20-500 mg/kg, i.e. this range has not change.

Lant also found that 48 washes did not differ much in fibre release compared to four washes indicating that the material reached a plateau where the emission is more or less constant from wash to wash.

3.2.2 Sampling approach and consumer relevancy

All three studies that met the criteria filtered the entire water volume from the washing machine and measured the total residual fibres by weighing the filters before and after filtration. In Fernandes' study, garments from real-life conditions generated 44 litres of water effluent, which was first filtered through a 63 µm filter, followed by a 1 µm filter. The release from both filters was measured. Lant did not mention the total water volume, but all the water from the washing of garments was collected and filtered through a 20 µm filter. The collected residual fibres were then washed in clean water

and re-filtered through a 22 μm filter. Dalla Fontana's fabric washes generated between 50-60 litres of water, which was filtered through a 40 μm filter.

Figure 1 provides a graphical representation of the results from **Table 4**, presenting the release of polyester fibres from the studies in section 3.2.1 in bar graphs. The first, darker bars represent the release from garments used in real-life conditions in Fernandes' study [8] where the release was so low it could not be measured for the first material. The light blue bars represent the release from new full-zip fleeces and T-shirts made from textured polyester in Lant's study [9]. The final orange bar shows the release from a polyester fabric, knitted from ring-spun staple fibres, in Dalla Fontana's study [10].

Although the three studies met all the criteria and used the entire water effluent volume to assess fibre release, comparing the data remains challenging due to the different pore sizes of the filters used. From Figure 1, it might be tempting to attribute the higher release in Fernandes' study to the use of older garments. However, a direct comparison is difficult, as each study employed different filter pore sizes when processing the water effluent. Since all studies used gravimetric methods to measure the release, everything that adhered to the filters was included. Dalla Fontana, using a 40 μm filter, likely lost a significant amount of smaller fragments that passed through the pores. For example, it has been seen previously [44] that there is a significant contribution of fragments in the size range of 5-15 μm and not an insignificant contribution for the 15-25 μm range too, also indicating that Lant with pore size 20 μm also miss a large fraction. In contrast, Fernandes, using a 1 μm filter, captured a much larger proportion of these smaller fragments.

All three studies provide valuable insights into fibre release during washing but the differences in filtration methods makes direct comparison difficult.

Another debatable parameter is the consumer relevance of the washing. For instance, Fernandes washed only one garment at a time, using just 2 ml of detergent per wash. Given that 44 litres of water were used in each wash cycle, this resulted in an unusually low detergent concentration. Consumers tend to overdose on detergent, as noted in the "Final Report - Ecodesign and Energy Label for Household Washing Machines and Washer Dryers" [45]. In contrast, Lant and Dalla Fontana used load sizes between 1.8-2.0 kg, which still falls on the lower end compared to the average of 82% full load used by consumers according to A.I.S.E 2020 [46]. Moreover, detergent use in Lant studies ranged from "no detergent" to "detergent pods" also differing from the most common consumer behaviour where laundry liquids and powder are the most frequently used. Another important distinction is that Fernandes used a wash temperature of 60°C, while the average wash temperature used by most consumers is 42.4°C [46].

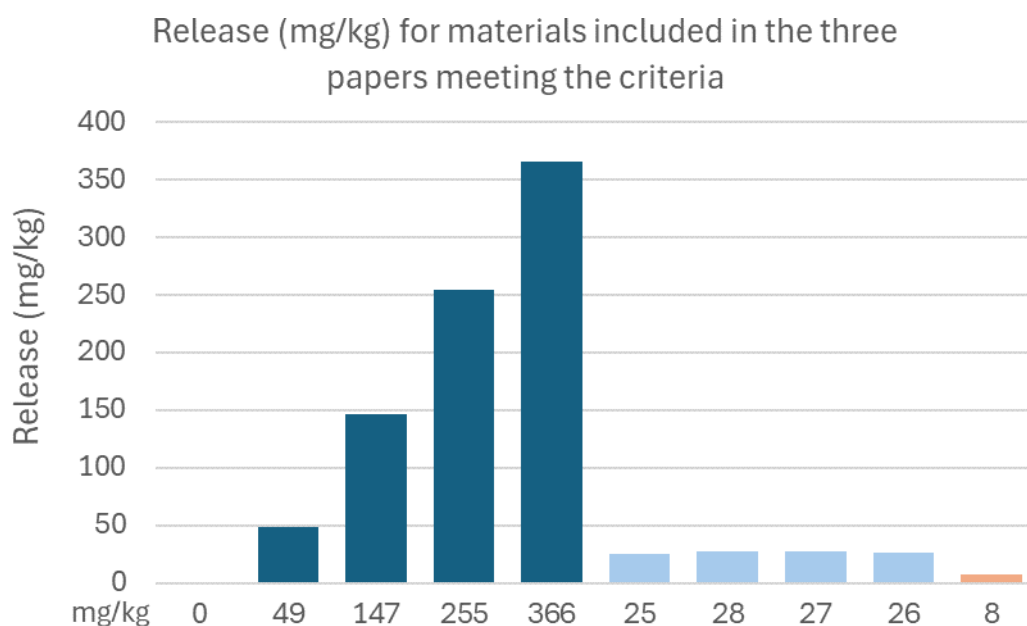


Figure 1 Graphical representation of fibre release (mg/kg) after washing, as presented in **Table 4**, nor the three studies meeting the criteria. Fernandes [8], shown in dark, used a filter with a 1 μm pore size; Lant [9] shown in light blue, used a 20 μm filter; and Dalla Fontana [10], shown in orange, used a 40 μm filter.

3.2.3 Fibre release – papers not meeting all criteria

Only three papers met all the predetermined criteria, while seven came very close. Some fell short because their results were not in the correct format, and others because the test materials were not washed at least five times. A summary of the distribution of wash cycles can be seen in **Table 5**.

Table 5 Number of wash cycles used for the 10 papers with European domestic washing machines. The grey marked references are the studies from **Table 4**.

Specific parameter	Author
Number of cycles 1	[8], [9], [11], [13], [14], [15], [16]
Number of cycles 2	[7], [13]
Number of cycles 3	[8], [13]
Number of cycles 4	[9], [13]
Number of cycles 5	[10], [14]
Number of cycles 7	[11]
Number of cycles 8	[9]
Number of cycles 10	[14]
Number of cycles 15	[14]
Number of cycles 16	[9]
Number of cycles 20	[14]
Number of cycles 32	[9]
Number of cycles 48	[9]

For **Table 6** it's not possible to compare the different values since they use different units, and in some cases, it's not entirely clear what the data represent—for example, whether the data are normalized, and if so, normalized against what. For instance, in Balzagui's study [14], there is hardly any difference from the first wash to the 20th wash which sounds strange because at least the first washes use to produce more fragments. Since the focus of this article was on comparing four different filter solutions, the emphasis was more on the efficiency of the filters retaining fibres (including other matter) than on the fibre release itself.

Table 6 Fibre release values for papers washing PES materials and the relevant washing machines with other units than mg/kg or not reaching the criteria of 5 washes.

Textile	Machine type	Number of washes	Number of released fibres	Author
1 kg 100% Terephthalate fleece jackets	Front-load	2	1700 N/50 mL (from graph after 2 wash, average of 3 values)	Kim [7]
Mixture of woven and knitted PES fleece fabric	Front-load	5 pre wash 1 5 10 15 20	n.d. 4.8 mg 3.3 mg 4.4 mg 3.3 mg 4.4 mg	Belzagui [14]
PES Face mask	Top-load	1	6.5 micro fibre/g	De Felice [15]
R1, 100% PES fleece fabrics	Front-load	7	3.95×10^7 MF/m ³ 98.86 MF/g	Pedotti [11]
R2 100% PES smarter polyester	Front-load	7	3.22×10^6 MF/m ³ 4.47 MF/g	Pedotti [11]
Eighteen T-shirts , Commercial, 100% polyester	Front-load	1 (no pre-wash)	102 mg/kg	De Falco [16]
Fleece jacket , knitted, filament, black, 100% PES	Front-load	1 with 57.8 g detergent	1751 mg/kg	Dreillard [13]
Fleece jacket , knitted, filament, black, 100% PES	Front-load	4 without detergent	485 mg/kg 72 59 53	Dreillard [13]

De Falco [16] and Dreillard [13] does provide results in mg/kg, but unfortunately, they don't contain values for 5 washes or more. However, it can be noted that these values fall within the range presented in **Table 4** with the exception of Dreillard's experiment where detergent was added. A pre-wash with detergent compared to without detergent showed almost a four time increase in fibre release. The author speculates it is probably due to the presence of water insoluble compounds at the surface of the filter and since the level of fibre release is measured gravimetrically the pollution will add to the weight. They did not continue with detergent testing.

Even if all 10 of these studies had successfully met all the criteria, there would still be significant variation in how the studies were conducted. Starting with the load mentioned in **Table 1**, one can already see a wide range in how much the machines were loaded and the significance of the load in a machine on the fibre release has been showed by Volgare [6] in **Table 2**. When the authors decided to use a certain wash program, (see **Table 7**), this affect wash parameters such as rotation (**Table 8**) and water volume used, program duration (**Table 9**), and temperature (**Table 10**) all important parameters that can affect fibre release.

It becomes even more evident that many factors of the washing procedure can influence the result and that there are not many papers using the same parameters. Parameters concerning the three papers fulfilling all set criteria is marked in grey in **Table 7-10**. Fernandes [8] used the highest washing temperature of 60°C in its rapid wash, whereas none of the other two papers [9], [10] used such high temperatures. Fernandes also observed the highest level of fibre release. However, no definitive conclusions can be drawn that the higher temperature was the cause of increased fibre release, as the garment/fabric washed in these studies were not the same. Additionally, the garment with the highest release was 15 years old, so age could also be a contributing factor—it's simply impossible to determine. It would have been favourable if Fernandes had also tested a program at 40 °C, as this would have allowed for ruling out the additional impact of temperature on the test material.

Table 7 Machine wash program *

Specific parameter	Author
Cold program	[14]
Cotton	[10]
Cotton Short	[9]
Delicate/Silk	[10]
Delicate synthetic	[11]
Rapid wash	[8]
Standard mode	[7]
Synthetic	[6], [13], [15]

Table 8 Number of revolutions and mentions of water volume *

Specific parameter	Author
Water volume mentioned	[6], [8], [10], [13], [14]
600 rpm	[10]
600/800 rpm	[11]
800 rpm	[15]
1000 rpm	[14]
1200 rpm	[6], [13], [16]
1400 rpm	[8], [10]
1600 rpm	[9]

Table 9 Cycle time *

Specific parameter	Author
30 minutes	[14]
40 minutes	[11]
43 minutes	[10]
48 minutes	[7]
60 minutes	[8]
79 minutes	[15]
85 minutes	[9]
90 minutes	[10]
107 minutes	[6]

Table 10 Washing temperature *

Specific parameter	Author
Temp no heating	[7], [14]
Temp ca 30 °C	[10], [11], [13], [15]
Temperature ca 40 °C	[6], [9], [10], [16]
Temp 60 °C	[8]

* The grey marked references are the studies from **Table 4**

3.3 Analysis and filtration

As if the impact on the results from how the test material was washed wasn't enough, the way analyses are conducted can also affect the outcome. Different results can arise depending on whether fibres are measured by weight or counted visually (**Table 11**). Errors in weighing have already been demonstrated in Dreillard's data in **Table 6**, where the use of detergent during washing led to an almost fourfold increase in weight—not because of higher fibre release, but due to contamination from using the detergent that ended up on the filter. This contamination was then weighed and mistakenly assumed to be from fibre release. In Dreillard's case, they identified what had happened, but if one is not as alert, significant errors can occur if the filter is not double-checked visually, preferably with magnification, to ensure that only fibres relevant to the analysis are present. By using coloured test materials, it is also easier to distinguish contamination from, for example, a white lab coat. In cases where the weight may come from other sources than the fibres of interest, it might be more accurate to select a number of fibres to represent a cross-section of the sample, which can then be scaled up to account for the entire sample. There are always margins of error, and extrapolating results in this way can lead to even larger margins of error. If something is slightly off at the beginning, it can be multiplied, leading to substantial inaccuracies by the end. It's also crucial that the samples taken come from a statistically sufficient portion to ensure that they truly represent the entire sample.

Another factor that can influence the result of the analysis is the type of filter used to either filter the entire volume of water from the washing machine or a partial volume that is then extrapolated to represent the entire volume. Filter size **Table 11** is crucial in this context. A filtration step is often included, and the choice of filter can significantly impact the results. The larger the pore size of the filter, the more fragments are missed and pass through the filtration. Previous studies [44] have shown that a substantial portion of the weight of the fragments comes from small fragments that barely qualify as fibres because they are so short and therefore do not meet the diameter-to-length ratio required to be classified as fibres, but they will add to the weight if gravimetric analysis is used. If a filter that is too coarse is used, a large part of the representative sample is lost, and this applies both if the identification is from weighed or counted fibres.

Table 11 Pore size of filters and method for quantification/identification – Full-scale washing machine. The grey marked references are the studies from **Table 4**.

Pore size	Identification method	Identification/validation equipment	Author
20 µm	Counted	Laser diffraction particle size analyzer Mastersizer 3000, Malvern Panalytical Ltd., FlowCam analysis with bench-top FlowCam dynamic particle imaging microscopy FlowCam 8100, Yokogawa Fluid Imaging Technologies, Inc.,) and VisualSpreadsheet® software (version 5.9.1.78).	[7]
63 µm 1 µm	Weighed	Balance Oxford A2204 Scanning electron microscopy (SEM) JEOL - JSM 6610LV FTIR	[8]
20 µm	Weighed	n/a	[14]
0.7	Both	Scale Mettler Toledo AG204 Nova NanoSEM 450 FEI scanning electron microscope using a GAD (Gaseous Analytical Detector) Optical microscope Olympus BX51	[13]
400 µm 60 µm 20 µm 5 µm	Weighed and calculated	Optical microscopy analysis LEICA M205C, software ImageJ (release 1.43u)	[6]
20 µm 0.2 µm	Counted	Stereo microscope Olympus SZX10, X4.725 - X94.5 software ImageJ v.1.5, FTIR Nicolet™ iN10 MX	[11]
400 µm 60 µm 20 µm 5 µm	Weighed	optical microscopy LEICA M205C scanning electron microscope Quanta 200 FEG	
20 µm	Weighed	n/a	[9]
40 µm	Weighed	Micro balance	[10]
25 µm	Counted	Leica EZ4 W stereomicroscope SEM (JEOL IDSJSMIT - 500) and FT-IR (Perkin Elmer) for confirmation	[15]

3.4 Filter solutions mentioned in the selected papers

Of the 55 publications, several looked at filter solutions designed to capture fibre fragments during washing. While this is not a primary focus of this review, a summary of the tested solutions is provided here. The studies include both established solutions and new designs that may eventually reach the market.

Similar to the washing and analytical methods, there is considerable variation in the design of these filters and their cut-off specifications. Some filters improve over time as captured fibres lead to the collection of more fragments; however, they eventually cease to function effectively when they become saturated with fibres. Some filters are integrated into the washing process, while others are installed at the drainage system to capture fragments there. A summary of the papers can be seen in **Table 12**.

Table 12 Tested filter solution for catching fibre fragments.

Specific parameter	Lowest pore size	Author
Commercially available microplastic filter A Commercially available microplastic filter B Disc-type polymeric membrane consisted of polyether sulfone (PES) Disc-type ceramic membrane was composed of zirconia-titania (Z-T)	65-70 µm 45 µm 1.0 µm 1.4 µm	[7]
External filter F1 External filter F2 External filter F3 Internal filter F4	Not applicable	[14]
TF1 PlanetCare prototype 1 (external filter) TF2 PlanetCare prototype 2 (external filter)	75 µm	[16]
Cora Ball GuppyFriend 4th element Lint LUV-R XFiltra PlanetCare	No mesh 50 µm 50 µm 150 µm 60 µm 200 µm	[47]

4 Conclusions and discussion

In summary, only three studies met the criteria established from an initial selection of 55 published studies. The analysis revealed that the range of fibre release from polyester varied significantly, showing values between 0-366 mg/kg for real-life aged garments and 6.5-55 mg/kg for new fabrics that had been washed four to five times. Notably, this value range is aligned with the previous report, which also identified three papers, presenting release levels between 20-500 mg/kg; thus, the findings confirm that the range has not changed.

The result from Lant indicated that washing materials 48 times did not significantly differ from those washed four times, suggesting that the materials reached a plateau where fibre emissions remain relatively constant across washes. Despite the attempt to filter relevant papers, the challenge of accumulating a substantial number of studies that meet all specified criteria is evident, given the diverse methodologies employed in washing studies and their subsequent analyses.

If certain criteria, such as correct unit measurements or the requirement for five wash cycles, were excluded, examining the parameters from the remaining studies would reveal substantial variations. This is due to that there are often only one or two papers for each parameter. This variability complicates direct comparisons among the three studies, as they differ in numerous aspects. Nonetheless, an exploration of specific parameters may provide insight into their potential impact on results.

Fernandes' study reported the highest levels of fibre release from polyester, that may be attributed to the use of the oldest garments (up to 15 years), which are generally less durable due to repeated washing and exposure to environmental factors. This study also utilized the highest washing temperature and a finer filter, capturing even the smallest fibres. Conversely, Dalla Fontana's study reported the lowest levels of fibre release, utilizing a well-defined fabric with double heat-sealing along the edges to minimize the release, combined with a filter of larger pore size that allowed smaller fibres and fragments to pass through. Lant's findings fell between those of the other two studies, and the filter used in their research had an intermediate pore size.

Overall, the findings from these studies highlight the complexities involved in understanding fibre release in polyester textiles. Given the significant variations in methodologies and results, further research is needed to establish clearer guidelines and standards for testing. This will help improve the comparability of future studies and ultimately contribute to more effective strategies for mitigating microfibre pollution in our environments.

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