A Comprehensive Literature Study on Microfibres from Washing Machines

The ubiquitous finding of microplastic in the abiotic and biotic environment has gained a lot of attention recently in the media, scientific community and among the general public. One of the known sources of microfibres is the washing of textiles. It would be a conceivable option to install filters in domestic washing machines that would silt out microplastics to prevent this pollution. The aim of this paper was to conduct a comprehensive literature search on microplastics filters in washing machines published already. Although the results of this research show that there has been an effort to find solutions for this problem in a worldwide context, there has been no known proven system that prevents microfibre release in the aquatic environment which does not have a harmful influence on the washing behaviour and/or washing results.

Key words: Micro plastic, textile laundry, filter systems, washing machines


Stichwörter: Mikroplastik, Textilwäsche, Filtersysteme, Waschmaschinen

1 Introduction

The total amount of plastics produced has increased rapidly since its mass production in the 1940s. A recent publication estimates that a total of 8,300 million tons (Mt) of virgin plastics not previously used or consumed have been produced so far. The world’s plastic production was 335 Mt in 2016, while Europe (European Union including Norway and Switzerland) produced 60 Mt [1].

Thompson estimated that 10% of the plastic debris ends up in the sea [2]. It was calculated in 2010 that 4.8 to 12.7 Mt of the total amount of 275 Mt plastic waste ended up in the ocean. Waste management systems are also a crucial parameter for the amount of plastic entering the ocean. However, these figures only reflect assumptions as no exact numbers are available [3].

Depending on the size, plastics and the corresponding degradation products (debris) are classified as mega-, macro-, meso- or microplastics. It is important to note that the definitions of plastic sizes are not standardised in a worldwide context.

There is also no common definition of microplastic in scientific research. Which size is defined as microplastic depends on the author. As a result, studies are not comparable. Barnes et al., for example, use the size of < 5 mm [4], but Browne et al. use < 1 mm [5] to define microplastic.

The European Commission (EC) recently defined microplastic as particles < 5 mm of water-insoluble macromolecular plastic (Decision (EU) 2017/1218). The processes by which the microplastic is obtained are also defined in the same decision: (a) a polymerisation process, such as polyaddition or polycondensation, or a similar process using monomers or other starting substances; (b) a chemical modification of natural or synthetic macromolecules; or (c) microbial fermentation. The lower size threshold is defined by the term “nanomaterial”, which means a natural, incidental or manufactured material containing particles in an unbound state or as an aggregate or agglomerate, and where one or more external dimensions for 50% or more of the particles in the number size distribution is in the size range 1 nm–100 nm, as stated in the same decision.

In addition, a distinction is made between primary and secondary microplastics. Primary microplastics are intentionally made for a specific purpose, for example, those used by the cosmetics industry as scrubbing particles [6]. Secondary microplastics are caused by the breakdown of larger plastic parts in the environment. This breakdown can be caused by chemical, physical or biological degradation or a combination of all three [7].

The EC adopted the first-ever Europe-wide strategy on plastics at the beginning of 2018 [8]. Under the new plans, it is foreseen that all plastic packaging on the EU market will be recyclable by 2030. The consumption of single-use plastics will also be reduced and the intentional use of microplastics (primary microplastics) will be restricted.

Significant sources of microplastic emission in Europe are (not sorted) washing of synthetic textiles, automotive tyre and brake wear, paint flakes and coatings, and pre-production plastics (pellets) [9].

Synthetic textiles fibres are, among others, polyamide fibres, polycrylonitrile, polyethylene terephthalate, modacryl fibres, polyesters, polyvinylchloride fibres and polyurethane/elastane fibres. Polyester dominates the market of synthetic fibres. Some 5,000 t of synthetic fibre was produced worldwide in 1940. By 2015, this amount had increased to 62.9 Mt. [10]

As of today, the impact of microplastics on the environment and especially on living organisms is the centre of intensive research worldwide. One reason for this interest has been the ubiquitous and persistent spread of microplastic in the oceans since the 1950s [11].
The “Joint group of experts on the scientific aspects of marine environmental protection” published two reports on the global assessment of sources, fate and effects of microplastic in the marine environment [11, 12]. As highlighted in this text, microplastics have been reported in more than 100 species and a lot of habitats. In addition, microplastics influence organisms at several levels: the sub-organic level (i.e. changes in gene expression, inflammation, tumour promotion) and at the level of biological organization (e.g. populations and assemblages).

It is also known that microplastics can be a source and sink of hazardous chemicals, as it has been shown that many chemical and toxic pollutants are bound to microplastic [13]. The effect of this in combination with other sources, such as water, sediment and diet, is currently under research. Pathogens, similar to chemicals, can also bind to microplastics and be carried by this binding over long distances [14].

It is generally known that the individual risk after exposure depends on several factors [11, 12]:

- Properties of the particles: Number, size distribution, shape, surface properties, polymer composition and density;
- Duration of the exposure;
- Kinetics of absorption and desorption of contaminants; and
- Individual biology of the organism affected.

The ubiquitous occurrence and the possible toxicity of microplastics prove that there is action needed to prevent and reduce microplastics and microfibres from polluting the environment.

The rise of plastics since the 1950s has brought many positive aspects for our everyday life. However, the environment has also been affected by this due to widespread pollution that impacts wildlife and ecosystems. Once plastic is in the environment it undergoes degradation leading to very small particles, also called debris. In the case that the debris size is <5 mm, it is called microplastics, as defined by the EC. The respective toxicity and environmental fate of microplastic is currently under scientific research.

Domestic washing, among others, is a source of microplastics, especially microfibres. There is no mechanism or component that is designed to prevent the emission of microplastics to surface water in the domestic washing machines currently used. The graphic overview of the content of this literature research is shown in Fig. 1. The goal of this paper is highlighted with question marks: Elaboration of a comprehensive review of scientific publications on microfilters already used in washing machines.

2 Methodology

This literature review was made following the guideline “Submission of scientific peer-reviewed open literature for the approval of pesticide active substances under Regulation (EC) No 1107/2009”, as published by the European Food Safety Agency [15].

2.1 Development of the protocol for the literature review

The first core step of the review is “developing the review protocol (including defining and refining the review question and developing the eligibility criteria for studies)” [15]. For this, the objective of the review is clarified, the criteria for studies relevant to the dossier are defined and a list of all relevant criteria is provided.

2.1.1 Clarify the objective of the review

At first, the problem is formulated: This review should cover all significant information linked to microfibres in domestic washing machines. Therefore, the following topics should be taken up.
● A comprehensive review of studies that deal with microfibres for use in washing machines.

In this context the following topics are also addressed, but no individual literature research was undertaken:

● A review of studies that deal with the amount of microfibres which occur during washing in washing machines.

● The spread of microfibres in the environment.

● Evidence for the effects of microfibres.

2.1.2 Define the criteria for studies relevant to the literature research

Common criteria for the inclusion or exclusion of scientific literature are language (mostly restricted to English), publication type and time span.

Only peer-reviewed publications were considered in this part of the review, thus, conference papers, talks, thesis and other grey literature are not included. In addition, no time span was specified, so that the individual time limits of the databases were used.

2.2 Searching for research studies

In this step, the sources (databases) of scientific literature are identified and the reasons why those were chosen are clarified. Search strings were developed for these databases. This was done using Boolean operators that connect the search terms/topics logically. The term “OR” was used to connect synonyms, for example, “domestic OR household”. The term “AND” was used when different search term topics were connected, for example, “washing machine AND fibre/fiber”. The total search processes were documented for each database, as seen in the next chapters.

2.2.1 Identify sources and establishment of search terms/strings

The purpose of this search is not only to find scientific publications that contain technical data on a possible microfiber filter, but also to determine the environmental impact of the microfibres. Consequently, PubMed, ScienceDirect and Web of Science were used as databases for the literature research.

In addition, a supplemental literature research step was included to identify literature that is not covered by the search databases. The search terms were recognised at step one by problem formulation. Starting by looking for the combination of search terms/topics logically. The term "AND" was used when different search term topics were connected, for example, “washing machine AND fibre/fiber”. The total search processes were documented for each database, as seen in the next chapters.

2.2.1.1 PubMed

PubMed, as highlighted on the internet page, is a non-commercial database that accesses the MEDLINE database of references and abstracts on life sciences and biomedical topics. The database is provided by the National Library of Medicine at the American National Institutes of Health. It covers mainly publications that were published after 1966, but also has a few earlier entries.

The search in PubMed was not restricted by title or abstract, thus, the full content was screened. Additionally, the time span was not further restricted.

The following search string was developed:

Search string:

(wash OR washing machine OR washing machines OR domestic OR household OR laundry)
AND
(filtration OR filter OR sieve OR experiment OR evaluation OR forensic evaluation OR forensic)
AND
(microplastic OR plastic OR fiber OR fibre OR debris OR polymer OR cloth OR textile)
AND
(effluent OR emission OR pollution OR water OR waste water OR refuse OR disposal OR marine environment)

2.2.1.2 ScienceDirect

In contrast to PubMed, ScienceDirect is a commercial database maintained by Elsevier. However, the search itself is free and titles and abstracts are accessible. It covers four main topics: physical sciences and engineering, life sciences, health sciences, and social sciences and humanities. When ScienceDirect was searched, the search was limited to the title, abstract and key words (TITLE-ABSTR-KEY). No time span was used for the other databases. The following search string was developed:

Search string:

TITLE-ABSTR-KEY (wash OR “washing machine” OR domestic OR household OR laundry)
AND
TITLE-ABSTR-KEY (filtration OR filter OR sieve OR experiment OR evaluation OR “forensic evaluation” OR forensic)
AND
TITLE-ABSTR-KEY (microplastic OR plastic OR fiber OR fibre OR debris OR polymer OR cloth OR textile)
AND
TITLE-ABSTR-KEY (effluent OR emission OR pollution OR water OR “waste water” OR refuse OR disposal OR “marine environment”)

2.2.1.3 Web of Science

Web of Science is a commercial scientific database provided by Clarivate Analytics. The database itself provides access to multiple other databases from a broad spectrum of cross-disciplinary research (it supports 256 disciplines). Web of Science offers to restrict the search to topic terms (TS), which means that the title, abstract, author keywords and Keywords Plus® are researched. The time was not further restricted, thus, the Web of Science time span was observed starting from 1945. The following search string was developed:

Search string:

TS = (wash OR washing machine OR washing machines OR domestic OR household OR laundry)
AND
TS = (filtration OR filter OR sieve OR experiment OR evaluation OR forensic evaluation OR forensic)
AND
TS = (microplastic OR plastic OR fiber OR fibre OR debris OR polymer OR cloth OR textile)
AND
TS = (effluent OR emission OR pollution OR water OR waste water OR refuse OR disposal OR marine environment)
The most relevant studies and reviews were also used as a starting point for the search for relevant publications. The corresponding reference lists were checked for additional references that were not found in the search. These were added to the Endnote library.

### 2.2.1.5 Identification by google scholar

The most relevant studies and reviews were also used as a starting point for the “cited by” feature. In the case that these cross-referenced papers were also of relevance for the literature review, the publication was added to the Endnote library.

### 2.2.2 Exclusion and inclusion criteria

The following inclusion and exclusion criteria were used to clarify the objective of the review protocol (Table 1).

### 2.3 Data management

The publications identified were exported into a “My EndNote” library. Subsequently, double entries were removed by using the feature “find duplicates”. This was followed by a manual duplicate removal, as the implemented feature alone does not find all the duplicates. The unique publications identified were then exported into an Excel list in which the following parameters were covered: Author(s), year, title and source.

The unique publications identified were then selected for their relevance in three subsequent rounds: (1) first by title, (2) then by abstract and (3) for their content. The exclusion criteria are shown in Table 1.

<table>
<thead>
<tr>
<th>Inclusion criteria</th>
<th>Exclusion criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Studies that cover filtration of microfibers/plastics in domestic washing machines</td>
<td>Wastewater from other sources than domestic</td>
</tr>
<tr>
<td>Studies in context to prevent domestic fibre pollution</td>
<td>Studies with pollution other than microfibers</td>
</tr>
<tr>
<td>Studies that describe the washing machines’ wastewater experiment</td>
<td>Filters that were not investigated for use in washing machines</td>
</tr>
<tr>
<td></td>
<td>Studies that focus only on the environmental impacts of microfibers</td>
</tr>
<tr>
<td></td>
<td>Studies published in languages other than English</td>
</tr>
<tr>
<td></td>
<td>Not relevant, because of another topic</td>
</tr>
</tbody>
</table>

Table 1 Inclusion and exclusion criteria applied in this search

### 2.2.1.4 Identification by citation in reviews

A considerable number of reviews were found in the initial search for relevant publications. The corresponding reference lists were checked for additional references that were not found in the search. These were added to the Endnote library.

### 3 Results

#### 3.1 Results of the study selection

The searches through PubMed and ScienceDirect found 302 and 384 references, respectively. The search through Web of Science identified a relatively larger number of 974 references. Therefore, a total of 1,660 publications were found and were all subsequently imported into a My EndNote library. A total of 428 publications were removed as duplicates by using the “find duplicate” feature of the programme and a consecutively performed manual duplicate elimination.

The decision tree of the literature research is shown in Fig. 2. The three data bases are shown highlighted in the boxes in the upper part of the figure, with the respective number of publications identified. The individual exclusion steps are shown in there boxes on the right side of the figure. A total of 1,232 publications were then assessed for the relevance of their title alone in a first selection step. This step led to the exclusion of 1,068 publications. The screening of the publications by abstract led to the exclusion of 120 more publications. Thus, only 44 relevant publications were screened for their full content. No publication passed all inclusion and exclusion criteria when the full content was screened.

As it has already been explained, the literature search found no publication that was of relevance regarding the research question: Are there any scientific publications on microfilters already used in washing machines designed for domestic use? However, many of the publications excluded covered similar topics. The respective exclusion criteria and the corresponding number of publications found are presented in Table 2. As shown, most of the publications excluded covered wastewater from other sources than washing machines. Those included wastewater from the dye industry, houses, salmon breeding and research institutions. Around 200 publications covered pollution other than microfibres, for example, organic dyes and solids. Another 177 publications focused on filters that were not utilised in washing machines, but in factories or houses, etc. Only a small number of publications (21) focused on the environmental impacts of microfibres. For more information on the individual publication plase refer to the link in footnote 1.

#### 3.2 Results of other sources

Google was also considered as an additional source in the context of this literature research in addition to the “traditional” literature search through databases such as PubMed. The search terms used were “European Commission microplastic study”, “UN microplastic study”, “Microplastic washing machine”, “Washing machine microfibre filter” and “Separating microplastics from water”. These terms were generally less focused that those used in the databases. A total of nine additional publications/reports were relevant.

Three of the publications only deal with the impact of microplastics on the environment. Consequently, they do not address any system for reducing release by a microfilter in washing machines (exclusion criteria 4). These publications are:

1. “Marine plastic debris and microplastics – Global lessons and research to inspire action and guide policy change” [16].

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1 A list of all references found can be downloaded from https://www.landtechnik.uni-bonn.de/forschung/haushaltstechnik/projekte/microfibre


Two search results are products which are supposed to reduce the microfibre pollution of textiles in washing machines. These systems are not filters per se but are washed with the textiles (Criteria 2). These products are:
1. Cora Ball™
2. Guppyfriend™

One search result investigated the options for reducing the environmental pollution by microplastics but did not address a system for reducing the release by washing machines (Criteria 3). This result is:
1. “Investigating options for reducing releases in the aquatic environment of microplastics emitted by (but not intentionally added in) products” by ICF and Eunomia (consultants).

One result is a mix between criteria two and one:
1. “PolyGone Technologies”

This system is not currently available, but the filter presented will be attached to the washing machine and supposed to prevent microfibre emissions arising from domestic washing (Criteria 5).

Another result is also a filtering system which is designed for washing machines and should clear the water of microplastics and fibres (Criteria 1).
1. Filtrol 160™ Lint Filter

Finally, a biomimetic filter system is proposed in the master thesis by Leandra Hamanns, entitled “A biomimetic Approach for Separating Microplastics from Water” that aims at separating microplastics from water. The system is based on the silk net-spinning larva of the caddis fly.

4 Discussion

A significant strength of this search is that it serves as a comprehensive systematic literature review of microfibre filters in domestic washing machines. As far as the author knows, this is the first research of its kind.

In addition, the literature review protocol is documented in such a way that the research itself can be reproduced at a later point in time. The documentation also involves the individual references, which are all documented in the list, which can be downloaded via the link given in footnote 1.

In this list, the individual reasons for in/exclusion are shown with the aim of transparency.

<table>
<thead>
<tr>
<th>Exclusion criteria</th>
<th>Number of publications excluded</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Wastewater from other sources</td>
<td>797</td>
</tr>
<tr>
<td>2. Pollution other than microfibres</td>
<td>200</td>
</tr>
<tr>
<td>3. Filters not investigated for washing machines</td>
<td>177</td>
</tr>
<tr>
<td>4. Environmental impact of microfibres</td>
<td>21</td>
</tr>
<tr>
<td>5. Another topic</td>
<td>29</td>
</tr>
<tr>
<td>6. Language other than English</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 2 Number of publications excluded sorted by exclusion criteria.

Figure 2 Decision tree of the literature research. The three data bases are shown in the boxes in the upper part of this figure with the respective number of publications identified. The individual exclusion steps are shown in the boxes on the right side of the figure.

2 https://coraball.com/
3 http://guppyfriend.com/
4 https://www.polygongnetologies.com/
6 Accessible via http://publica.fraunhofer.de/eprints/urn_nbn_de_0011-n-3997875.pdf
A second important strength of this research is the long history which was used for the searches. No cut-off criteria for the time frame was defined for any of the databases. This results in the fact that the research also includes references dating back to the starting date of each database. In other words, no relevant reference was excluded by a temporal criterion.

A limitation of this search is the focused search protocol. The goal of this literature research was to identify available filters that prevent microfibre pollution by domestic washing machines. This question was translated in a fourth step search string. Consequently, a relatively low number of relevant references were found and irrelevant references were not identified. A focused search like this also risks that partly relevant publications are not identified in the first place. A focused search string like this also risks that partly relevant publications are not identified in the first place.

A search in Science Direct, for example, with a less focused search string. Consequently, a relatively low number of relevant references were found and irrelevant references were not identified. A focused search like this also risks that partly relevant publications are not identified in the first place. A focused search string like this also risks that partly relevant publications are not identified in the first place.

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synthetic textiles fibres as a source of environmental microplastic pollution [24]. The individual textile samples were washed according to ISO 105-C06 standard protocol for washing coloured fabrics. However, the author used sample sizes of 10 × 10 cm instead of 10 × 4 cm. Samples were washed at 60°C for 30 min, individually in separate containers in the Gyrowash. The washing machine wastewater was filtered. In this case a Whatman® glass microfibre filter (grade GF/C), as described by [18], was also used, with the exception that in this case a pore size of 1.2 μm instead of 1.6 μm was used. The author found that fleece (as an example of loosely constructed yarn) shed more. This was also observed for worn fabrics. The author recommends smarter textile construction, prewashing and vacuum exhaustion at production sites, and the use of more efficient filters in households washing machines to reduce shedding.

Pirc et al. characterized the emission of microplastic fibres from microfibre fleece during domestic washing [25]. The authors used an external, removable disk-shaped stainless-steel filter with a diameter of 85 mm and openings of 200 × 200 μm. The average relative fibre emission was determined utilizing this custom-built system. This was done for three washing styles: no additives, detergent and both detergent and softer. The washing experiments at 30°C and 600 rpm lasted 15 min.

As a result, the author states that most of the fibres identified ranging in size between 20 and 200 μm were caught. In the context of the three different washing styles, the author concludes that there is a relatively small effect. However, only microfibre fleece was washed in this study. Thus, the study is only of limited value, since this is not realistic for domestic washing. In the case that a more realistic set up (e.g. washing of various textiles) was chosen, this could affect the filter and, therefore, also the amount and type of pollution. Nevertheless, this publication shows that it is possible to filter microplastics out of wastewater stemming from domestic washing machines.

Hartline et al. measured the emission of microplastic fibres from various synthetic garments during domestic washing [26] by comparing new and aged garments (prepared according to the individual manufacturer’s protocols).

Two kinds of washing machines were compared: top-loading and front-loading machines. In the case of the top-loading machine (43 L capacity), the washing programme involved a 29.6°C warm cycle: 12 min wash, 14 min rinse and 4 min spin (30 min in total). A total volume of 136 L output water was collected. The washing programme of the front-loading machine (45 L capacity) consisted of a 29°C–41°C warm cycle of 24 min in total, consisting of 8 min wash, 10 min rinse and 6 min spin at 1200 rpm. A total of 36 L of output water was collected. The textiles (jackets) were washed one at a time and without detergent. The fibres released and captured were of two size classes (> 333 μm or between 20 and 333 μm). This involved Nitex®

<table>
<thead>
<tr>
<th>Author</th>
<th>Publication</th>
<th>Year</th>
<th>Definition used</th>
<th>Matrix</th>
<th>Sampling</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Browne</td>
<td>Accumulation of microplastics on shorelines worldwide: sources and sinks</td>
<td>2011</td>
<td>&lt;1 mm</td>
<td>Sediment</td>
<td>1.6 μm Whatmann GF/A, according to Thompson et al., 2004</td>
<td>Attenuated total reflectance/Fourier transform infrared spectroscopy</td>
</tr>
<tr>
<td>Klein</td>
<td>Occurrence and spatial distribution of microplastics in river shore sediments of the Rhine-Main area in Germany</td>
<td>2015</td>
<td>&lt;5 mm</td>
<td>Sediment</td>
<td>Sieves (mesh size 63, 200 and 630 μm), 1.6 μm Whatman GF/A, according to Thompson et al., 2004</td>
<td>Attenuated total reflectance/Fourier transform infrared spectroscopy</td>
</tr>
<tr>
<td>Besseling</td>
<td>Microplastic in a macro filter feeder: humpback whale (Megaptera novaeangliae)</td>
<td>2015</td>
<td>&lt;5 mm</td>
<td>Gastrointestinal tract samples of a female humpback whale (Megaptera Novaeangliae)</td>
<td>Sieves (mesh size 1 and 0.5 mm), Double washing bag (inner mesh size 300 μm and outer 120 μm), according to Bravo Rebollo et al., 2013 [23]</td>
<td>Fourier transform infrared spectroscopy</td>
</tr>
<tr>
<td>Castro</td>
<td>Evaluation of microplastics in Jurujuba Cove, Niterói, RJ, Brazil, an area of mussel farming</td>
<td>2016</td>
<td>&lt;5 mm</td>
<td>Sea water</td>
<td>Plankton net (Conical-cylinder with a 40 cm opening, 150 μm mesh &amp; length of 1.5 m)</td>
<td>Attenuated total reflectance/Fourier transform infrared spectroscopy</td>
</tr>
<tr>
<td>Carney</td>
<td>Quantifying shedding of synthetic fibres from textiles; a source of microplastics released into the environment</td>
<td>2017</td>
<td>unclear</td>
<td>Gyrowash wastewater with detergent</td>
<td>Whatman® glass microfibre filters (grade GF/C, 1.2 μm)</td>
<td>Light microscope, magnification ×40</td>
</tr>
<tr>
<td>Almroth</td>
<td>Microfiber masses recovered from conventional machine washing of new or aged garments</td>
<td>2016</td>
<td>&lt;5 mm</td>
<td>Washing machine wastewater without detergent</td>
<td>Plankton net (Nitex® 52 nylon filters, &gt; 335 μm &amp; 20 μm)</td>
<td>Photograph (processing &amp; analysis by ImageJ)</td>
</tr>
<tr>
<td>Pirc</td>
<td>Emissions of microplastic fibres from microfiber fleece during domestic washing</td>
<td>2016</td>
<td>&lt;5 mm</td>
<td>Washing machine wastewater with detergent</td>
<td>Removable disk-shaped stainless-steel filter (diameter of 85 mm, openings of 200 × 200 μm)</td>
<td>Gravimetric</td>
</tr>
</tbody>
</table>

Table 3 Comparison of different definitions, techniques and tools used by the authors to sample microplastics
52 nylon filters manufactured by Aquatic Research Instruments. These filters were originally used for the quantitative plankton analysis and allow vertical and horizontal towing applications. The fibres were then analysed regarding weight. It is noteworthy that the amount of fibres released differed for the two washing machine types. The mass per garment ranged from about 0 g to 2 g (0.3% of the unwashed garment mass) for all washing treatments. The top-loading machines accounted for about seven times more fibres compared to the front-loading machines. In addition, mechanically aged garments showed increased fibre release compared to new garments. The authors then considered published wastewater treatment plant influent characterization and microfibre removal studies, and hypotheses that washing synthetic jackets or sweaters account for most microfibers entering the environment.

In conclusion, the publications show that the washing of textiles using domestic washing machines causes microfibre pollution. A detailed comparison of the references is shown in Table 4. The size definition, the amount of pollution, the washing style, the spin rate (rpm), the type of washing machine, the washing time and the garment are included in this table.

Regarding Table 4, the mass of pollution seems to depend on the garment, age of garment, washing machine type, washing machine programme (heat and spin) and textile construction. By comparison, the amount of pollution does not depend so much on the individual washing behaviour, such as detergents or softeners.

In addition, the researchers used different microfibre sampling methods. Here, they used stainless-steel, nylon and glass micro filters.

It would be good for better comparability and validity to establish a standardized test method and test equipment in an international context. The standardized test methods could include topics such as washing style, garment composition and washing programme.

### 4.1.3 Wastewater treatment

A lot of publications were identified in the context of this literature research that deal with wastewater treatment in general terms. That means that these do not refer to domestic washing machines and/or microplastics. Instead, these publications focus on parameters such as chemical oxygen demand, turbidity, chemical substances (organic dyes), total suspended solids or suspended solids. Most of the publications cover nano- or ultrafiltration membranes, therefore, having a smaller cut-off than that needed for the filtration of microplastics as defined by the EC (<5 μm) [8].

However, for the sake of completeness, the respective filtering techniques will be briefly introduced in the following.

Cao et al., for example, describe a polycrylonitrile nanofibrous membrane reinforced with jute cellulose nanowhiskers for water purification showing a high filtration efficiency of 7–40 nm particles would be particularly useful for applications in the domestic drinking water and industrial wastewater treatment [27]. A polyethersulfone/polyvinylpyrollidone ultrafiltration membrane is described by Sumisha et al. [28]. The membrane with an ultrafiltration of 10 KDa shows that the modified polyester membranes used are suitable for the treatment of surfactant, detergent and oil from laundry wastewater.

A ceramic membrane was developed by Weber et al. that showed separation properties in the nanofiltration range and permeability rates clearly superior to that of polymer nanofiltration membranes [29]. Jedidi et al. also characterized a ceramic membrane that can be used for crossflow microfiltration [30]. When an average pore size of 0.25 μm is used, the water permeability is 475 L/hm² bar. The authors highlight that they observed a decrease of turbidity and chemical oxygen demand values (retention rate of about 75%) and a total colour removal. Dilaver et al. underline the importance of ceramic membranes as a good alternative for hot wastewater recovery in the textile industry [31]. In this publication, several membranes with four different molecular weight cut-off sizes (300, 50, 15 and 3 KDa) were evaluated for pollutant removal efficiency, whereby the smallest cut-off (3 KDa) showed the highest efficiency.

In addition to wastewater, one publication covered the water influent of an aquaculture system [32]. The system included three components: a swirl separator, a floating plastic bio clarifier and a fluidized sand filter. The removal efficiency of the swirl separator itself was reported to be over 90% for particles larger than 250 μm.

A summary of the publications is presented in Table 5, where the author(s), the publication title, the treatment system and the specifics of the wastewater are shown.

The analysis of the publications shows that microfibre pollution is not specifically addressed in textile industry wastewater treatment systems. The researchers use various types of wastewater treatment, such as nanofibrous, ultrafiltration and ceramic membranes, to reduce the number of pollutants other than microfibres. Depending on their results, one can imagine that most of the systems can filter, respectively separate the microfibres. How these techniques are transferable and applicable to domestic washing machines for microfibre filtration should be investigated in the future.

#### 4.1.4 Evaluation of the other references found in other sources

The references found in other sources (see chapter 3.2) generally give a good overview of microplastics and microfibres in the environment.

The reports by ICF and Eunomia determine that microplastics from textiles, which are mostly microfibres, are the third ranked source of microplastics to surface water in European (EU 28 nations) waterways. That means 72,500–300,000 t microplastics emissions to surface water per year, compared with 4,000–23,000 t microfibres from washing textiles per year.

In addition, the rather unfocused search in Google shows that there are already three systems that aim at filtering microfibres out of domestic washing machines. It is important to note that these systems were not part of any peer-reviewed publication, thus, they were also not found within the framework of the literature search in PubMed, ScienceDirect and Web of Science.

In addition to missing scientific information about the efficiency and restriction of the washing behaviour, these three microfibre pollution prevention solutions available show that there is a public interest in this issue. However, none of them is available as a filter for microfibres installed directly in a washing machine.

#### 4.2 General evaluation

This research shows that there is no scientific description of microfilters in washing machines.

Some of the results deal with the sampling of microplastics and show that microplastics can be filtered by simple filters, such as the Nitex® 52 nylon filters. This filter was originally designed for the sampling of plankton. Various studies have used it to separate microplastics and water.
<table>
<thead>
<tr>
<th>Author</th>
<th>Publication</th>
<th>Year</th>
<th>Definition used</th>
<th>Pollution</th>
<th>Washing style</th>
<th>Temperature</th>
<th>Spin rate</th>
<th>Washing machine</th>
<th>Washing time</th>
<th>Garment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Browne</td>
<td>Accumulation of microplastics on shorelines worldwide: sources and sinks</td>
<td>2011</td>
<td>&lt; 1 mm</td>
<td>Single garment over 19000 per wash</td>
<td>No additives</td>
<td>60°C</td>
<td>600 rpm</td>
<td>3 front-loading (Bosch WAE24468GB, John Lewis JWM1203 and Siemens Extra Lasse XL 1000)</td>
<td>40 min</td>
<td>polyester blankets, fleeces, shirts</td>
</tr>
<tr>
<td>Almroth</td>
<td>Quantifying shedding of synthetic fibres: a source of microplastics released into the environment</td>
<td>2017</td>
<td>Not defined</td>
<td>Fleece fabrics</td>
<td>Fabric samples with detergent</td>
<td>60°C</td>
<td>SS-EN ISO 105-C06 standard protocol for washing coloured fabric</td>
<td>Gyro wash one bath 815/8</td>
<td>30 min</td>
<td></td>
</tr>
<tr>
<td>Pirc</td>
<td>Emissions of microplastic fibres from microfiber fleece during domestic washing</td>
<td>2016</td>
<td>&lt; 5 mm</td>
<td>Average emissions in weight %: no additive: 0.00108; detergent: 0.00140; detergent and softener: 0.00124</td>
<td>Three washing styles: no additives, detergent, and both detergent and softener</td>
<td>30°C</td>
<td>600 rpm</td>
<td>Front-loading Bosch model Maxx7</td>
<td>15 min</td>
<td>6 identical fleece blankets (120 x 70 cm)</td>
</tr>
<tr>
<td>Hartline</td>
<td>Microfiber masses recovered from conventional machine washing of new or aged garments</td>
<td>2016</td>
<td>&lt; 5 mm</td>
<td>Average emissions in weight %: 0.3 of the unwashed garment masses, top-loading machines seven times more than others</td>
<td>No additives</td>
<td>Front-loading 29.4°F; top-loading 29.6°F</td>
<td>Top-loading no data; front loading: 1200 rpm</td>
<td>Top-loading (Whirlpool model WET3330XQ2) and front-loading (Samsung WF42H000AWA2)</td>
<td>Top-loading 30 min; front-loading: 24 min</td>
<td>10 polyester samples (5 new and 5 aged)</td>
</tr>
</tbody>
</table>

Table 4  Comparison of different definitions, pollution, washing styles, spin rates, washing machines, washing times and garments used by the authors.
Whether this filter can be used in washing machines is the topic of further research.

However, individual research uses different techniques because there is no international standard for the sampling or identification of fibres. This leads to the fact that the research is not comparable. The data are, however, suitable to calculate the theoretical necessities of a filter in washing machines.

In the context of washing machines and their practical everyday use, the use of detergents and softeners also needs to be considered. The literature shows that many of the researchers did not use any kind of softener or detergent to prevent the filters clogging. This is because some detergent ingredients are insoluble, such as zeolites. Up to 20% of the powder used can be zeolites. This means, for example, that by using 100 g of washing powder, 20 g of zeolites can clog the filter. Nevertheless, the fact that detergents and softeners are not considered is unrealistic.

Hartline [26] states that the average emission of microfibres is 0.3% of the garment mass per washing when washing fully synthetic garments. That means about 10 g of microfibres is washed out for each load of 3 kg of synthetic fibres per wash.

When this mass is added to the 20 g of zeolites, the filter must work in the presence of an average mass of 30 g of potential clogging substance.

One can use only liquid detergents or washing powder without insoluble ingredients to prevent this when a microfibre filter is utilized in washing machines.

In addition to filters for microfibres, this research identified a lot of filtering techniques used in different industries and on various pollution sources. Some of the systems might also be useable for microfilters in washing machines.

A ceramic membrane microfilter, for example, with a pore size of 0.25 μm and a water permeability of 475 L/h m² bar, such as the one Jedidi et al. presented [30], could be utilized. If the pressure is raised from one to four bar, the permeability is about 1800 L/h m² bar. The amount of wastewater, determined by Hartline et al., is 136 L from a top-loading machine or 36 L from a front-loading machine [26]. The surface needed is calculated by setting the time of filtering to one hour and the system pressure to four bar (Table 6).

The real physical properties of the membrane must be investigated by experimentation where other parameters, such as clogging, can also be considered as the numbers are esti-

<table>
<thead>
<tr>
<th>Author</th>
<th>Publication</th>
<th>Year</th>
<th>Treatment system</th>
<th>Kind of wastewater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cao</td>
<td>Robust polyacrylonitrile nanofibrous membrane reinforced with jute cellulose nanowhiskers for water purification</td>
<td>2013</td>
<td>Polyacrylonitrile nanofibrous membrane reinforced with jute cellulose nanowhiskers</td>
<td>Applications in domestic drinking water and industrial wastewater treatment</td>
</tr>
<tr>
<td>Sumisha</td>
<td>Treatment of laundry wastewater using poly-ethersulfone/polyvinylpyrrolidone ultrafiltration membranes</td>
<td>2015</td>
<td>Polyethersulfone/polyvinylpyrrolidone ultrafiltration membrane</td>
<td>Laundry wastewater</td>
</tr>
<tr>
<td>Weber</td>
<td>Characteristics and application of new ceramic nanofiltration membranes</td>
<td>2003</td>
<td>Ceramic membrane</td>
<td>Textile wastewater</td>
</tr>
<tr>
<td>Jedidi</td>
<td>Preparation of a new ceramic microfiltration membrane from mineral coal fly ash: Application to the treatment of the textile dying effluents</td>
<td>2011</td>
<td>Ceramic membrane</td>
<td>Wastewater of washing baths in the textile industry</td>
</tr>
<tr>
<td>Dilaver</td>
<td>Hot wastewater recovery by using ceramic membrane ultrafiltration and its reusability in textile industry</td>
<td>2018</td>
<td>Ceramic membrane</td>
<td>Textile wastewater</td>
</tr>
<tr>
<td>Pfeiffer</td>
<td>Sieve analysis for determining solids removal efficiency of water treatment components in a recirculating aquaculture system</td>
<td>2008</td>
<td>A swift separator, a floating plastic bead bioclarifier and a fluidized sand filter</td>
<td>Recirculating aquaculture systems</td>
</tr>
</tbody>
</table>

Table 5 Comparison of treatment systems and wastewater used by the authors

<table>
<thead>
<tr>
<th>Wastewater in L</th>
<th>Rounded surface needed in m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>0.02</td>
</tr>
<tr>
<td>86</td>
<td>0.048</td>
</tr>
<tr>
<td>136</td>
<td>0.076</td>
</tr>
</tbody>
</table>

Table 6 Membrane surface calculated by a wastewater amount of 36, 86 and 136 L and by a pressure of four bar and one hour of filtering

It is necessary to apply a high pressure at the membrane surface for effective filtering. Consequently, it is necessary to install a high-pressure pump with the appropriate power.

Additionally, the fact that the debris collection system and pump filter already installed should be in front of the microfibre collection filter to prevent the clogging/destruction should also be considered. Moreover, the filter system should be installed in a way that is easy to clean or be changed. A warning system that detects and reports clogging, and capacity constraints of the filter should also be installed. Consequently, the washing machine should also have an overflow device to bypass the filter when it is clogs. This is necessary to prevent undesirable overflow and remind the user to clean or change the filter. Finally, a solution needs to be found to avoid the filtered microfibres being transferred back to the sewage system, for example, when the microfibre filters are washed out. A bag solution similar to that on vacuum cleaners may produce the result required.

This literature review generally showed that there are many efforts to identify and/or to quantify the sources of microfibres and microplastics in waterways. Worldwide research is currently ongoing that aims at developing technologies that prevent and/or reduce environmental pollution by microplastics to minimize adverse effects on the environment and wildlife.

References


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