Textile Microfibers Reaching Aquatic Environments: A New Estimation Approach

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Highlights

- Microfibers global flow to aquatic environments is 0.28 million tons/year.
- Alternatives to reduce these microfibers could achieve a reduction of 30-65%.
- Selected factors: municipal treated waters, washers' type, and volume of effluents.

Abstract

Textile microfibers are one of the most important sources within primary microplastics. These have raised environmental concerns since its recent identification as pollutants. However, there are still no accurate models to assess their contribution to the microplastic pollution. Hence, in this study, a method to estimate the mass flow of microfibers detached from household laundry that reaches aquatic environments has been developed. The method considers a set of parameters related to the detachment of microfibers, which are, basically: (1) the detachment rate of microfibers from different textile garments, (2) the volume of laundry effluents, (3) the percentage of municipal water that has been treated, (4) the type of used-water treatment applied, and, (5) the proportion of front- versus top-loading washing machines. In this way, 0.28 million tons of microfibers per year were estimated to reach aquatic environments, which is approximately half than the last published valuation. Finally, hypothetical situations were simulated to evaluate the reduction of microfibers by the modification of some of the parameters at different levels (consumer, government entities, and industry). Thus, depending on the implanted alternatives, microfibers that reach the aquatic environments could be reduced between 30% to 65%.

Capsule: This work provides a base model to estimate the mass flow of textile microfibers from household laundry into aquatic environments.

Keywords: Microplastic; Microfiber; Detachment; Pollution; Contamination.

1 INTRODUCTION

Microplastics (synthetic polymers < 5 mm in diameter) are a mix of pollutants that have been identified in every explored ecosystem. In numerical terms, it has been estimated that there are between 15 to 51 trillion buoyant microplastics in the marine environments (van Sebille et al. 2015). However, these represent a minor fraction of the total extent of the MPs polluting the oceans (UNEP and GRID-Arendal 2016). Sources of microplastics (*MPs*) are mainly distinguished between *primary*, those emitted into the environment in a MP size range; and *secondary*, those generated in the environment from degradation and fragmentation processes of larger plastic debris. In this way, primary MPs include a wide variety of sources (e.g., microfibers detached from textile garments, plastic pellets, tire dust); while secondary MPs have their origin in mismanaged plastic garbage (Boucher and Friot 2017).

Regarding their impacts, its ingestion across the trophic chain is evident, as these particles have been found in at least 200 species (Collignon et al. 2012; Fossi et al. 2014; GESAMP 2015a). Also, measured effects include MPs' retention, trophic transfer, increased mortality, and endocrine disruption, among others (Rochman et al. 2014; Jemec et al. 2016; Welden and Cowie 2016; Nelms et al. 2018). Moreover, MPs can behave as long-distance vectors for invasive species and hydrophobic contaminants (Rochman et al. 2013; Browne et al. 2013). Also, these pollutants have been extensively identified in products for human consumption as seafood, tap and bottled water, and table salt (Van Cauwenberghe and Janssen 2014; Rochman et al. 2015; Yang et al. 2015; Schymanski et al. 2018). Nevertheless, human health risks are still an unknown area that needs further investigation.

To understand the causes, impacts, and possible solutions, evaluations concerning the sources' contributions must be done. In this way, first attempts to estimate the flow of textile microfibers (*MF*) to aquatic environments have already been executed. Most renowned estimations concerning MFs have established its flow between 0.2 to 0.5 million tons per year (Eunomia 2016; Boucher and Friot 2017). However, in a recent publication, it was noticed that an inappropriate factor was being applied in the calculations of previous publications (Belzagui et al. 2019). In particular, a fibre linear weight of 300 grams per 10,000 meters (300 dtex) was considered. However, a MF is an individual filament that has a linear weight between 1 to 5 dtex (1-5 g per 10,000 m) (Gacén 1995). Besides, most of the estimations previously reported do not include a full description of the applied criteria, making a difficult task to replicate or update the results.

Henceforth, this research aims to establish a replicable baseline model to estimate the total generation of MFs from household laundering and the fraction of these that reach aquatic environments. The model is applied to several hypothetical scenarios. Results of estimations are discussed and MFs reduction strategies at government, industrial, and consumer levels are evaluated. The main parameters considered to establish the model, are the following: the range of MFs detachment rates per textile garment and washing cycle in a steady-state; worldwide trends of household washing machines (in particular, the proportion of washers' type and volume of laundry water effluents); municipal water treated per world region (specifically, percentage and technologies applied); and proportion of synthetic materials (mainly polyester, acrylic, and polyamide) used in the manufacturing of textile garments.

2 METHODOLOGY

An extensive literature research was done to develop a new approach to estimate the MFs' flow to aquatic environments. Taking this into account, a research of the data regarding the textile MFs' detachment rates, types of washers and trends of their usage, the MF removal in municipal water treatment plants, and the geographic distribution of these data, was carried out. The washing machine trends, the efficiency of MFs' removal in municipal water treatment plants, and the geographic contribution of both parameters are discussed in sections 3.1 and 3.2. According to the collected information, the main parameters and values to be included in our calculations were organized and combined to develop the equations shown in section 3.3. On the other hand, to evaluate the MFs' contribution on a regional basis, the world was divided into 10 sections (see Supplementary Information for details of the countries included in each section), following the criteria commonly used in the literature:

- North America
- Latin America and the Caribbean
- Europe
- Newly Independent States (NIS)
- Pacific OECD and South Korea,
- Central Asia and China
- South Asia
- Other Pacific Asia
- Middle East and North Africa
- Sub-Saharan Africa

Based on this information, the equations are subsequently used to estimate current values (section 3.4), which are then compared with former estimations (section 3.5).

3 RESULTS AND DISCUSSIONS

3.1 WASHING MACHINE TRENDS

The number of washers and their annual volume of water consumption were calculated for 2020 on the bases of Barthel and Götz 2013 studies. These authors estimated that in 2013 there were 840 million household washing machines, with an annual water effluent of 19.2 billion m^3. From their published tendencies, it can be foreseen that in 2020 it will increase up to 1.1 billion washing machines and a water consumption of 22.2 billion m^3. The new estimation of regional distribution of the washers and their annual water consumption can be seen in Figures 1 (a) and (b).

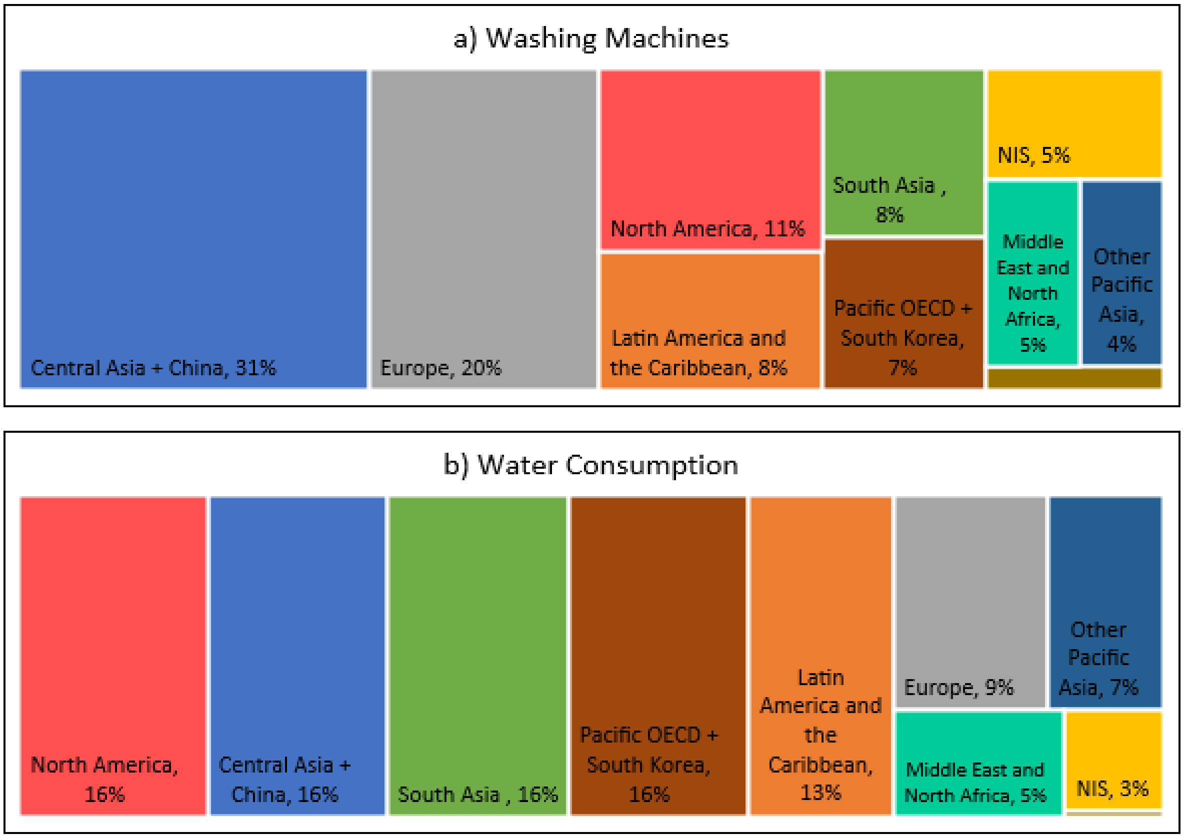

Figure 1. *Trends for 2020 for* ***(a)*** *Washing machines distributed across the world. And* ***(b)*** *Worldwide water consumption for household launderings. In both cases, the smallest quadrangle corresponds to Sub-Saharan Africa (1% washing machines and 0.2% water consumption).*

As seen when comparing Figures 1 (a) and (b), there is no direct relation between the number of washing machines and their water effluents. This is mainly a consequence of three aspects: the type of washing machine, the usage of newer and more efficient technologies regarding water and energy consumptions, and also the different regional behaviors on the selection of laundering programs.

The global yearly average water consumption for household laundry can be obtained as the quotient of the global discharged water and the total number of washers. This value was estimated at 19 m^3/washer (Supplementary Information, Equation 1s). Hence, the regional efficiency of water consumption can be estimated from its variation to the global average. In Figure 2, these variations are shown as positive when the water consumption is more efficient, and as negative when it is the opposite condition.

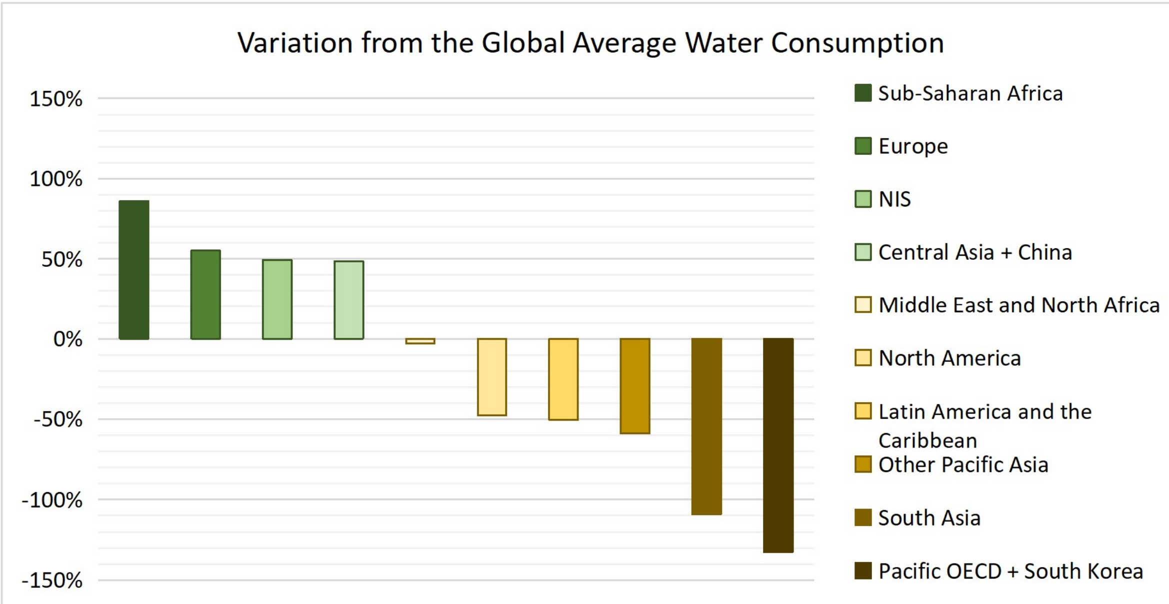

Figure 2. *Regional variations from the global average use of water for the year 2020 (19 m³ per washing machine). Positive percentages are more efficient in water consumption.*

Concerning the type of washing machines, they can be divided into two groups: front- and top-loading washers (*FL and TL, respectively*). Their proportion across the globe has been only reported for certain regions (see Figure 3) (Pakula and Stamminger 2010). In general, traditional top-loading washers use between 2 and 4 times more water than front-loading ones (Consumer Reports 2017). In the present work, a relation of 3 has been assumed, which is the average of both values. The estimation of MFs has been done considering three different scenarios of FL:TL proportions, which are explained in Section 3.4.

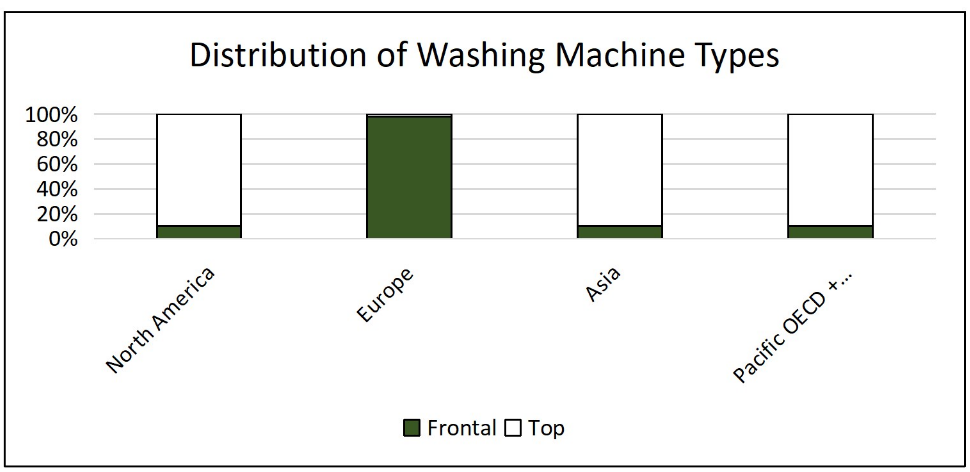

Figure 3. *Percentage of frontal (FL) versus top-loading (TL) washing machines used in different regions of the world.*

As can be seen in Figures 2 and 3, most regions with high a proportion of top-loading washing machines have an intensive water consumption. On the other hand, Europe is in the opposite situation. It is worth to mention that the washing machine type is an important predictor for the MF detachment rate of a garment. In fact, it has been reported that TL detaches 7 times more MFs than FL per washing cycle (Hartline et al. 2016). Also, despite that the trends show that the washing machine types have been progressively shifting towards FL, the replacement will be slow. Hence, the proportion of FL versus TL is not expected to change in the next years (Pakula and Stamminger 2010).

3.2 MFs Removed in Used-Water Treatment Plants (UWTP)

As stated in different publications, in the UWTPs' processes the MFs are partially transferred from the liquid to the solid (sludge) stream. Hence, the rate of used-water treated at UWTPs is an important parameter to predict the proportion of MFs that will be discharged into water bodies, especially in those regions where a high percentage of the municipal used-water is treated.

Globally, between 75% to 80% of municipal used-water is discharged untreated into water receptors (Pham and Kuy 2013; ONU 2017). However, the proportion of the population connected to urban UWTPs has a wide variation across the world. For instance, 97% of the municipal water is treated in Central European countries, whereas in Latin America and Asia this value decreases to 20% (Mara 2004; Sato et al. 2013; Eunomia 2016; EEA 2017). In this way, the MFs flowing in the effluent of the washing machines will have different fates depending on the existence of a UWTP.

In addition, the technologies installed between the regions are also unequal. This is a consequence of the cost of the technologies, as well as the regional economic status and legislation. Advanced treatment facilities are more expensive than primary and secondary processes. Hence, these are largely found in developed regions like Europe or North America (ADB 2011; Pham and Kuy 2013; Sato et al. 2013; Van Puijenbroek et al. 2015; Japan Sewage Works Association 2017; Government of Canada 2017; EEA 2017; ONU 2017). This can be furtherly seen in Figure 4.

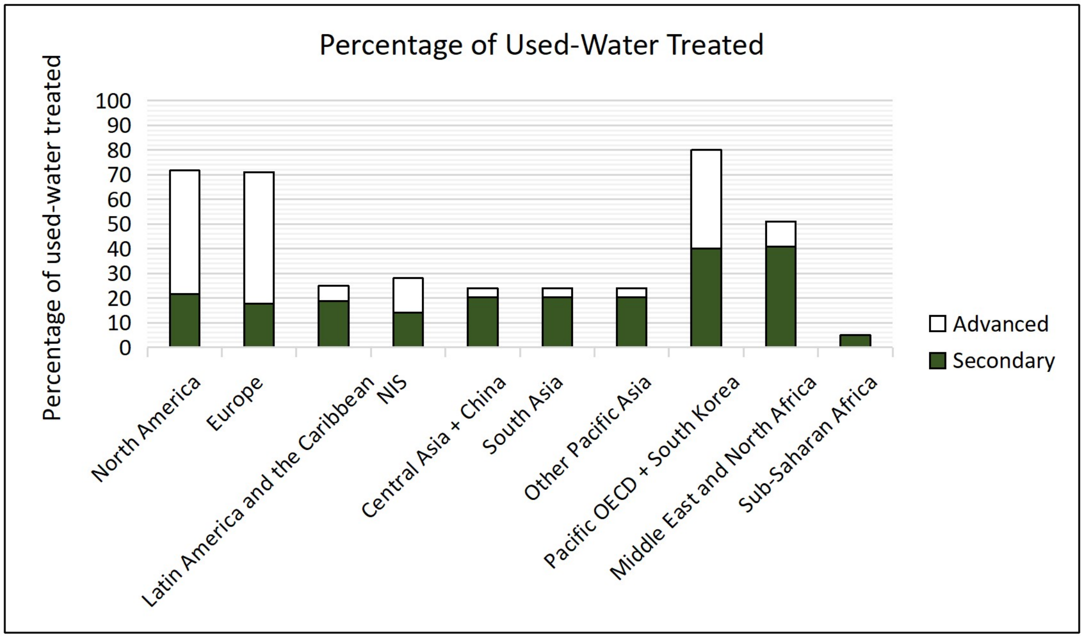

***Figure 4**. Percentage of municipal used-water treated and the proportion of applied technologies in the different regions of the world.*

As explained before, the presence of a UWTP will be an important predictor of the fate of a MF. In addition, the removal efficiency from the liquid stream will differ between different technologies. These were estimated at 89% and 98% for secondary and advanced treatments, respectively (see Table 1). However, it must be noticed that MPs do not disappear in a UWTP, instead, they are only removed from the liquid and transferred to the solid stream, i.e., to the sludge. Henceforth, the MPs *transfer efficiencies* for different technologies can be seen in Table 1.

***Table 1.** Percentage of MPs transferred to the sludge for different used-water treatment technologies.*

Reference	Treatment		
	Primary	Secondary	Advanced
Magnusson and Norén 2014	-	-	99.9
Gasperi et al. 2015	-	90.0	-
Talvitie et al. 2015	50.0	97.8	-
Michielssen et al. 2016	84.1	93.8	97.2
	88.4	89.8	99.4
Murphy et al. 2016	78.3	98.4	-
Carr, Liu, and Tesoro 2016	-	-	99.9
Leslie et al. 2017	-	72.0	-
Mintenig et al. 2017	-	-	97.0
Talvitie, Mikola, Setala, et al. 2017	97.0	99.9	99.9
Talvitie, Mikola, Koistinen, et al. 2017	-	-	40.0[(1)]
	-	-	98.5

	-	-	97.1
	-	-	95.0
	-	-	99.9
Gündoğdu et al. 2018	-	73.0	-
	-	79.0	-
Gies et al. 2018	-	99.0	-
Magni et al. 2019	-	84.0	-
Average (% of transferred MPs to the sludge)	**79.6**	**88.8**	**98.4**

1) This value is discordant; hence, it was removed from the data when calculating the average MP transfer efficiency.

As seen in Table 1, UWTPs provide a significant microplastic reduction from the liquid stream. Nonetheless, given the high volumes that they treat, the remaining amount in the water effluent is still considerable. Also, as MPs are mostly transferred to the sludge, depending on the final disposal of this by-product, these pollutants might still be released into the environment (e.g., as compost) (Habib, Locke, and Cannone 1998; Zubris and Richards 2005; Bayo et al. 2016; Mahon et al. 2017; Li et al. 2018; Corradini et al. 2019). Indeed, a rough estimation has found that MFs annually dumped with the composted sludge into agricultural lands are between 6.3×10^4 to 4.3×10^5 tons in Europe and 4.4×10^4 to 3.0×10^5 tons in North America (Nizzetto, Futter, and Langaas 2016). However, there is a lack of information regarding the MPs presence and its impacts on terrestrial environments.

3.3 Emission of Microfibers to the Environment: Developed Equations

By considering the parameters explained in the previous sections, an equation has been developed to achieve the following estimations: (a) the quantity of MFs reaching aquatic environments, and (b), the effects that different mitigation strategies could have on the MFs' pollution.

Before introducing this equation, some parameters should be defined. Firstly, a volume distribution factor for each type of washer is required to relate the proportion of front (F) and top (T) loading washers and their volume of effluents. These factors, called "W_F" and "W_T", are obtained from the Equations 1a and 1b:

$$W_F = \frac{P_F \cdot V_F}{(P_F \cdot V_F) + (P_T \cdot V_T)} \qquad (\mathbf{1a})$$

$$W_T = \frac{P_T \cdot V_T}{(P_F \cdot V_F) + (P_T \cdot V_T)} \qquad (\mathbf{1b})$$

Where,

$W_F; W_T$ Volume distribution factor for the effluents of front (F) and top (T) loading washers.
P_F, P_T Proportion of each type of washer.
V_F, V_T Average volume of effluent from each type of washer.

Also, an additional factor of MFs detachment between top- and front-loading washers "y" is introduced, which can be calculated from the Equation 2:

$$y = \frac{M_T}{M_F} \cdot \frac{V_F}{V_T} \qquad \mathbf{(2)}$$

Where,

y Factor of MF detachment between top- and front-loading washers.
M_F, M_T MFs detached in front (F) and top (T) loading washers.
V_F, V_T Average volume of effluent from each type of washer.

In this way, the Equation 3, developed to calculate the annual flux of MFs reaching aquatic environments, is described hereafter:

Microfibers detachment | Municipal treated waters

$$\boldsymbol{F_A} = f_{MF} \cdot Q_{WM} \cdot [D_{UA} + I_{UA}(1 - R)] \cdot S \cdot (W_F + y \cdot W_T) \qquad \mathbf{(3)}$$

Laundry effluents | Synthetic vs. Natural | Washing machine type

Where,

$\boldsymbol{F_A}$ **Annual flux of MFs reaching aquatic environments, in MF/year.**
f_{MF} Flux of MFs per liter of water effluent in a front-loading washer, in MF/L.
Q_{WM} Annual volumetric flow of washing machines effluents, in L/year.
D_{UA} Proportion of municipal used-water directly discharged to aquatic environments.
I_{UA} Proportion of treated municipal used-water.
R Proportion of retained MFs as a function of the existing municipal used-water treatment technologies.
S Proportion of synthetic versus natural fibers used globally in the manufacture of textile garments.
W_F Volume distribution factor for front-loading washers, (Eq. 1a).
y Factor of MF detachment rate between top versus front-loading washing machines (Eq. 2).
W_T Volume distribution factor for top-loading washers, (Eq. 1b).

When the total mass of MFs generated or emitted from the laundering process has to be estimated (F_E , annual flux of MFs emitted, in MF/year), the Equation 3 is reduced to the Equation 4:

$$\boldsymbol{F_E} = f_{MF} \cdot Q_{WM} \cdot S \cdot (W_F + y \cdot W_T) \qquad \mathbf{(4)}$$

Excluding f_{MF}, S and y, all factors were applied for a determined region of the world. Hence, the sum of all F_E gives the global mass of MFs emitted and the sum of F_A gives those reaching aquatic environments. Also, for the parameter f_{MF}, minimum and maximum values were applied (see Table 2).

Also, to express the annual flux of MFs in mass units, the procedure of Belzagui et al. 2019 was applied. According to this method, the linear weight of an individual filament fiber is calculated with Equation 5:

$$\boldsymbol{C} = \emptyset^2 \cdot \frac{\pi \cdot \gamma}{400} \qquad (\mathbf{5})$$

Where,

C	Linear weight of the MFs, expressed in *decitex* (1 dtex = 1 g per 10,000 m).
$\emptyset$	Average diameter of the MFs, in µm (19 µm, see Table 2).
γ	Specific weight of the fibers, in g/cm^3.

Then, by applying the values of F_E, F_A and C obtained from Equations 3, 4, and 5, the annual mass flux of MFs is estimated with the Equation 6:

$$\boldsymbol{mF_{MF}} = F_{A\ or\ E} \cdot C \cdot \bar{L}_{MF} \cdot \frac{1}{10^9} \qquad (\mathbf{6})$$

Where,

mF_{MF}	Annual mass flux of MFs, in ton MF/year.
$\bar{L}_{MF}$	Average length of MFs, in mm (0.343 mm, see Table 2).
C	Linear weight of the MFs. In this equation, the value must be applied in g/m.

3.4 Emission of Microfibers to the Environment: Estimations

Initial approaches

The developed equations were applied to estimate the MFs emitted from household laundering and reaching the aquatic environments. With this purpose, the following approaches were made:

1. The current proportion of synthetic textile fibers from the overall production is approximately 0.62 (Oerlikon 2010; The Fiber Year Consulting 2018); this value corresponds to "S" in Eq. 3.
2. The volume proportion factors (W_F and W_T) were calculated by means of Equations 1a and 1b, assuming an average volume of effluent between top- and front-loading washers of 3:1 (See Supplementary Information, Eq. 2s and 3s).

3. Top-loading washers detach 2.2 times more MFs per liter than front-loading ones. This value corresponds to “y” in Equation 3 and was calculated by applying Hartline et al. 2016’s values to Equation 2 (See Supplementary Information, Eq. 4s).
4. An average loading of 75% of a common washing machine was considered (Pakula and Stamminger 2010). This corresponds to 4 kg of garments washed per laundry cycle.
5. As there is no information regarding the washer type for some regions, **three different scenarios were established**. In all these scenarios, regions with information maintain their known proportions. However, to include the possible settings, regions without information were considered to have ratios of front versus top-loading (FL:TL) washers of 7:3, 5:5, and 3:7 in scenarios S1, S2, and S3, respectively (see complete data in Supplementary Information, Tables SI4 to SI6).
6. The minimum and maximum MFs detachment rates, and the physical characteristics of the MFs are shown in Table 2.

Table 2. *Published MFs` detachment rates and their physical characteristics.*

Characteristic	Units	Belzagui et al. 2019	De Falco, Gullo, et al. 2018
Minimum MF detachment (1)	MF/L	**30 303 (2)**	80 000 (3)
Maximum MF detachment (1)	MF/L	196 970 (2)	**236 000 (3)**
MF length	mm	0.30	0.38
MF diameter	µm	20	18
Average linear weight (4)	dtex	3.8	
Average MFs’ mass	MF/mg	**7 587**	

(1) MFs detached from a 4 kg front-loading washing machine.
(2) Calculated from Belzagui et al. 2019 by extrapolating their results to 4 kg of garments load.
(3) Calculated from De Falco, Gullo, et al. 2018 by extrapolating their results to 4 kg of garments load and assuming a washing machine effluent of 60 L.
(4) The specific weight of polyester was used as it is the most produced material. Hence, a value of 1.38 g/cm^3 was applied in Equation 5.
Data in light blue was used for the optimistic and pessimistic MF detachment rates.

Emission of MFs

After applying minimum and maximum MFs’ detachment rates in Equations 3 and 4, a range of values for the three scenarios (S1, S2, and S3) were estimated. Henceforth, on a worldwide base, the total generated MFs from household laundering ranged from 0.47 to 0.49 million tons of MFs per year, or 3.6×10^{18} to 3.7×10^{18} MFs particles per year. Scenario S2 is illustrated in Figure 5, where it can be seen that most of the MFs are generated in North American and Asiatic countries.

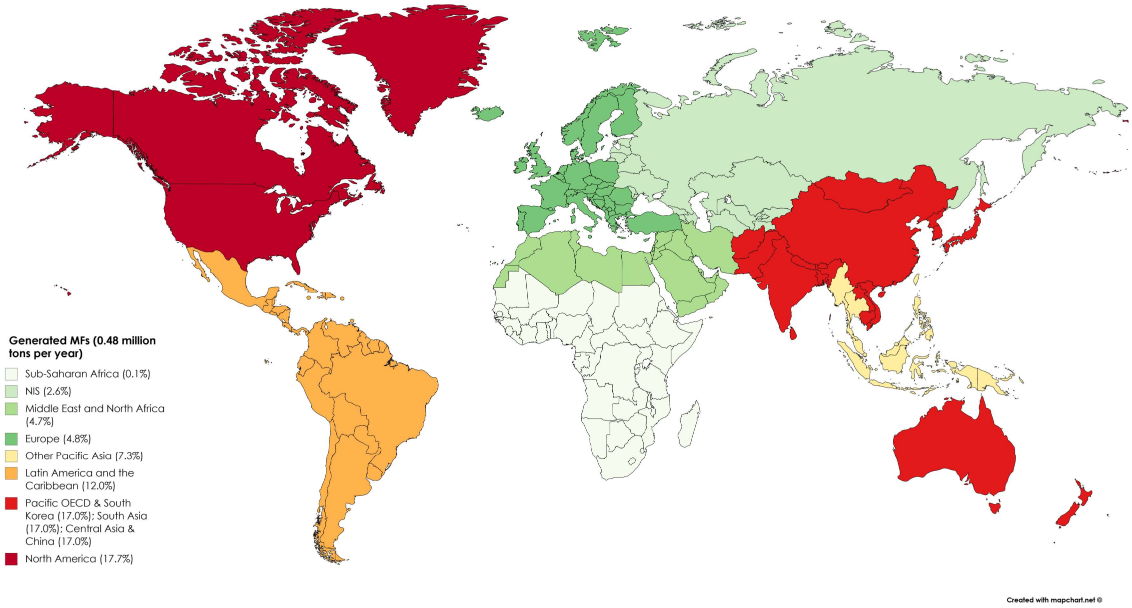

Figure 5. *Total emitted mass of microfibers from household laundering (scenario 2). The relative contribution of each region is classified into three levels: lower (green), medium (yellow), and higher (red), illustrated with different intensities.*

However, the MFs reaching aquatic environments are only those that are not subjected to any UWTP or MF retention system (Figure 6). In this case, the mass flow of MFs flowing to aquatic environments was found to fluctuate between 0.27 to 0.28 million tons of MFs per year. This means that 2.1×10^{18} to 2.2×10^{18} MFs particles are being annually discharged into aquatic environments. In Figure 6 it can be seen that Asia is the most polluting region in terms of MFs reaching aquatic environments, followed by Latin America and the Caribbean. On the other hand, North America and Pacific OECD & South Korea have a lower impact than expected on water systems due to the application of retention measures. From these data, it can be approximated that the quantity of MFs being retained by UWTPs is 0.20 million tons per year, or around 40% of the total generated MFs. Unfortunately, these MFs will have an uncertain disposal and might still end up as litter. In Figure SI1 (Supplementary Information) each regional change between the MFs emitted and those reaching aquatic environments can be visualized.

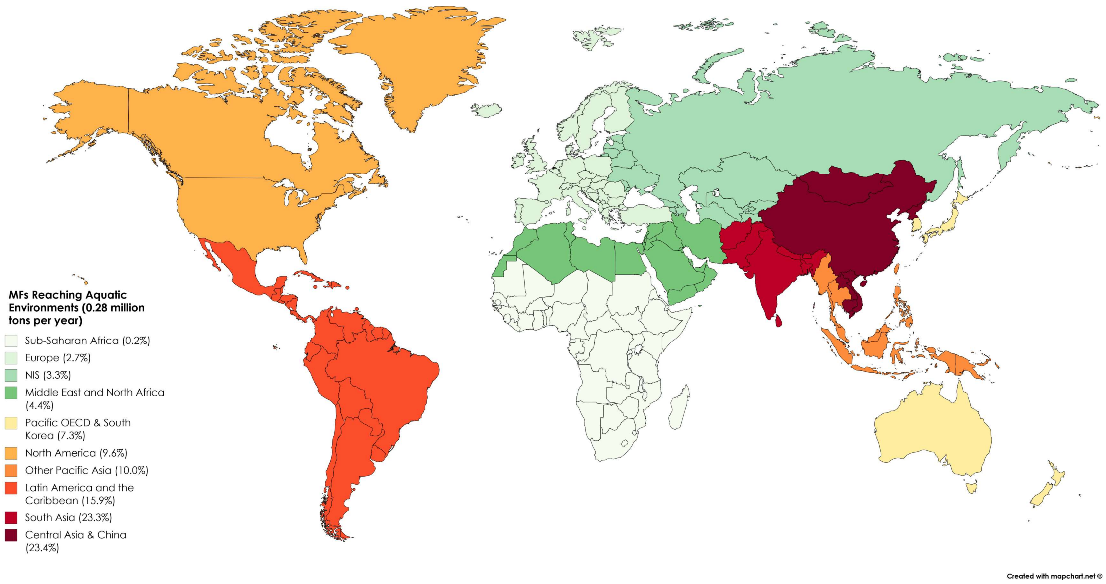

Figure 6. *Mass flow of microfibers reaching aquatic environments (scenario 2). The relative contribution of each region is classified into three levels: lower (green), medium (yellow), and higher (red), illustrated with different intensities.*

The high proportion of MFs that reaches aquatic environments from Asia (65%) is consistent with the considerable load of MPs exported by their rivers (Schmidt, Krauth, and Wagner 2017), and with the elevated concentrations of MPs found in the North Pacific ocean (van Sebille et al. 2015). Besides, on a regional basis, the order of MF contribution to aquatic environments has no variation in any of the established scenarios. Hence, the simulated variations do not seem to have a major impact on the worldwide analysis. Finally, results were analyzed and the following conclusions were obtained:

- The volume of water discharged from the washers is an important predictor for the MFs' release, as greater volumes can be related to larger laundry programs. Also, the water consumption provides an intrinsic idea of two components: (1) the behavioral trends of every region about the selection of the washing program, partially reflecting the awareness of the consumers concerning the best use of the washing machines; and (2), the type and/or efficiency of the washing machine mostly used.

- Concerning the washing machine type, it was found to be as influential as the other parameters. This was proven by developing a hypothetical situation in which the proportion of washer types in Asia and North America was inverted from the existing front- versus top-loading washers of 0.1:0.9 to 0.9:0.1 (see Section 3.6).

- According to our calculations, about 40% of the worldwide MFs generated in washing machines are retained in UWTPs. A priori, this might seem an unexpected value as only 20% of world municipal waters are treated before the discharge. However, it is because some regions, as North America, generate a high percentage of the MFs but also treat a high proportion of their municipal waters. On the other hand, three observations are worth to be mentioned: (1), the worldwide percentage of treated water is still very low, meaning that most of the washers' effluents are being directly discharged to water receptors; (2), it should be noted that even primary treatments can be used as systems to reduce MFs from reaching aquatic environments. This means that their implementation in regions without UWTPs will considerably reduce the flow of MFs to aquatic environments; and (3), the implementation of UWTPs will not reduce the generation of MFs, and these do not disappear in UWTPs, instead, they are transferred to the sludge. In this way, these particles will be dumped to the soil if the sludge is used as compost. Hence, UWTPs are not a solution to the reduction of *MFs flowing to the environment*.

- Finally, it must be mentioned that regions with low washing machine ownership will also contribute to the pollution of MFs when doing the garments' hand-washing. These MFs are out of the limits of this study, as there is no reliable information available on that specific subject. Further sources of textile MFs that were out of the limits of this study are, for instance: industrial textile processes, drying, and usage of garments, etc. In this way, the expected total quantity of MFs reaching the environments will be higher than the estimations made in this work.

3.5 COMPARISON WITH PREVIOUS ESTIMATIONS

A previous global estimation of the total quantity of MFs flowing to the oceans was made by Boucher and Friot 2017. An approximation of the equation applied in their work can be found in the Supplementary Information (Equation 5s). In that research, the central value was calculated at 0.5 million tons of MFs per year. As seen in Section 3.4, the result found in this study is approximately 50% lower than their estimation. In Boucher and Friot 2017's methodology, the main approach was based on the number of laundries per capita. In contrast, in this study the volume of effluent from washing machines is used. However, it was found that an incorrect value was applied in one of their parameters. Specifically, a linear weight of 300 dtex was used to calculate the mass of the MFs. As explained before, a common linear weight for a MF is between 1 to 5 grams per 10,000 meters (1 to 5 dtex). If updated information and a correct linear weight for the MFs is applied in Equation 5s, the mass flow of MFs reaching aquatic environments is estimated at 0.19 million tons per year. As seen, it provides an estimation 30% lower than the one calculated with the equations proposed in this study.

From these results, some observations and comments regarding the different methodologies need to be done. The type of washers (TL or FL) is an important factor in the MF detachment of a textile garment that needs to be included in these approximations (Hartline et al. 2016). Used-water treatment plants (UWTP) must be also considered when estimating the quantity of MFs reaching aquatic environments. Also, the trends of the world population aren't intrinsically related to the tendencies of the washing machines demand and usage (Supplementary Information, Section 15). Hence, by using the volume of effluent per washing machine and region the needs for assumptions are reduced. Finally, studies should be careful with the in the units and the order of magnitude of the parameters applied to do the estimations.

3.6 Recommendations for MFs Reduction

Hereafter, a set of hypothetical situations is presented to estimate the attained improvements from different possible MFs' reduction strategies. In this way, in situations HA, HB, and HC one single parameter was modified, whereas in the situation HD all the modifications were combined (see SI, Tables SI7 to S10). In this sense, new hypothetical situations were created for manufacturers (HA), consumers (HB), and government (HC) levels. A summary of the situations is shown in Figure 7, where each central value is compared with scenario S2 (50% of front- and top-loading washing machines in regions without data).

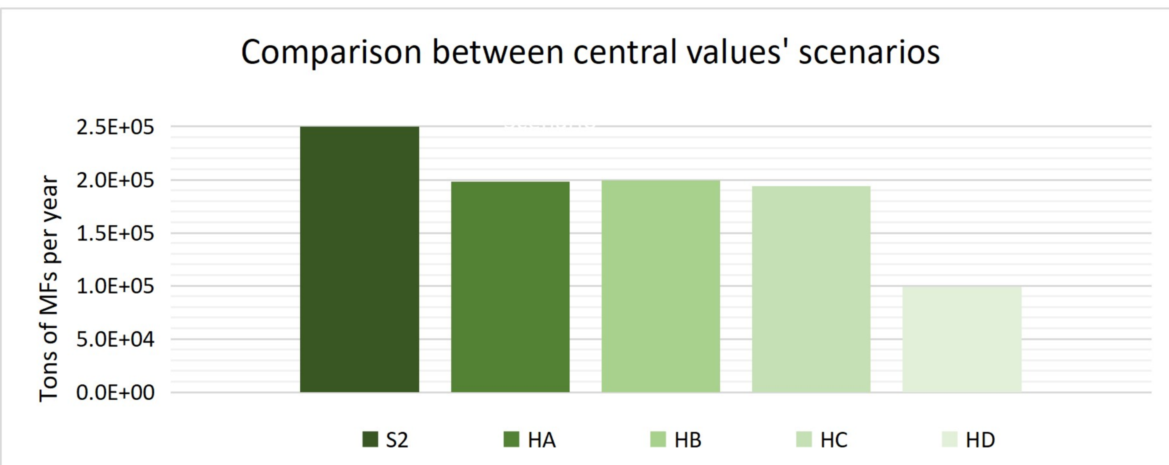

Figure 7. *MFs released to aquatic environments. Comparison between the central value scenario S2, and the hypothetical situations HA (the type of washing machine), HB (consumers and water usage), HC (water treatment plants), and HD (combined effect).*

The hypothetical situations shown in Figure 7 are explained hereafter:

Washing Machine Manufacturers (HA): As shown before (see "washing machine trends"), regions of Asia and North America have a 0.1:0.9 proportion of front- versus top-loading washers. Hence, a new hypothetical situation HA was considered by inverting them to 0.9 FL versus 0.1 TL. This modification resulted in a global MF reduction of 29%. It must be noticed that changing from TL to FL reduces the detachment of MFs. Hence, this strategy could have a major role in reducing not only MFs from reaching aquatic systems but to the whole environment too. However, other solutions or mitigation strategies are also feasible. For instance, improved designs of TL washing machines that cause less stress to the garments, or the marketing of new washing machines with built-in MFs' filters. Finally, manufacturers should also include in their brochures a qualification category regarding MFs emissions or stress induced to the garments in the washing machines. In this way, consumers could consider this factor when acquiring a new washer.

Consumers (HB): The population awareness on the MFs' contamination and their capacity to reduce their contribution are important subjects that must be continuously consolidated. In the last years, social media platforms have been increasingly making publications on this topic (GESAMP 2015b; Wagner and Lambert 2018; SAPEA 2019). Also, the words "Microplastic and Microfiber" have been appearing in newspapers and digital screens (e.g., BBC 2018; Ian Sample 2019; Tutton and Pisa 2019; Jeremy Hobson 2019; Stephen Leahy 2019). Consumers' contributions related to some MFs' reduction strategies are available on the web. Some examples reported as "better practices" are: washing less but enough, filling up the washing machine, using liquid detergents, selecting colder and quicker laundry settings, among others (Mermaids 2017; Plastic Pollution Coalition 2017). In addition, there are commercially accessible capturing MFs technologies, which work by capturing the MFs either inside the washing machine (GuppyFriend 2019; CoraBall 2019) or in the effluent (Environmental Enhancements 2019; Filtrol 2019). These technologies have accomplished a MF reduction in the washer effluent of 26% to 87% (McIlwraith et al. 2019). Nevertheless, the final disposal of the retained MFs has not yet been afforded. On the other hand, using more natural than man-made fibers has also been mentioned within the possible solutions. This declaration is controversial, as nowadays most of the cotton industry relies on a highly pollutant and environmentally unsustainable production (Garcia et al. 2019). Hence, there are no justified studies to claim that specific statement.

The hypothetical situation HB was created by decreasing the water consumption in regions with a high consumption rate to the current worldwide average of 19 m^3/washer. Thus, a reduction of 29% on the generation of MFs can be achieved. This measure can be accomplished by instructing consumers to use quicker but adequate laundry programs and/or more efficient washers. It must be highlighted that this strategy will reduce the MFs' generation and, consequently, a decrease in the emission of MFs to the whole environment.

Government Entities and Used-Water Treatment Plants (HC): The existence of a UWTP has been demonstrated to play a relevant role to remove MFs from the liquid stream. Situation HC was applied in regions with a low percentage (<50%) of treated water. If these regions were to build enough installations to treat 60% of their municipal used-waters (without making any changes in their current proportion of treatment technologies), a global MF reduction of 31% could be achieved. Nevertheless, further investigation is needed to develop possible treatments for the MFs in the sludge, as this strategy will still introduce MFs into the environment.

As seen in Figure 7, a MF reduction of approximately 65% could be achieved in the situation **HD** where all strategies of scenarios are combined. Also, each hypothetical situation has a different scope in the reduction of MFs. Situation HC (used-water treatment plants) only avoids MFs from reaching aquatic environments. On the other hand, situations HA (washing machine type) and HB (consumers' usage) could achieve a real MF reduction, as they reduce the generation of these particles. In this way, if only HA and HB scenarios were conducted, a MF reduction of approximately 50% could be attained (see Table SI11).

Changes in the **textile industry** were out of the limits of this study, as there is no reliable data regarding MFs' reduction techniques applied in the manufacturing process of textile articles. However, as can be seen in studies on textile MFs, there is a wide variation on the MFs detachment rates. Hence, the textile industry can play a key factor in the reduction of these pollutants by enhancing their processes and products towards reducing MFs release. Some recommendations have already been published; for instance, a *Life European* project evaluated textile procedures as the spinning, cutting, dyeing, among others. In this way, they compiled a guideline of "better practices" for the textile industry (Mermaids 2018). In addition, investigations are working forward for possible techniques to reduce the MF detachment from the garments. For example, a reduction of 90% of the MFs release was obtained by applying pectin, poly-lactic acid, and polybutylene succinate onto polyamide fibers (De Falco, Gentile, et al. 2018; De Falco et al. 2019). Nonetheless, further investigation is required to develop sustainable techniques to avoid or reduce the MF detachment rates from textile articles.

As a recommendation, and based on what was seen throughout this article, there are some important gaps in the input data. Hence, some of the main parameters related to the MFs detachment that are advisable to consider to improve the estimations are: the operational conditions of the washing cycles (temperature, centrifugation, etc.); the physical properties related to the manufacture of garments (type of fabric, torsion, etc.) and the different strategies that will be implemented to reduce the MF detachment or to retain the generated ones. Once the influence of these parameters has been established, the equations proposed in this work to calculate the MFs detachment can be upgraded to obtain more accurate estimations.

4 CONCLUSIONS

An estimation of the mass flow of microfibers (MFs) to aquatic environments was accomplished by developing a new calculation methodology. The method applies a set of known-parameters that are linked to the MFs' pollution, which are: (1) MFs detachment rate from different textile garments; (2) volumes of laundry effluents; (3) percentage of municipal used-water treated per world region; (4) type of water treatment applied, and (5) proportion of front- versus top-loading washing machines. In this way, different scenarios were studied and a central value of 0.28 million tons per year of MFs was obtained, which is approximately 50% lower than previously published.

On a regional basis, 65% of all the MFs that reach aquatic environments come from Asia. The explanation for this major influence is a combination of the high proportion of top-loading washing machines, an inefficient water-usage in the washing cycles, a low rate of municipal water treated, and a high population density. In contrast, other regions such as Europe have a relatively low contribution to the MFs' pollution, basically, as a consequence of the opposite conditions. On the other hand, when estimating the overall mass of generated MFs in the laundering process, North America gets situated in the first place with 18% of the global MF generation, from where a high proportion of these MFs is retained in municipal water treatment plants.

In addition, three hypothetical situations were analyzed with the attempt to quantify the impacts on the MFs release and to make positive proposals able to be applied at government, industries, and consumer levels. Concerning the washing machine types, the current proportion of front- versus top-loading washers in the Asian region was inverted. In this way, a global MFs release reduction of 29% was accomplished. Regarding the consumers, regions with high consumption of water per laundry were matched to the worldwide average. Thus, the attained MF reduction was of 29%, meaning that it is an efficient and sizeable MF reduction strategy. Additionally, at a governmental level, the evaluation was done by increasing the percentage of treated water in regions with a low used-water treatment rate. By doing so, a global MFs' reduction of 31% MFs was achieved. Finally, if all strategies were combined, a MF reduction of 65% could be achieved. However, it must be noticed that while all measurements decrease MFs from reaching aquatic environments, only modifications in the washer type and washing behaviors (e.g., lower but sufficient washing time) could efficiently reduce the detachment of MFs. Henceforth, major importance should be applied in those strategies that tackle the generation of MFs.

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