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Review

# Synthetic microfibers in the marine environment: A review on their occurrence in seawater and sediments

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ABSTRACT

The objective of this review is to summarize information on microfibers in seawater and sediments from available scientific information.

Microfibers were found in all reviewed documents. An heterogeneous approach is observed, with regard to sampling methodologies and units. Microfibers in sediments range from 1.4 to 40 items per 50 mL or 13.15 to 39.48 items per 250 g dry weight. In the case of water, microfibers values ranges from 0 to 450 items·m$^{-3}$ or from 503 to 459,681 items·km$^{-2}$. Blue is the most common color in seawater and sediments, followed by transparent and black in the case of seawater, and black and colorful in sediments.

Related with polymer type, polypropylene is the most common in water and sediments, followed by polyethylene in water and polyester in water and sediments. Some polymers were described only in water samples: high-density polyethylene, low-density polyethylene and cellophane, whilst only rayon was reported in sediments.

## 1. Introduction

Plastics were first noticed in oceans in the 1970s (Buchanan, 1971; Carpenter and Smith, 1972) when plastic production was still far below current levels. Plastics are usually synthetic organic polymers of high molecular mass, most commonly derived from petrochemicals. Plastics are versatile materials that are inexpensive, lightweight, strong, durable, corrosion-resistant and can persist in the marine environment for a long time (see e.g. Tamara, 2015). The most commonly used polymers are polypropylene (PP), low-density polyethylene (LDPE), polyvinyl chloride (PVC), high-density polyethylene (HDPE), polystyrene (PS) and polyethylene terephthalate (PET), which together account for approximately 85% of the total plastic demand worldwide (Plastics Europe, 2016).

Related with fibers, textile manufacturing begins with fiber, which can be harvested from natural resources, manufactured from cellulosic materials or made from synthetic materials. As an example, viscose is made from natural sources (usually wood pulp) and rayon is a manufactured fiber which is neither natural nor artificial. Although it comes like viscose from cellulose, which occurs naturally in plants and also other materials, it has undergone several chemical processes before it is turned into its present form and it is called a semisynthetic fiber (see e.g. Ganster and Fink, 2009). It is called a regenerated cellulose fiber because it is made with cellulose fiber which is reformed or reconstructed. Synthetic fibers (like nylon) accounted for 61% of total fiber production in 2011 (Platzer, 2013).

A recent estimate suggested there could be between 7000 and 35,000 tons of plastic floating in the open ocean (Cózar et al., 2014). Another study estimated that more than five trillion pieces of plastic and > 250,000 tons are currently floating in the oceans (Eriksen et al., 2014). Microplastics are an emerging pollutant in the marine environment (Law and Thompson, 2014). Microplastics (MPs) are synthetic polymers measuring < 5 mm in diameter (Arthur et al., 2009) and are derived from a wide range of sources including synthetic fibers from clothing (Browne et al., 2011), polymer manufacturing and processing industries (Lechner and Ramler, 2015) and personal care products (Fendall and Sewell, 2009). Sources of MPs are known only generally as follows: they emerge from direct use of small particles (primary MPs) or from fragmentation of larger plastic debris (secondary MPs). Once in the sea, microplastics are transported around the globe by ocean currents, as direct consequence microplastics have been found in almost every marine habitat around the world (Cole et al., 2011).

Fibers are among the most prevalent types of microplastic debris observed in the natural environment (Browne et al., 2011). Microfibers (from hereinafter MFs) essentially are secondary MPs because they are mainly released by the use of synthetic polymers in garments, nets and other materials but not used directly in applications, as far as we know. These synthetic microfibers are typically manufactured from nylon,

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polyethylene terephthalate (PET), or polypropylene (PP).

There is a large amount of materials in our daily life that are made of fibers, either synthetic or natural (furniture, textile, etc.) (Engelhardt, 2016). The small size of MFs (below 5 mm in length but with a high relation length/radius) makes them available for interaction with marine biota in different trophic levels. As pointed out recently by Cole (2016) fibrous microplastics may pose an even greater threat than spherical particles for marine biota. An emerging issue in this field is nanoscopic and microscopic fibrous materials (e.g., asbestos fibrils, carbon nanotubes) that could result in carcinogenesis and fibrosis, whereas particles of the same material in particulate form are often benign (Cole, 2016).

Despite the fact that fibers are found in worldwide oceans, only until recently fibers and microfibers have been observed as an important issue in the marine environment (see e.g. Browne et al., 2011), but due to the high risk of airborne contamination during sampling and processing, in some studies (see e.g. Cózar et al., 2015; Suaria et al., 2016) fibers and microfibers are excluded. Even then, it is important to understand their distribution in the marine environment and their implications on marine habitats and marine biota. A recent study (Mizraji et al., 2017) highlighted that MFs have been reported as the major plastic form in the gut of diverse marine species, including vertebrates and invertebrates.

In this study we review for first time (as far as we know), the studies on fibers in seawater and marine sediments. Despite no many attention was pointed out in microfibers until very recently, they are distributed worldwide and actually are an emerging issue and many studies on ecotoxicology are carried out using fibers (see e.g. Cole, 2016).

The objectives of this review are: (1) to summarize the properties, nomenclature and discuss the sources of MFs to the marine environment; (2) to evaluate the sampling methodologies and identification methods by which MFs are detected in the marine environment; (3) and to ascertain spatial and temporal trends of MFs abundance from worldwide studies in oceans and seas.

## 2. Review of available literature

We conducted an extensive literature review using the ISI Web of Knowledge, Web of Science and Scopus databases. Based on the search parameters: microplastic, fiber and marine environment a total of 100 original publications were retrieved, dating back to 1960 until 2017.

Among all publications we selected those who follow our aim. The majority of paper researches (87%) were published from 2015 onwards (see Fig. 1). In addition to peer-reviewed papers, conference proceedings, posters and dissertations were also included in this review.

The information that was gathered from these publications included: i) the extraction technique, ii) microfibers abundance and distribution, iii) polymer color, and in case of microfiber polymer identification iv) type of polymer.

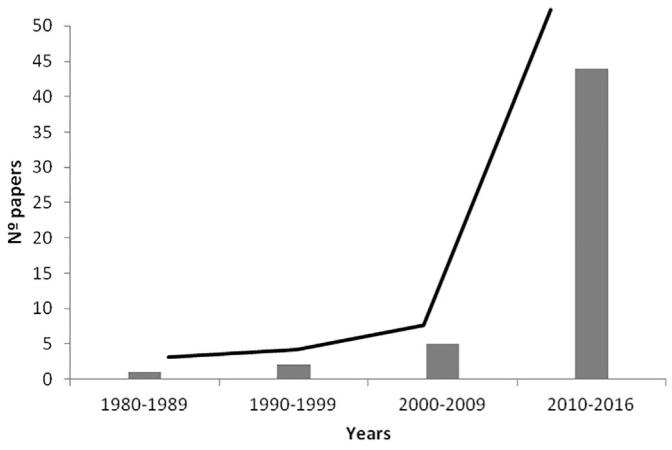


**Fig. 1.** Number of publications related to microfibers in the marine environment since 1976.

## 3. Sampling methodologies

The sampling methodologies of microplastics are different according to the environmental compartment studied; seawater or sediments.

### 3.1. Seawater

After the bibliographic review, a total of 43 articles related to abundance of plastic fibers in seawater were found (surface, sub-surface and water column). Twenty eight articles (~67%) focus on the sea surface. In this case, fibers were collected with manta trawls or other types of neustonic nets (Doyle et al., 2011; Morét-Ferguson et al., 2010) whose mesh size ranged between 330 and 500 μm, being 333 μm the most common net (Rios et al., 2010). Other authors used 150 μm plankton nets (Day et al., 1989). The trawl time fluctuate from 10–20 min (Kang et al., 2015; Lusher et al., 2015), to 60 and 90 min, (Enders et al., 2015; Eriksen et al., 2013; Faure et al., 2015). The trawl speed was around 3 knots (Gallagher et al., 2016; Lima et al., 2014). Other instruments, such as the continuous plankton recorder (CPR) were also used (Thompson et al., 2004). Only Dubaish and Liebezeit (2013), collected surface samples with PE bottles at 20 cm of depth. In all cases samples were filtered after collection. The mesh size varies between 80 μm (Nel and Froneman, 2015) and 500 μm (Amélineau et al., 2016), being the most common 300 μm (see Table 1).

For the sub-surface water sampling, eight articles focused on waters between 1 and 6 m depth (Table 1). Different types of pumps were used for collecting water. The most common is the continuous intake system located on the forward starboard side of the vessels, generally at 3 to 6 m depth (Lusher et al., 2014, 2015). This system collected and filtered the particles by a steel sieve with 250–300 μm of mesh size (Desforges et al., 2014; Enders et al., 2015). Setälä et al. (2016) employed other impeller pump at 0.5 m of depth, with a mesh size smaller (100 and 300 μm), around 2 $m^3$ was filtered. These authors and Cole et al. (2014) used the manta trawl (200 or 333 μm) to evaluate the fibers in this compartment.

Only Song et al. (2014, 2015) studied microplastic pollution in the surface microlayer (first 400 μm) in the southern coast of Korea. They collected samples by hand with a sieve. All plastics adhered to the sieve by surface tension were kept.

The laboratory processing of samples prior to the visual sorting, and polymer identification when possible, involves usually three steps: density separation, filtration and sieving as described by Hidalgo-Ruz et al. (2012) in their review. The density separation technique is based on the differences in density between plastic and sediment particles. This consists in the use of hypersaline solutions (normally NaCl or $ZnCl_2$,) to separate MPs by density differences. Typical densities for sand or other sediments are ~2.7 g $cm^{-3}$.

### 3.2. Sediments

In the present review, only nine articles determined plastic fibers in surface marine sediments. The most used sampling methodologies (in three papers) are box corer and mega corer dredges (see Table 2). These devices main advantage, in comparison with other dredges, is that the sediments deformation is minimal, allowing stratification sampling and an accurate reconstruction of the chronology.

Once the dredge was on board, the box was removed and the first layer of sediments was obtained (~0–5 cm). Afterwards the samples were homogenized and distributed in suitable containers and immediately frozen at − 20 °C until further analysis (Strand and Tairova, 2016; Vianello et al., 2013; Woodall et al., 2014).

**Table 1**
Summary table of reviewed studies on microfibers in seawater. The classification is by environmental compartments (surface, surface microlayer, sub-surface and water column). Abbreviations: PES (polyester), PE (polyethylene), PP (polypropylene), LDPE (low-density polyethylene), HDPE (high-density polyethylene), PA (polyamide or nylon) and rayon. *Average range. **Range. [a]% tows with fibers and [b]fibers < 5 mm.

| Compartment | Location | Date | Items·m$^{-3}$ | Items·km$^{-2}$ | % fibers | Fiber length (μm) | More abundant | Colors | Polymer | Mesh (μm) | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Surface micro-layer | Southern Coast of Korea | 2012 | 450 ± 410 | | | 200–2000 | 500–1000 | Colored | PP > PE | 2000 | Song et al., 2014, 2015 (22) |
| Surface water | Southwestern Cape Province | 1977–1978 | | 503 ± 1940 | | > 900 | | Blue > green = white | PP > PA | 900 | Ryan, 1988 (34) |
| Surface water | North Pacific Ocean | 1985–1988 | | 100–2600* | | > 500 | | Transparent > white > blue | PP | 500 | Day et al., 1989 (36) |
| Surface water | North Pacific Ocean | 1987–1988 | | | 81.5%[a] | > 53 | 500 | Transparent > white > blue | | 53 | Shaw and Day, 1994 (31) |
| Surface water | North Pacific central gyre | 1999 | | 36,857 | | > 355– > 4760 | > 4760 | | PP | 333 | Moore et al., 2001 (14) |
| Surface water | Scotland and Iceland | 1960–2000 | 0.01–0.045* | | | | | | | | Thompson et al., 2004 (12) |
| Surface water | Swedish west coast | | 50–2400** | | | > 80 | | Blue > black > red | | 80 | Norén, 2007 (13) |
| Surface water | Kuroshio Current area | 2000–2001 | | 4079[b] | | > 330 | 3.000 | | | 330 | Yamashita and Tanimura, 2007 (32) |
| Surface water | North Atlantic | 1991–1995/ 2004–2007 | | | 8.2% | 335– > 15,000 | 2000–4000 | | HDPE > LDPE > PP | 335 | Morét-Ferguson et al., 2010 (19) |
| Surface water | North Pacific Central Gyre | 2005 | | | 16.2% | 333– > 5000 | | | PE > PP | 333 | Rios et al., 2010 (33) |
| Surface water | Northeast Pacific | 2006 | 0–0.03* | | | < 1000– > 10,000 | | | PP | 505 | Doyle et al., 2011 (15) |
| Surface water | Jade System | 2011 | 0.088 ± 0.082 | | | < 100–1000 | | | | 40 | Dubaish and Liebezeit, 2013 (11) |
| Surface water | South Pacific subtropical gyre | 2011 | | 3622 | | > 355– > 4750 | > 4750 | | PP | 333 | Eriksen et al., 2013 (16) |
| Surface water | Equatorial Atlantic | 2003–2004 | | | 22.5% | > 300 | ≤ 1000 | White > black > colored | | 300 | Ivar do Sul et al., 2013 (26) |
| Surface water | waters around Australia | 2011–2012 | | | 6.5% | < 2500– > 10,000 | | White > blue > others | PE > PP | 333 | Reisser et al., 2013 (17) |
| Surface water | Western Tropical Atlantic Ocean | 2011–2013 | | | 4,2–73,4%[a] | < 1000– > 10,000 | | | | 300 | Ivar do Sul et al., 2014 (27) |
| Surface water | Baltic Sea | 2013 | 0–0.7* | | | > 333 | | | | 333 | Magnusson, 2014 (29) |
| Surface water | East China Sea | 2013 | | | 83.2% | > 500 | 500–1000 | Colored > transparent > black | | 333 | Zhao et al., 2014 (23) |
| Surface water | Mediterranean basin | 2013 | | | 2.3% | 200–5000 | < 1000 | | | 200 | Cózar et al., 2015 (35) |
| Surface water | Salish Sea and the Inside Passage | 2011–2012 | | | 0.7% | > 335 | | | | 335 | Davis and Murphy, 2015 (38) |
| Surface water | Western Mediterranean Sea | 2011–2012 | | 2594 | | > 333–5000 | | | | 330 | Faure et al., 2015 (43) |
| Surface water | Southern Sea of Korea | 2012 | 0.34–319* | | | 50–2000 | | | PES | 50 | Kang et al., 2015 (22) |
| Surface water | Artic waters | 2014 | | | 95% | > 333 | | Black > blue | Rayon > PES = PA | 333 | Lusher et al., 2015 (20) |
| Surface water | Southern Adriatic Sea | 2013 | | | 19.2% | > 200 | | White > transparent > black | PE > PES > PP | 200 | Suaria et al., 2015 (45) |

(*continued on next page*)

**Table 1** (*continued*)

| Compartment | Location | Date | Items·m$^{-3}$ | Items·km$^{-2}$ | % fibers | Fiber length (μm) | More abundant | Colors | Polymer | Mesh (μm) | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Surface water | Qatar EEZ | 2015 | | | 23.3% | > 120 | | Blue > brown > black | LDPE > PP = cellophane | 120 | Castillo et al., 2016 (30) |
| Surface water | Jurujuba Cove | 2015 | | | 21.6–28.6% | 250– > 5000 | | Colorful > transparent > black | | 150 | Castro et al., 2016 (41) |
| Surface water | Gulf of Finland | 2013 | 0–0.7* | | | > 333 | | | | 333 | Setälä et al., 2016 (39) |
| Surface water | San Francisco Bay | 2015 | | 5168–459,681** | | > 355– > 4750 | 355–999 | | | 333 | Sutton et al., 2016 (42) |
| Sub-surface | English Channel | 2013 (500 m) | | | 60% | < 250– > 5000 | 1000–5000 | Black > blue > red | PA > PP > PE | 200 | Cole et al., 2014 (18) |
| Sub-surface | NE Pacific Ocean | 2012 (4.5 m) | | | 75% | < 100– > 1000 | 100–500 | Brightly colored | | 62.5 | Desforges et al., 2014 (21) |
| Sub-surface | Northeast Atlantic Ocean | 2013 (3 m) | | | 95.9% | > 250 | > 1250–2500 | Blue > black > grey | PES > PA | 250 | Lusher et al., 2014 (25) |
| Sub-surface | Yangtze Estuary | 2013 (1 m) | | | 79.1% | > 32 | | Transparent > colored > white | | 32 | Zhao et al., 2014 (23) |
| Sub-surface | Atlantic Ocean | 2014 (3 m) | | | 40% | > 10 | < 900 | Colored > black > blue | PE > unknown > PA | 10 | Enders et al., 2015; Lenz et al., 2015 (28) |
| Sub-surface | Artic waters | 2014 (6 m) | | | 95% | > 250 | | Black > blue | Rayon > PES = PA | 250 | Lusher et al., 2015 (20) |
| Sub-surface | North Pacific Gyre | 2007 (1 m) | 0.001–0.003* | | | > 0.7 | | | PP > PE | 0.7 | Mendoza and Jones, 2015 (44) |
| Sub-surface | Gulf of Finland | 2013 (0.5 m) | 0–4.8** | | | > 100 | | | | 100 | Setälä et al., 2016 (39) |
| Water column | Goiana Estuary | 2012–2013 | | | 1.4% | > 300 | | Red > blue | | 300 | Lima et al., 2014 (37) |
| Water column | South Africa | 2014 | | | 90% | > 80 | | Blue > black > red | | 80 | Nel and Froneman, 2015 (24) |
| Water column | Greeland Sea | 2005 & 2014 | | | 97.2% | > 500 | | Dark | PES > LDPE > HDPE | 500 | Amélineau et al., 2016 (40) |
| Water column | Solent estuarine complex | 2013 | | | 54.8% | > 300 | 500 | Black > white > blue | PE > cellophane > PP | 300 | Gallagher et al., 2016 (10) |

**Table 2**
Summary table of reviewed studies on microfibers in marine sediments. Abbreviations: PES (polyester), PE (polyethylene), PP (polypropylene), LDPE (low-density polyethylene), HDPE (high-density polyethylene), PA (polyamide or nylon) and rayon. *Average range.

| Location | Date | Items·50 mL sedim | Items·250 g DW | % fibers | Colors | Polymer | Extraction method | Reference |
|---|---|---|---|---|---|---|---|---|
| Plymouth | | 2.5–5.5 | | | Brightly colored | | Ekman grab | Thompson et al., 2004 (3) |
| Belgian Coast | | | 13.15–19.05 | | | PP, PA, PVA | Van Veen grab | Claessens et al., 2011 (4) |
| Lagoon of Venice | | | | 11 | Blue, red | PP | Box corer | Vianello et al., 2013 (7) |
| Singapore Coast | 2012 | | 2.7–10.7* | | Transparent, blue, red | PP, PVC, PA | Steel spatula | Nor and Obbard, 2014 (6) |
| Subpolar N Atlantic | | 10–15 | | | Blue, black, green | PES = PA, AC | Boxcorer | Woodall et al., 2014 (1) |
| NE Atlantic | | 6–40 | | | Blue, black, green | PA, AC > PES | Boxcorer | Woodall et al., 2014 (1) |
| Mediterranean | | 10–35 | | | Blue, black, green | PES > PA, AC | Boxcorer | Woodall et al., 2014 (1) |
| SW Indian | | 1.4–4 | | | Blue, black, green | PA, AC = PES | Megacorer | Woodall et al., 2014 (1) |
| Atlantic Ocean | | | | 100 | | PES > CV | ROV | Woodall et al., 2015 (2) |
| South of Portugal | 2013 | | | 80.6 | Black > green > blue | CV | Divers | Frias et al., 2016 (5) |
| North Sea | 2015 | | | 40.6 | Blue > black > white | | Box corer | Strand and Tairova, 2016 (9) |
| Baltic Sea | 2015 | | 39.48 | | | | Hand-operated dredge | Zobkov and Esiukova, 2016 (8) |

Van Veen grab was used only in one study in the Belgian coast (Claessens et al., 2011). This method did not allow a stratification sediment sampling. Another dredge was used by Zobkov and Esiukova (2016) in the Baltic Sea. They used a rectangular hand operated drag with mouth size of 200 × 100 mm. In both cases, the samples were homogenized and stored for further analysis.

Frias et al. (2016) used divers to sample sediments from the southern Portuguese coast whilst Nor and Obbard (2014) used a steel spatula in Singapore's coastal mangrove. In this case, the authors preserved the samples with ethanol 96% for further analysis. ROV was used to collect sediments in greater depth samples (> 800 m) in some points of the north Atlantic and Indian Ocean (Woodall et al., 2014, 2015). We did not found details about the sample stratification, if any, in these references.

After sampling the sediments, different approaches can be used to separate the microplastic fragments (as far as we know there is no specific method for microfibers in seawater or sediments) from the sandy or muddy matrix. The most common approach is to extract microplastics from the sediment using a density separation technique, as described for seawater samples, with similar filtration and sieving processing prior to visual sorting, and polymer identification when possible. For more details on extraction methods for sediment samples we encourage to see Van Cauwenberghe et al. (2015).

## 4. Quantification and characterization of microfibers

### 4.1. Units

An aspect that we considered in the reviewed papers was the units used to express the results. In seawater studies (55% of the studied papers), units such as a number of fibers per $m^3$ in the 28% of the papers and number of fibers per $km^2$ in 17% were used (see Fig. 3c).

Regarding the articles of fibers in marine sediments (45% of papers), around 33% of the publications expressed their results in number of fibers per dry weight and 22% of total reviewed papers used number of fibers per volume of sediment. Other units were used, as % of fibers related to microplastic particles.

It is remarkable, the lack of homogenization in units used in the studies. We transformed some results in order to compare them. For example, all the sediment studies that showed their results as number of fibers or items per dry weight (DW) sediment in kg, were standardized as items per 250 g DW (Claessens et al., 2011; Zobkov and Esiukova, 2016). For those expressing their results as items per sample, we transformed them to % fibers in total sample (Gallagher et al., 2016; Woodall et al., 2015).

In the case of seawater studies, the main conversion units applied were those to transform items (MFs) per L to items (MFs) per $m^3$ (Dubaish and Liebezeit, 2013; Rios et al., 2010; Song et al., 2015) and fibers in total of microplastics to % of fibers (Ivar do Sul et al., 2013; Lusher et al., 2014).

### 4.2. Fiber length

Fiber length was reported in 80% of papers. Some authors describe the synthetic fiber length by different size categories: < 1 mm, 1–2.5 mm, 2.5–5 mm, 5–10 mm and > 10 mm (e.g. Doyle et al., 2011). Other authors do not provided detailed information about size range. The fibers length range varies from > 100 μm to > 15 mm, although the last size could not be considered to be a microfiber, as only fibers of < 5 mm can be named as MFs following microplastics definition (Arthur et al., 2009).

The most abundant values in surface water ranged from 500 to 1000 μm up to 4750 μm (Eriksen et al., 2013; Shaw and Day, 1994). In the surface microlayer, the size was 500–1000 μm (Song et al., 2014, 2015) and in sub-surface waters the size ranged from 1 to 5 mm (Cole et al., 2014). Only one article referred to the water column, and the most abundant fibers size was 500 μm (Gallagher et al., 2016). Regarding sediments, only Vianello et al. (2013) mention that the most abundant fibers size ranged from 800 to 1000 μm.

### 4.3. Fiber color

Visual examination is the most common method used to identify microplastics, although it can have a relatively high error rate (Löder et al., 2015). There are different aspects that help us to identify and catalog fibers like size and shape. One of them is color. Synthetic fibers are often easier to identify in the marine environment by their characteristic colors, but black and transparent are most difficult to distinguish. Potential microfibers could have homogeneous colors, shininess or unnatural colors (Lusher et al., 2015).

Diverse color classifications could be done varying from eleven categories: black/gray, blue, brown, green, orange, red/pink, tan, transparent, white, yellow, and mixed or unidentified as proposed by Day et al. (1990) to two groups: dark and light suggested by Amélineau et al. (2016). In between different classifications have been put forward by several authors (see e.g. Castro et al., 2016; Ivar do Sul et al., 2013; Ryan, 1988). Castro et al. (2016) indicate that colorful materials provide a strong evidence of an anthropogenic origin. Gallagher et al. (2016) also recognize that color is a helpful tool for identifying the plastic origin and according to Cole et al. (2014) this simplifies their identification.

Although color is perhaps not the most pertinent characteristic in determining environmental impact (Gallagher et al., 2016) it is directly related to the adsorption of contaminants and can be associated with concentration of POPs (Persistent Organic Pollutants) (Castro et al., 2016). Also Ivar do Sul et al. (2014) pointed out that color distribution

of floating plastics could be an indicator of the residence time of plastic particles on the sea surface. By the contrary Shaw and Day (1994) observed that residence time could have no effect on color distribution, possibly due to the fact that all plastics would be at seawater temperature and decomposition rates would not vary with color due to differential heating.

### 4.4. Techniques to identify polymer type

Identification of microplastic items collected is a challenge due to: i) small particle size, ii) brittleness of samples, and iii) high rate of weathering of the material due to the mechanical and photo degradation as well as hydrolysis (Horvat et al., 2015). In addition, sample manipulation is a time consuming process.

The first step is visual sorting in order to distinguish between plastics and other materials. In the next step optical or dissecting microscope is used for size, shape and color determination of microplastic particles. Finally, in order to identify microplastics polymers a subsample of particles are randomly chosen and characterized.

Different techniques can be used for this aim, for example, Fourier Transform Infrared spectroscopy (FTIR) (Frias et al., 2016), Pyrolysis–Gas Chromatography (Fischer and Scholz-Bottcher, 2017), Microspectrophotometry, Scanning Electron Microscopy (SEM) (Woodall et al., 2015), Raman spectroscopy (Lenz et al., 2015) or it is even possible to analyze samples for carbon, hydrogen and nitrogen (CHN) content (Morét-Ferguson et al., 2010).

Among them, FTIR micro spectroscopy (μ-FTIR) has been the most commonly used technique for MP identification in recent studies. This tendency is probably due to the FTIR ability to confirm the polymer type of microplastics, which can also provide additional information such as origin (Song et al., 2014).

Numerous studies used in this review have employed only visual identification for microplastic classification (54% of papers) but when microfibers polymers were identified with a technique, FTIR was the most used (39%). In three studies Raman spectroscopy were selected (Enders et al., 2015; Lenz et al., 2015; Lusher et al., 2014) and only Morét-Ferguson et al. (2010) proposed CHN analysis.

In the case of analyzing microfibers using FTIR, the spectrum for each particle was compared with several polymer spectra libraries and the detection threshold for a correct identification of polymers was set to a match of at least > 60% (Avio et al., 2015; Lusher et al., 2013), then the proportion of microplastics among debris were recalculated. The spectra obtained from the samples usually did not match in the library as closely as it is desirable (see e.g. Frias et al., 2016). There are different reasons to explain it: i) environmental degradation and weathering of the MFs surfaces, ii) inefficient particle recovery, and iii) misidentification of particles (Gallagher et al., 2016).

## 5. Microfibers in seawater and sediments

### 5.1. MFs values

The bibliographic review shows an heterogeneity in the geographical distribution of the studies (see Fig. 2). In general, the North hemisphere concentrates most of the studies (85%), especially in the north coast of Europe. On the other hand in the Southern hemisphere only eight articles study the pollution by plastic fibers, seven in seawater and one in sediments.

The fiber abundance in the marine environment by oceanic regions is as follows:

*Atlantic*:

A significant number of papers that analyzed Atlantic waters and seabed were found. About 30% of the studies in the southern Atlantic concentrated in the Brazil and Argentinean coast. In this area the plastic fibers percentages in surface waters reported by Castro et al. (2016) in the subtropical zone and Ivar do Sul et al. (2013) in the equatorial Atlantic are very similar: 21.6 to 28.6% and 22.5% of MFs related to total microplastics, respectively. Away of these results is the 1.4% of fibers found by Lima et al. (2014) in water column in an intermediate zone.

In the north hemisphere, Morét-Ferguson et al. (2010) collected samples in surface water around the Atlantic western coast, from New York to Caribbean coast. The fiber content was around 8% of the total plastic concentration, much lower than 40% of fibers reported by Enders et al. (2015) and Lenz et al. (2015) in sub-surface waters from Caribbean Sea to North Sea (in front of Belgian coast). The highest percentage of MF was found by Lusher et al. (2014) in sub-surface waters in front of Ireland coast where 95.9% of total microplastics were fibers.

In the seabed several areas were analyzed in boreal hemisphere (Frias et al., 2016; Woodall et al., 2014, 2015) with concentrations that ranged from 6 to 40 fibers per 50 mL in the NE Atlantic and 80.6% microfibers related to total microplastics around the Iberian Peninsula. In Plymouth coast (UK), Thompson et al. (2004) recounted between 2.5 and 5.5 microfibers per 50 mL of sediment. It is remarkable that no study was found in the sediments of southern hemisphere.

*Pacific*:

As it can be observed in Fig. 2, all the studies about pollution by MFs in the Pacific are focused on seawater, with an exception of the Singapore's coastal zone (Nor and Obbard, 2014) in which the abundance of fibers in sediments ranges from 2.7 to 10.7 items per 250 g dry weight of sediment.

Different regions were studied: Eriksen et al. (2013) found an average value of 3622 fibers per $km^2$ in the south subtropical gyre, one of the areas with a highest contamination by microplastics. Several papers studied the north Pacific (Davis and Murphy, 2015; Doyle et al., 2011; Sutton et al., 2016) and more concretely their subtropical gyre (Day et al., 1989; Desforges et al., 2014; Rios et al., 2010).

In this region the comparison between results is very complicated due to the lack of uniformity in the units, but the values pointed out by Sutton et al. (2016) are noteworthy with ranges between 5168 and 459,681 MFs per $km^2$ in the surface water of San Francisco Bay (USA). However, in this same area but for sub-surface water the values were much lower: 0.001–0.003 MFs per $m^3$ (Mendoza and Jones, 2015). Rios et al. (2010) in another study in the central gyre determinates that 16% of the microplastics were fibers.

In the western Pacific the abundance of fibers varies between 450 fibers per $m^3$ (Song et al., 2015) to 0.15–0.70 fibers per $m^3$ (Kang et al., 2015) in the same zone. Yamashita and Tanimura (2007) estimated the MF content in the Kuroshio Current area to be 4079 MFs per $km^2$. It is worth pointing out the maximum value observed in the Yangtze estuary (China), 10,200 items per $m^3$, in which 79% of the microplastics were microfibers (Zhao et al., 2014).

*North Sea and Arctic waters*:

It is worth mentioning the abundance of studies around the coasts of the North Sea and Baltic Sea, especially in surface water (Dubaish and Liebezeit, 2013). In Swedish waters values fluctuates between 50 and 2400 fibers per $m^3$ (Norén, 2007). In the water column only Gallagher et al. (2016) studied this region and their results showed 54.8% of fibers related to the total microplastics.

In Greenland waters, Amélineau et al. (2016) studied the water column and their results showed high values with 97% of fibers related to total microplastics. This concentration is similar to that observed by Lusher et al. (2015) in the Arctic surface waters (Barents Sea) with 95% of fibers related to total microplastics.

In sediments, the higher values were approximately 40 MFs per 250 g of dry sediment in the Baltic Sea (Zobkov and Esiukova, 2016). In the North Sea MFs represented around 40% of the total (Strand and Tairova, 2016). Claessens et al. (2011) carried out a study along the Belgian coast and the values were ranged from 13 to 19 fibers per 250 g of dry sediment. Woodall et al. (2014) collected samples in Arctic Ocean, and the numbers of fibers extracted were 10–15 per 50 mL of

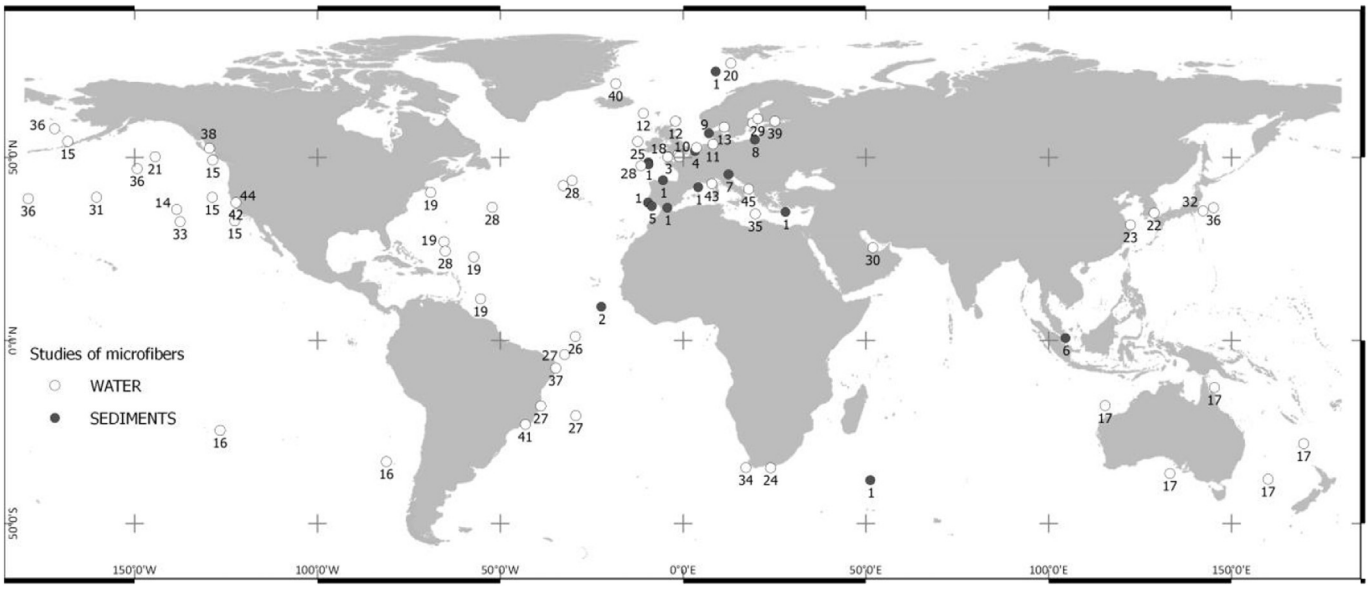


**Fig. 2.** Worldwide distribution of studies on microfibers in the marine environment (seawater and sediments). (The numbers refers to the ID code to identify the study in Tables 1 and 2.)

sediment.

*Mediterranean Sea*:

The percentage of fibers analyzed in the Mediterranean waters by Cózar et al. (2015) was 2.3% related to total microplastics while in the Adriatic Sea, Suaria et al. (2015) found significantly higher values with 19% of MFs related to total microplastics. In the western Mediterranean Faure et al. (2015) analyzed the surface water and their results showed 2594 fibers per $km^2$.

Regarding sediments, fibers oscillated between 10 and 15 fibers per 50 mL of sediments (Woodall et al., 2014) or 11% of total microplastics in the lagoon of Venice (Vianello et al., 2013).

*Other areas*:

Woodall et al. (2014) were the only authors who analyzed sediments in SW Indian Ocean. In this case concentrations ranged between 1.4 and 4 fibers per 50 mL of sediment.

Only one paper studied the surface waters around Australia (Reisser et al., 2013) and their results showed the concentration of MFs were 6%. Another zone studied by Castillo et al. (2016) was the Persian Gulf, and the concentrations of MFs were approximately 23%.

### 5.2. MFs colors

Among all studies, blue is the most common color in seawater and sediment, followed by transparent and black in the case of seawater, and black and colorful in sediments (Fig. 3b). A possible explanation to this tendency could have already been proposed by Shaw and Day (1994). They hypothesized that some marine organisms feeding at the surface tend to mistake white (and other light-colored) plastic objects smaller than 0.5 mm as food items and ingest them. Amélineau et al. (2016) and Zhao et al. (2014, 2016) also hypothesized this, because those colors are easily detected as targets by marine organisms due of their resemblance with preys. In the case of the dominance of blue color, we hypothesize that probably is due to the combination of two factors; is not attractive for ingestion and is a very popular color worldwide (jeans, shirts, etc.).

### 5.3. MFs synthetic polymers

It is expected that dense plastics such as nylons ($\sim$1.12–1.15 $g{\cdot}cm^{-3}$), polyvinyl chloride (PVC, 1.38–1.41 $g{\cdot}cm^{-3}$) and polyethylene terephthalate (PET, 1.38–1.41 $g{\cdot}cm^{-3}$) tend to sink in the water column (Andrady, 2011), whilst light polymers: polyethylene (PE, 0.89–0.98 $g{\cdot}cm^{-3}$), polypropylene (PP, 0.85–0.92 $g{\cdot}cm^{-3}$) and polystyrene (PS, 1.04–1.06 $g{\cdot}cm^{-3}$) will float (Vianello et al., 2013).

Position of plastics in the water column is affected by polymer density; in a stable environment, particles are distributed only by their density. However, turbidity of seawater produced by storms and wind would imply surface mixing which could redistribute microplastics in the water column (Lusher et al., 2014). Plastic polymers less dense than seawater float at the sea surface which allows them to be dispersed in the marine environment until biofouling formation and degradation may change the apparent density of polymers or are ingested by marine biota (Enders et al., 2015; Galgani et al., 2000; Ioakeimidis et al., 2014; Morét-Ferguson et al., 2010).

Furthermore, polymers less dense than seawater (at a Salinity = 35 and Temperature = 15 °C; $\rho$ = 1.026 $g{\cdot}cm^{-3}$) could float and, transported by ocean currents, accumulate in convergent zones (Lusher et al., 2014). Morét-Ferguson et al. (2010) CHN analyses suggested that plastic particles are increasing in density during their residence in the open ocean mainly due to biofouling. Another possible mechanism for this density increase, related with degradation of materials, was proposed time ago by Van Krevelen and Nijenhuis (1972). They hypothesized that in the presence of sunlight, all plastics undergo chemical reactions in which polymer molecules are cross linked, causing embrittlement, an increase in density and also reducing the physical stress needed for fragmentation.

In regard to microfibers, our review shows that similar types of polymers are found in surface waters and sediments (Fig. 3a). Thompson et al. (2004) were the first to observe this aspect in microplastics, suggesting that polymer density was not a major factor influencing distribution of microplastics at sea. From the reviewed literature, only twenty six articles in sea surface and water column and six in sediments identify the polymer type (see Fig. 3a). In both cases PP is the main polymer, found in 13 and 3 articles in water and sediment, respectively, followed by PE in water (5) and PES (3) in water and sediment. Some polymers were described only in water samples: PE (5), HDPE (1), LDPE (1), cellophane (2), whilst only rayon (1) was reported in sediments.

It is hypothesized by Enders et al. (2015) that the presence of PE only in seawater samples (both low- and high-density) is due to its low density (LDPE $\sim$ 0.89–0.93 $g{\cdot}cm^{-3}$ y HDPE $\sim$ 0.94–0.98 $g{\cdot}cm^{-3}$). On the other hand, cellophane was only present in seawater, despite of its high density ($\rho \sim$ 1.40–1.53 $g{\cdot}cm^{-3}$). Related with sediments, rayon was only present in marine sediment samples, probably due to its high

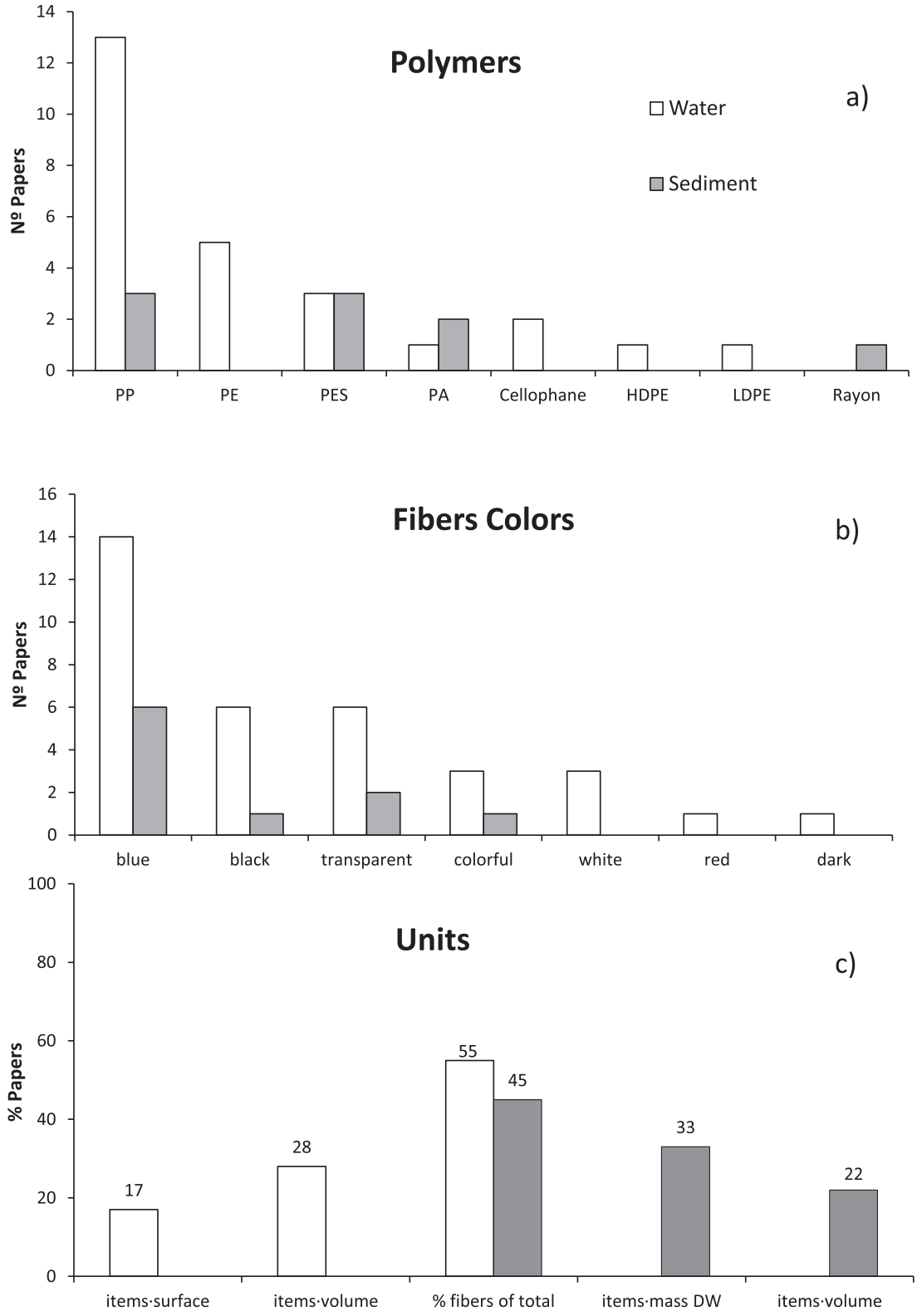


**Fig. 3.** a) Main polymers observed in the reviewed studies. Abbreviations: PES (polyester), PE (polyethylene), PP (polypropylene), LDPE (low-density polyethylene), HDPE (high-density polyethylene), PA (polyamide or nylon) and rayon. b) Main colors of fibers in the reviewed studies. c) Main units used to express fibers abundance in seawater and sediments in the reviewed studies (%).

density ($\rho \sim 1.53\ g{\cdot}cm^{-3}$). As pointed out by Lefteri (2003), PP is one of the most common polymers identified due its intrinsic characteristics: resistance to high temperatures and wide application. In addition, its relatively low cost makes it very popular in consumer products.

## 6. Contamination controls

Contamination of samples is a relevant issue when dealing with microfibers because this material is present in lab material and garments. Clothing made from synthetic fibers such as acrylic, rayon,

polyester and nylon are common and therefore potential sources of contamination when working in the lab. Fibers are ubiquitous in the everyday life and have been documented in studies that have focused on diverse substrata from human skin to car seats (Free et al., 2014; Grieve and Biermann, 1997; Liebezeit and Liebezeit, 2014; Marnane et al., 2006; Owen et al., 1992; Palmer and Burch, 2009; Roux and Margot, 1997; Was-Gubala, 2004; Zhao et al., 2014), thus the possibility of post-sampling contamination is high. But excluding MFs may bias the quantification and interpretation of the effects of microplastics in the marine environment. In addition, the techniques used for sampling seawater could under sample microfibers. Therefore, the quantities on MFs in the marine environment could be higher than expected.

In addition a few recent studies have reported laboratory background contamination levels, contamination mitigation techniques or used procedural blanks (Cole et al., 2014; Fries et al., 2013; Lusher et al., 2014; Nuelle et al., 2014;Obbard et al., 2014). The presence of high levels of fibers in the lab was demonstrated by Nuelle et al. (2014).

As a result of this high probability of cross contamination, some studies on microplastic pollution have intentionally excluded microfibers in their analyses (Cózar et al., 2014; Dekiff et al., 2014; Goldstein and Goodwin, 2013; Van Cauwenberghe et al., 2013). However, when included in studies, fibers are a large proportion of the microplastics recovered from sediment, ice and waters (Browne et al., 2011; Claessens et al., 2011; Desforges et al., 2014; Mathalon and Hill, 2014; Obbard et al., 2014; Thompson et al., 2004; Woodall et al., 2014).

As Woodall et al. (2014, 2015) recommend, it is necessary to implement protocols to prevent plastic contamination from the processing environment. With this aim controls to monitor air and water supplies are desirable to be taken during all processing phases. Furthermore lab coats, cotton or 100% natural fiber clothing and gloves should be worn when working to reduce contamination (Lusher et al., 2014) and even it would be advisable that scientists are covered by a clean, 100% white cotton boiler suit, lab coat and headscarf (Woodall et al., 2015).

Extra prevention strategies can be adopted: work inside the fume hood, clean surfaces with alcohol or wear nitrile gloves (Castillo et al., 2016; Lusher et al., 2014); acid-wash and/or rinse thoroughly with clean deionized water all apparatus prior to use, use consumables directly from packaging and, as far as possible, use not plastic equipment (Cole et al., 2014; Lusher et al., 2015; Nel and Froneman, 2015); after filtration, the collected samples are immediately covered and/or wrapped in aluminium foil (Lusher et al., 2014).

Overall reviewed articles, only 15 (~30%) took some contamination control into account. Essentially the protocol followed by controls was the same as the samples. For this reason procedural blanks were run in parallel during all phases of the analytical procedure and did not indicate any sources of potential contamination (Cole et al., 2014; Enders et al., 2015; Lusher et al., 2015; Norén, 2007; Rios et al., 2010; Song et al., 2014, 2015; Sutton et al., 2016).

Embracing these protocols to avoid samples contamination is especially important when working with low microplastics concentrations (Setälä et al., 2016). It has been demonstrated that analytical methods may be improved in some laboratories with relatively small cost precautions. For example, Torre et al. (2016) minimized the flow of airborne contamination by 95% using a plastic sheet covering the stereo microscope used to identify the microfibers.

## 7. Sources of fibers to the marine environment

Microfibers are found in marine and freshwater environments; however, their specific sources are not yet well understood. In our daily life we use a large amount of materials that are made of fibers, either synthetic or natural. Plastic fibers are among the most common constituents in indoor dust (see e.g. Gyntelberg et al., 1994; Macher, 2001). So far, a few freshwater bodies have been studied and little information is provided regarding the inputs/sources and pathways of microfibers (see e.g. Dris et al., 2015a; Wagner et al., 2014).

Some studies showed relatively high concentrations of microplastics in rivers and gave first insight on the role of urban areas in this pollution (Dris et al., 2015b; Mani et al., 2015; McCormick et al., 2014). A recent study detected the presence of man-made fibers in the atmospheric fallout in the Parisian agglomeration (Dris et al., 2016). Habib et al. (1998) showed that synthetic fabric fibers were an easily detected indicator of sludge and sewage effluent in the environment. High amounts of microplastic particles and fibers have also been detected in the vicinity of industrial plants involved in paper production (Dubaish and Liebezeit, 2013). The observed fibers in these studies are often textile fibers (Dris et al., 2016; Pauly et al., 1998).

Browne et al. (2011) were the first to identify washing as a source of pollution with plastic fibers. They reported that a single garment can shed > 1900 fibers per wash and that all garments released > 100 fibers per liter of effluent. Dubaish and Liebezeit (2013) reported a release of 0.033–0.039% wet fibers from a polyester garment per washing. It is important to mention that more than half of textiles used are plastic polymer based; according to Sundt et al. (2014) the world synthetic fiber consumption was 55 million tons in 2013 out of a total consumption of 90 million tons fibers.

As mentioned by Pirc et al. (2016) effluent from commercial laundries and cleaning workshops set up in public service or companies will, without any filtering of the effluent water or air, be point sources of microplastic fibers just like home laundries. A study by the Norwegian Environment Agency (Sundt et al., 2014) estimated the annual fiber release from laundries and households in Norway at 100 and 600 tons, respectively.

A recent study by Petersson and Roslund (2015) shows that yarn and textile type combined with usage are the principal drivers of fiber release during washing. In this sense, MF concentrations in sea-surface water samples, correlated with the production volume of synthetic fibers in manufacturing (Thompson et al., 2004).

It is well known that wastewater treatment plants are an important source of microfibers, to rivers and estuaries, and finally to the sea (Talvitie et al., 2015). Habib et al. (1998) as well as Zubris and Richards (2005) reported synthetic fibers as an indicator of municipal sewage sludge use in soils, indicating fiber presence in wastewaters as well as spreading routes.

Other important sources of fibers are curtains, furniture and carpet made with synthetic clothing that are shedding fibers every day, the old interior paint on the wall gives away flakes and chips, mattresses discard polyurethane particles, and even electronics might give away some plastic dust (Brandsma et al., 2014; Marklund et al., 2003; Rauert et al., 2014). Probably more significant and much larger emissions of plastic fibers would be shed from plastic equipment discarded, abandoned or stored outdoors for a long time (Rees et al., 2014). Other relevant source for the marine environment could be plastic fibers derived from fishing elements like fishing gears and lines.

## 8. Conclusions and outlook

Microfibers have been found in seawater and sediments of almost every marine habitat around the world (see Table 1 and Fig. 2). Due to the rapid development of microplastic research, there is a lack of consistency in sampling and extraction techniques used to quantify microplastics in the marine environment, and microfibers (due to its special characteristics) are even more affected by this. As a result of the large variety in techniques applied, comparison of reported microplastic concentrations between studies is often impossible or requires additional calculations based on assumptions (e.g. sediment densities).

The majority of these method inconsistencies can be related to: i) differences in the lower and upper size limit implemented, ii) the sensitivity of the applied extraction technique, and iii) differences in sampling technique leading to a wide variety of reporting units. There is a need for standardization due to the special characteristics of fibers. It is important to note that fibers are found at sea in a higher number

compared to other plastic micro particles like pellets or fragments. Adoption of consistent protocols allows for comparisons across studies which are of vital importance when identifying areas/years/seasons of high impact.

The presence of microfibers in our daily live is difficult to control and the cross contamination affects all steps of the process; from sampling to polymer identification. Methodologies ensuring a minimal contamination are critical in order to a proper evaluation of their concentration in the environment.

The widespread distribution and accumulation of microfibers in the marine environment raises concerns regarding the interaction and potential effects of MFs on marine biota. As microfibers interact with plankton and sediments, both suspension and deposit feeders may accidentally or selectively ingest microfibers. When MFs are ingested, the leaching of adsorbed pollutants and additives could be a source of toxic substances influencing the organisms and entering into the food web leading all the way to humans.

Implications of nanometer-sized plastic particles ('nanoplastics') constitute a very recent area of the environmental sciences. Nanoplastics are of specific interest because of their nano-specific properties, which fundamentally differ from those of the same polymer type in bulk form. We didn't find any reference to this particles in the marine environment but probably this aspect will emerge in the next years.

As microplastic research, in general and specifically microfibers, is still in its infancy, there are many more unanswered questions, the answers to which are required to build on current and future knowledge to develop a clearer picture of their impact in the marine environment and biota.

What is clear is that further research is required to understand the environmental implications of microfibers in more detail and to establish effects in natural populations. Nevertheless, it seems that synthetic fibers are a threat to the marine environment and measures to reduce their input to the marine environment should be taken straightforward.

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