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Briefing Note on Microplastics Literature Review

APPLiA – Home Appliance Europe – and its members are concerned when it comes to the political and societal discussion about the release of microplastics in the environment. Facing a plethora of scientific data and worrying extrapolations on the overall emission of microplastic from textiles, we are interested in contributing to the development of reliable scientific data that could aid to understand the magnitude of the issue.

For this reason, APPLiA commissioned the **Research Institutes of Sweden** (**RISE**) to carry out a literature review on the microplastic emission from textile laundry. RISE is a research institute, which has a lot of experience in the field of textile research and microplastics. It has been involved in specific research projects on microplastics (MinShed) and has conducted research for the Swedish government on the efficiency of microplastic filtering devices.

The main purpose of this critical review was to collect and compare current published data on the release of microplastic/microfibers (MP/MF) from textiles during laundry. Among others, the main findings[1] highlighted in the study are the following:

- The values for MF shedding are higher for the experiments performed at lab-scale indicating a harsher treatment compared to full-scale commercial washing machines[2]. Therefore, it is also concluded that **lab-scale results should not be translated or extrapolated** to simulate full-scale domestic washing machines.
- After carefully defining the experimental conditions, the finding estimates **roughly 20-500 mg of MFs per kg polyester textiles being released during 2nd – 5th wash cycles**[3].
- Textiles show significantly higher fiber shedding during initial washes, which then stabilizes after a certain amount of wash cycles. Thus, it is **not advisable to extrapolate fiber shedding** from studies that only performed 1 or 2 washing cycles.
- In order to estimate the overall emission of microfibers released to the water, RISE **calculated a bottom up scenario** and reported it in the literature review.
- More research on a broader range of textiles and also on the long-term behavior of the textiles is needed in order to gain a more reliable statistical base.

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[1] The findings and conclusion can be consulted at page 23 of the Literature Review

[2] This is not only a finding from the Literature Review, but it was also further proved by the De Falco (2019) - *The contribution of washing processes of synthetic clothes to microplastic pollution*.

[3] This estimation was done after making a few selections (see p. 20 of the literature review). The values represent at large the average of the 2nd-5th wash cycle as only few studies perform long term test. However, there is evidence that the emission is reaching an even lower plateau level after the fifth wash.

APPLiA - Home Appliance Europe represents home appliance manufacturers from across Europe. By promoting innovative, sustainable policies and solutions for EU homes, APPLiA has helped build the sector into an economic powerhouse, with an annual turnover of EUR 50 billion, investing over EUR 1.4 billion in R&D activities and creating nearly 1 million jobs.

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Literature review

Microplastic emissions from textile laundry including emission scenarios for EU

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Literature review

Microplastic emissions from textile laundry including emission scenarios for EU

Summary

The main purpose of this critical review was to collect and compare current published data on Microplastics/microfiber (MP/MF) release from textiles during laundry. Some review papers have previously been published on shedding from textiles during laundry, however it is difficult to achieve a complete overview as most reviews only contain part of the published studies. There are also huge variations in the reported values on MP/MF released, this is due to variation in both samples and great differences in experimental methods (both wash conditions and characterization methods). It is also difficult to distinguish which data is reliable, and it is sometimes impossible to compare the reported data, as MP/MF release can be reported in different units (e.g. weight, number). Some studies are also lacking detailed information concerning the methods, e.g. sample selection, pretreatments and wash load as well as specifics about the fabric being tested. The discrepancies between different studies can be expected to continue until a standardized protocol has been established.

Although there are differences in experimental conditions, some trends as to which factors cause MP/MF shedding can be seen, e.g. fabric and yarn construction, sealing of edges, number of wash cycles, temperature and use of detergent. In order to narrow down the vast range of reported data on MP/MF release, some limitations were made to provide more relevant results for the purpose of this review. As the review mainly considers real life conditions from domestic households in Europe, the focus is on full-scale domestic, front-loaded washing machines. As most data is reported on polyester, this is the sample type focused on in this review. There is a greater release of MP/MF during the first wash cycle and thus, for narrowing down the range of release, only studies reporting several wash cycles were considered. Given these limitations, MFs from textiles during laundry are approximated to be in the range of 20-500 mg/kg. The lower range of 20-50 mg/kg can be considered a realistic range according to two out of the three selected studies. However, higher values (> 200 mg/kg) were reached when samples were collected with very fine filters.

The estimated range of emissions were also used to develop rough scenarios on the overall microplastics emission (per kg laundered textiles) coming from household washing to water in Europe. One scenario included the first wash and one scenario excluded the first wash. Including the first wash resulted in a range of 30-1 060 mg/kg, corresponding to 425 tons up to 15 075 tons MP/MF emissions per year in Europe. Excluding the first wash resulted in 20-500 mg/kg and a MP/MF emission scenario of 285 tons up to 7 110 tons per year.

Contents

Aim and Objectives

The purpose of this literature review is to provide a critical evaluation of the current literature in the field of microplastic (MP)/microfiber (MF) emissions/shedding from textiles during laundry.

More specifically this review has the following objectives:

- Screening of literature and collection of technical data. The review is delimitated to not include studies on MPs in natural environments and it does not include any information on toxicology/risks with MPs or MFs. Furthermore, the review has focused on comparison of data only for polyester (PET) as this is the most investigated type of synthetic polymer, e.g. fleece, is considered to be one of the largest sources to MF shedding.
- Comparison and evaluation of sample selection, sample preparation, different conditions and parameters during washing, evaluation methods, assumptions and calculations of emissions
- Critical assessment of methods used including comments on both methodology and results
- Recommendations

Method

A list of initial studies was provided by the client (APPLiA) and was used as a starting point for the extended literature search. All the articles in the list were collected and read and an Excel spreadsheet was created where technical parameters were summarized. The literature search was then extended to include further studies. The main tool for finding new references was the database Sci-Finder-n (licensed software provided by the American Chemical Society). References cited in selected literature was also included. The review also includes “grey literature” such as reports, and documents provided by various authorities and organizations. The software Mendeley (version 1.19.4) was used as a reference library. The main literature search was conducted during December 2019, with complementary additions until the middle of March 2020.

Definitions used in the literature:

- Microplastics (MPs) – defined as particles smaller than 500 µm which can be of any shape. The following definition of MPs has also been suggested: “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”. (1)
- Microfibers (MFs) – very fine fibers (approx. 3-10 µm in diameter), spun as endless filaments, can be of both synthetic and natural origin. The length to diameter ratio is also rather high, on the order of 10^3, which is another important characteristic of MFs, and although an MF is typically referred to as a synthetic fiber in textile engineering, MFs also include fibers with natural origin. (2)

Results & Discussion

Release of microplastics (MPs) into the environment has become a scientific "hot topic" during the last decade. One source of MPs that is often discussed is MPs in the form of MFs that originates from textiles and are shed during laundry. Thus, there is a large number of papers describing shedding of MPs from textiles, e.g. (3–6). However, to date, there are no standardized methods available, which leads to large variations in the results presented in the published literature. The size ranges and the morphology of the MPs differ greatly, which also leads to huge variations in the estimated amounts of MF release to the environment. Most papers that performed tests in lab-scale report the shedding of MFs as *number of particles per area or fibers per filter* whereas in tests in commercial domestic washing machines the majority instead used the unit *mg of particles per kg fabric*. This means that the numbers will be very dependent on detected sizes and morphologies, and a large number does not necessarily mean a large amount - if calculated by weight.

A lot of effort is put into creating and developing more standardized methods, and even though there is no standardized method yet available, many authors have put much work into their own research and method development to ensure that they get reliable results. There could, however, still be a large amount of potentially important parameters that are not investigated in different studies. For example, only a few studies have evaluated different construction parameters of the fiber and in the yarns, also the impact of different water volumes used in the washing procedure need to be investigated further to get a better understanding of the most important parameters. Since most studies have their own focus areas, they also have different approaches to evaluate and to find out how the shedding occurs and what may be the underlying cause. As most authors also points out, the shedding that occurs from washing textiles is a complicated issue and most of the researchers are aware of that there is a need for further research and standardization in this area. All in all, a comprehensive comparison between results from different research groups and published data is not straightforward. Some review papers exist in the field (3,7–10); however, most papers only include comparison between a few different methods. In the current literature review, we have compared as many methods as possible and evaluated the data of the estimated amounts of MP/MF release, in order to be able to narrow down the range of estimated amount of MP/MF released during textile laundry.

The following section will take the various technical parameters into account in more detail.

Sample selection

The type and amounts of textiles that are used in the different studies are parameters that can influence the amount of shed MP/MFs during washing and will be described more detail in the subsections below.

Sample type

The majority of all the studies tested different synthetic fibers but authors (11–18) used PET (e.g. fleece) exclusively as material in their studies. Of the studies that provided information about construction parameters, knitted fabric was used more frequently than weaved fabrics. Only a few authors described that they used weaved fabrics (5,19–21). There are probably further studies that have used weaved material in the experiments, but this information is in that case lacking. If the fabric originates from a garment, the authors usually provide some information about the kind of garment (11,14,16,18,20,22–26) and from where it was purchased. Authors of at least five different studies (15,21,27–29) consider that the yarn construction is of importance in the context of shedding and have therefore included information about the yarn construction. According to some researchers (16,30,31), different design parameters in the fiber, yarn and garment construction are important factors regarding MP release and should be taken into larger consideration. As an example Carney Almroth (27) mentions that the amount of shedding is related to how tightly the yarn is knitted into the fabric. Thus, it can be argued that studies testing purchased products (without any knowledge about the manufacturing process) will only provide results relating to the shedding of the specific garment and repeatability would be hard. To get the whole picture over MP/MF shedding one needs to investigate more steps in the manufacturing process of the garments. There is always a risk that foreign particles (e.g. dust and other polymeric particles as well as metal, glass and biological material) will stick to the surface in different steps of the manufacturing process (32).

Sample size or weight of the textile

Many washing tests are performed at lab-scale, while others are conducted according to real life conditions with a commercial domestic washing machine or a standard washing machine. Depending on which method that is used; the fabric size is adapted to fit the equipment. Smaller parts from a garment is usually cut out if a lab-scale method is performed, while one or more whole garments often are used in real life tests in washing machines. When textile parts are cut out from a garment the edges of the fabric become more exposed and could cause higher shedding amounts if they are not sealed before tests, read more in chapter Pre-treatments.

Depending on what kind of results one is looking for, tests in lab scale or commercial washing machine tests can be of different interest. When testing garments/textiles in lab scale it is naturally easier to keep control over different parameters, but at the same time it is difficult to achieve results that reflect real life conditions. Commercial domestic washing machine tests can, if the parameters are traceable and repeatable, give a more realistic picture of the MP/MF shedding. The collection of shed MP/MFs can however be more complicated from commercial domestic washing machines, since there is a risk that they get stuck in small inaccessible spaces in the machine. Jönsson 2018 (32) in fact claims that it is impossible to clean the machine thoroughly between the test rounds. In which case, it is important that one can make sure that the MP/MFs are collected in a controlled way. If not all MP/MFs are collected, the results will be misleading. Another possible problem with using a full-scale washing machine is that the filters could clog under the collection process due to the large amounts of fibers. If there are too many MP/MFs on the filter it will also be hard to later analyze and count the MP/MFs. For this reason, one either needs to use a gravimetric method or perform a second filtration step in order to obtain a smaller amount of fibers onto each filter, which is possible to analyze by counting (manually or automatic). If the aim is to know more about the chemical composition of the shed particles, the gravimetric method is not preferable since it does not provide any information on this. The risk is that a large proportion of unwanted particles are included in the weighing, which then can give a misleading result of the actual amount of released MP/MFs. These potential problems can be easier to avoid if lab-scale tests are conducted as the sample size is smaller and therefore sheds less. Regardless of which method is used (washing machine or lab-scale) it is possible to perform additional analyses to identify parts of the collected content on the filter using, e.g. Fourier transform infrared spectroscopy (FTIR) or scanning electron microscopy (SEM).

Contamination

It has also been discussed that contamination of samples for MP/MF evaluation could occur from e.g. clothing, equipment and dust particles from the surroundings (13,29). Thus, measures to avoid any contamination is of importance. Most published papers from recent years describe the precautions taken to avoid contamination in detail and are validating the effectiveness by e.g. setting up blank control samples. Researchers generally rinse all equipment, avoid using materials made of plastic, wear lab coats of natural fabrics and cover the samples to avoid airborne contamination, in order to make sure that the MP/MFs that are registered and analyzed only come from the actual samples. For papers where such precautions have been made, it can be expected that contamination has a negligible influence on the results. However, for earlier papers where no such information is described, it can be assumed that some contamination may have occurred and that the reported estimated values should most likely be somewhat lower.

Pre-treatments

Sometimes textiles go through a pretreatment before the wash tests are conducted. The purpose can be, e.g., to remove dust particles and loose fibers from the fabric (15,20,21,26–28,31), or to simulate aging of the material (22,23,27). The approaches of performing the pretreatments are diverse as there is no specific standard that describes how a garment should be pre-washed before further washing tests. Thus, researchers have developed their own methods of pre-washing. Some studies that pre-wash the garment before the tests claim that this is an important step. The main reason is that loose particles in form of dust or microplastics from surrounding environment may be stuck on the surface. If these are not removed before the actual washing process, the amount of released MP/MFs can be overestimated.

Instead of washing the fabric (17,32) vacuum cleaning of the fabric is another way to remove dirt on the fabrics prior to washing. If the packaging process of the fabric is unknown, Hartline (23) describes that they simply gently shake the garment to remove loose fibers and dust particles before further tests.

Another approach regarding pre-treatment is to seal the edges of the fabric before washing. The reason for this is to reduce any errors in the estimated amount of shed fibers, as this process allows them to only consider fibers released from the actual fabric, i.e. not those from the edges (32). Many researchers (19,21,26,28,31,33) believe that sewing with a regular sewing machine is enough to ensure that the edges do not contribute to the amount of shed fibers. Other authors (12,14,32) believe that an ordinary seam will not reduce the shedding from the edges, instead they seal the edges using heat so that the fibers melt together and therefore ensure that no shedding can occur from the cut edges. A third approach is to glue the edges with textile glue, something that e.g. Haap 2019 (20) did.

Replicates/statistics

There are large variations in the number of samples used in the reviewed studies; from only one sample (which also can be one garment) (5,11,28,34) up to 8–10 pieces (28,32). The majority, however, use between three and eight samples for each wash cycle. The accuracy of the results will probably mirror the number of samples. Testing a washing process only once or using only one fabric makes it difficult to evaluate, as it is unlikely to get a statistically accurate result.

How many replicates that are necessary is difficult to answer since it most likely also depends on the method applied.

Which fabric quality is being used in the different studies will also have an impact on the result, and there are not much specifications of the fabric itself that is likely to have an impact (for example mechanical and chemical finishes).

Wash studies

The tables below highlight different parameters used in the wash studies. The references mentioned are those that have described their individual steps. The lack of information of the method description in some studies causes difficulties in comparing and assessing the reliability of the method in later steps. The intention with the tables is to illustrate the large variations that have been used by different authors and it can be concluded that all methods differ in some way or another, e.g., water quantity, use of detergent, temperature, time and number of cycles washed. All these differences make it almost impossible to compare the methods against each other. Still, some parameters or variations described can be valued as more important according to the reliability of the method. In relation to the presented tables, the parameters are discussed according to the possibility of fiber mitigating.

Firstly, the parameters between commercial domestic washing machines are discussed while studies performed in lab-scale are presented and discussed later. A few authors have used both methods to be able to draw further conclusions. For example, Zambrano 2019 (28) reported that approximately forty times more mass was shed per weight of fabric for samples washed in lab-scale compared to home laundering. This lies in line with the general agreement that lab-scale generates more shedding. Regarding the size of the shed MFs, Zambrano reported that longer MFs (>200 µm) were obtained in the home laundering experiments, compared to the lab-scale tests. His hypothesis is that the lower intensity action used in home laundering machines does not break off as many smaller MFs as the lab-scale equipment. During lab-scale washing, there is a more intense mechanical action because of the metal balls that are included during washing in this method.

Conditions/methods used during laundry- Full-scale washing machine

For the papers describing wash tests in commercial domestic washing machines, the majority used a front-loaded washing machine. A possible explanation is that most studies in this literature review are performed in Europe where front-loaded washing machines are by far the most common type. McIlwraith 2019 (8) chose to wash in a top-loading machine since he claims that this type can cause more shedding, which the results of the study also pointed out. Yang 2019 (12) used a front-loading washing machine and a pulsator machine to evaluate if there is any significant difference between the machine types. The results also showed that the pulsator machine caused a greater amount of shedding. Belzagui 2019 (5) performed tests in a commercial domestic washing machine to mimic real-life conditions and these authors claim that lab-scale equipment do not simulate the shedding in a realistic way.

Regarding the selection of washing program, only a few authors mention which specific washing program that was used. Depending on, for example, the brand of the washing machine, the washing programs can vary a lot (e.g. duration of main wash, total washing time, rpm, temperature). In order to get a more scientific approach, it would be of interest if more information about the specific washing program used was presented in the published literature. Instead of information about specific washing programs, most studies have chosen to describe temperature, time and rpm separately. In order to simulate a washing process that reflects real-life conditions, many of the studies found it necessary to include detergent in the washing process. Those who actively opted out detergents did so because of the risk that residues of detergent can clog the filters. Not fully dissolved detergents can also cause errors in the forthcoming analyses. The use of detergent and its influence on the shedding has, among others, been tested by Zambrano 2019 (19) and Napper 2016 (17). Zambrano pointed out that it was a clear increase in shedding amount when detergent was used. Napper also showed that more fibers tended to shed during use of detergent, but the pattern was not as clear as for Zambrano since several parameters were compared in the same experiments in this case. Pirc 2016 (16) on the other hand, reported that detergent had no significant effect on the shedding. Gustafsson 2019 (33) explains that even if detergent seems to increase the amount of shedding, it can at the same time protect the fabric from mechanical stress because of the cushioning effect from the surfactant. De Falco 2018 (19) tested the impact of softeners and showed results that pointed at that usage of e.g. softeners could decrease the shedding by 35 %. Napper 2016 (26) seems to have an opposite opinion and instead claims that softener usage could significantly increase the shedding on polyester-cotton blend fabrics.

Table 1. Type of washing machine, wash program and detergent

Specific parameter	Author
Front-load machine	(5,11,35,14,16,19,24–26,33,34)
Top-load machine	(18,28,29)
Both top and frontload machine	(22,23)
Both frontload and a pulsator machine	(21)
Information given about chosen wash program	(12,16,24,34,35)
Detergent	(5,12,35,14,16,21,24,26,28,29,33)

Only a few authors have studied the amount of water in washing machines and what impact it could have on the results. In addition, the ratio between water and textiles in the washing machine is not fully investigated. The ratio between water volume and fabric is according to Kelly 2019 (14) the most influential factor regarding to MF release. Kelly et al. even claim that this factor contributes to a greater extent of shedding than the agitation, as previously thought. On the other hand, details on agitation and rotations per minute (rpm) is mentioned by many, however it is not clear whether these authors consider this to have a significant role for the shedding or not.

Table 2. Number of revolutions, mentions of water volume and use of tumble dryer

Specific parameter	Author
Water volume mentioned	(5,14,21,23,29)
Tumble dryer used after washing	(16,28)
600 rpm	(11,16)
1000 rpm	(5)
1200 rpm	(12,23,24,34)
1400 rpm	(25,26,33)
1600 rpm	(35)

Another parameter where there is large variations between the different studies is the number of washes performed during the experiments. Since the majority does not mention the number of wash cycles, the assumption was drawn that they only have been washed once and that the results were based on this first wash. Those who have washed several times usually provide a more comprehensive statistical calculation on how the MF release appears after different numbers of washes. For example, Zambrano 2019 (28) studied how the MF release differed when the same material was washed 3 times. The result indicated that there was a consistent decrease in the number of MFs released with increasing number of washing cycles, however there was still a significant number of MFs released also during the third washing cycle. Kelly 2019 (14) pointed out that after four wash cycles, there were fewer MFs released compared wash cycle 1. Together with other authors (33), this strengthens the theory that the MF release seems to decrease when the number of cycles increases until it reaches a plateau around 5-10 cycles.

Table 3. Number of wash cycles

Specific parameter	Author
No of cycles 1	(11,19,22,23,35,36)
No of cycles 2	(12)
No of cycles 3	(28,33)
No of cycles 4	(14,25)
No of cycles 5	(5,26,33,34)
No of cycles 8	(35)
No of cycles 10	(16,24,29)
No of cycles 16	(35)

Yang 2019, Pirc 2016 och Belzagui 2019 (5,16,21) used a quick-wash program which can be appropriate if one only wants to compare different materials with each other. However, it can be problematic to use the results in a later comparison where average shedding from a commercial domestic washing machine is intended to be calculated. The main reason for this is that the total duration of most wash programs used in households are longer than 15 minutes. Belzagui (5) explained that the quick program was selected in order to save energy and water when the tests were performed. For De Falco 2019 (24) it was of great interest to simulate an ordinary household wash and therefore they used a regular synthetic program for 107 minutes. Laia Piñol 2015 (37) have compared different durations of common wash programs in home environment and showed in the study that domestic wash cycles usually last between one hour to two hours including rinsing. So, in our opinion, the authors that have been washing between 1-2 hours seem to simulate a home-wash in the most realistic way.

Table 4. Washing time

Specific parameter	Author
15 minutes	(5,16,21)
20 minutes	(29)
30 minutes	(22,23,25,35)
60 minutes	(33)
75 minutes	(26,34)
85 minutes	(35)
107 minutes	(24)

Furthermore, there are variations in the amount of shedding between the studies that have used different washing temperatures. Cotton 2020 (35) evaluated the shedding at two different temperatures 25 °C and 40 °C. The results confirmed what Yang 2019 (21) earlier pointed out; there is a significantly higher MF release at higher temperatures. The results showed that if the temperature was reduced, it could have a significant impact on the MF mitigation. Yang 2019 (21) indicates that decreasing the temperature from 60°C to 30°C could reduce the shedding up to 97%. Most studies were performed at a temperature of 40 °C, which is a commonly used washing temperature in Europe. As there are now newly published studies that point out that the shedding correlate with the temperature, it may be an idea to try to use the same temperature when performing tests in the future.

Table 5. Washing temperature

Specific parameter	Author
Temp no heating	(5,18,29)
Temp 25 °C	(35)
Temp between 30-40 °C	(22,23)
Temp ca 30 °C	(16,21,26)
Temperature ca 40 °C	(11,12,21,24–26,33–35)
Temp 46 °C	(28)
Temp 60 °C	(21)

Conditions/methods used during laundry- Lab-scale

When washing in Gyrowash or similar lab equipment (according to the standard ISO 105-C06:2010 as is commonly referred to), the results may in some cases be approximated by the results of up to five domestic or commercial launderings at temperatures not exceeding 70 °C (38).

Regarding the use of detergents when washing, the same argument applies in lab-scale as in commercial washing tests; detergents simulate the washing procedure in a more realistic way. However, there is still a risk for the filters to clog during the filtration process, since the filters used in lab-scale washing usually have a smaller pore size than those used in commercial washing machines. Petersson 2015 (15) argued that detergents with different alkalinity could affect the shedding but did not investigate this more closely due to that other issues in their study were considered as more important to examine. Among others, Carney Almroth 2017, Åström 2016 and De Falco 2018 (19,27,30), performed washing tests both with and without detergent. Their results confirmed the results from other studies that washed in full-scale machines (26,28) and indicated that washing with detergent increased the amount of shed fibers. In contrast, Kelly 2019 (14) showed that the detergent did not have any effect on the MF release. As with many parameters in the textile laundry studies, the relatively low amount of data and the diversity of reported values unfortunately makes our evaluation of the effects of the different parameters inconclusive.

Table 6. Type of lab-scale equipment and use of detergent

Specific parameter	Author
Gyro-wash equipment	(12,15,17,27,30,32)
Other lab-scale equipment	(14,19,20,28,31)
Detergent	(12,14,15,17,19,20,27,28,30,31)

Again, the water volume is considered to be of great importance according to Kelly 2019 (14) who especially investigated this parameter using a tergotometer. The conclusion of that study was that a higher water volume increased the MF shedding. They also indicated that a higher mechanical agitation did not affect the shedding as much as earlier thought.

Whether it matters using de-ionized (DI) water or not has not been investigated by any of the reviewed studies, but the majority uses DI water, probably to ensure that the water quality is always the same.

Many of the studies refer to ISO standard methods (38,39) developed for testing color fastness of a fabric. The methods have set parameters including water amount, time and temperature; therefore, it could simplify the comparison between different studies when they were conducted according to the standard.

Table 7. Type of water and water volume – Lab-scale

Specific parameter	Author
Water volume mentioned	(14,15,19,20,31,32)
Regular tap water used	(14)
Distilled water used	(12,19,28,31,32)
Tests are based on existing methods used for color fastness in lab-scale.	(15,19,20,27,31,32)

Similar as for the studies on commercial washing machines, the majority of articles do not mention the number of wash cycles, and again the assumption has been drawn that they only have been washed once and that the results are based on this first wash. Kelly 2019 compared the shedding between cycle 1 and 4 and saw that it was less shedding after the fourth wash than the first wash. However, this pattern was not as clear in lab-scale as in full-scale washing tests. In contrast, Hernandez 2017 (31) did not see any reduction in the shedding amount over more washing cycles, instead there was a steady average release regardless of the number of wash cycles.

Table 8. Number of wash cycles – Lab-scale

Specific parameter	Author
No of cycles: 2	(27)
No of cycles: 3	(20)
No of cycles: 4	(14)
No of cycles: 5	(27,31)
No of cycles: 10	(27)

The impact of different washing times is not fully investigated, however De Falco 2018 (19) drew the conclusion that that washing time together with a higher temperature and mechanical action affected the shedding and resulted in a higher level. On the other hand, Kelly 2019 (14) compared a 15 minute express wash to a 60 minute wash with the result that there were no significant difference in shed fibers. This could, according to Kelly, indicate that most fibers are shed during the first 15 min of the wash.

Table 9. Washing time – Lab-scale

Specific parameter	Author
15 min lab-scale	(14)
30 min lab-scale	(15,20,27)
45 min lab-scale	(12,19,31)
60 min lab-scale	(14,17,32)

As mentioned above, De Falco 2018 (19) reported that the relation between temperature, washing time and mechanical action could cause greater shedding if the parameters' values were increased. However, Hernandez 2017 (31) did not find any significant difference in the shedding when textiles were washed at different temperatures. Zambrano 2019 (28) who tested two different temperatures came to the same conclusion, i.e. that the temperature caused greater shedding, nevertheless there was no significant difference for the investigated polyester material. There are only a few studies that have examined the impact of different temperatures in lab-scale, thus, currently, it is not possible to draw any solid conclusions. Still, there is a clear picture that increased temperatures cause greater shedding in the full-scale washing tests and therefore it is reasonable to believe that it also applies for lab-scale testing.

Table 10. Washing temperature – Lab-scale

Specific parameter	Author
Temp 15 °C	(14)
Temp 25 °C	(28)
Temp 40°C	(12,17,19,20,28,31,32)
temp 60 °C	(15,19,27)
temp 75 °C	(19)

Correlations between wash parameters and MF shedding

It is clear from the summarized data above that there are great variations in parameters used in the different studies; for samples, pre-treatments as well as wash conditions. Thus, it is impossible to make clear comparisons of results as no study is like another and the amount of data for making statistically credible conclusions is simply too small. Nevertheless, there are indications of some trends when looking at the results from all the reviewed papers.

First, the values for MF shedding are higher for the experiments performed at lab-scale, indicating a harsher treatment compared to full-scale commercial washing machines. This could possibly be explained by the metal balls that are included to simulate a mechanical stress to the fabric (28). Both methods also indicate that there is a correlation between higher temperature and higher MF release. But, one thing that is a bit unexpected when comparing results from lab-scale and washing machine is the big difference in the increase of MFs between the two methods. De Falco 2018 (19) who washed in lab-scale concluded that increasing the temperature from 40°C to 60°C could increase the shedding with up to 40%. Yang 2019 (21) on the other hand who washed in a regular washing machine at same temperatures had an amazing increase of 1250 % between 40°C and 60°C. There could also be significant differences in the shedding between different commercial machine types, e.g. a top-loaded washing machine compared to a front-loaded machine. Hartline 2016 (23) compared the shedding amount in a front-loaded machine with a top-loaded and claims that that a top-loaded machine causes greater shedding. Their results actually indicate that a top-loaded washing machine can cause 7 times higher shedding than a front-loaded machine.

The results from using various wash temperatures and duration times are however inconclusive and, in some cases, even contradictory, which makes it impossible to draw any conclusions on these parameters. As an example; you can read that those who washed with a temperature at 40 °C and had an agitation of 1200 rpm varied the duration of the washing procedure between 30 to 107 minutes (23,24,34). So even if two parameters were similar, the third parameter (in this case washing time) varied a lot, which again made it difficult to compare the results. Also, the authors have not taken the rotating action (e.g. on/off agitation) during the wash cycle into consideration, which probably has a larger impact than the final spinning.

The use of detergent also seems to have an influence on the amount of MF shedding, leading to higher values. A higher MF release was confirmed when using detergent both in studies at lab-scale and in washing machines. According to De Falco 2018 (19) detergent could actually cause an increase of MF shedding with up to 2500 % when testing in lab-scale. Åström (30) also conducted tests in lab-scale, and although they saw an increase in the shedding, it was not as high numbers as De Falco 2018 presented. The results of Åström instead showed that detergent could cause an increase of shedding with up to 79%. Zambrano 2019 (28), on the other hand, found out that detergent could increase the shedding with up to 133%.

The correlation between water ratio and fabric in the washing machine is according to Kelly 2019 (14) another influential factor when it comes to amounts of MF shedding. At present, there is only this study that has evaluated this correlation and therefore it is hard to draw any conclusions. Finally, it is clear from the presented results that the amount of MF release will be higher during the first wash cycle and will successively decrease until it levels out around wash cycle 5-10.

Characterization of MPs/MFs

The MP/MF released during the washing experiments are afterwards collected in some way, and usually the first step is a filtration step. Table 11 and Table 12 show the pore size of the filters used by each researcher. The sizes are presented in increasing order. If any additional analysis tool was used to identify material or validate the number or type of MFs, this has been mentioned in the table under identification/validation equipment.

Filtration procedure

Those who only weight their filters will most likely have an error margin because of detergent residues, dust, or other polymeric particles as well as metal, glass and biological material that all can be present in textiles and will be included in the total weight.

As the quantities of MP/MFs are very small, it is a risk that this will result in a rather high overestimation. Even though weighing is an easy way to characterize MF shedding, the gravimetric method most likely does not give a correct picture of the shedding. The advantage of the gravimetric analysis is that it is a quick way of measuring.

When it comes to manual counting of fibers, there is a high risk of errors since the human factor will probably affect the result. Many studies mention that it is difficult to count the entire filter because it would take far too long time. Therefore, most studies have divided the filters into different sections and selected some to represent whole surface of the filter. The biggest advantage with manual counting is that no unwanted particles will be counted, for example, dust particles or detergent residues. Kelly 2019 (14) mentions that one of the biggest disadvantages, as with subsampling, is that MFs are rarely evenly distributed over the filter, therefore the results will probably not represent the actual number of shed MFs.

In addition to these two most used methods of estimating MFs, some have used automatic fiber counting analysis. They then analyze the filters in microscopes that are connected to a software program that can calculate fibers on the surface according to set settings. The method is considered as more reliable, as the margin of error with the human factor is minimized. Since there are set parameters according to shape and length of those MFs that should be included in the counting, the unwanted particles with incorrect shape are not included in the counting. In this way, dust or detergent residues will not be included in the counting. The disadvantage with automatic counting of fibers is that the software programs cannot count fibers that are put into bundles. At worst case scenario, many fibers may not be detected by the analysis program. This can, to some extent, be avoided since a manual examination of the filter surface is performed after the automatic counting. The operator can then manually count the fibers not included from the beginning in the automatic analysis.

Some studies have combined gravimetric analysis with counting. This can give a more realistic picture of the size range of the collected fibers and the actual numbers. However, automatic counting of fibers using an analysis program in combination with a gravimetric analysis should present the most trustworthy result according to number of shed MFs.

Table 11. Pore size of filters and method for quantification/identification – Full-scale washing machine

Pore size	Identification method	Identification/validation equipment	Author
0.7 µm	Weighted/Manually counted	Microbalance (Mettler Toledo XP56) and Optical stereoscopic microscope (Nikon SMZ-1B, magnification ×35)	(34)
1.2 µm **20 µm**	Weighted	OHAUS Champ bench scale	(28)
1.6 µm	Manually counted	-	(11)
5 µm	Manually counted	Optical stereomicroscope OLYMPUS SZ61	(21)
5 µm	Manually counted	Optical microscope Leica M80, software ImageJ (release 1.43u)	(19)
5 µm **20 µm** **60 µm** **400 µm**	Weighted	Scanning Electron Microscope (SEM) Quanta 200 FEG, (PH2O = 0.7 torr) Light microscope LEICA M205C	(24)
8 µm **63 µm**	Weighted	Analytical balance (Sartorius, ED124S)	(29)

500 µm			
10 µm	Manually counted	Light microscope Leica M80, Image-J analysis	(18)
20 µm **333 µm**	weighted	Photographed using a tripod mounted digital SLR camera (Nikon D3200)	(22,23)
20 µm	Manually counted	Stereomicroscope (Carton Stereo Zoom SC) and electronic microscope or SEM (PHENOM ProX Desktop)	(5)
20 µm	Weighted/Manually counted	Stereo microscope (Leica ZOOM 2000, 10,5x - 45x)	(25)
20-25 µm	Weighted	Scanning electron microscopy (JEOL, 7001F) Light microscope LEICA M205C, Image J analysis	(26)
50 µm		Microscope of model LRI, OLYMPUS BX53.	(33)
20 µm	Weighted	Renishaw InVia confocal Raman microscope, HPNIR laser of wavelengths 532 nm and 785 nm.	(35)
200 µm	Weighted	FTIR (Perkin Elmer, Spectrum One), Scanning electron microscopy (SEM, Carl Zeiss supra 35VP), stereomicroscopy (Leica DMS 1000)	(16)

Table 12. Pore size of filters and method for quantification/identification – Lab-scale

Pore size	Identification method	Identification/validation equipment	Author
0.45 µm	Manually counted	Digital Microscope, VHX Digital Microscope Multi Scan Lens	(31)
0.65 µm	Automatic counting	Optical microscope Leica DM4000M, software Cleanliness Expert v4.9	(32)
0.65 µm **5 µm** **100 µm**	Automatic counting	Optical microscopy technique with automatic fiber identification software	(17)
1,2 µm	Manually counted	Microscope with a magnification of 40 x	(30)
1,2 µm	Manually counted	Microscope, Carl Zeiss: 475002-9902	(15)
1.2 µm	Manually counted	Light microscope Carl Zeiss: 475,002–9902 Lyca with a magnification of 40×	(27)
1.2 µm	Manually counted	HiRes Fiber Quality Analyzer (FQA), OpTest Equipment Inc.	(28)
5 µm	Manually counted	Scanning electron microscopy	(19)
5 µm	Manually counted	Scanning electron microscope, SEM Quanta 200FEG, PH2O = 0.7 torr. Fourier transform infrared spectroscopy (FTIR). Optical microscope Leica M80.	(12)
8 µm	Dynamic Image Analysis (DIA)	Dynamic Image Analysis (DIA) Scanning electron microscope (JSM-5610 LV, Jeol).	(20)
20 µm **22 µm**	Calculating by using DigiEye	DSLR camera	(14)

As seen in Table 11 and Table 12, there are large variations regarding the pore sizes used in the filtration step. The biggest variation is seen in the washing machine studies, where the filters range from 0.7 µm - 500 µm. For the lab-scale tests the differences are somewhat lower; between 0.45 – 100 µm. Different studies will therefore collect and analyze different sizes of MFs, which will lead to difficulties when comparing results between different studies.

For example, McIlwraith (18) mentions that even though a small pore size was used when collecting fibers, it was not possible to count the fibers below 100 µm in length which was related to limitations in the analysis program used. Jönsson et al. (32) on the other hand were able to analyze fibers down to 5 µm, but actively chose to focus and count MFs ≥100 µm. At the same time, Pirc 2016 (16) mentions that the majority of fibers found in their study were in the order of 20–200 µm. If this is true and applicable to other studies, it means that studies that put the limit to ≥100 µm could possibly count only about half of the fibers.

Size distribution of MFs

Regarding size distribution, it is unfortunately the same pattern as for other types of results, i.e. there are large variations and no distinct trends when it comes to the values presented for fiber lengths and fiber length distributions. De Falco et al. (2019)(24) reported fibers in the range of 120-1500 µm when filters with mesh sizes of 5-400 µm were used. The fibers in the higher range were captured for the filters with larger mesh sizes, and vice versa. Sillanpää et al. (2017)(34), who used a very fine filter of 0.7 µm, stated that the fiber lengths were between 100 to 1000 µm. Pirc et al. (2016) (16) reported that most fragments were in the range of 20-200 µm with very few long fibers (max ca. 700 µm). The most surprising result was published by Napper et al. (2016)(26), who reported an average fiber length of collected fibers of 7.79 mm after using filters of a pore size of 20-25 µm.

Calculation of emissions

As mentioned previously, the type of samples and methods used vary significantly in the different studies, which makes it impossible to make reliable comparisons. All data is summarized below in Table 13 -Table 15, where the ranges of MFs are presented as the total range (from lowest presented value to highest) in the cited studies, independent of the conditions used in the experiments. To the greatest extent possible, the data will be presented as mg/kg, however many units have been used and, in some cases, there is only such data available.

Data in Table 13 and Table 14 concerns full-scale washing and Table 15 show results from lab-scale methods. At the end of this section, Table 16 will show more specific values, based on delimitations discussed and agreed with the client (APPLiA) which will result in a more narrow range of calculation of emissions. The delimitations are illustrated in Figure 1.

Table 13 Estimated amounts of shed MFs presented in Mg/kg. The presented values show the total range of presented values in the various studies – Full-scale washing machine.

Textile	Machine type	No of washes	Number of shed fibers [mg/kg]	Number of shed fibers – first wash [mg/kg]	Author
Fleece, anti-pilling fleece, softshell and technical sport shirts, 100% PET	Front-load	5	~200-3300	1200-3300 (0.12-0.33% w/w)	(34)
Interlock, 100% PET	Top-Load	3	~7[a]	~12[a]	(28)

30-50% synthetic fibers	Front-load		12-640		(10)[b]
T- shirts, 100% PET	Front-load	4	At 4th wash: ~46	85–205	(14)
Twelve t-shirts, dark colors, mixed material (CO/PET)	Front-load	16	At 8th wash: ~128 At 16th wash: ~87	~138	(35)
Blouse, GB, 100% PET (65% recycled)	Front-load	10		~49	(24)
T-shirt, BT, 100% PET	Front-load	10	30-40[c]	~125	(24)
T-shirt, RT, 100% PET	Front-load	10		~124	(24)
Fleece blankets, 100 % PET	Front-load	10	29-37[d]	80-210	(16)
T-shirts, 100% PET	Front-load	2[e]		93-157	(12)
Jacket D, 100% PET	Front-load	1		~210[f]	(23)
Fleece shirt, 100% PET	Household machine	4	~1150[g]		(25)

[a] Approx. values, taken from a graph.
[b] Review article based on five different studies, thus a broad range.
[c] Average value based on all 10 washes presented in the graph in Fig. 6.
[d] Average value based on all 10 washes and all three series.
[e] Two repetitions (not consecutive wash cycles), new garments were used each time
[f] Calculated by adding values of jacket mass recovered (in wt%) for 20 µm filter and 333 µm filter from Table S3.
[g] This is an estimation done according to the information given from the study that: *'The total microplastic fiber mass emitted was ≈ 1.09 g which corresponded to ≈ 0.46 percent of the garments initial weight.'* We assume that the estimated mass is the total mass from four washes, and thus divided the mass into four to be able to compare the results with other studies.

Table 14 Estimated amounts of shed MFs presented in different units. The presented values show the total range of presented values in the various studies – Full-scale washing machine.

Textile	**Machine type**	**No of washes**	**Number of shed fibers**	**Author**
Jacket D, 100% PET	Front-load	1	20 µm :3-242 mg/wash of 3 jackets	(22,23)
Jacket E, 100% PET	Front-load	1	20 µm: 171-236 300 µm: 87-500 mg/wash of 3 jackets	(22,23)
Jumper, 100% PET	Front-load	5	1st wash: 2.79 mg 5th wash: 1.63 mg	(26)
Blanket, 100% PET	Front-load	1	120 fibers/liter	(40)
Shirt, 100% PET	Front-load	1	160 fibers/liter	(40)
Fleece, 100% PET	Front-load	1	290 fibers/liter	(40)
Garments, 100% PET	Front load	5	30 000 fibers/m^2	(5)

Fleece, 100% PET	Front-load	1	143,1 mg/filter	(33)
Fleece, 100% PET	Front-load	3	70,2 mg/filter	(33)
Fleece, 100% PET	Front-load	5	61,5 mg/filter	(33)
Jacket, Patagonia D 100% PET	Top load	1	20 µm: 337- 580 300 µm: 690-1580 mg/wash of 3 jackets	(22,23)
Jacket, Budget D 100% PET	Top load	1	20 µm: 636-730 300 µm: 1014-1757 mg/wash of 3 jackets	(22,23)
Fleece, 100% PET	Top load	1	4040–5560 fibers/liter	(18)
T-shirt, 100% PET	Top load	10	5.640- 11.235 mg/wash	(29)
Plain weave, 100% PET	Front-load	1	386–19767 fibers/ m^2	(21)
Plain weave, 100% PET	Pulsator	1	799–24906 fibers/ m^2	(21)

Table 15 Estimated amount of shed MFs presented in different units. The presented values show the total range of presented values in the various studies – Lab-scale washing.

Textile	**Machine type**	**No of washes**	**Number of shed fibers**	**Author**
Fleece jersey, 100 % PET	Lab-scale	1	55098-123529 fibers/m^2	(17)
Fleece, 100 % PET	Lab-scale	1	58170-125948 fibers/m^2	(17)
Micro fleece, 100 % PET	Lab-scale	1	121242-167255 fibers/m^2	(17)
1, Fleece, 100% PET	Lab-scale	1	104200-131200 fibers/m^2	(27)
Microfleece, 100% PET	Lab-scale	1	111400-130600 fibers/m^2	(27)
2, Fleece, 100% PET	Lab-scale	1	87300-99100 fibers/m^2	(27)
Knitted, 100% PET	Lab-scale	1	200-1600 fibers/m^2	(27)
100% PET	Lab-scale	1	42533 fibers/m^2	(32)
Interlock, 100% PET	Lab-scale	1	4- 75 mg/kg**Fel! Bokmärket är inte definierat.**	(31)
Jersey, 100% PET	Lab-scale	5	5-25 mg/kg**Fel! Bokmärket är inte definierat.**	(31)
PEC, Plain weave, 100% PET	Lab-scale	1	12- 255 mg/kg	(19)
PEP, Double knit jersey,100% PET	Lab-scale	1	13–399 mg/kg	(19)

Jersey, 100% PET	Lab-scale	1	20–150 mg/kg**Fel! Bokmärket är inte definierat.**	(31)
Interlock, 100% PET	Lab-scale	5	25- 75 mg/kg**Fel! Bokmärket är inte definierat.**	(31)
T-shirts, 100% PET	Lab-scale	1	54–120 mg/kg**Fel! Bokmärket är inte definierat.**	(14)
T-shirts, 100% PET	Lab-scale	4	51–75 mg/kg**Fel! Bokmärket är inte definierat.**	(14)
T-shirt, 100% PET	Lab-scale	1	219 mg/kg	(12)
Workwear fabric, 50%PET/50%CO	Lab-scale	1	PET: 40- 62 fibers/g CO: 317+-35 fibers/g	(20)
100% PET	Lab-scale	1	1900- 7000 fibers/g**Fel! Bokmärket är inte definierat.**	(28)

Summary over overall assumptions of emissions from different studies

Bruce 2016 & Hartline 2016 (22,23) assumed that 100,000 people can release between 170 kg and 441 kg of MFs per day. Sillanpää (34) calculated the annual mass of polyester shedding from washing machines could be around 154 tons. Magnusson (10), who also estimated the weight of released MFs, presented numbers between 8-845 tons of MFs only in Sweden annually. Belzagui (5) who presented the number of fibers instead of the total weight assumed that the number of MFs reaching the oceans could be 1.4x1017 yearly.

Furthermore, De Falco 2018 (12) assumes that 549 913 MFs can shed from 1 kg of washed fabric in a washing machine. An earlier study from the same author (19) presented shed fibers in the range of 1 200 000-3 540 000 per kg of washed fabric or 0.516-1.524 g MFs per (6 kg) wash, i.e. 86-254 mg/kg. The latest study from the same author (24) shows numbers of shed MFs from 640 000 to 1 100 000 per kg of washed fabric depending of what fabric used. Zambrano (28) show results up to 500 000 fibers per kg of washed fabric. Napper (26) found out that PET can shed around 496 030 fibers per (6 kg) wash. Browne 2011 (40) on the other hand wrote that more than 1900 fibers can shed from each wash, a significant lower estimation than many other studies.

Cesa 2019 (29) estimated mean values of 18.400 and 69.600 fibers per wash cycle, and McIlwraith (18) numbers between 90,700 to 138,000 per wash cycle. Those amounts are way higher than 1900 MFs reported by Browne, but still closer to his results than to the other studies that estimate numbers of shed MFs to several millions per wash.

Another study that has investigated the MF shedding in a slightly different way is De Falco 2020 (41). They have investigated the amounts of released MF under wearing compared to the shedding when washing the garments. With some assumptions made in the report indicate that one person could release approximately 2.98 × 108 MFs per year by washing, and 1.03 × 109 to air by wearing the garments.

Approach to narrow down the range of released MFs

In order to narrow down the vast range of estimated numbers on MF release, some delimitations and estimations need to be made. In the current literature review, the focus is on:

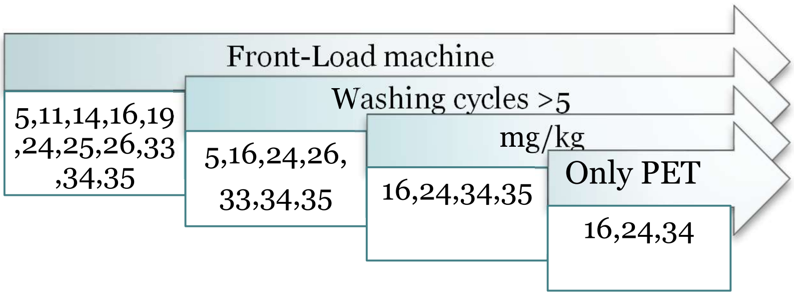
- Front-loaded, full-scale washing machines.
  We find that the data presented in such studies provides a more realistic representation of the actual shedding of MFs during textile laundry for households in Europe.
  (https://textilemission.bsi-sport.de/fileadmin/assets/bilder/Konferenz_in_Bruessel_10.12.2019/Prof._Ellen_Bendt_Hochschule_Niederrhein_Dec_10_2019.pdf, see slide 14)

- Only studies that present data from more than the first wash are included.
  As the data of MF release is much higher during the first wash cycle, which most likely is due to loose fibers from the manufacturing and transport etc., we find that data presented from only one wash cycle is unreliable.

- Only studies that present their results in mg/kg are included.

- Garments and fabric only consisting of 100 % PET are included.

Figure 1 Illustrated method of narrowing down the range of MFs



The range of released MFs are based on three different studies that fit the above criteria and the specific data, e.g., sample type, use of detergent, and pore size of filters from these studies are presented in Table 16 below. The data in Table 16 constitutes a broad range of overall shedding of MFs from textiles during laundry, which is approximated to be 20-500 mg/kg when the fabric has been washed 5 times, and when the values from the first wash are excluded from the calculation. Thus, although the studies have been selected according to the common features shown in Figure 1, there is still a large variation (a factor of 25) in the data. One reason for this is most likely depending on the pore size of the filter used, but also on other factors (differences) between the studies, such as different types of textiles and fabric construction, wash load, and the type of detergent or not, see Table 16.

Table 16 specific values, based on delimitations discussed which will result in a more narrow range of calculation of emissions.

Textile	Total no of washes	Wash load	Pore size [µm]	Detergent	Shed fibers at first wash [mg/kg]	Shed fibers at last wash [mg/kg]	Mean value all washes [mg/kg]	Mean value without 1st wash [mg/kg]	Author
Fleece blankets, 100 % PET	10	640 g	200	3 series; one without detergent, one with liquid detergent, one with both detergent and fabric softener	80-210	10.2-14.6	No detergent: 35.8 Detergent: 28.6 Detergent+softener: 37.2	No detergent: 2th -5th wash: 33.8 2th -10th wash: 21.9 Detergent: 2th -5th wash: 27.1 2th -10th wash: 20.9 Detergent+softener: 2th -5th wash: 29.1 2th -10th wash: 20.3	(16)
T-shirt, BT, 100% PET	5 and 10	2-2.5 kg	5-400	Yes, liquid	125	5th wash: 17 10th wash: 10	1st-5th wash: ~50 1st-10th wash: ~30.5	2th -5th wash: ~31 2th -10th wash: ~20	(24)
Fleece-AP, 100%PET	5	762.5 g	0.7	Yes, liquid	1200	~200	~500	~300	(34)
Fleece nAP,100%PET	5	740.3 g	0.7	Yes, liquid	1400	~500	~600	~400	(34)
Softshell, 96%PET, 4% EL	5	1097.2 g	0.7	Yes, liquid	2250	~200	~750	~375	(34)
Tech support, 100% PET	5	445.3 g	0.7	Yes, liquid	3300	~300	~1060	~500	(34)

Conclusion and Recommendations

Our findings from the literature review clearly show the great variations that have so far been used in experiments and characterization of MP/MF release from the textile laundry. The data is most often too small and too diverse to be able to draw reliable conclusions from. However, there are some trends or indications that can be made from the collected published literature. The first wash seems to result in a higher amount of MF released and it is thus important to perform experiments with several wash cycles. Parameters such as wash load and use of detergent also seem to have an effect on released MFs, where use of detergent and medium wash load seem to result in somewhat higher amounts of released MFs.

Overall, the lab-scale methods are more similar in the descriptions and the results from different studies are therefore easier to compare and evaluate when assessing the amount of shed MFs. However, lab-scale methods are not developed to simulate real life conditions but rather to compare different materials or construction parameters. Thus, both types of experiments (lab-scale and full-scale) are relevant but results from lab-scale should not be translated or extrapolated to simulate full-scale domestic washing machines.

The parameters and methods used for the full-scale domestic washing machines have varied a lot in the reviewed literature, as well as the units used to report the amount of released MFs. Thus, we have made some selections and limitations to narrow down the range of released MFs and to make the results more relevant for our case (real life conditions for domestic full-scale washing machines in Europe). Our estimation after making such choices, as well as our recommendation to not include the values of the MF release during the first wash cycle, is that roughly 20-500 mg/kg MFs are released from polyester textiles during laundry. The values of Pirc et al. (2016) and De Falco (2019) are in good agreement with each other and represents an estimation of ca 30-50 mg/kg MF release on average and reaching plateau levels of ca 10-15 mg/kg after ten wash cycles. However, for studies conducted with finer pore size of the filters, the values are much higher, and levels of ca 200-500 mg/kg are reported also after five wash cycles. One challenge with very small pore sizes is that also other substances get caught on the filter and therefore one can end up weighing more matter than the actual MP/MFs. Another challenge is that one often cannot filtrate the whole amount of liquid due to clogging of the filter which is also a factor of uncertainty. Given the challenges it is still clearly indicated that by using large pore sizes one does not catch all the MPs.

At present it is not advisable to extrapolate fiber shedding until the plateau is reached when investigating the impact from the washing machine. As yet, there is not enough data to conclude if a higher initial shedding leads to a higher plateau of a fiber shedding resulting in overall more shedding or if the plateau is just reached earlier leaving the long term shedding not affected.

Scenarios regarding emissions to water from laundry in Europe

Introduction

Using the range of emissions per kg laundered textiles from the literature review, scenarios to estimate the overall microplastics emissions coming from household washing to water in Europe could be developed. The following data and estimations were used for the scenarios:

- microplastics emissions per kg/laundered textiles
- estimated laundry per capita and year
- share of synthetics
- number of inhabitants in Europe
- percentage of combined sewer overflow/storm overflow (the part of the waste water not reaching the waste water treatment plants due to overflow in the system as heavy rain etc)
- average retention rate at the waste water treatment plants

Due to the uncertainties concerning some of the data a conservative approach was chosen. This is not to use any underestimated values or emissions.

Base data used in the scenario

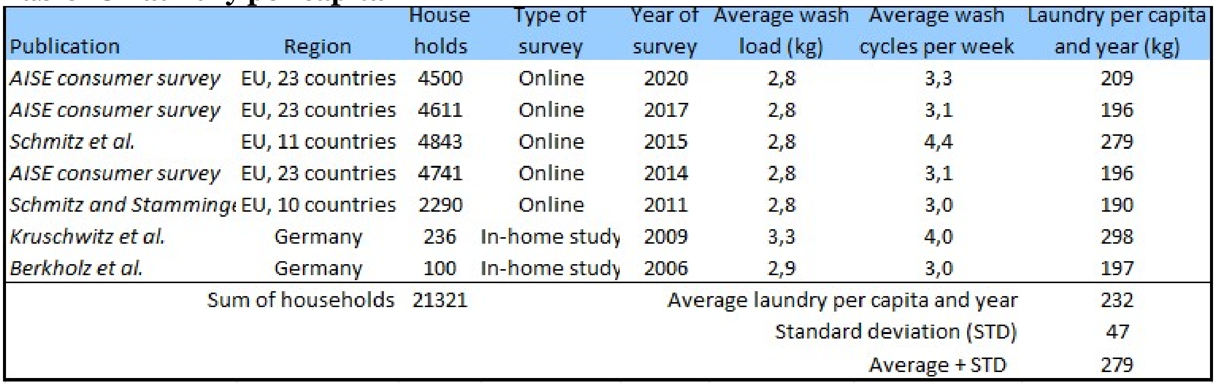
Table 17 Laundered synthetic textiles per year in EU Member States including the UK.

Base data		Unit
Laundry per capita and year	265	kg
Number of inhabitants in EU[1]	513 471 676	persons
Share of synthetics	55%	
Sum of laundered synthetics	74 838 500	tons

Estimation of laundry per capita

For the estimate on how much laundry per capita is washed annually within EU/Europe the following publications has been considered, see Table 18 below.

Table 18 Laundry per capita



Publication	Region	House holds	Type of survey	Year of survey	Average wash load (kg)	Average wash cycles per week	Laundry per capita and year (kg)
AISE consumer survey	EU, 23 countries	4500	Online	2020	2,8	3,3	209
AISE consumer survey	EU, 23 countries	4611	Online	2017	2,8	3,1	196
Schmitz et al.	EU, 11 countries	4843	Online	2015	2,8	4,4	279
AISE consumer survey	EU, 23 countries	4741	Online	2014	2,8	3,1	196
Schmitz and Stamminge	EU, 10 countries	2290	Online	2011	2,8	3,0	190
Kruschwitz et al.	Germany	236	In-home study	2009	3,3	4,0	298
Berkholz et al.	Germany	100	In-home study	2006	2,9	3,0	197
	Sum of households	21321		Average laundry per capita and year			232
						Standard deviation (STD)	47
						Average + STD	279

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[1] Using the number of inhabitants in EU Member States including the UK. (2019). https://ec.europa.eu/eurostat/databrowser/view/tps00001/default/table?lang=en

Note: Average wash load size for the online surveys was estimated from Statista's "Average load size of washing machines in 2014, by region". The references used for Table 18 can be found in Appendix A.

There were in principle no studies that contain all data needed for this estimation, only two smaller German studies from 2006 and 2009. Partial data from a number of extensive online studies was used, for example Schmitz et al.'s study, which involved questionnaire responses from 4843 households from 11 European countries, and A.I.S.E. commissions a pan-European survey's on consumer habits 2017, which included questionnaire responses from 4611 households, from 23 European countries. An estimate of average laundry machine load can be found in Statista's "Average load size of washing machines in 2014, by region" where Europe had a 2.8 kg result (Statista is a global provider of market and consumer data). This is consistent with the small local German study by Kruschwitz et al., which demonstrated 3.3 ± 0.8 kg (averaged over all household sizes).

The relatively old German studies from 2006 and 2009 was kept in the overall average calculation. This was done as they are in-home studies based on a monthly journal, which add another dimension to the on-line questionnaires, and still with consistent results. In conclusion, the average laundry per capita and year based on these six studies, with in total 16 821 participating households, an average of 224 ±42 kg was calculated. The highest value, 265 kg, is further used for the overall calculations in Table 19 and 20.

Estimation of percentage of synthetic fibers

Concerning percentage of synthetic fibers, this is a difficult number to estimate. The world production of fibres has seen a continuous increase in the share of synthetics, reaching its peak in 2015 and is today ca 62% of the market ("The Fiber Year 2019, World Survey on Textiles and Nonwovens", The Fiber Year GmbH.) However, this number cannot directly be translated to the share of synthetics in an average load of household wash since not all synthetic fibers produced are used for textile production. There are still also many households that have a larger proportion of cotton or other natural fibers. Of the 106.5 million tons of produced fibers, 41 million tons were textile filament yarns and it can be assumed that this is mainly for synthetic textile production (second largest category was short staple fibers (ca 35 million tons) which includes more of the natural fibers). Thus, the number of 55% share of synthetics in the scenario is considered to be a reasonable, however rough estimate.

Range of emissions

The values represent the range of average emissions of microplastics from the selected articles that met our criteria:

- front-loaded, full-scale washing machines
- more than one wash cycle
- data presented in mg/kg (or possible to re-calculate to mg/kg)
- garments and fabrics only consisting of 100 % PET

The range of microplastics emissions excluding the first wash from the articles that met our criteria is 20 - 500 mg/kg, see "Conclusion and Recommendations". The range of microplastics emissions including the first wash from the articles that met our criteria is roughly 30 - 1 060 mg/kg, see Table 16. Using the same base data (see Table 17) the high emission scenario shows approximately double the amount of emission, from 500 mg /kg up to 1 060 mg/kg.

Scenario 1- First wash excluded

Table 19, Excluding the first wash

Emissions to water - base scenario		Unit	Low emission scenario	High emission scenario
Emission from 1kg of laundered textiles		mg/kg	20	500
Annual fiber emission to wastewater		tons	1 497	37 419
Combined sewer overflow (SCO) incl storm water overflow	10%			
Emission to water from CSO		tons	150	3 742
Retention rate at WWTP	90%			
Emission after WWTP-treatment		tons	135	3 368
Sum of emissions to water		tons	**285**	**7 110**

From the Base data (Table 17) the amount of laundered synthetic textiles is 74 838 500 tons per year. Multiplying this value with the low range and the high range of emissions one gets the amount of annual fiber emission in tons discharged in the wastewater. However, not all wastewater reaches the wastewater treatment plants (WWTP) due to overflow in the systems. In this scenario we estimate that 10% of the emissions are not treated at the WWTPs. This means that, for the low emission scenario in Table 19, 150 tons reaches the recipient untreated. The WWTP has an estimated retention rate of 90% which means that the rest of the wastewater containing 1 347 tons (1497 -150 tons) of microplastics will be reduced to 135 ton. Finally, adding the 135 tons passing through the WWTPs to the 150 tons of untreated wastewater sums up to 285 tons of microplastic emissions to the water. The same calculation used in Table 20.

Scenario 2-First wash included

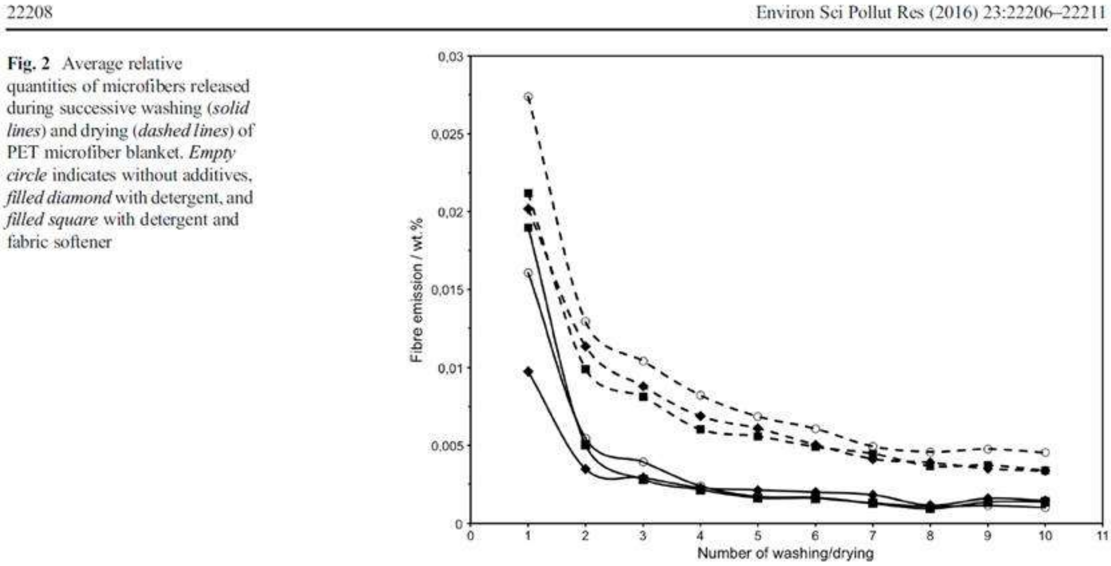
Table 20, Including the first wash

Emissions to water - base scenario		Unit	Low emission scenario	High emission scenario
Emission from 1kg of laundered textiles		mg/kg	30	1060
Annual fiber emission to wastewater		tons	2 245	79 329
Combined sewer overflow (CSO) incl. stormwater overflow	10%			
Emission to water from CSO		tons	224	7 933
Retention rate at WWTP	90%			
Emission after WWTP-Treatment		tons	202	7 140
Sum of emissions to water		tons	**425**	**15 075**

There are many reasons to the broad range of emissions, e.g. one factor that has a large impact on the results is the pore size of the filters used in the studies. There is also a general lack of information about the samples (type of fabrics, fabric construction) used in the different studies. It is also a reasonable hypothesis that many of the studies used a lower quality of fleece or weave to have enough mass to weigh.

The one study in the literature review that includes 10 wash cycles[2] had an average level of emissions of 29-37 mg/kg, depending on the use of detergent and/or fabric softener. It is therefore anticipated that the level of microplastic emissions will successively be lower after further wash cycles hence leading to a lower average, see Figure 2.

Figure 2. Excerpt from Pirc U, Vidmar M, Mozer A, Kržan A. *"Emissions of microplastic fibers from microfiber fleece during domestic washing", Environ Sci Pollut Res. 2016;23(21):22206–11)*



22208 Environ Sci Pollut Res (2016) 23:22206–22211

Fig. 2 Average relative quantities of microfibers released during successive washing (*solid lines*) and drying (*dashed lines*) of PET microfiber blanket. *Empty circle* indicates without additives, *filled diamond* with detergent, and *filled square* with detergent and fabric softener

Figure 2 show the quantity of released microplastics in w% after 1 to 10 consecutive washes (solid lines) and tumble drying (dashed lines).

However, the data is too limited to draw any conclusions about the long-term average. As the other studies do not include more than five washing cycles, the lower plateau level is yet to be investigated. The estimated 20-500 mg/kg of microplastic release (excluding the first wash) is considered to be a realistic range considering the great variation in the published data and is therefore used in the first scenario (see Table 19). Using the same analogy and including the first wash, the range of released microplastics is roughly 30 - 1 060 mg/kg (see Table 20). Including the first wash in the scenario is to be considered a very conservative approach since the high value from the first wash has a large impact on the average of five washes compared to the anticipated long-term average.

Combined sewer overflow / storm overflow

There is no published reliable study on storm overflow rates for Europe, 10% is a qualified estimation using a conservative approach with reference to the report "Plastics in the Environment"[3], contact with EurEau (European Federation of National Associations of Water Services)[4],The European Commission - Directorate Sustainable resources/Water and Marine Resources[5], The German Environmental Agency[6] and Swedish Water[7]. In Sweden and Germany the combined sewer overflow (CSO) is very low,

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[2] Pirc U, Vidmar M, Mozer A, Kržan A. "Emissions of microplastic fibers from microfiber fleece during domestic washing", Environ Sci Pollut Res. 2016;23(21):22206–11),

[3] https://www.umweltbundesamt.de/en/publications

[4] www.eureau.org

[5] https://ec.europa.eu/jrc,

[6] www.umweltbundesamt.de

[7] https://www.svensktvatten.se/om-oss/in-english/

within the range of 0,7-1,5%. However, in many European countries the storm overflow (precipitation - heavy rain runoff) and the CSO are discharged in the same pipes and therefore it is very difficult to find separate values. To be sure not to underestimate the emission of microplastics from textile laundry, a relatively high value of 10% was chosen even though the dominant part of the water in the CSO is storm water runoff.

Retention rate at WWTP

In our critical review regarding waste water treatment plants (WWTP) we came to the conclusion that 90 % retention is a representative value in line with the conservative approach. The results were based on 22 articles, see Appendix B. WWTPs has previously been suggested to be a significant source of microplastics to the environment. However, even though WWTPs are not optimized for microplastic removal, the different treatment steps in modern WWTPs are efficient also for removal of microplastics and microfibers. According to our recent literature review, a majority of the studies reported retention rates above 95% and in several cases up to 98-99%. Thus, the value of 90% retention rate can be considered a conservative estimate.

It should be noted that the methods used in the different studies (i.e. pore sizes of filters and analytical methods) does have an impact on the reported data and that a finer pore size generally results in a higher count of microplastics, and consequently a somewhat lower retention rate. On the other hand, data reported in studies without chemical characterization (visual count only) have a tendency to overestimate the amount of microplastics.

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The following papers and reports were included in the current literature review but are not cited in this document. More information about these papers can however be found in the appended Excel sheet.

- Book chapter that reviews an understanding of sources and pathways of microplastics (42)
- Information on sources and fate of microplastic particles in the aquatic and terrestrial environment, and on their uptake and effects, mainly in aquatic organisms, is reviewed (43)
- Estimation of the total number of plastic particles and their weight floating in the world's oceans from 24 expeditions across all five sub-tropical gyres (44)
- Environmental risk assessment done for microplastics (<5 mm) in the marine environment by estimating the order of magnitude of the past, present and future concentrations based on global plastic production data (45)
- The report provides an update and further assessment of the sources, fate and effects of microplastics in the marine environment, carried out by Working Group 40 (WG40) of GESAMP (The Joint Group of Experts on Scientific Aspects of Marine Protection) (46)
- Overview of numerical models, including their spatial and temporal resolution, limitations, availability, and what we have learned from them. Also focus on floating marine micro-plastics (<5 mm diameter) (47)
- Review of 68 studies comparing the methodologies used for the identification and quantification of microplastics from the marine environment (48)
- Review that critically evaluates the current literature on the presence, behavior and fate of microplastics in freshwater and terrestrial environments (49)
- Book chapter that critically reviews the literature on the effects of plastic ingestion on the bioaccumulation of organic chemicals, emphasizing quantitative approaches and mechanistic models (50)
- Focus on biodegradability of plastics and the challenges and misconceptions in the area (51)
- Presents a global model of plastic inputs from rivers into oceans based on waste management, population density and hydrological information. The model is calibrated against measurements available in the literature (52)
- Book chapter about microplastics in the marine environment and their distribution, interactions and effects (53)
- Book chapter about microplastics in the marine environment and their sources, consequences and solutions (54)
- Characterizing microplastics in sewage sludge from Norwegian domestic wastewater treatment plants applying different wastewater and sludge treatment technologies (55)
- Book chapter that reviews the methodology presently used for assessing the concentration of microplastics in the marine environment with a focus on the most convenient techniques and approaches (56)
- Report that reviews the current understanding of the occurrence, distribution and effects of microplastics on the marine environment (57)
- The paper critically reviews the state-of-the-science on microplastics types and particle concentrations in freshwater ecosystems, MP and nanoplastics uptake and tissue

translocation, MP/NP-induced effects in freshwater organisms, and capabilities of MP/NP to modulate the toxicity of environmental chemicals (58)

- Focusing on freshwater MP, the review briefly identify gaps of knowledge and deduce research needs (59)
- The Handbook of Environmental Chemistry : The authors explore the state of the science, including the major advances and challenges, with regard to the sources, fate, abundance, and impacts of microplastics on freshwater ecosystems (60)
- Authors use the largest dataset of microplastic measurements assembled to date to assess the confidence they can have in global estimates of microplastic abundance and mass (61)
- A review of the literature with the following objectives: to summarise the properties, nomenclature and sources of microplastics; to discuss the routes by which microplastics enter the marine environment; to evaluate the methods by which microplastics are detected in the marine environment; to assess spatial and temporal trends of microplastic abundance; and to discuss the environmental impact of microplastics (62)
- The atmospheric fallout of microplastics was investigated in two different urban and sub-urban sites (63)
- Review that summarize information on microfibers in seawater and sediments from available scientific information (64)
- Review about methods currently used for sampling and detection of microplastics in water and sediment, and identifying flaws in study design and suggesting promising alternatives (65)
- Study about framing the problem with microplastics emissions from household laundry from a socio-economic perspective (66)

Appendix

Appendix A: References used for Table 18:

Schmitz A, Alborzi F, Stamminger R. Large Washing Machines Are Not Used Efficiently in Europe. Tenside Surfactants Detergents. 2016;53:227-34.

Kruschwitz A, Karle A, Schmitz A, Stamminger R. Consumer laundry practices in Germany. International Journal of Consumer Studies. 2014;38.

Miilunpalo S-M, Räisänen R. Clean Laundry with Pure Conscience - A Study on Laundry Practices Among Finnish Consumers. International Journal of Consumer Studies. 2018.

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Appendix B. Table B1. Emissions of microplastics in the final effluents from waste water treatment plants (WWTPs).

Location	Treatment type	# of WWTPs	Analytical methods	Finest mesh (µm)	Effluent conc. (P/L)	Removal (%)	Reference
Sweden	Secondary	1	Visual/FTIR	300	0.00825	99.9	(Magnusson et al. 2014)
Finland	Secondary	1	Visual/FTIR/Raman	250	1	98.3	(Lares et al. 2018)[a]
Finland	Pilot: Tertiary, membrane bioreactor	1	Visual/FTIR/Raman	250	0.4	99.3	(Lares et al. 2018)
USA	*Secondary/Tertiary*	*12*	*Visual*	*125*	*0.004-0.195*		*(Mason et al. 2016)*
USA	Secondary	1	Visual/FTIR/Raman	125	0.023-0.2		(Dyachenko et al. 2017)
USA	*Secondary/Tertiary*	*8*	*Visual*	*125*	*0.024-0.19*		*(Sutton et al. 2016)*
France	*Secondary*	*1*	*Visual*	*100*	*14-50*	*83-95*	*(Dris et al. 2015)*
Scotland	Secondary	1	Visual/FTIR	65	0.25	98.4	(Murphy et al. 2016)
Canada	Secondary	1	Visual/FTIR	64	0.5	99	(Gies et al. 2018)
Italy	Tertiary	1	Visual/FTIR	63	0.4	84	(Magni et al. 2019)
USA	Secondary/Tertiary	7	Visual/FTIR	45	0.00088	99.9	(Carr et al. 2016)
USA	*Secondary*	*3*	*Visual*	*43*	*1-30*	*85.2-97.6*	*(Conley et al. 2019)*
Australia	Primary	1	Visual/FTIR	25	1.5		(Ziajahromi et al. 2017)
Australia	Tertiary	2	Visual/FTIR	25	0.21-0.28	>90	(Ziajahromi et al. 2017)
China	n.a.	11	Visual/FTIR	25	3.6-13.6	89.2-97.2	(Xu et al. 2019)[b]
Russia	*Mech. treat. & purification*	*1*	*Visual*	*20*	*16 fibers, 7 synth. part. and 125 black part.*	*96*	*(HELCOME 2014)*
USA	*Secondary*	*1*	*Visual*	*20*	*5.9*	*95.6*	*(Michielssen et al. 2016)*
USA	*Tertiary*	*1*	*Visual*	*20*	*2.6*	*97.2*	*(Michielssen et al. 2016)*
USA	*Pilot: Tertiary: anaerobic membrane reactor*	*1*	*Visual*	*20*	*0.5*	*99.4*	*(Michielssen et al. 2016)*
Finland	Tertiary	1	Visual/FTIR	20	0.7-3.5	92-99.1	(Talvitie et al. 2017b)
Finland	Tertiary	4	Visual/FTIR	20	0.005-0.3	40[c]-99.9	(Talvitie et al. 2017a)
Germany	Secondary/Tertiary	12	Visual/FTIR-imaging	20	0.01-9	Up to 97	(Mintenig et al. 2017)
France	Tertiary	1	Visual/Raman	20	2.84	98.8	(Kazour et al. 2019)
Denmark	Secondary/Tertiary	10	Visual/FTIR-imaging	10	54	99.3 (98.3 by weight)	(Simon et al. 2018)
Netherlands	Secondary/Tertiary	7	Visual/FTIR	0.7	51-81	72	(Leslie et al. 2017)
Spain	Secondary	1	Visual/FTIR	0.45 (paper filter)	0.31	90.3	(Bayo et al. 2020)

[a] Include all textile fibers, incl. natural fibers

[b] The WWTPs in this study include both domestic and industrial sources

[c] The low retention value of 40% relates to results after disc filter filtration, all other treatments resulted in retention values above 95%

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