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Inamuddin
Mohd Imran Ahamed
Eric Lichtfouse *Editors*

Water Pollution and Remediation: Organic Pollutants

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Water Pollution and Remediation: Organic Pollutants

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Preface

Water and air, the two essential fluids on which all life depends, have become global garbage cans

Jacques-Yves Cousteau

Earth's surface and ground waters are severely affected by the discharge of contaminants. Organic pollutants originate from industrial effluents, domestic sewage, water treatment plants, urban turn-off, agriculture, aquaculture, pulp and paper making, food processing, tannery, and various industries. Massive point-source pollution such as industrial pollution during fabrication, storage, processing, and transportation is of particular concern because the amount of discharged pollutants is usually high, thus inducing immediately severe health impact on ecosystems. Whereas, diffuse pollution such as low pesticide and drug levels in waters induce diseases in the long run. As a countermeasure, there is a need for efficient methods and techniques to remove organic pollutants from wastewater. This book reviews the occurrence, analysis, toxicity, and remediation technologies of water organic pollutants. Chapters discuss the treatment of pollutants such as hydrocarbons, microplastics and plastics, phthalates, polycyclic aromatic hydrocarbons, pharmaceutical drugs and metabolites, oil spill, petroleum hydrocarbons, personal care products, tannery waste, and dyes and pigments.

Chapter 1 by Godoy et al. includes a summary of techniques for sampling, extraction, purification, and identification of microplastics, a review of publications on the abundance of microplastics in different aquatic ecosystems around the world, and a brief synthesis of researches about sorption of chemicals on microplastics. Chapter 2 by Tahir et al. provides highlights on the nature of plastics, types, sources, consumption, effects, and pollution caused by excessive use of plastics. Techniques used for the identification of plastics present in water and the different remediation techniques such as primary, mechanical, chemical treatment, and recycling are elaborated. Finally, the chapter focuses on the health impact and utilization of degradable plastics. Chapter 3 by Muneer et al. discusses water pollution caused by plastics. Three strategies to tackle water pollution caused by nanoplastics, microplastics, and macroplastics are discussed: scientific methods, community involvement, and government policies. Chapter 4 by Jain et al. narrates how plastics and e-wastes contaminate our water system and their hazardous effect on living beings. All aspects of plastic and e-waste, such as types of plastics and e-waste, effects on marine and freshwater life, solution for prevention, and prospects are discussed.

Chapter 5 by Rachna et al. reviews concentrations, impact, and remediation of polycyclic aromatic hydrocarbons (PAH) in rivers and sediments, with focus on functionalized nanomaterials to degrade PAHs. Chapter 6 by Ghosh and Chakraborty presents aerobic granulation as a rapid, eco-friendly, and cost-effective technology for treatment of recalcitrant, hydrocarbon-rich wastewater. The chapter

gives mechanisms, factors, characteristics, and techniques of aerobic granulation and applications to the oil remediation. Chapter 7 by Denaro et al. reviews the use and synergy of bacteria and algae to degrade petroleum hydrocarbons. Chapter 8 by Samanta and Mitra presents the types of petroleum hydrocarbons polluting waters and their abatement by physical, chemical, and biological methods. Chapter 9 by Mustapha examines aspects of pharmaceuticals such as active metabolites, influxes, distribution, analysis, fate, and transport routes. Chapter 10 by Saggioro reviews advanced oxidation processes (AOP) such as heterogeneous processes using TiO_2; homogeneous processes using ozone, ultraviolet, hydrogen peroxide, and the Fenton reagents; and coupling AOP and other treatment processes for the removal of personal care products, for example, triclosan and triclocarban, and pharmaceuticals compounds: carbamazepine, diclofenac, and ibuprofen. Chapter 11 by Othman et al. reports advanced technologies for the treatment of oily industrial wastewater, such as flotation, coagulation, biological treatment, membrane filtration, and electrochemical treatment.

Chapter 12 by Fatehi et al. details the source of oil contaminants and two types of oil removal technologies: remediation by physical, thermal, and chemical methods and bioremediation. Chapter 13 by Dheenadayalan and Thiruvengadathan reviews sources, health effects, and remediation of organic pollutants in waters. Remediation includes physical, chemical, and biological methods. Chapter 14 by Karim et al. proposes the application of soil as a heterogeneous Fenton catalyst for the abatement of organic pollutants. Performance of clay, laterite, and volcanic soils to decompose hydrogen peroxide in water medium is explained. Chapter 15 by Sun et al. discusses properties, toxicity, contamination levels, analysis, and treatment of waters contaminated by phthalates.

Chapter 16 by Patel et al. discusses adverse effects, treatment technologies, and management processes of tannery waste. Chapter 17 by Ashraf et al. compares methods for the treatments of dyes and pigments, such as physical, chemical, and biological techniques. Chapter 18 by Akram presents the methodologies used for the treatment of textile waste, with focus on nanomaterials such as silica and iron-based magnetic materials such as sorbents and photocatalysts. Synthetic and biomaterials-based composites are also discussed as next-generation materials for wastewater treatment.

Aligarh, India — Inamuddin
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Chapter 1
Microplastic Pollution in Water

V. Godoy, M. A. Martín-Lara, A. I. Almendros, L. Quesada, and M. Calero

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Abstract Microplastics are ubiquitous in almost all environments, including freshwater, seawater, and coastal environments. Recently, researches about microplastics have increased due to their serious ecological and health impacts. In this chapter, firstly, the sources of microplastics are summarized. Then, the most important techniques for sampling, extraction, purification, and identification of microplastics are discussed. Next, abundance of microplastics in different aquatic ecosystems around the world is synthesized. According to reviewed publications, the rivers

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and coasts of East Asia, the Mediterranean Sea, the Portuguese coasts, the rivers of England, and parts of the eastern United States were the most polluted areas. The vast majority of microplastics were composed of polyethylene (PE), polypropylene (PP), or polystyrene (PS), and the forms that predominated were fibers, fragments, and pellets. Finally, a brief revision of publications based on sorption of chemicals on microplastics and their effect on freshwater organisms is also reported.

Keywords Microplastics · Marine debris · Freshwater · Emerging contaminants · Sorption · Polymer identification · Risk assessment

1.1 Introduction

In the last years, contamination produced by microplastics has become a concern problem due to the environmental damage they cause and their harmful effects on organisms. These particles can be primary, which are manufactured by humans with some proposal, or secondary, which result from the physical and chemical degradation of macroplastics in the environment (Cole et al. 2011). Primary microplastics can be found in some personal care products, drilling fluids for extracting oil or natural gas, sandblasting for cleaning, some boat paints, or the loss of pellets from a plastic manufacturing industry (Duis and Coors 2016; Sundt et al. 2014). On the other hand, secondary microplastics can be produced by the tire wear, the washing of synthetic clothes, or the physical-chemical degradation of larger macroplastics (De Falco et al. 2018; Karlsson et al. 2018; Sommer et al. 2018).

Microplastics are found in almost every marine and freshwater environment on the Earth and also on beaches, sediments, bottled water, or food (Hamid et al. 2018; Novotna et al. 2019; Vandenberg et al. 2007). Figure 1.1 shows sampling of sediment on a Spanish beach in order to determine the presence of microplastics. The amount of microplastics in aqueous media is still increasing due to the growth in worldwide plastic production, which was 348 Mt in 2017 (Plastics Europe 2018). Research on these particles and their concentration in the marine and freshwaterenvironments has not ceased to grow. There are citations of the presence of microplastics in all types of environments, including those considered to be the most virgin or distant from the sources of production of these particles, such as the depths of the oceans or Arctic ice (Obbard et al. 2014; Woodall et al. 2014). Not only their widespread distribution is important, but they are accessible to consumption by an extensive diversity of organisms.

One of the most important environmental problems caused by microplastics is ingestion by aquatic organisms when confused with plankton (Egbeocha et al. 2018; Fossi et al. 2012; Taylor et al. 2016). The presence of microplastics in the digestive tract of marine species has been demonstrated in numerous studies. There are a lot of species that are affected by this problem, such as molluscs, cetaceans, bivalves, pinnipeds, and zooplankton (Botterell et al. 2019; De Sá et al. 2018; Gallo et al. 2018; Lusher 2015; Nelms et al. 2019). These studies showed that almost all

Fig. 1.1 Sampling of microplastics on a Spanish beach

commonly used polymers can be ingested by organisms, especially polyethylene and polystyrene.

Microplastics also have the capacity to adsorb contaminating substances that are present in the watercourses, i.e., pharmaceuticals, heavy metals, or pesticides (Bakir et al. 2014; Brennecke et al. 2016; Li et al. 2018). This implies a high risk for marine fauna and for human health, although the effects are still poorly defined. Some studies have reported negative effects of these pollutants on feeding behavior, reproduction, and growth of marine organisms (Anderson et al. 2016; Botterell et al. 2019; Bouwmeester et al. 2015; De Sá et al. 2018; Schirinzi et al. 2017; Wright and Kelly 2017; Wright et al. 2013).

The main problems when studying and analyzing microplastics are their small size, which makes it difficult to choose the right technique to identify them. This means the absence of a standard method for extracting microplastics from samples and their quantification. The analysis of microplastics goes through different phases, in which a different technique must be applied. Collection is the first phase, which can take place in water or in sediments. Sediment can be dry or wet when microplastics are going to be removed, whereas in water samples it is common to use nets, pumps, or sieves (Prata et al. 2019). Microplastics must then be extracted from water and sediment samples with the objective of being quantified and characterized. This separation usually is based on density, as each polymer has a different value. Density methods usually used NaCl, NaI, or $CaCl_2$ solutions in water, in order to increase the density (Masura et al. 2015; Quinn et al. 2017; Sánchez-Nieva et al. 2017).

Finally, when microplastics have been extracted, numerous techniques can be employed for their identification. Most studies usually make a first visual

Fig. 1.2 Analysis of microplastics in Fourier transform infrared spectroscopy equipment, in order to find out their chemical composition

classification, followed by the application of more complex techniques such as Fourier transform infrared spectroscopy (Fig. 1.2), micro Raman, scanning electron microscopy, the application of pigments such as Nile red, or gas chromatography-mass spectrometry (Eriksen et al. 2014; Godoy et al. 2019; Maes et al. 2017; Rocha-Santos and Duarte 2017). The objectives are to identify the composition of the microplastics, the presence of additives, and the morphology and determine the size. The use of one or other technique depends to a great extent on the size of the microplastic, the type of extraction previously done, the nature of the original sample, or simply on the techniques available in each laboratory.

In the present chapter, research has dedicated to the distribution of microplastics in marine and freshwaterenvironments around the world, providing data on concentrations and characterization of these particles. Prior to this research, the main sources of current microplastic emissions have also been described, as well as the most frequent techniques used in the characterization of these microparticles.

1.2 Sources of Microplastics

To study microplastic sources, it can be distinguished between two kinds of microplastics, primary and secondary. According to Cole et al. (2011), primarymicroplastics are defined as microscopic particles manufactured by humans with some proposal. Most primary microplastics in the environment are dumped from products routinely used in households, such as facial or body cleansers, airblasting media, or drug vectors used in medicine (Li et al. 2016). On the other hand, secondary microplastics are generated by the disintegration or fragmentation of macroplastics into particles of smaller size (Ryan et al. 2009). Figure 1.3 shows the difference between the appearance of primary and secondary microplastics.

Primary microplastics, such as polyethylene beads (with sizes between 10 and 106 μm) pictured (Fig. 1.3a), are typically uniform in shape and composition. Secondary microplastics are typically much more diverse in size, shape, color, and composition than primary microplastics, as can be seen in a sample trawled from a Spanish beach (Fig. 1.3b).

Syberg et al. (2015) reported a complete summary of sources of primary and secondary microplastic. In personal care products, primary microplastics are usually composed of thermoplastic polymers such as polyethylene, polypropylene, styrene copolymers, or polymethyl methacrylate. They are added to provide the personal care products some interesting characteristics such as ability to form a film, abrasion, shine, and viscosity (Napper et al. 2015; UNEP 2015). On the other hand, drilling fluids often contain reinforced Teflon particles, and in recent decades, they have become more commercially available. The main sources of emissions to the environment are sludge wastes, which are not always collected and treated in the appropriate way to eliminate these microparticles (Sundt et al. 2014).

Microplastics are also present in pressure sandblasting for cleaning, in the form of acrylic polymers, melamine, or polyester to remove rust and paint on machines, engines, and boat hulls. The problem arises when these products are not used in

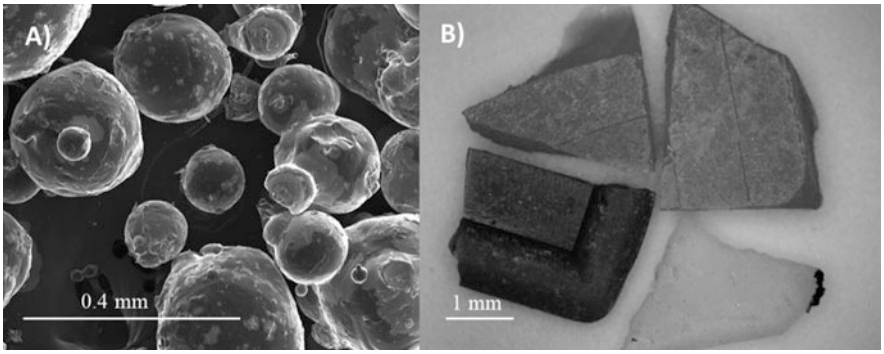

Fig. 1.3 (**a**) Primary microplastics from a cosmetic product; (**b**) secondary microplastics from a beach (Source: Original production)

closed systems with subsequent fluid recovery, making it very easy for them to end up in the environment through wastewater (Duis and Coors 2016). Microplastics can also be part of paints used for ships, increasing the emission of microparticles into the environment as the paint degrades and chip (Sundt et al. 2014). Pellets of virgin polymers can also be a source of primary microplastics. These pellets can be lost unintentionally during transport. Also, a loss of these pellets can be performed in the polymer processing facilities (Van Cauwenberghe et al. 2013). In fact, large ports and local plastic industries near the coast are the main sources of pellet contamination of the ocean and seawaters.

The main sources of secondary microplastics are tire wear and the washing of synthetic textile apparel. Tire wear accounts for approximately 5–10% of the world's total amount of microplastics ending up in the oceans (Kole et al. 2017). On the other hand, the washing of synthetic garments results in the release from two sources. Detergents may contain microplastics, and if there are no adequate filters for wastewater or water vapor, release to the environment occurs. In addition, a standard garment with some polymer can release up to 100 fibers per wash into the environment, and some garments have been shown to release up to 1900 fibers per wash (Browne et al. 2011).

Another source of secondary microplastics is the generation through the fragmentation of larger plastics. This happens when larger plastic waste is deposited on beaches or floating in water, exposed to solar radiation and weathering agents. Gradually, these wastes lose their mechanical and structural properties; their surfaces break down and decompose into smaller pieces until they reach the size of a microplastic (Auta et al. 2017).

It is hard to identify specifically how all these microplastics reach the water, but plastic debris can easily enter the different watercourses and oceans in different ways that include dumping or littering, effluents of water treatment plants, ineffective waste management, and even stormwater drainage systems. In Fig. 1.4, a schematic diagram shows the key sources and drive pathways.

1.3 Overview of Methods Used for the Sampling, Extraction, Purification, and Identification of Microplastics in the Environment

1.3.1 Sampling

Water Samples

Nets of different mesh sizes are the preferred technique used for sampling microplastics in waters. Particularly, bongo nets, plankton nets, and near-bottom trawls are extensively used for water column sampling, while manta trawls and neuston nets are used for surface water sampling (Wang and Wang 2018). Other

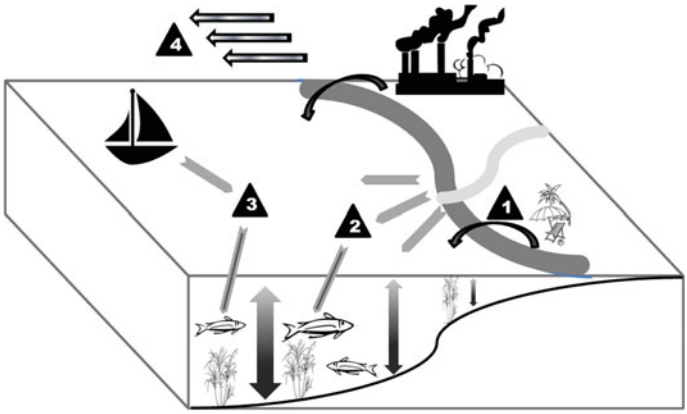

Fig. 1.4 Diagram of the main sources of microplastic emissions and their distribution flow through the marine environment; (1) microplastics from beaches; (2) and (3) microplastics from river estuaries and from maritime human activities, respectively, and their possible ingestion by organisms; (4) microplastics emitted to the air (Source: Original production)

tools used in water sampling are vessels or plankton traps (Crawford and Quinn 2017; Silva et al. 2018).

Some of the main factors that influence the sampling with nets and, therefore, the results of each study are the mesh size used and the network area that acts as a filter. According to the data collected in the literature, the nets usually have a length of 3–4.5 m, and most of the meshes are 300 μm size. It implies that not all microplastics are collected in commonly used sampling techniques. In addition, other techniques are occasionally used to evaluate microplastics in water. Particularly, the use of a cascade of filters is a very promising technique developed by -4H-JENA engineering GmbH, yet under development.

Sediment Samples

In the case of sediments, sampling is relatively easy. However, currently there is no official procedure for the sampling in terms of sampling depth, amount of collected sample, or location. Therefore, the comparison between data produced by different authors is restricted. At present, sediments of beaches are more often studied. Sampling work is performed on the whole beach. With respect to the location of the sample on the beach, the applied sampling strategies include random sampling in several sites, following perpendicular (vertically from the water edge) and parallel (horizontally to the water) lines. Transects are a common approach when conducting a beach sampling using quadrats of various sizes (Hanvey et al. 2017).

With regard to sampling depth, taking samples in the first 5 centimeters is the most common technique, although sampling at a greater depth has also been found in published works (Claessens et al. 2011). Authors as Hanvey et al. (2017) think that

this procedure underestimates the levels of plastics, as sampling is only centering on the surface layer. Another point of interest is the quantity of sample, because some works collected less than 500 g of sediments, whereas others can reach about 10 kilograms (Hidalgo-Ruz et al. 2012).

As a general rule, the sampling is performed with the following instruments: (1) a sampling tool of a nonplastic material (usually a small spoon or shovel), (2) a frame that specifies the sampling area, and (3) a container also of a nonplastic material in which the collected sample is stored are required.

Biological Samples

The schemes for the biological sampling are diverse and strongly determined by the organism that will be analyzed. Normally, zooplankton, fish species, or crustaceans are getting by nets or traps. Also, smaller invertebrate organisms can be collected directly by hand. Generally, the interest is in the digestive system, tract, or excretions of the organism. Then, a dissection to release the intestinal content or the entire digestive system is performed (Lusher et al. 2013).

1.3.2 Extraction and Purification of Microplastics

Density Separation

The flotation technique is the most used for the extraction of microplastics from sediment samples. The objective is to take advantage of the difference in density between the most common plastic polymers, which range from 0.28 to 1.47 $g \cdot cm^{-3}$, and the sedimentary matrix, which has a density of approximately 2.55 $g \cdot cm^{-3}$. Particularly, a concentrated salt solution is prepared and put into contact with the sediment sample. The solid-liquid mixture is agitated during a certain time and then is left to decant. The plastic particles remain in suspension while grains of sand decant. Afterward, the microplastics are recovered from the supernatant by filtration.

Despite being a cheap and environmentally friendly procedure, not all common polymers are extracted using a concentrated salt solution. For example, high-density polymers as polyvinyl chloride or polyethylene terephthalate (PET), among others, end up settling with the sediment because the salt solution has a low density of approximately 1.2 $g \cdot cm^{-3}$. Therefore, high-density solutions are used to overcome this drawback, for example, sodium iodine solution (1.8 $g \cdot cm^{-3}$), zinc chloride solution (1.5–1.7 $g \cdot cm^{-3}$), or sodium polytungstate solution (1.4 $g \cdot cm^{-3}$) (Nuelle et al. 2014; Imhof et al. 2012; Liebezeit and Dubaish 2012; Corcoran et al. 2009).

The flotation technique is adequate to extract high-size microplastics reaching recoveries of 80–100% (Fries et al. 2013); however, microplastics with a particle size lower than 500 μm are more difficult to extract. In this sense, consecutive extraction stages are suggested to get better recoveries.

Matrix Removal and Purification of Microplastic Samples

For a correct identification of the microplastics, it is necessary to eliminate all the organic and inorganic compounds adhered to the surface thereof. In addition, particularly matrix removal, it is necessary to remove microplastic from biological samples. The softest method to clean samples is washing with fresh water (McDermid and McMullen 2004). Other purification techniques have also been used in the literature, for example, ultrasonic cleaning, treatments with hydrogen peroxide, and treatments with mineral acids (Andrady 2011; Cooper and Corcoran 2010; Liebezeit and Dubaish 2012).

Other authors have used mainly 37% of hydrochloric acid (HCl), various concentrations of sodium hydroxide (NaOH), and 30% of hydrogen peroxide (H_2O_2) or a specific mixture of them, for the tissue digestion of biotic samples (Claessens et al. 2013; Davidson and Dudas 2016; Dehaut et al. 2016; Löder and Gunnar 2015; Lusher 2015; Zhao et al. 2017). However, special care must be taken in the use of these techniques because some plastics can react especially to strong acid or alkaline solutions (Liebezeit and Dubaish 2012; Claessens et al. 2013). It notably restricts the applicability of these reagents. In this sense, the most promising technique is the use of enzymatic digestion which has shown good preliminary results (Cole et al. 2014; Catarino et al. 2017).

1.3.3 Quantification and Identification of Microplastics

Manual Counting by Visual Identification

The use of microscopes is widely extended to identify microplastics (Hanvey et al. 2017). The main drawbacks of this technique are the limitation in the identification of particles below a certain size and an excessive slowness. Another major drawback is that the quality of the data produced depends to a large extent on the microscope used, the characteristics of the person performing the study, and the sample matrix (i.e., sediment or intestinal content). Finally, mistakes by counting nonplastic particles as plastic can be made. According to all the limitations mentioned, the error rate of the visual classification increases with decreasing particle size and can fluctuate from 20% to 70% (Eriksen et al. 2013; Hidalgo-Ruz et al. 2012). This is the reason why it is important to analyze then the particles by other methods for a correct identification of plastics (Dekiff et al. 2014; Hidalgo-Ruz et al. 2012).

Norén (2007) suggests the following criteria for the visual identification of larger microplastics: (1) in the plastic particle, no structure of biological origin should be distinguished, (2) the plastic fibers must have a folded three-dimensional shape and a similar thickness to assure that there is no biological origin, (3) the particles should be of homogeneous color, and (4) those transparent or whitish particles should be inspected with the support of fluorescence at high magnification to exclude an organic origin.

Fourier Transform Infrared Spectroscopy

Fourier transform infrared spectroscopy is applicable to a wide variety of chemical applications, such as the case of polymers and organic compounds. It is the most used technique to identify polymer in sediment samples. It uses the infrared spectrum of emission or absorption generated using infrared radiation to excite the sample, which allows to identify the type of plastic accurately (Frias et al. 2010; Harrison et al. 2012; Ng and Obbard 2006; Reddy et al. 2006; Thompson et al. 2004; Vianello et al. 2013). When the infrared radiation reaches a sample, part of the radiation is absorbed by the sample, and another part passes through it. The resulting information is a characteristic spectrum associated to the chemical structures presented in the sample. In microplastic identification application, one important advantage of Fourier transform infrared spectroscopy is it allows the analysis of polymers without destroying the sample.

Pyrolysis-Gas Chromatography in Combination with Mass Spectrometry

Another technique that allows evaluating the chemical composition of plastic particles is pyrolysis-gas chromatography in combination with mass spectrometry. Currently, this technique is widely applied to synthetic and natural polymers. In this technique the polymers are converted to products of lower molecular weight by the action of heat. The composition and relative abundance of the products obtained in the pyrolysis are characteristic for a given polymer. The correct determination of this information allows the identification of materials that cannot be determined in any other way. Then, this technique is based on the analysis of thermal degradation products generated during the thermal processing of the sample (Fries et al. 2013; Nuelle et al. 2014).

The main disadvantages of this technique are that particles must be placed manually in the pyrolysis tube and lower particles cannot be manipulated manually. In addition, the method lets the analysis of only one sample per test, and, therefore, large quantities of sample are not suitable for processing. Finally, compared with spectroscopic methods, the major disadvantage is that it is destructive.

Raman Spectroscopy

Raman spectroscopy, together with the Fourier transform infrared spectroscopy, is another important and commonly used spectroscopy technique that provides chemical information of microplastics (Araujo et al. 2018; Cole et al. 2013; Imhof et al. 2012, 2013; Murray and Cowie 2011; Van Cauwenberghe et al. 2013). The analysis is based on the examination of light dispersed by sample when a monochromatic laser source (between 500 and 800 nm) impacts on it. The result is a characteristic Raman spectrum that allows the identification of each type of polymer. It is a

nondestructive technique allowing the recovery of the sample for further analysis (Shim et al. 2017). In microplastic identification, one of the great advantages of this technique is that it can be coupled with microscopy which lets the identification of smaller microplastics (Strungaru et al. 2019).

Scanning Electron Microscopy and Energy-Dispersive X-Ray Spectroscopy

Scanning electron microscopy generates an image of the surface of the microplastic based on interaction of an electron beam with the sample (Rocha-Santos and Duarte 2015). The scanning electron microscopy technique provides full information about the shape, size, and topography of the plastic particles. According to the provided images, the source of the microplastics, i.e., decomposed fragments of larger plastics or primary microplastics, can be predicted (Zbyszewski and Corcoran 2011). Also, scanning electron microscopy can be combined with energy-dispersive X-ray spectroscopy to determine elemental composition and identify inorganic additives in microplastics fragments. For example, scanning electron microscopy-energy-dispersive X-ray method was used by Fries et al. (2013) to analyze the existence of aluminum, barium, carbon, oxygen, titanium, sulfur, and zinc on microplastic particles.

1.4 Microplastics in Freshwater Environments

Microplastic pollution has gained considerable attention in freshwater systems, despite the fact that a large number of works are still devoted to the study of the marine environment. Freshwaterenvironments are a recognizable way to carry microplastics from land-based sources to the aquatic environment. Studies about microplastics in freshwaterenvironments are increasing in attention due to the great quantities of plastic found in lakes, rivers, and even drinking water and because of its harmful effects on the environment and human health.

1.4.1 Global Microplastic Concentration and Distribution in Different Freshwater Ecosystems

Microplastics vary geographically, depending on environmental factors, especially hydrodynamic conditions and anthropogenic factors (Besseling et al. 2017; Imhof et al. 2017; Kim et al. 2015; Sarafraz et al. 2016). In this section, the most important concentrations of microplastics present in the literature over the last decade have been collected and selected. These data are presented on maps of different locations,

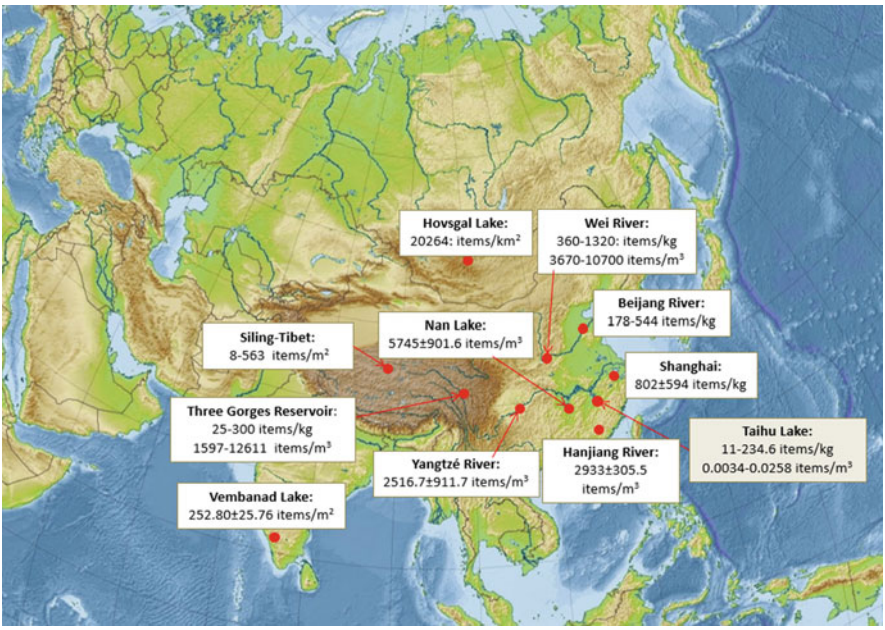

Fig. 1.5 Abundance of microplastics in sediment and water samples from different freshwater systems, i.e., rivers or lakes, across Asia. The abundances present in sediments are expressed in items per m^2 or items per kg, while the abundances in water are expressed in items per m^3 (Sources of data: Di and Wang (2018), Free et al. (2014), Peng et al. (2018), Sruthy and Ramassamy (2017), Su et al. (2016), Wang et al. (2017a, b), Zhang et al. (2016), Ding et al. (2019). Source of figure: Original production)

in Asia, Africa, Europe, and North America, in order to determine their geographical distribution. This information is presented in Figs. 1.5, 1.6, 1.7, and 1.8.

The samples found in rivers and lakes mainly from freshwater sources contain a large amount of microplastics, which is then reflected in the amount of microplastics found in the seas and oceans, as rivers are one of the main transport routes. Based on the sediment typology, it can be observed how in Europe, in Sweden (Lysekil), 8360 items per kg were found (Magnusson and Noren 2014), while in North America, in Canada (St. Lawrence River), 13,832 items per m^2 were found (Castañeda et al. 2014). On the other hand, with focus on the microplastics found in water samples, the highest concentrations are found in North America. In the United States (Los Angeles River), 12,932 items per m^3 were obtained (Moore et al. 2011), while in Chicago River 6.69E6 items per m^2 were obtained (McCormick et al. 2014).

Figure 1.5 represents the microplastic abundance and distribution in Asia. This continent contains the largest contamination by microplastics. The biggest concentrations of these particles are present along river and lakes. Studies have reported high concentrations of microplastics in Wei River, where 360–1320 items per kg of sediment were found (Ding et al. 2019), or Beijing River, where 178–544 items per kg of sediment were counted (Wang et al. 2017a). Other studies have reported high

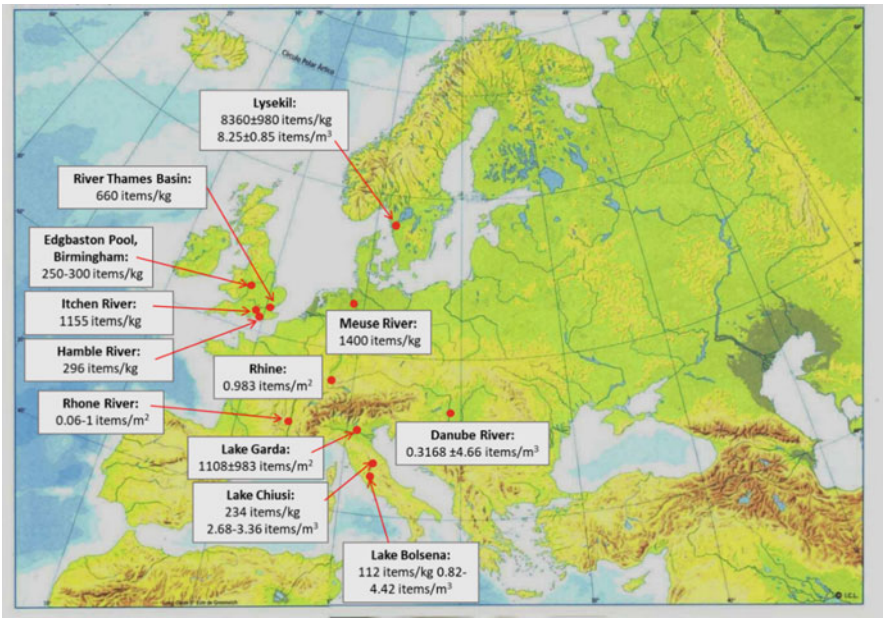

Fig. 1.6 Abundance of microplastics in sediment and water samples from different freshwater systems, i.e., rivers or lakes, across Europe. The abundances present in sediments are expressed in items per m^2 or items per kg, while the abundances in water are expressed in items per m^3 (Sources of data: Fischer et al. (2016), Gallagher et al. (2016), Horton et al. (2017a, b), Imhof et al. (2013), Lechner et al. (2014), Leslie et al. (2017), Magnusson and Noren (2014), Mani et al. (2015), Schmidt et al. (2018), Vaughan et al. (2017). Source of figure: Original production)

concentrations of microparticles in lakes, i.e., in the Nan Lake, where more than 5745 items per m^3 were found (Wang et al. 2017a). Lake Hovsgol and those lakes within the Siling Lake basin (northern Tibet) were studied showing significant concentrations of microplastics, 0.02 items per m^2 and 8–563 items per m^2 (Zhang et al. 2016), respectively, although these locations have little human activity. This may be due to inappropriate waste management in low-density populations.

Figure 1.6 represents a map of Europe with the main accumulations of microplastics. The most contaminated areas were Lysekil (Sweden), where quantities of 8360 items per kg in sediments and 8.25 items per m^3 in water were estimated (Magnusson and Noren). In Meuse River (Netherlands), 1400 items per kg (sediments) were estimated (Leslie et al. 2017), whereas in Itchen River (UK), 1155 items per m^3 (water) were estimated (Gallagher et al. 2016).

North America is represented in Fig. 1.7, with the main areas where microplastics accumulate. The most contaminated areas are Canada and the United States. Chicago River (USA) contained about $6.69E10^6$ items per m^2 (McCormick et al. 2014), while St. Lawrence River (Canada) contained 13,832 items per m^2 (Castañeda et al. 2014). There are also other rivers, such as Los Angeles River, that have high concentrations

Fig. 1.7 Abundance of microplastics in sediment and water samples from different freshwater systems, i.e., rivers or lakes, across North America. The abundances present in sediments are expressed in items per m^2, items per km^2, or items per kg, while the abundances in water are expressed in items per m^3 (Sources of data: Anderson et al. (2017), Ballent et al. (2016), Castañeda et al. (2014), Corcoran et al. (2015), Eriksen et al. (2013), McCormick et al. (2014), Moore et al. (2011). Source of figure: Original production)

of microplastics around 12,932 items per m^3. On the other hand, lakes have lower amounts of microplastics than rivers, which may be mainly due to the currents.

Figure 1.8 represents the microplastic abundance and distribution in Africa; there is a great lack of data and studies on microplastics in fresh water. Nel et al. (2018)

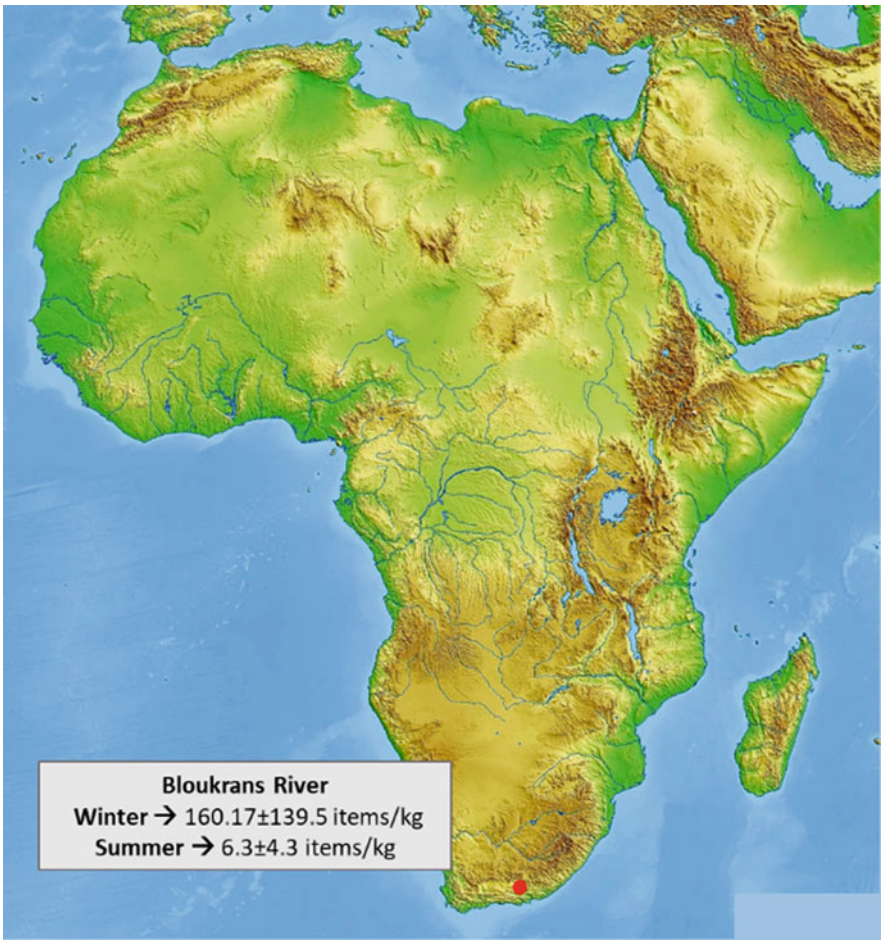

Fig. 1.8 Abundance of microplastics in sediment and water samples from different freshwater systems, i.e., rivers or lakes, across Africa. The abundances present in sediments are expressed in items per kg (Source of data: Nel et al. (2018). Source of figure: Original production)

carried out a study along the Bloukrans River of South Africa and found microplastic densities in beach sediments between 6.3 ± 4.3 items per kg in summer season and 160.1 ± 139.5 items per kg of sediment in winter season. Higher concentrations were obtained in winter, associated with the flow of the river, and this in turn associated with the transport of microplastics.

Microplastics are not only found in rivers and lakes, but there are also studies where significant amounts of microplastics have been detected in potable water. Novotna et al. (2019) collected results of some important studies that found significant amounts of plastic in both the public supply and the bottled water. The public source that contains more microplastics is treated water in Czech Republic with 628 microplastics by liter (Pivokonsky et al. 2018). On the other hand, the bottled

water where more microplastics were found in account 6298 microplastics by liter (Oßmann et al. 2018). Also, Schymanski et al. (2018) found 117 microplastics by liter in returnable plastic bottles, and Mason et al. (2018) estimated a concentration of 932 and 1411 microplastics by liter in plastic bottles of brand Nestle Pure Life and Gerolsteiner, respectively.

1.4.2 Type, Size, and Morphology of Microplastics in Freshwater

With respect to microplastic sizes, they can be distributed into six different groups: category 1 (0.5 mm), category 2 (0.5–1 mm), category 3 (1–2 mm), category 4 (2–3 mm), category 5 (3–4 mm), and category 6 (4–5 mm). Figure 1.9 shows the size distribution of the samples both on the water surface and in sediments of the samples collected at Wei River, China.

The most abundant microplastics were of category 1 in all samples including water and sediment samples. Category 2 and category 3 were the second and third most important, while samples belonging to group 4, 5, and 6 were insignificant. Similar results have been obtained in other freshwater locations such as in Qinghai Lake (China), Lake Garda (Italy), Three Gorges (China), Laurentian Great Lakes (USA), and Taihu Lake (China) (Di and Wang 2018; Eriksen et al. 2013; Imhof et al. 2016; Su et al. 2016; Xiong et al. 2018). The most abundant fraction was the size lower than 0.5 mm in all the mentioned locations, especially in water surface. Some of them realized that the predominant fraction in sediments was 0.5–1 mm. In sum,

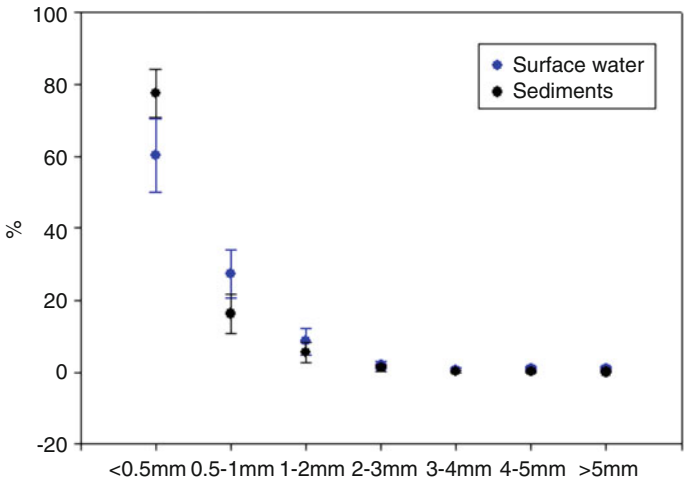

Fig. 1.9 Size distribution of the samples both on the water surface and in sediments of the samples collected in Wei River, China. The data are expressed as a percentage of microplastics within each size group (Source: Modified after Ding et al. (2019))

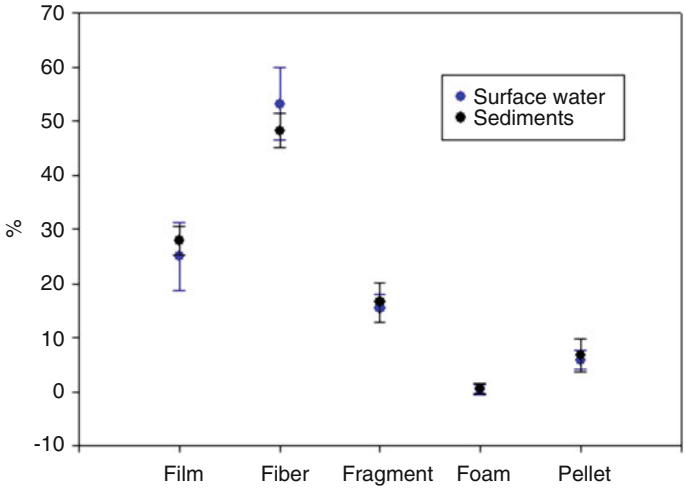

Fig. 1.10 Morphology distribution of the samples both on the water surface and in sediments of the samples collected in Wei River, China. The data are expressed as a percentage of microplastics within each morphology (Source: Modified after Ding et al. (2019))

the most abundant microplastic particles in freshwater had a size less than 1 mm, while it is insignificant with the presence of microplastics greater than 2 mm.

The most studied shapes were fragments, fibers, film, foam, or pellet, but beads, lines, spherules, sheets, flakes, paint, foil, and nurdle can also be found. For example, the results of a study carried out by Ding et al. (2019), which analyzed the morphology of different samples obtained in Wei River in China, are shown in Fig. 1.10.

The difference between the samples obtained in surface water and sediments can be due to the reaction that samples produce in the outdoors with the organic products. Fibers and films were the most dominant, whereas pellets and foams were the less abundant types of microplastics in Wei River. Fiber was the dominant species in surface water and sediment samples, where it represented approximately half of the samples studied. The origin of these microplastics was attributed to the decomposition of agricultural plastics and wastewatereffluents containing fibers from clothes (Claessens et al. 2011). Similar results were obtained in other freshwater locations such as in Tibetan Plateau lakes (China) or in Three Gorges (China), where fiber was dominant, accounted for 28.6–90.5% in water surface and 33.9–100% in sediments (Di and Wang 2018; Zhang et al. 2016).

With respect to microplastic colors, the most common were blue, green, red, transparent, and white (Di and Wang 2018). With regard to the composition of microplastics, the different polymers found in freshwater are due to two main factors: the demand for plastics and the density of the polymers. The annual demand of plastics in Europe is presented in Fig. 1.11, where it can be seen that the most consumed plastics are polyethylene and polypropylene.

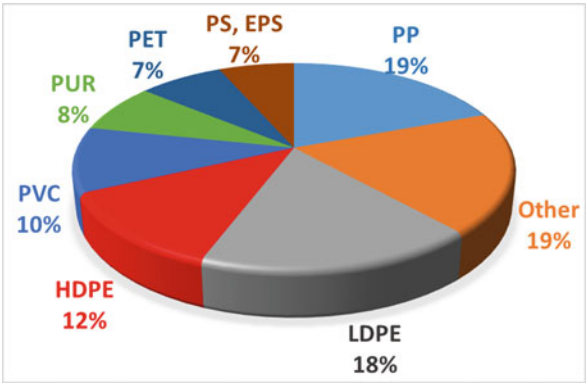

Fig. 1.11 Distribution of demand for different types of plastics in Europe in 2017 (Source: Modified after Plastics Europe (2017))

Polyethylene and polypropylene have densities below 1 g per cm^3; polystyrene has a density close to that of 1 g per cm^3; polyvinyl chloride and polyethylene terephthalate have densities of 1.3–1.7 g per cm^3. The higher the density, the easier the sedimentation occurs, which is the main reason why less polyvinyl chloride and polyethylene terephthalate are found (Koelmans et al. 2019). Table 1.1 shows the different polymers found in some freshwater studies. The most commonly found polymers are polyethylene, polypropylene, and polystyrene.

1.5 Microplastics in Marine Environments

Microplastics are found in almost every marine environment on the Earth. Both research on these particles and concentrations in the marine environment have not ceased to grow. There are citations of the presence of microplastics in all types of environments, including those considered to be the most virgin or distant from the sources of production of these particles, such as the depths of the oceans or Arctic ice (Obbard et al. 2014; Woodall et al. 2014). Microplastics are present in the marine and coastal environments and accessible to ingestion by a wide variety of organisms.

Although the harmful effects of microplastics into the food chain are not yet well known, it has been demonstrated that one of the main problems is the capacity of these particles to absorb hydrophobic compounds on their surface, accumulating them and entering the living organisms that consume them including humans (Brennecke et al. 2016; Llorca et al. 2018; Li et al. 2018; Wu et al. 2019). An important environmental effect derives from the fact that microplastics not only adsorb pollutants from water but they also release additives or persistent organic compounds into the environment (Bakir et al. 2014; Moore 2008). These compounds have been described by the US Environmental Protection Agency as a risk to human health, as they enter and accumulate in the food chain.

Table 1.1 Summary of polymers found in different freshwater locations

Country	Location	Composition	References
China	Shanghai	PP, PE, rayon, cotton+viscose, phenoxy resin, poly (vinyl stearate)	Peng et al. (2018)
China	Three Gorges Reservoir	PE, PP, PS	Di and Wang (2018)
China	Beijing River	PE, PP, copolymer, paint particle	Wang et al. (2017a)
China	Taihu Lake	CP, PET, PE, PA, PP	Su et al. (2016)
China	Hanjiang River	PA, PE, PET, PP, PS	Wang et al. (2017b)
China	Yangtze River	PA, PE, PET, PP, PS	Wang et al. (2017b)
China	Sha Lake	PA, PE, PET, PP, PS	Wang et al. (2017b)
China	Nantaizi Lake	PA, PE, PET, PP, PS	Wang et al. (2017b)
China	Nan Lake	PA, PE, PET, PP, PS	Wang et al. (2017b)
China	Siling, Tibet	PE, PET, PP, PS, PVC	Zhang et al. (2016)
India	Vembanad Lake	HDPE, LDPE, PS, PP	Sruthy and Ramasamy (2017)
UK	River Thames basin	PP, PES, PET, PS, PE	Horton et al. (2017a, b)
UK	Itchen River	PE, PP, CP	Gallagher et al. (2016)
UK	Hamble River	PE, PP, CP	Gallagher et al. (2016)
Italy	Lake Bolsena	PE, PP, PET, PVC	Fischer et al. (2016)
Italy	Lake Chiusi	PE, PP, PET, PVC	Fischer et al. (2016)
Italy	Lake Garda	PA, PE, PP, PS, PVC	Imhof et al. (2013)
Sweden	Lysekil	PE, PP	Magnusson and Noren (2014)
Germany	Rhine	PA, PE, PP, PS, PVC	Mani et al. (2015)
Canada	Ontario Lake	PE, PS, PUR, PP, PVC, PET, PMMA, polyvinyl acetate, PMMA-PS, ABS, nylon, phenoxy or epoxy resin, polymethylsiloxane	Ballent et al. (2016)
Canada	St. Lawrence River	PE, PP, nitrocellulose	Castañeda et al. (2014)

ABS acrylonitrile butadiene styrene, *CP* cyclopentadienyl complex, *HDPE* high-density polyethylene, *LDPE* low-density polyethylene, *PA* polyamide, *PE* polyethylene, *PET* polyethylene terephthalate, *PMMA* polymethyl methacrylate, *PP* polypropylene, *PS* polystyrene, *PSS* poly (styrenesulfonate), *PUR* polyurethane, *PVC* polyvinyl chloride

1.5.1 Global Microplastic Concentration and Distribution in Different Marine Ecosystems

The first study that reported the presence of microplastics in seawater was conducted by Carpenter and Smith (1972). They estimated average microplastic concentrations of 3500 items and 290 g per km^2 in the western Sargasso Sea. With this discovery, the scientists tried to alert society about the problem of that contamination, but their warning was ignored. At present, microplastics are much more abundant and distributed all over the seas, oceans, and beaches, as revealed by numerous studies over the last decade (Auta et al. 2017; Cole et al. 2011; Guo and Wang 2019; Hamid et al. 2018; Hidalgo-Ruz et al. 2012; Kane and Clare 2019).

Microplastics have low density in general, which means that they can easily float on the water surface or in the water column (Piperagkas et al. 2018). Microplastics with density higher than that of seawater tend to sink down in sediments, where they accumulate, while those with low density float on the sea surfaces (Alomar et al. 2016; Suaria and Aliani 2014). Density can change when microplastics are degraded by the action of external agents or when biofouling caused by organisms occurs. In addition, Eriksen et al. (2014) verified that the movement of microplastics is also controlled by marine currents and oceanic gyres. According to that study, ocean margins are zones of plastic migration, while subtropical gyres are areas of accumulation. Therefore, the distribution of microplastics in marine environments is controlled by a wide range of causes.

In this section, the most important concentrations of microplastics present in the literature over the last decade have been collected and selected. These data are presented on maps of the continents of the world, in order to determine the geographical distribution of microplastics. Figure 1.12 represents the microplastic abundance and distribution in Europe. This continent contains the largest contamination by microplastics, along with East Asia. The biggest concentrations of these particles are present along the coast of Algarve (Portugal), in the lagoon of Venice, and in the Rhine estuary (Frias et al. 2016; Vianello et al. 2013; Mani et al. 2015). This can be due to the fact that microplastic particles tend to accumulate in areas characterized by lower water movement, such as an estuary or a lagoon.

Other studies have reported high concentrations of microparticles in beaches, for example, in Canary Islands, where more than 1600 items per m^2 in the beach of Lambra were found (Herrera et al. 2018). The authors reached the conclusion that debris accumulation depended mainly of coastline orientations and meteorological conditions. In addition, the subtropical oceanic gyre affects the way in which the currents vary from the coast to the open ocean during the year (Navarro-Pérez and Barton 2001). The same occur to some remote areas where high amounts of microplastics are recorded, i.e., Scapa Flow (UK), which accounted between 730 and 2300 items per kg of sediment, or Vik (Iceland), with 792 items per kg (Blumenröder et al. 2017; Lots et al. 2017). This is mainly caused by the oceanic currents. Other factors that can affect the pollution distribution are the salinity, temperature, shape of the coast line, or coastal activities (Cincinelli et al. 2019).

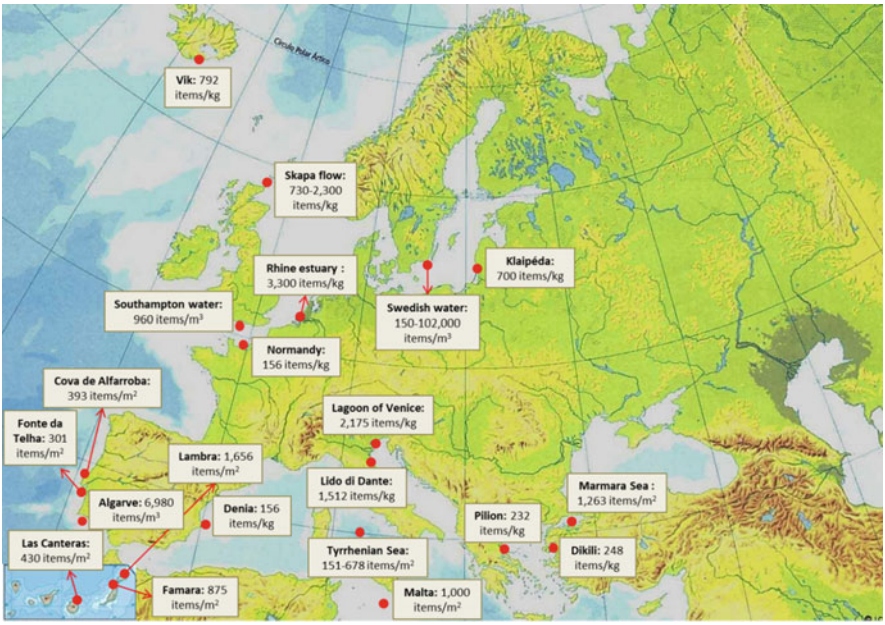

Fig. 1.12 Abundance of microplastics in sediment and water samples from different marine systems, i.e., beaches, estuaries, or marine water, across Europe. The abundances present in sediments are expressed in items per m^2 or items per kg, while the abundances in water are expressed in items per m^3 (Sources of data: Blumenröder et al. (2017), Fastelli et al. (2016), Frias et al. (2016), Herrera et al. (2018), Lots et al. (2017), Mani et al. (2015), Martins and Sobral (2011), Tunçer et al. (2018), Turner and Holmes (2011), Vianello et al. (2013). (Source of figure: Original production)

The first study that reported the abundance of floating plastic debris in the Mediterranean Sea was conducted by Morris (1980), who determined a concentration of about 1300 items per km^2 near Malta. A similar study was conducted later by Turner and Holmes (2011), who reported a concentration of 1000 items per m^2 in the Maltese beaches. The average plastic concentration in Mediterranean surface waters is 243,853 items per km^2 (Cózar et al. 2015). This concentration is much lower in the water column, where a limited number of studies have reported low concentrations of microplastics (Cincinelli et al. 2019; Fossi et al. 2012; Xiong et al. 2018).

Figure 1.13 represents a map of Asia with the main accumulations of microplastic debris. The most contaminated areas are, as in Europe, the estuaries of the rivers Yangtze, Nakdong, and Pearl, where quantities of 4137 items per m^3 in water, 27,606 items per m^2 in sediments, and 5959 items per m^2 in sediments were estimated, respectively (Fok and Cheung 2015; Lee et al. 2013; Zhao et al. 2014). Compared to European marine ecosystems, Asia is much more contaminated with microplastics. China is the third major producer of plastic waste in the world (Plastics Europe 2018). Therefore, it is not surprising that their coastlines are so

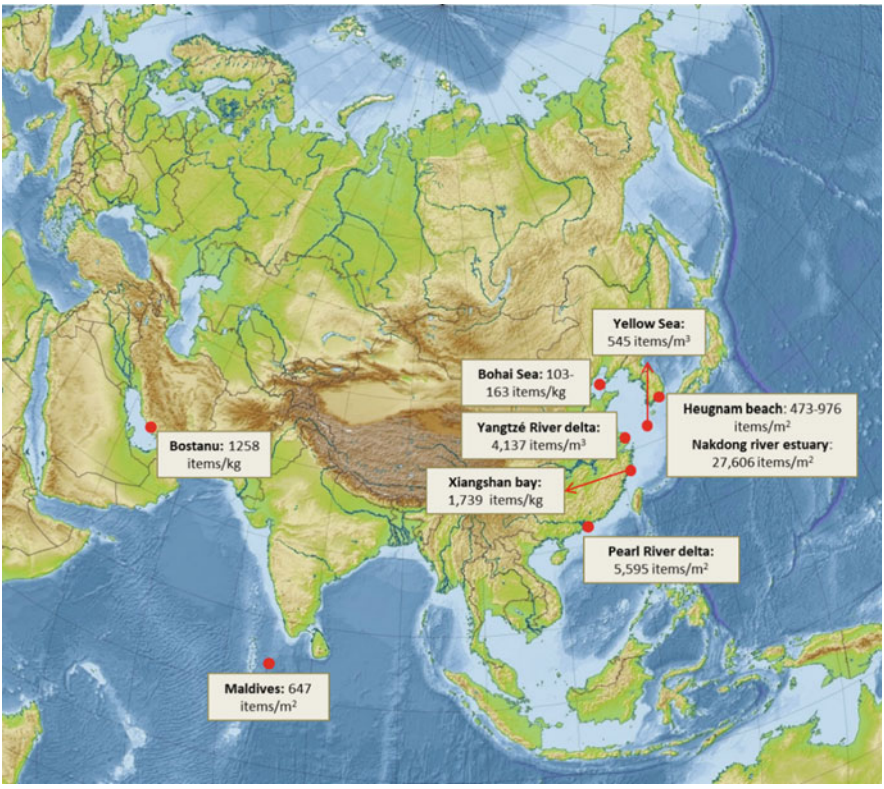

Fig. 1.13 Abundance of microplastics in sediment and water samples from different marine systems, i.e., beaches, estuaries, or marine water, across Asia. The abundances present in sediments are expressed in items per m^2 or items per kg, while the abundances in water are expressed in items per m^3 (Sources of data: Chen et al. (2018), Fok and Cheung (2015), Heo et al. (2013), Imhof et al. (2017), Lee et al. (2013), Naji et al. (2017), Zhao et al. (2014), Zhu et al. (2018). Source of figure: Original production)

polluted by microplastics. Despite this, Kang et al. (2015) have shown that the release of microplastic is higher in raining season than in waterless season.

Beaches in India are not so polluted by microplastics. It was found between 2 and 178 items per m^2, in contrast to the results obtained for the Maldives Islands, where more than 600 items per m^2 were reported (Imhof et al. 2017; Karthik et al. 2018). The origin of the contamination in this isolated island could be generated in the nearby islands in Maldives, where tourism is more frequent. Debris can also enter this island from many coastal areas of the Indian Ocean. Eriksen et al. (2014) estimated the amount of microplastics in surface waters along the Indian Ocean between 7000 and 8000 items per km^2.

On the other hand, average concentrations in open seas have also been measured. Isobe et al. (2015) investigated the concentrations of microplastics in the East Asian Seas around Japan and obtained a total particle concentration of about 1.72 million

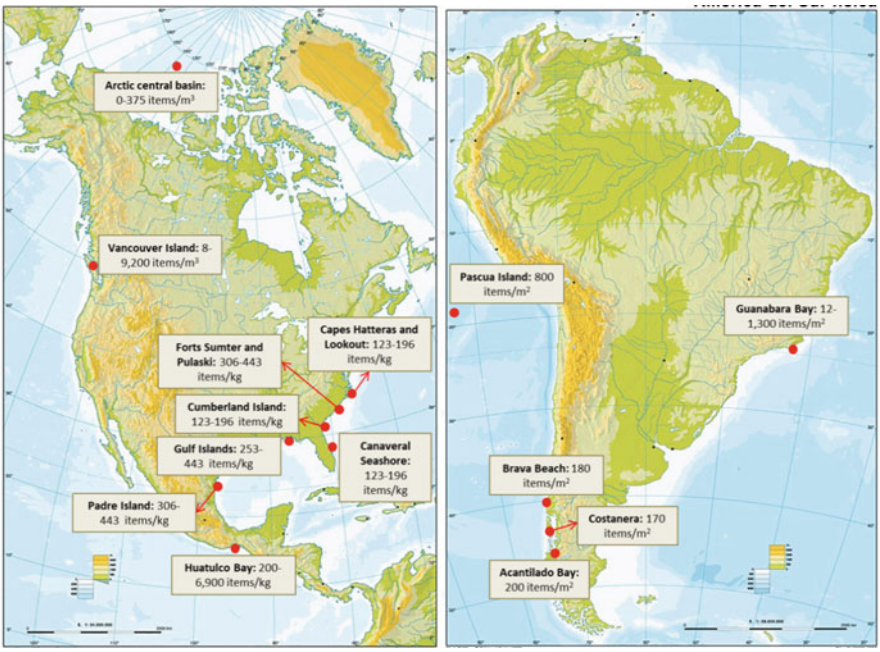

Fig. 1.14 Abundance of microplastics in sediment and water samples from different marine systems, i.e., beaches, estuaries, or marine water, across North and South America. The abundances present in sediments are expressed in items per m^2 or items per kg, while the abundances in water are expressed in items per m^3 (Sources of data: Desforges et al. (2014), Gomes de Carvalho and Baptista (2016), Hidalgo-Ruz and Theil (2013), Kanhai et al. (2018), Retama et al. (2016), Yu et al. (2018). Source of figure: Original production)

items per km^2. Another study conducted in the northwestern Pacific (Pan et al. 2019) recorded about 10,000 items per km^2, a very lower concentration than that obtained in Japanese seas. Compared to Mediterranean data, seas in Asia are much more contaminated.

North and South America are represented in Fig. 1.14, with the main areas where microplastics accumulate. The most contaminated area is the coast along North and South Carolina, where microplastics can account for more than 400 items per kg of sediment (Yu et al. 2018). Authors considered that nearby urbanization core and the presence of large rivers that discharge water into that area are factors that influence the amount of microplastics found. North and South America are bordered by oceans Pacific and Atlantic on the west and the east, respectively. These oceans exhibit strong currents, wave and hurricane action, tides, and in general a high dynamic action, which determine microplastic distribution.

Another contaminated area is the Gulf of Mexico, which accounts for more than 110 items per m^2 in sediment (Wessel et al. 2016). Authors determined that the microplastic composition and abundance were related to the exposition to marine currents. Therefore, the areas more exposed to marine currents have bigger and

denser microplastics than that found in locations less influenced by marine activity. On the other side of the Gulf of Mexico is Huatulco Bay, whose beaches exhibit a moderate to high microplastic concentration (Retama et al. 2016). Authors reported that microplastics in these beaches are mostly resulting from intensive tourist activities. With respect to the western coast of North America, Desforges et al. (2014) carried out a quantification of microplastics in the Pacific Ocean and coastal British Columbia. The authors found that the highest concentrations were located in Vancouver Island and nearby locations, whereas Pacific offshore waters exhibited less number of particles per m^3 of water.

Hidalgo-Ruz and Thiel (2013) found an extensive contamination of microplastics along the coast of Chile, in South America. This area presents an average contamination of 30 items per m^2, although in some beaches 200 items per m^2 can be reached. The sources of origin are, as in most beaches and coastal areas, the proximity of urban cores and economic activities such as aquaculture. Easter Island has an abundance of microplastics higher than the rest of the Chilean coast. This is due to the transport of particles by ocean currents, a phenomenon that generates an accumulation zone in the center-east of the South Pacific (Abreu and Pedrotti 2019). On the eastern coast of South America, Gomes de Carvalho and Baptista (2016) and Olivatto et al. (2019) determined the contamination caused by microplastics in beaches and surface water, respectively, of Guanabara Bay (Brazil). During the summer, microplastic concentrations at the beaches ranged from 12 to 1300 items per m^2, whereas this concentration decreased in winter. This is caused by the great inputs of water entering the estuary during the rainy season in summer.

In Africa (Fig. 1.15), there is a great lack of data and studies on microplastics in coasts and marine environments, with the exception of South Africa. This country has a wide plastic manufacturing industry, but recycling is limited and insufficient (Verster et al. 2017). Therefore, it has a huge proportion of waste managed improperly entering the environment. Nel and Froneman (2015) carried out a study along the southeastern coastline of South Africa and found that microplastic densities in beach sediments were between 688 and 3308 items per m^2, whereas in the water column ranged from 257 to 1215 items per m^3. Kanhai et al. (2017) estimated the average amount of microplastics in water of the offshore of Namibia and the west coast of Morocco, but contamination was very scarce in comparison to other areas of the world (between 6 and 8 items per m^3).

1.5.2 Type, Size, and Morphology of Microplastics in Marine Ecosystems

The main composition of microplastics present in marine environments is based on polyethylene, polypropylene, and polystyrene, as they represent the majority of the plastic waste generated in the world (Plastics Europe 2018). Thus, it is expected that

Fig. 1.15 Abundance of microplastics in sediment and water samples from different marine systems, i.e., beaches, estuaries, or marine water, across Asia. The abundances present in sediments are expressed in items per m^2, while the abundances in water are expressed in items per m^3 (Sources of data: Kanhai et al. (2017), Nel and Froneman (2015). Source of figure: Original production)

these are the most plastic waste generated and, consequently, the main composition of microplastics. However, the vast majority of microplastic fibers are composed by polyamide or polyester, since they come from the synthetic clothing that people use (Cesa et al. 2017). For example, chlorinated polyethylene, polyamide, and polypropylene predominate (76%) in Arctic sediments (Bergmann et al. 2017). Polyester and acrylic fibers are the most abundant polymers in sediments from the North Atlantic, Mediterranean, and southern Indian Ocean (Woodall et al. 2014). Polyethylene and polypropylene are the predominant polymers in the northern Pacific Ocean (Pan et al. 2019).

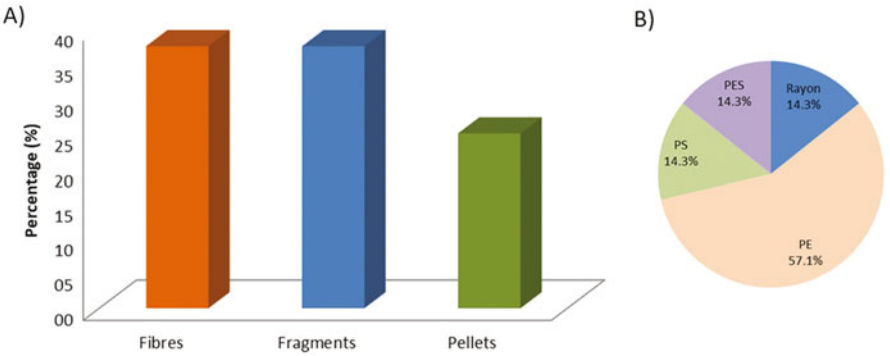

Fig. 1.16 Main shapes and compositions of microplastics from marine ecosystems in Europe. (**a**) Percentage of studies that found fibers, fragments, and pellets as the main shapes among microplastics; (**b**) percentage of studies that found polyethylene (PE), polyether sulfone (PES), polystyrene (PS), and rayon as predominant composition in microplastics (Source: Original production)

These compositional variations reflects not only the wide variety of land and marine sources that can originate microplastics but also the differences in the transport processes caused by the marine currents (Peng et al. 2018), as it is detailed in Sect. 1.4.1. Also important is that PE and PP are polymers with a low relative density, which float in water, unlike polyethylene terephthalate or polyvinyl chloride. This is the main reason why these floating polymers are identified in greater proportion than the others, with higher density. Below are diagrams of the most frequent composition and morphology of microplastics for each continent (Figs. 1.16, 1.17, and 1.18). The data of each diagram are based on information obtained from 10 studies carried out in each continent.

Figure 1.16 represents the most abundant morphologies and composition of microplastics analyzed in seawater and sediments from Europe. Fibers and fragments are the most abundant morphologies, while polyethylene stands out as the main component of these microplastics. Rayon is a semisynthetic fiber used in textile elements and is the most abundant microplastic on the beaches of the Algarve (Portugal) (Frias et al. 2016). On the other hand, granulated pellets come from plastic manufacturing industries. Polyethylene and polypropylene fragments usually come from industrial areas or from the degradation of larger plastic containers (GESAMP 2019). Harbors and vessels have also been identified as sources of fibrous plastic particles (Gewert et al. 2017).

In terms of particle sizes, the smallest detected were 0.06 mm, and the largest were up to 5 mm. Most particles were in the range of 0.1–1 mm, although there are studies that managed larger sizes of 2–5 mm (Martins and Sobral 2011; Turner and Holmes 2011). Increased temperature as a result of prolonged exposure to solar radiation could justify faster disintegration of terrestrial microplastics. Microplastics

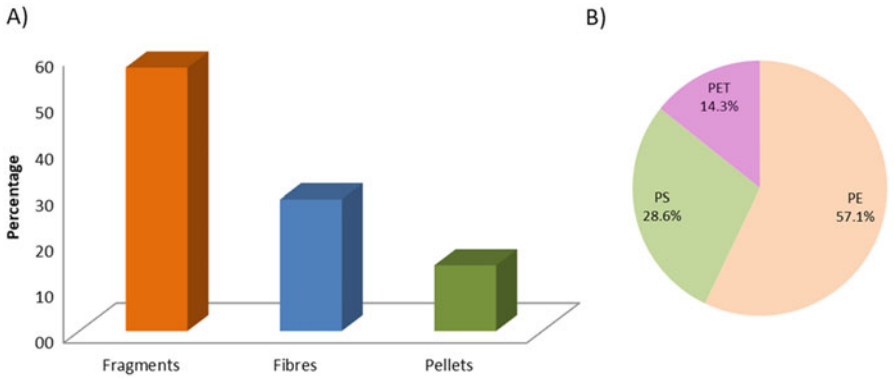

Fig. 1.17 Main shapes and compositions of microplastics from marine ecosystems in Asia. (**a**) Percentage of studies that found fibers, fragments, and pellets as the main shapes among microplastics; (**b**) percentage of studies that found polyethylene (PE), polystyrene (PS), and polyethylene terephthalate (PET) as predominant composition in microplastics (Source: Original production)

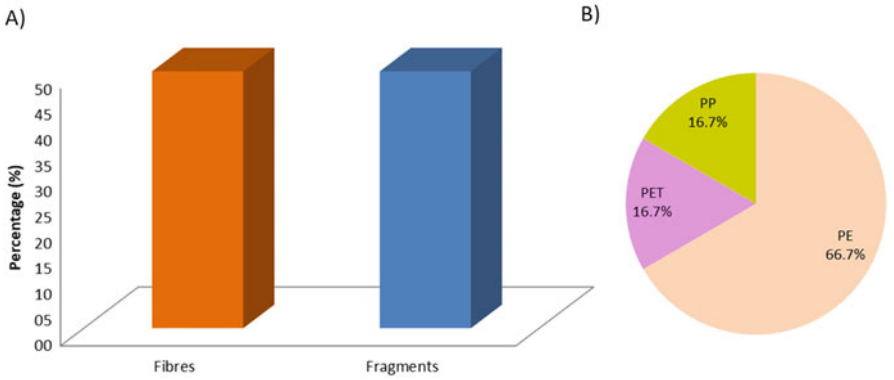

Fig. 1.18 Main shapes and compositions of microplastics from marine ecosystems in North and South America. (**a**) Percentage of studies that found fibers and fragments as the main shapes among microplastics; (**b**) percentage of studies that found polyethylene (PE), polyethylene terephthalate (PET), and polypropylene (PP) as predominant composition in microplastics (Source: Original production)

floating in water do not experience the same temperature increase for the same sun exposure due to the thermoregulatory effect of water. Therefore, size differences between studies can be found (Cooper and Corcoran 2010).

Figure 1.17 shows the main shapes and compositions of microplastics found in waters and coasts along the Asia continent. In contrast to Europe, in Asia fragments are the predominant forms, while polyethylene was once again the most abundant, followed by the polystyrene. At the estuaries of China's main rivers, it is not

surprising that the main composition of microplastics is polystyrene, because expanded polystyrene is widely used in cork boxes for the transport of food in southern China and Hong Kong (Fok and Cheung 2015). When this waste is not managed properly, these boxes can be transported to the oceans, seas, and beaches by means of rivers and stormwater drainage systems. The fragments are usually microplastics resulting from the physical-chemical degradation of larger plastics exposed to the action of heat, wind, and waves (Andrady 2015). On the other hand, polyethylene terephthalate is also a fiber very common in textile industry, as polyamide (nylon).

All particle sizes were in the range of 0.1–5 mm. In some areas the smallest microplastics (between 0.5 and 1 mm) were more abundant, as is the case in the northwest Pacific (Pan et al. 2019). In other locations, such as beaches in southern India, larger microplastics between 1.2 and 4.5 mm were more abundant (Karthik et al. 2018). On the other hand, equal abundance of fragments and fibers was found in studies carried out in both North and South America, and the preferred composition is polyethylene, followed by polyethylene terephthalate and polypropylene in equal proportions (Fig. 1.18).

In some areas of North America, the presence of rayon fibers was also detected (Yu et al. 2018), as was the case on the beaches of the Algarve (Portugal). As mentioned above, polyethylene terephthalate is a synthetic fiber widely used in the textile industry. The release of textile fibers into the environment is frequent and abundant, due to the large number of household and industrial washes carried out every day. A standard wash of 5 kg of synthetic clothing can release 6,000,000 fibers into the environment, although it depends on the type of washing machine and detergents used, making it a very difficult source to quantify (De Falco et al. 2018).

Other authors suggested that microplastics in North American waters may also come from fishing, recreational boating, and wastewater effluent (Desforges et al. 2014). On the other hand, in Guanabara Bay, microplastics are mainly fragments, which come from the degradation and breakage of larger plastics on the coast (Gomes de Carvalho and Baptista 2016). Most of the small plastic debris found on beaches from Guanabara Bay possibly come from fishing, rivers, harbor activities, and other local sources. The predominant particle size in these studies is lower than 1 mm, although larger microplastics can be found, especially fragments, with sizes exceeding 2–3 mm (Wessel et al. 2016).

In Africa, the few available studies show a dominance of fibers over other morphologies. The predominant composition in the area of Morocco and Namibia is EPS and PA, probably coming from the detachment of synthetic textile garments (Kanhai et al. 2017).

In sum, the most frequent polymer found in the studies reviewed was polyethylene, which corresponded approximately to 60% of those studies. Polystyrene was the second representative in Europe and Asia, with 14.3% and 28.6%, respectively. It is important to take into account that polypropylene was the second polymer found

in almost every reviewed study on every continent. Other components such as rayon or polyether sulfone (PES) were also representative in certain sites such as Portuguese coast, sediments in South Carolina, or coast from Turkey, Greece, Iceland, or France (Lots et al. 2017). These results agreed with the fact that PE, PP, and PS are three polymers very common and account for approximately 90% of the 348 million tons of plastics produced annually (Edo et al. 2019).

1.6 Interactions Among Microplastics and Other Pollutants Presented in Aquatic Environments

Microplastics can adsorb and concentrate a significant number of environmental toxins, which can be transferred to organisms (Mato et al. 2011; Leon et al. 2018). Particles do not only adsorb, but they can also desorb emitting into the environment toxic compounds such as additives or plasticizers, which negatively affect the organisms exposed (Cole et al. 2011; Neves et al. 2015).

There are some environmental factors that affect the balance between chemicals and microplastics as well as accumulation and transport of these pollutants (Murphy et al. 2016). These factors are exposure to sunlight, pH, residence time, and temperature, among others. Between pollutants that microplastics can accumulate, metals are the most studied (Hodson et al. 2017; Brennecke et al. 2016). They are frequently added as catalysts, pigments, and stabilizers during plastic manufacturing (Fahrenfeld et al. 2019; Nakashima et al. 2012). They can also adsorb organic pollutants, especially pharmaceuticals (Li et al. 2018; Llorca et al. 2018). This accumulation of contaminants mainly occurs in freshwater systems, where the concentrations of these chemicals are expected to be higher due to proximity to the sources that produce and discharge them (Horton et al. 2017a, b).

As mentioned above, concentrations of metals in freshwater are generally higher than in coastal areas. These concentrations depend mainly on location, sampling time, and anthropogenic activities (Guo and Wang 2019). Some authors studied the concentration of heavy metals in freshwater from the Beijing River, China (Wang et al. 2017a, b). The average results of this work are shown in Table 1.2.

Table 1.2 Mean concentrations of metals in the microplastics and surface sediments from Beijing River littoral zone

	μg per g (mg element per g sample)	
	Microplastics	Sediments
Nickel	1.326 ± 0.543	0.039 ± 0.012
Cadmium	8.271 ± 5.442	1.146 ± 0.811
Lead	78.975 ± 28.609	41.47 ± 13.007
Copper	258.9 ± 153.654	36.738 ± 23.139
Zinc	8242.525 ± 4020.627	183.863 ± 86.186
Titanium	22841.05 ± 8329.956	20718.913 ± 5836.971

Source: Wang et al. (2017a, b)

The concentrations of cadmium and zinc on microplastic surface get hold of 22841.05 ± 8329.96 μg per g and 8242.52 ± 4020.63 μg per g, respectively.

Organic contaminants such as antibiotics are widespread in aquatic environments. The affinity of these contaminants for microplastics is conditioned in many cases by their polarity and hydrophobicity. The sorption capacities of nonpolar organic contaminants are higher on nonpolar than polar polymers (Hüffer and Hofmann 2016). Some authors synthesized concentrations on freshwater in order to study the adsorption of organic contaminants in microplastics. Some of the published results are shown in Table 1.3.

The sorption capacity of organic compounds on microplastics is high, although the sorption capacities of different antibiotics on a specific type of plastic differed greatly. Sorption of antibiotics studied on microplastics decreased in the following order: ciprofloxacin > amoxicillin > trimethoprim > tetracycline (Li et al. 2018).

Sorption affinities vary depending on the polymer type and the nature of the pollutants. Thus, different types of polymers have different adsorption behaviors for the same pollutant. This could be attributed to the differences in the polarity and the functional groups of each polymer (Guo et al. 2012).

1.6.1 Effects of Microplastics on Freshwater Organisms

There is reasonably extensive evidence related to the harm caused by plastic waste in aquatic ecosystems. This can have a range of negative impacts on infrastructure and fishing. In addition, this could affect a wide range of freshwater organisms as a consequence of entanglement and ingestion. According to Scherer et al. (2017), there are some freshwater species that ingested microplastics with demonstrated effects on them, such as *L. varigatus*, *C. riparius*, *G. pulex*, *Gammarus fossarum*, *P. acuta*, or *D. magna*. Some studies on fish have shown that microplastics and associated toxins are bioaccumulated and cause problems such as intestinal damage and changes in metabolic profiles or are even lethal. Some of these effects on freshwater organisms are presented in Table 1.4.

Table 1.3 Summary of current studies of organic pollutantsorption on microplastics

Types	Organic contaminants	Microplastics	C_0	Sorption capacity	Reference
Polycyclic aromatic hydrocarbons	Phenanthrene	Polyethylene, polystyrene, and polyvinyl chloride (100–150 μm)	10–200 μg per L	303.03–714.29 μg per g	Wang et al. (2018a)
	Phenanthrene	Polypropylene, polyethylene, and polyoxymethylene (2–3 mm)	100 μg per L	–	Karapanagioti and Klontza (2008)
	Pyrene	Polyethylene, polystyrene, and polyvinyl chloride (100–150 μm)	0–100 μg per L	78.7–333 μg per g	Wang et al. (2018a, b)
Polyfluoroalkyl substances	Polyfluoroalkyl substances	High-density polyethylene and polystyrene (10 μm)	1–20 μg per L	34–210 μg per g	Llorca et al. (2018)
Antibiotics	Ciprofloxacin	Polypropylene	50 mg per L	0.615 mg per g	Li et al. (2018)
		Polystyrene		0.416 mg per g	
		Polyvinyl chloride		0.453 mg per g	
		Polyethylene		0.2 mg per g	
		Polyamide		2.2 mg per g	
	Trimethoprim	Polypropylene		0.102 mg per g	
		Polystyrene		0.174 mg per g	
		Polyvinyl chloride		0.481 mg per g	
		Polyethylene		0.154 mg per g	
		Polyamide		0.468 mg per g	
	Amoxicillin	Polypropylene		0.294 mg per g	
		Polyvinyl chloride		0.523 mg per g	
		Polyethylene		0.1131 mg per g	
		Polyamide		22.7 mg per g	
	Tetracycline	Polyamide		3.84 mg per g	

Table 1.4 Effects of microplastic particles on freshwater organisms

Species	Polymer	Parameter	Most significant effects	Reference
Chironomus tepperi	Polyethylene	Mortality	Increase at 1–4, 10–27, and 43–54 µm	Ziajahromi et al. (2018)
		Development	Decrease of body length at 1–4, 10–27, and 43–54 µm	
			Decrease of body parts at 10–27 µm	
			Delay at 10–27 µm	
		Emergence	Decrease of emerging rate	
Gammarus fossarum	Polyamide	Assimilation	Decrease in assimilation efficiency	Blarer and Burkhardt-Holm (2016)
	Polymethylmethacrylate	Development	Decrease in wet weight	Straub et al. (2017)
		Assimilation	Decrease in assimilation efficiency	
	Polyhydroxybutyrate	Development	Decrease	
Gammarus pulex	Polystyrene	Development	Decrease	Redondo-Hasselerharm et al. (2018)
Hyalella azteca	Polyethylene	Mortality	Increase. Dose dependent	Au et al. (2015)
		Reproduction	Decrease	
	Polypropylene	Mortality	Increase. Dose dependent	
		Development	Decrease. Dose dependent	
Thamnocephalus platyrus	Polystyrene	Mortality	Increase (4.03 mg per l)	Booth et al. (2013)
Hyalella azteca	Polyethylene	Mortality	Lethal (217.73 mg per l)	Lenz et al. (2015)
Caernorhabditis elegans	Polyamide	Mortality	Increase (0.5 mg per m^2)	Lei et al. (2018)
		Development	Decrease of body length	
		Reproduction	Decrease of embryo numbers	
		Cellular response	Decrease of calcium concentration	
	Polypropylene	Mortality	Increase (0.5 mg per m^2)	
		Development	Decrease of body length	
		Reproduction	Decrease of embryo numbers	

	Polyethylene	Mortality	Increase (0.5 mg per m^2)	
		Development	Decrease of body length	
		Reproduction	Decrease of embryo numbers. Decrease of brood size	
		Cellular response	Decrease of calcium concentration	
	Polyvinyl chloride	Mortality	Increase (0.5 mg per m^2)	
		Reproduction	Decrease of embryo numbers. Decrease of brood size	
		Cellular response	Decrease of calcium level in intestines	
	Polystyrene	Cellular response	Induction of intestinal reactive oxygen species production and increase in defecation cycle length from up 10 µg per l. Dose dependent	
		Behavior	Decrease of locomotion from up 10 µg per l. Dose dependent	
		Reproduction	Decrease of reproduction from up 1010 µg per l. Dose dependent	
		Development	Transgenerational effects on F1 generation in terms of intestinal ROS production, locomotion, and reproduction form up 100 10 µg per l	
Daphnia magna	Polyethylene	Mortality	Increase (57.43 mg per l)	Raimondo et al. (2007)
	Polystyrene	Mortality	Increase (0.66 mg per l)	Booth et al. (2013)
Brachionus koreanus	Polystyrene	Reproduction	Increase of reproduction time for 0.05 µm at 10 µg per ml	Jeong et al. (2016)
			Decrease of fecundity at 0.5 µm	
		Life span	Life span affected for 0.05 and 0.5 µm	
		Cellular response	Increase in reactive oxygen species level. Increase in phosphorylation status of p-JNK and p-p38 at 0.05 µm	

Sources: Connors et al. (2017), Scherer et al. (2017), Haegerbaeumer et al. (2019)

References

Abreu A, Pedrotti ML (2019) Microplastics in the oceans: the solutions lie on land. Field Actions Sci Rep [Online], Special Issue 19

Alomar C, Estarellas F, Deudero S (2016) Microplastics in the Mediterranean Sea: deposition in coastal shallow sediments, spatial variation and preferential grain size. Mar Environ Res 115:1–10. https://doi.org/10.1016/j.marenvres.2016.01.005

Anderson PJ, Park BJ, Palace VP (2016) Microplastics in aquatic environments: implications for Canadian ecosystems. Environ Pollut 218:269–280. https://doi.org/10.1016/j.envpol.2016.06.074

Anderson PJ, Warrack S, Langen V (2017) Microplastic contamination in Lake Winnipeg, Canada. Environ Pollut 225:223–231. https://doi.org/10.1016/j.envpol.2017.02.072

Andrady AL (2011) Microplastics in the marine environment. Mar Pollut Bull 62(8):1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030

Andrady AL (2015) Persistence of plastic litter in the oceans. In: Bergmann M et al (eds) Marine anthropogenic litter. Springer Open, Berlin, pp 57–72. https://doi.org/10.1007/978-3-319-16510-3_3

Araujo CJ, Nolasco MM, Ribeiro AMP, Ribeiro-Claro PJA (2018) Identification of microplastics using Raman spectroscopy: latest developments and future prospects. Water Res 142:426–440. https://doi.org/10.1016/j.watres.2018.05.060

Au Y, Bruce TF, Bridges WC, Klaine SJ (2015) Responses of Hyalella azteca to acute and chronic microplastic exposures. Environ Toxicol Chem 34:2564–2572. https://doi.org/10.1002/etc.3093

Auta HS, Emenike CU, Fauziah SH (2017) Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions. Environ Int 102:165–176. https://doi.org/10.1016/j.envint.2017.02.013

Bakir A, Rowland S, Thompson C (2014) Transport of persistent organic pollutants by microplastics in estuarine conditions. Estuar Coast Shelf Sci 140:14–21. https://doi.org/10.1016/j.ecss.2014.01.004

Ballent A, Corcoran PL, Madden O (2016) Sources and sinks of microplastics in Canadian lake Ontario nearshore, tributary and beach sediments. Mar Pollut Bull 110(1):383–395. https://doi.org/10.1016/j.marpolbul.2016.06.037

Bergmann M, Wirzberger V, Krumpen T, Lorenz C et al (2017) High quantities of microplastic in Arctic deep-sea sediments from the Hausgarten Observatory. Environ Sci Technol 51(19):11000–11010. https://doi.org/10.1021/acs.est.7b03331

Besseling E, Quik JT, Sun M (2017) Fate of nano-and microplastic in freshwater systems: a modeling study. Environ Pollut 220:540–548. https://doi.org/10.1016/j.envpol.2016.10.001

Blarer P, Burkhardt-Holm P (2016) Microplastics affect assimilation efficiency in the freshwater amphipod Gammarus fossarum. Environ Sci Pollut Res 23:23522–23532. https://doi.org/10.1007/s11356-016-7584-2

Blumenröder J, Sechet P, Kakkonen JE et al (2017) Microplastic contamination of intertidal sediments of Scapa Flow, Orkney: a first assessment. Mar Pollut Bull 124:112–120. https://doi.org/10.1016/j.marpolbul.2017.07.009

Booth AM, Justynska J, Kubowicz S, Johnsen H, Frenzel M (2013) Influence of salinity, dissolved organic carbon and particle chemistry on the aggregation behaviour of methacrylate-based polymeric nanoparticles in aqueous environments. Int J Environ Pollut 52:15–31. https://doi.org/10.1504/IJEP.2013.056358

Botterell ZLR, Beaumont N, Dorrington T, Steinke M, Thompson RC, Lindeque PK (2019) Bioavailability and effects of microplastics on marine zooplankton: a review. Environ Pollut 245:98–110. https://doi.org/10.1016/j.envpol.2018.10.065

Bouwmeester H, Hollman PCH, Peters RJB (2015) Potential health impact of environmentally released micro- and nanoplastics in the human food production chain: experiences from nanotoxicology. Environ Sci Technol 49:8932–8947. https://doi.org/10.1021/acs.est.5b01090

Brennecke D, Duarte B, Paiva F, Caçador I, Canning-Clode J (2016) Microplastics as vector for heavy metal contamination from the marine environment. Estuar Coast Shelf Sci 178:189–195. https://doi.org/10.1016/j.ecss.2015.12.003

Browne MA, Crump P, Niven SJ et al (2011) Accumulation of microplastic on shorelines worldwide: sources and sinks. Environ Sci Technol 45:9175–9179. https://doi.org/10.1021/es201811s

Carpenter EJ, Smith KL (1972) Plastics on the Sargasso sea surface. Science 175 (4027):1240–1241. https://doi.org/10.1126/science.175.4027.1240

Castañeda RA, Avlijas S, Simard MA (2014) Microplastic pollution in St. Lawrence river sediments. Can J Fish Aquat Sci 71:1767–1771. https://doi.org/10.1139/cjfas-2014-0281

Catarino AI, Thompson R, Sanderson W, Henry TB (2017) Development and optimization of a standard method for extraction of microplastics in mussels by enzyme digestion of soft tissues. Environ Toxicol Chem 36:947–951. https://doi.org/10.1002/etc.3608

Cesa FS, Turra A, Baruque-Ramos J (2017) Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings. Sci Total Environ 598:1116–1129. https://doi.org/10.1016/j.scitotenv.2017.04.172

Chen M, Jin M, Tao P, Wang Z et al (2018) Assessment of microplastics derived from mariculture in Xiangshan Bay, China. Environ Pollut 242:1146–1156. https://doi.org/10.1016/j.envpol.2018.07.133

Cincinelli A, Martellini T, Guerranti C, Scopetani C et al (2019) A potpourri of microplastics in the sea surface and water column of the Mediterranean Sea. TrAC 110:321–326. https://doi.org/10.1016/j.trac.2018.10.026

Claessens M, Meester SD, Landuyt LV, Clerck KD, Janssen CR (2011) Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Mar Pollut Bull 62:2199–2204. https://doi.org/10.1016/j.marpolbul.2011.06.030

Claessens M, Van Cauwenberghe L, Vandegehuchte LB, Janssen CR (2013) New techniques for the detection of microplastics in sediments and field collected organisms. Mar Pollut Bull 70 (1–2):227–233. https://doi.org/10.1016/j.marpolbul.2013.03.009

Cole M, Lindeque P, Halsband C, Galloway TS (2011) Microplastics as contaminants in the marine environment: a review. Mar Pollut Bull 62:2588–2597. https://doi.org/10.1016/j.marpolbul.2011.09.025

Cole M, Lindeque P, Fileman E, Halsband C, Goodhead R, Moger J, Galloway TS (2013) Microplastic ingestion by zooplankton. Environ Sci Technol 47:6646–6655. https://doi.org/10.1021/es400663f

Cole M, Webb H, Lindeque PK, Fileman ES, Halsband C, Galloway TS (2014) Isolation of microplastics in biota-rich seawater samples and marine organisms. Sci Rep 4:4528–4535. https://doi.org/10.1038/srep04528

Connors KA, Dyer SD, Belanger SE (2017) Advancing the quality of environmental microplastic research. Environ Toxicol Chem 36(7):1697–1703. https://doi.org/10.1002/etc.3829

Cooper DA, Corcoran PL (2010) Effects of mechanical and chemical processes on the degradation of plastic beach debris on the island of Kauai, Hawaii. Mar Pollut Bull 60(5):650–654. https://doi.org/10.1016/j.marpolbul.2009.12.026

Corcoran PL, Biesinger MC, Grifi M (2009) Plastics and beaches: a degrading relationship. Mar Pollut Bull 58:1363–1369. https://doi.org/10.1016/j.marpolbul.2008.08.022

Corcoran PL, Norris T, Ceccanese T et al (2015) Hidden plastics of Lake Ontario, Canada and their potential preservation in the sediment record. Environ Pollut 204:17–25. https://doi.org/10.1016/j.envpol.2015.04.009

Cózar A, Sanz-Martín M, Martí E et al (2015) Plastic accumulation in the Mediterranean Sea. PLoS One 10:e0121762. https://doi.org/10.1371/journal.pone.0121762

Crawford CB, Quinn B (2017) Microplastic collection techniques. In: Microplastic pollutants. Elsevier, Amsterdam, pp 179–202. https://doi.org/10.1016/B978-0-12-809406-8.00008-6

Davidson K, Dudas SE (2016) Microplastic ingestion by wild and cultured manila clams (Venerupis philippinarum) from Baynes Sound, British Columbia. Arch Environ Contam Toxicol 71(2):147–156. https://doi.org/10.1007/s00244-016-0286-4

De Falco F, Gullo MP, Gentile G, Di Pace E et al (2018) Evaluation of microplastic release caused by textile washing processes of synthetic fabrics. Environ Pollut 236:916–925. https://doi.org/10.1016/j.envpol.2017.10.057

De Sá LC, Oliveira M, Ribeiro F, Rocha TL, Futter MN (2018) Studies of the effects of microplastics on aquatic organisms: what do we know and where should we focus our efforts in the future? Science of the Total Environment Elsevier BV. https://doi.org/10.1016/j.scitotenv.2018.07.207

Dehaut A, Cassone AL, Frère L, Paul-Pont I (2016) Microplastics in seafood: benchmark protocol for their extraction and characterization. Environ Pollut 215:223–233. https://doi.org/10.1016/j.envpol.2016.05.018

Dekiff JH, Remy D, Klasmeier J, Fries E (2014) Occurrence and spatial distribution of microplastics in sediments from Norderney. Environ Pollut 186:248–256. https://doi.org/10.1016/j.envpol.2013.11.019

Desforges JPW, Galbraith M, Dangerfield N et al (2014) Widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean. Mar Pollut Bull 79:94–99. https://doi.org/10.1016/j.marpolbul.2013.12.035

Di M, Wang J (2018) Microplastics in surface waters and sediments of the three gorges reservoir, China. Sci Total Environ 616-617:1620–1627. https://doi.org/10.1016/j.scitotenv.2017.10.150

Ding L, Mao RF, Guo X, Yang X, Zhang Q, Yang C (2019) Microplastics in surface waters and sediments of the Wei River, in the northwest of China. Sci Total Environ 667:427–434. https://doi.org/10.1016/j.scitotenv.2019.02.332

Duis K, Coors A (2016) Microplastics in the aquatic and terrestrial environment: sources (with a specific focus on personal care products), fate and effects. Environ Sci Eur 28(1):1–25. https://doi.org/10.1186/s12302-015-0069-y

Edo C, Tamayo-Belda M, Martínez-Campos S, Martín-Betancor K et al (2019) Occurrence and identification of microplastics along a beach in the Biosphere Reserve of Lanzarote. Mar Pollut Bull 143:220–227. https://doi.org/10.1016/j.marpolbul.2019.04.061

Egbeocha CO, Malek S, Emenike CU, Milow P (2018) Feasting on microplastics: ingestion by and effects on marine organisms. Aquat Biol 27:93–106. https://doi.org/10.3354/ab00701

Eriksen M, Mason S, Wilson S et al (2013) Microplastic pollution in the surface waters of the Laurentian Great Lakes. Mar Pollut Bull 77:177–182. https://doi.org/10.1016/j.marpolbul.2013.10.007

Eriksen M, Lebreton LCM, Carson HS, Thiel M et al (2014) Plastic pollution in the World's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS One 9 (12):111913. https://doi.org/10.1371/journal.pone.0111913

Fahrenfeld NL, Arbuckle-Keil G, Beni NN, Shannon L, Bartelt-Hunt (2019) Source tracking microplastics in the freshwater environment. TrAC 112:248–254. https://doi.org/10.1016/j.trac.2018.11.030

Fastelli P, Blašković A, Bernardi G et al (2016) Plastic litter in sediments from a marine area likely to become protected (Aeolian Archipelago's islands, Tyrrhenian sea). Mar Pollut Bull 113:526–529. https://doi.org/10.1016/j.marpolbul.2016.08.054

Fischer EK, Paglialonga L, Czech E et al (2016) Microplastic pollution in lakes and lake shoreline sediments – a case study on Lake Bolsena and Lake Chiusi (central Italy). Environ Pollut 213:648–657. https://doi.org/10.1016/j.envpol.2016.03.012

Fok L, Cheung PK (2015) Hong Kong at the Pearl River Estuary: a hotspot of microplastic pollution. Mar Pollut Bull 99:112–118. https://doi.org/10.1016/j.marpolbul.2015.07.050

Fossi MC, Panti C, Guerranti C, Coppola D et al (2012) Are baleen whales exposed to the threat of microplastics? a case study of the Mediterranean fin whale (Balaenoptera physalus). Mar Pollut Bull 64:2374–2379. https://doi.org/10.1016/j.marpolbul.2012.08.013

Fries E, Dekiff JH, Willmeyer J, Nuelle MT, Ebert M, Remy D (2013) Identification of polymer types and additives in marine microplastic particles using pyrolysis-GC/MS and marine scanning electron microscopy. Environ Sci Process Impacts 15:1949–1956

Free CM, Jensen OP, Mason SA et al (2014) High levels of microplastic pollution in a large, remote, mountain lake. Mar Pollut Bull 85:156–163. https://doi.org/10.1016/j.marpolbul.2014.06.001

Frias JP, Sobral P, Ferreira AM (2010) Organic pollutants in microplastics from two beaches of the Portuguese coast. Mar Pollut Bull 60(11):1988–1992. https://doi.org/10.1016/j.marpolbul.2010.07.030

Frias JP, Gago J, Otero V et al (2016) Microplastics in coastal sediments from Southern Portuguese shelf waters. Mar Environ Res 114:24–30. https://doi.org/10.1016/j.marenvres.2015.12.006

Fries E, Dekiff JH, Willmeyer J, Nuelle MT, Ebert M, Remy D (2013) Identification of polymer types and additives in marine microplastic particles using pyrolysis-GC/MS and marine scanning electron microscopy. Environ Sci Process Impacts 15:1949–1956. https://doi.org/10.1039/c3em00214d

Gallagher A, Rees A, Rowe R et al (2016) Microplastics in the Solent estuarine complex, UK: an initial assessment. Mar Pollut Bull 102:243–249. https://doi.org/10.1016/j.marpolbul.2015.04.002

Gallo F, Fossi C, Weber R, Santillo D, Sousa J, Ingram I, Nadal A, Romano D (2018) Marine litter plastics and microplastics and their toxic chemicals components: the need for urgent preventive measures. Environ Sci Eur 30(13):13. https://doi.org/10.1186/s12302-018-0139-z

GESAMP (2019) In: Kershaw PJ, Turra A, Galgani F (eds) Guidelines or the monitoring and assessment of plastic litter and microplastics in the ocean, Rep. Stud. GESAMP No. 99. GESAMP, London, 130p

Gewert B, Ogonowskia M, Barth A, MacLeoda M (2017) Abundance and composition of near surface microplastics and plastic debris in the Stockholm Archipelago, Baltic Sea. Mar Pollut Bull 120:292–302. https://doi.org/10.1016/j.marpolbul.2017.04.062

Gomes de Carvalho D, Baptista JA (2016) Microplastic pollution of the beaches of Guanabara Bay, Southeast Brazil. Ocean Coast Manage 128:10–17. https://doi.org/10.1016/j.ocecoaman.2016.04.009

Godoy V, Blázquez G, Calero M, Quesada L, Martín-Lara MA (2019) The potential of microplastics as carriers of metals. Environ Pollut 255. https://doi.org/10.1016/j.envpol.2019.113363

Guo X, Wang J (2019) The chemical behaviors of microplastics in marine environment: a review. Mar Pollut Bull 142:1–14. https://doi.org/10.1016/j.marpolbul.2019.03.019

Guo X, Wang X, Zhou X, Kong X, Tao S, Xing B (2012) Sorption of four hydrophobic organic compounds by three chemically distinct polymers: role of chemical and physical composition. Environ Sci Technol 46:7252–7259. https://doi.org/10.1021/es301386z

Haegerbaeumer A, Mueller MT, Fueser H, Traunspurger W (2019) Impacts of micro- and nano-sized plastic particles on benthic invertebrates: a literature review and gap analysis. Front Eviron Sci 7:17. https://doi.org/10.3389/fenvs.2019.00017

Hamid FS, Bhatti MS, Anuar N, Mohan P, Periathamby A (2018) Worldwide distribution and abundance of microplastic: how dire is the situation? WM&R 36(10):873–897. https://doi.org/10.1177/0734242X18785730

Hanvey JS, Lewis PJ, Jennifer Lavers L, Nicholas Crosbie D, Pozode K, Clarke BO (2017) A review of analytical techniques for quantifying microplastics in sediments. Anal Methods 9:1369–1383

Harrison JP, Ojeda JJ, Romero-González ME (2012) The applicability of reflectance micro-Fourier-transform infrared spectroscopy for the detection of synthetic microplastics in marine sediments. Sci Total Environ 416:455–463. https://doi.org/10.1016/j.scitotenv.2011.11.078

Heo NK, Hong SH, Han GM et al (2013) Distribution of small plastic debris in cross-section and high strandline on Heungnam Beach, South Korea. Ocean Sci 48:225–233. https://doi.org/10.1007/s12601-013-0019-9

Herrera A, Asensio M, Martínez I et al (2018) Microplastic and tar pollution on three Canary Islands beaches: an annual study. Mar Pollut Bull 129:494–502. https://doi.org/10.1016/j.marpolbul.2017.10.020

Hidalgo-Ruz V, Theil M (2013) Distribution and abundance of small plastic debris on beaches in the SE Pacific (Chile): a study supported by a citizen science project. Mar Environ Research 87-88:12–18. https://doi.org/10.1016/j.marenvres.2013.02.015

Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M (2012) Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ Sci Technol 46:3060–3075. https://doi.org/10.1021/es2031505

Hodson ME, Duffus-Hodson CA, Clark A, Prendergast-Miller MT, Thorpe KL (2017) Plastic bag derived-microplastics as a vector for metal exposure in terrestrial invertebrates. Environ Sci Technol 51:4714–4721. https://doi.org/10.1021/acs.est.7b00635

Horton AA, Svendsen C, Williams RJ et al (2017a) Large microplastic particles in sediments of tributaries of the River Thames, UK – abundance, sources and methods for effective quantification. Mar Poll Bull 114:218–226. https://doi.org/10.1016/j.marpolbul.2016.09.004

Horton AA, Walton A, Spurgeon DJ, Lahive E, Svendsen C (2017b) Microplastics in freshwater and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. Sci Total Environ 586:127–141. https://doi.org/10.1016/j.scitotenv.2017.01.190

Hüffer T, Hofmann T (2016) Sorption of non-polar organic compounds by micro-sized plastic particles in aqueous solution. Environ Pollut 214:194–201. https://doi.org/10.1016/j.envpol.2016.04.018

Imhof H, Schmid J, Niessner R, Ivleva NP, Laforsch C (2012) A novel, highly efficient method for the separation and quantification of plastic particles in sediments of aquatic environments. Limnol Oceanogr Methods 10:524–537. https://doi.org/10.4319/lom.2012.10.524

Imhof HK, Ivleva NP, Schmid J, Niessner R, Laforsch C (2013) Contamination of beach sediments of a subalpine lake with microplastic particles. Curr Biol 23:867–868. https://doi.org/10.1016/j.cub.2013.09.001

Imhof HK, Laforsch C, Wiesheu AC, Schmid J, Anger PM, Niessner R et al (2016) Pigments and plastic in limnetic ecosystems: a qualitative and quantitative study on microparticles of different size classes. Water Res 98:64–74. https://doi.org/10.1016/j.watres.2016.03.015

Imhof HK, Sigl R, Brauer E et al (2017) Spatial and temporal variation of macro-, meso- and microplastic abundance on a remote coral island of the Maldives, Indian Ocean. Mar Pollut Bull 116:340–347. https://doi.org/10.1016/j.marpolbul.2017.01.010

Isobe A, Uchida K, Tokai T et al (2015) East Asian seas: a hot spot for pelagic microplastics. Mar Pollut Bull 101:618–623. https://doi.org/10.1016/j.marpolbul.2015.10.042

Jeong CB, Won EJ, Kang HM, Lee MC, Hwang DS, Hwang UK et al (2016) Microplastic size-dependent toxicity, oxidative stress induction, and p-JNK and p-p38. Activation in the Monogonont Rotifer (Brachionus koreanus). Environ Sci Technol 50:8849–8857. https://doi.org/10.1021/acs.est.6b01441

Kane IA, Clare MA (2019) Dispersion, accumulation, and the ultimate fate of microplastics in deep-marine environments: a review and future directions. Front Earth Sci 7:80. https://doi.org/10.3389/feart.2019.00080

Kang JH, Kwon OY, Lee KW et al (2015) Marine neustonic microplastics around the southeastern coast of Korea. Mar Pollut Bull 96:304–312. https://doi.org/10.1016/j.marpolbul.2015.04.054

Kanhai LDK, Officer R, Lyashevska O et al (2017) Microplastic abundance, distribution and composition along a latitudinal gradient in the Atlantic Ocean. Mar Pollut Bull 115:307–314. https://doi.org/10.1016/j.marpolbul.2016.12.025

Kanhai LDK, Gårdfeldt K, Lyashevska O, Hassellöv M, Thompson RC, O'Connor I (2018) Microplastics in sub-surface waters of the Arctic Central Basin. Mar Pollut Bull 130:8–18. https://doi.org/10.1016/j.marpolbul.2018.03.011

Karapanagioti HK, Klontza I (2008) Testing phenanthrene distribution properties of virginplastic pellets and plastic eroded pellets found on Lesvos island beaches (Greece). Mar Environ Res 65 (4):283–290. https://doi.org/10.1016/j.marenvres.2007.11.005

Karlsson TM, Arneborgb L, Broströmc G, Carney B, Gipperthe L, Hassellöva M (2018) The unaccountability case of plastic pellet pollution. Mar Pollut Bull 129:52–60. https://doi.org/10.1016/j.marpolbul.2018.01.041

Karthik R, Robin RS, Purvaja R, Ganguly D et al (2018) Microplastics along the beaches of southeast coast of India. Sci Total Environ 645:1388–1399. https://doi.org/10.1016/j.scitotenv.2018.07.242

Kim IS, Chae DH, Kim SK et al (2015) Factors influencing the spatial variation of microplastics on high-tidal coastal beaches in Korea. Arch Environ Contam Toxicol 69:299–309. https://doi.org/10.1007/s00244-015-0155-6

Kole PJ, Löhr AJ, Van Belleghem FA (2017) RagasWear and tear of tyres: a stealthy source of microplastics in the environment. Int J Environ Res Public Health 14(10):1265. https://doi.org/10.3390/ijerph14101265

Koelmans AA, Mohamed Nor NH, Hermsen E, Kooi M, Svenja M, De France M, J. (2019) Microplastics in freshwaters and drinking water: critical review and assessment of data quality. Water Res 155:410–422. https://doi.org/10.1016/j.watres.2019.02.054

Lechner A, Keckeis H, Lumesberger-Loisl F et al (2014) The Danube so colourful: a potpourri of plastic litter outnumbers fish larvae in Europe's second largest river. Environ Pollut 188:177–181. https://doi.org/10.1016/j.envpol.2014.02.006

Lee J, Hong S, Song YK et al (2013) Relationships among the abundances of plastic debris in different size classes on beaches in South Korea. Mar Pollut Bull 77:349–354. https://doi.org/10.1016/j.marpolbul.2013.08.013

Lei L, Wu S, Lu S, Liu M, Song Y, Fu Z et al (2018) Microplastic particles cause intestinal damage and other adverse effects in zebrafish Danio rerio and nematode Caenorhabditis elegans. Sci Total Environ 619–620:1–8. https://doi.org/10.1016/j.scitotenv.2017.11.103

Lenz R, Enders K, Stedmon CA, Mackenzie DMA, Nielsen TG (2015) A critical assessment of visual identification of marine microplastic using Raman spectroscopy for analysis improvement. Mar Pollut Bull 100:82–91. https://doi.org/10.1016/j.marpolbul.2015.09.026

Leon VM, Garcia I, Gonzalez E, Samper R, Fernandez-Gonzalez V, Muniategui-Lorenzo S (2018) Potential transfer of organic pollutants from littoral plastics debris to the marine environment. Environ Pollut 236:442–453. https://doi.org/10.1016/j.envpol.2018.01.114

Leslie HA, Brandsma SH, Van Velzen MJM et al (2017) Microplastics en route: field measurements in the Dutch river delta and Amsterdam canals, wastewater treatment plants, North Sea sediments and biota. Environ Int 101:133–142. https://doi.org/10.1016/j.envint.2017.01.018

Li WC, Tse HF, Fok L (2016) Plastic waste in the marine environment: a review of sources, occurrence and effects. Sci Total Environ 566–567:333–349. https://doi.org/10.1016/j.scitotenv.2016.05.084

Li J, Zhang K, Zhang H (2018) Adsorption of antibiotics on microplastics. Environ Pollut 237:460–467. https://doi.org/10.1016/j.envpol.2018.02.050

Liebezeit G, Dubaish F (2012) Microplastics in beaches of the East Frisian islands Spiekeroog and Kachelotplate. Bull Environ Contam Toxicol 89:213–217. https://doi.org/10.1007/s00128-012-0642-7

Llorca M, Schirinzi G, Martínez M, Barceló D, Farré M (2018) Adsorption of perfluoroalkyl substances on microplastics under environmental conditions. Environ Pollut 235:680–691. https://doi.org/10.1016/j.envpol.2017.12.075

Löder MGJ, Gunnar G (2015) Methodology used for the detection and identification of microplastics – a critical appraisal. In: Bergmann M et al (eds) Marine anthropogenic litter. Springer Open, Heidelbderg, pp 201–227. https://doi.org/10.1007/978-3-319-16510-3_8

Lots FA, Behrens P, Vijver MG et al (2017) A large-scale investigation of microplastic contamination: abundance and characteristics of microplastics in European beach sediment. Mar Pollut Bull 123:219–226. https://doi.org/10.1016/j.marpolbul.2017.08.057

Lusher A (2015) Microplastics in the marine environment: distribution, interactions and effects. In: Bergmann M et al (eds) Marine anthropogenic litter. Springer Open, Heidelbderg, pp 245–307. https://doi.org/10.1007/978-3-319-16510-3_10

Lusher AL, McHugh M, Thompson RC (2013) Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. Mar Pollut Bull 67(1–2):94–99. https://doi.org/10.1016/j.marpolbul.2012.11.028

Maes T, Jessop R, Wellner N, Haupt K, Mayes AG (2017) A rapid-screening approach to detect and quantify microplastics based on fluorescent tagging with Nile Red. Nat Sci Rep 7:44501. https://doi.org/10.1038/srep44501

Magnusson K, Noren F (2014) Screening of microplastic particles in and downstream a wastewater treatment plant. IVL Swedish Environmental Research Institute report. http://naturvardsverket.diva-portal.org/smash/record.jsf?pid=diva2%3A773505&dswid=325

Mani T, Hauk A, Walter U et al (2015) Microplastics profile along the Rhine River. Sci Rep 5:17988. https://doi.org/10.1038/srep17988

Martins J, Sobral P (2011) Plastic marine debris on the Portuguese coastline: a matter of size? Mar Pollut Bull 62:2649–2653. https://doi.org/10.1016/j.marpolbul.2011.09.028

Masura J, Baker J, Foster G, Arthur C (2015) Laboratory methods for the analysis of microplastics in the marine environment: recommendations for quantifying synthetic particles in waters and sediments, NOAA Technical Memorandum NOS-OR&R-48. NOAA Marine Debris, Silver Spring

Mason SA, Welch VG, Neratko J (2018) Synthetic polymer contamination in bottled water. Front Chem 6:407. https://doi.org/10.3389/fchem.2018.00407

Mato Y, Isobe T, Takada H, Kanehiro H, Ohtake C, Kaminuma T (2011) Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. Environ Sci Technol 35:318–324. https://doi.org/10.1021/es0010498

McCormick A, Hoellein TJ, Mason SA et al (2014) Microplastic is an abundant and distinct microbial habitat in an urban river. Environ Sci Technol 48:11863–11871. https://doi.org/10.1021/es503610r

McDermid KJ, McMullen TL (2004) Quantitative analysis of small-plastic debris on beaches in the Hawaiian Archipelago. Mar Pollut Bull 48(7–8):790–794. https://doi.org/10.1016/j.marpolbul.2003.10.017

Moore CJ (2008) Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. Environ Res 108(2):131–139. https://doi.org/10.1016/j.envres.2008.07.025

Moore CJ, Lattin GL, Zellers AF (2011) Quantity and type of plastic debris flowing from two urban rivers to coastal waters and beaches of Southern California. Revista de Gestão Costeira Integrada JICZM 11:65–73. https://doi.org/10.5894/rgci194

Morris RJ (1980) Floating plastic debris in the Mediterranean. Mar Pollut Bull 11(5):125. https://doi.org/10.1016/0025-326X(80)90073-9

Murphy F, Ewins C, Carbonnier F, Quinn B (2016) Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. Environ Sci Technol 50:5800–5808. https://doi.org/10.1021/acs.est.5b05416

Murray F, Cowie PR (2011) Plastic contamination in the decapod crustacean Nephrops norvegicus (Linnaeus, 1758). Mar Pollut Bull 62(6):1207–1217. https://doi.org/10.1016/j.marpolbul.2011.03.032

Naji A, Esmaili Z, Khan FR (2017) Plastic debris and microplastics along the beaches of the Strait of Hormuz, Persian Gulf. Mar Pollut Bull 114:1057–1062. https://doi.org/10.1016/j.marpolbul.2016.11.032

Nakashima E, Isobe A, Kako SI, Itai T, Takahashi S (2012) Quantification of toxic metals derived from macroplastic litter on Ookushi Beach, Japan. Environ Sci Technol 46:10099–10105. https://doi.org/10.1021/es301362g

Navarro-Pérez E, Barton ED (2001) Seasonal and interannual variability of the Canary Current. Sci Mar 65(Suppl. 1):205–213. https://doi.org/10.3989/scimar.2001.65s1205

Nel HA, Froneman PW (2015) A quantitative analysis of microplastic pollution along the South-Eastern coastline of South Africa. Mar Pollut Bull 101:274–275. https://doi.org/10.1016/j.marpolbul.2015.09.043

Nel HA, Dalu T, Wasserman RJ (2018) Sinks and sources: assessing microplastic abundance in river sediment and deposit feeders in an austral temperate urban river system. Sci Total Environ 612:950–956. https://doi.org/10.1016/j.scitotenv.2017.08.298

Nel HA, Dalu T, Wasserman RJ (2018) Sinks and sources: assessing microplastic abundance in river sediment and deposit feeders in an austral temperate urban river system. Sci Total Environ 612:950–956. https://doi.org/10.1016/j.scitotenv.2017.08.298

Nelms SE, Barnett J, Brownlow A, Davison NJ, Deaville R, Galloway TS, Lindeque PK, Santillo D, Godley BJ (2019) Microplastics in marine mammals stranded around the British coast: ubiquitous but transitory? Sci Rep 9:1–8. https://doi.org/10.1038/s41598-018-37428-3

Napper, Bakir IE, Rowland A, Thompson SJ, Characterisation RC (2015) Quantity and sorptive properties of microplastics extracted from cosmetics. Marine Pollution Bulletin, Volume 99, Issues 1–2, 15 October. https://doi.org/10.1016/j.marpolbul.2015.07.029

Neves D, Sobral P, Ferreira JL, Pereira T (2015) Ingestion of microplastics by commercial fish off the Portuguese coast. Mar Pollut Bull 101:119–126. https://doi.org/10.1016/j.marpolbul.2015.11.008

Ng KL, Obbard JP (2006) Prevalence of microplastics in Singapore's coastal marine environment. Mar Pollut Bull 52(7):761–767. https://doi.org/10.1016/j.marpolbul.2005.11.017

Norén F (2007) Small plastic particles in coastal Swedish waters. N-research report. KIMO, Sweden, p 11

Novotna K, Cermakova L, Pivokonska L, Cajthaml T, Pivokonsky M (2019) Microplastics in drinking water treatment – current knowledge and research needs. Sci Total Environ 667:730–740

Nuelle MT, Dekiff JH, Remy D, Fries E (2014) A new analytical approach for monitoring microplastics in marine sediments. Environ Pollut 184:161–169. https://doi.org/10.1016/j.envpol.2013.07.027

Obbard RW, Sadri S, Wong Y, Khitun AA, Baker I, Thompson RC (2014) Global warming releases microplastic legacy frozen in Arctic Sea ice. Earth's Future 2:315–320. https://doi.org/10.1002/2014EF000240

Oßmann BE, Sarau G, Holtmannspotter H, Pischetsrieder M, Christiansen SH, DickeSmall-sized W (2018) DickeSmall-sized microplastics and pigmented particles in bottled mineral water Water Res 141:307–316

Olivatto CA, Martinsa MC, Montagner C, Henry TB, Carreira R (2019) Microplastic contamination in surface waters in Guanabara Bay, Rio de Janeiro, Brazil. Mar Pollut Bull 139:157–162. https://doi.org/10.1016/j.marpolbul.2018.12.042

Pan Z, Guo H, Chen H, Wang S et al (2019) Microplastics in the Northwestern Pacific: abundance, distribution, and characteristics. Sci Total Environ 650:1913–1922. https://doi.org/10.1016/j.scitotenv.2018.09.244

Peng G, Xu P, Zhu B et al (2018) Microplastics in freshwater river sediments in Shanghai, China: a case study of risk assessment in mega-cities. Environ Pollut 234:448–456. https://doi.org/10.1016/j.envpol.2017.11.034

Piperagkas O, Papageorgiou N, Karakassis I (2018) Qualitative and quantitative assessment of microplastics in three sandy Mediterranean beaches, including different methodological approaches. Estuar Coast Shelf Sci 219:169–175. https://doi.org/10.1016/j.ecss.2019.02.016

Pivokonsky M, Cermakova L, Novotna K, Peer P, Cajthaml T, Janda V (2018) Occurrence of microplastics in raw and treated drinking water. Sci Total Environ 643:1644–1651

Plastics Europe (2017) An analysis of European plastics production, demand and waste data. Plastics – the Facts 2017. Plastics Europe, Brussels

Plastics Europe (2018) An analysis of European plastics production, demand and waste data. Plastics – the facts 2018

Prata JC, Da Costa J, Duarte AC, Rocha-Santos T (2019) Methods for sampling and detection of microplastics in water and sediment: a critical review. TrAC 110:150–159. https://doi.org/10.1016/j.trac.2018.10.029

Quinn B, Murphy F, Ewins C (2017) Validation of density separation for the rapid recovery of microplastics from sediment. Anal Methods 9:1491. https://doi.org/10.1039/C6AY02542K

Raimondo S, Montague BJ, Barron MG (2007) Determinants of variability in acute to chronic toxicity ratios for aquatic invertebrates and fish. Environ Toxicol Chem 26:2019–2023. https://doi.org/10.1897/07-069R.1

Reddy SM, Basha S, Adimurthy S, Ramachandraiah G (2006) Description of small plastics fragments in marine sediments along the Alang-Sosiya ship-breaking yard, India. Estuar Coast Shelf Sci 68:656–660. https://doi.org/10.1016/j.ecss.2006.03.018

Redondo-Hasselerharm PE, Falahudin D, Peeters ETHM, Koelmans AA (2018) Microplastic effect thresholds for freshwater benthic macroinvertebrates. Environ Sci Technol 52:2278–2286. https://doi.org/10.1021/acs.est.7b05367

Retama I, Jonathan MP, Shruti VC et al (2016) Microplastics in tourist beaches of Huatulco Bay, Pacific coast of southern Mexico. Mar Pollut Bull 113:530–535. https://doi.org/10.1016/j.marpolbul.2016.08.053

Rocha-Santos T, Duarte AC (2015) A critical overview of the analytical approaches to the occurrence, the fate and the behavior of microplastics in the environment. TrAC 65:47–53. https://doi.org/10.1016/j.trac.2014.10.011

Rocha-Santos T, Duarte AC (2017) Characterization and analysis of microplastics, vol 75, 1st edn. Elsevier, Amsterdam. 302 pp

Ryan PG, Moore CJ, Van Franeker JA, Moloney CL (2009) Monitoring the abundance of plastic debris in the marine environment. Philos Trans R Soc B: Biol Sci 364:1999–2012. https://doi.org/10.1098/rstb.2008.0207

Sánchez-Nieva J, Perales JA, González-Leal JM, Rojo-Nieto E (2017) A new analytical technique for the extraction and quantification of microplastics in marine sediments focused on easy implementation and repeatability. Anal Methods 9:6371. https://doi.org/10.1039/C7AY01800B

Sarafraz J, Rajabizadeh M, Kamrani E (2016) The preliminary assessment of abundance and composition of marine beach debris in the northern Persian Gulf, Bandar Abbas City, Iran. MBAI 96:131–135. https://doi.org/10.1017/S0025315415002076

Scherer C, Brennholt N, Reifferscheid G, Wagner M (2017) Feeding type and development drive the ingestion of microplastics by freshwater invertebrates. Sci Rep 7:17006. https://doi.org/10.1038/s41598-017-17191-7

Schmidt N, Thibault D, Galgani F et al (2018) Occurrence of microplastics in surface waters of the Gulf of Lion (NW Mediterranean Sea). Prog Oceanogr 163:214–220. https://doi.org/10.1016/j.pocean.2017.11.010

Schymanski D et al (2018) Analysis of microplastics in water by micro-Raman spectroscopy: release of plastic particles from different packaging into mineral water. Water Res 129:154–162. https://doi.org/10.1016/j.watres.2017.11.011

Sci Total Environ. (2019) Jun 1;667:427–434. https://doi.org/10.1016/j.scitotenv.2019.02.332

Shim WJ, Hong SH, Eo SE (2017) Identification methods in microplastic analysis: a review. Anal Methods 9:1384–1391. https://doi.org/10.1039/C6AY02558G

Silva AB, Bastos AS, Justino CIL, Da Costa JP, Duarte AC, Rocha-Santos TAP (2018) Microplastics in the environment: challenges in analytical chemistry – a review. Anal Chim Acta 1017:1–19. https://doi.org/10.1016/j.aca.2018.02.043

Sommer F, Dietze V, Baum A, Sauer J, Gilge S, Maschowski C, Gieré R (2018) Tire abrasion as a major source of microplastics in the environment. Aerosol Air Qual Res 18:2014–2028. https://doi.org/10.4209/aaqr.2018.03.0099

Sruthy S, Ramasamy EV (2017) Microplastic pollution in Vembanad Lake, Kerala, India: the first report of microplastics in lake and estuarine sediments in India. Environ Pollut 222:315–322. https://doi.org/10.1016/j.envpol.2016.12.038

Straub S, Hirsch PE, Burkhardt-Holm P (2017) Biodegradable and petroleum-based microplastics do not differ in their ingestion and excretion but in their biological effects in a freshwater invertebrate Gammarus fossarum. Int J Environ Res Public Health 14:14. https://doi.org/10.3390/ijerph14070774

Strungaru SA, Jijie R, Nicoara M, Plavan G, Faggio C (2019) Micro- (nano) plastics in freshwater ecosystems: abundance, toxicological impact and quantification methodology. TrAC 110:116–128. https://doi.org/10.1016/j.trac.2018.10.025

Su L, Xue Y, Li L et al (2016) Microplastics in Taihu Lake, China. Environ Pollut 216:711–719. https://doi.org/10.1016/j.envpol.2016.06.036

Suaria G, Aliani S (2014) Floating debris in the Mediterranean Sea. Mar Pollut Bull 86:494–504. https://doi.org/10.1016/j.marpolbul.2014.06.025

Sundt P, Schulze P, Syversen F (2014) Sources of microplastics-pollution to the marine environment. Project Report. (108 pp. Norway)

Syberg K, Khan FR, Selck H, Palmqvist A, Banta GT, Daley J, Sano L, Duhaime MB (2015) Microplastics: addressing ecological risk through lessons learned: microplastics ecological risk. Environ Toxicol Chem 34:945–953. https://doi.org/10.1002/etc.2914

Taylor ML, Gwinnett C, Robinson LF, Woodall LC (2016) Plastic microfibre ingestion by deep-sea organisms. Nat Sci Rep 6:33997. https://doi.org/10.1038/srep33997

Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AWG, McGonigle D, Russell AE (2004) Lost at sea: where is all the plastic? Science 304:838. https://doi.org/10.1126/science.1094559

Tunçer S, Artüz B, Demirkol M, Artüz L (2018) First report of occurrence, distribution, and composition of microplastics in surface waters of the Sea of Marmara, Turkey. Mar Pollut Bull 135:283–289. https://doi.org/10.1016/j.marpolbul.2018.06.054

Turner A, Holmes L (2011) Occurrence, distribution and characteristics of beached plastic production pellets on the island of Malta (central Mediterranean). Mar Pollut Bull 62:377–381. https://doi.org/10.1016/j.marpolbul.2010.09.027

UNEP (2015) report Plastic in Cosmetics: Are We Polluting the Environment Through Our Personal Care?

Van Cauwenberghe L, Vanreusel A, Mees J, Janssen CR (2013) Microplastic pollution in deep-sea sediments. Environ Pollut 182:495–499. https://doi.org/10.1016/j.envpol.2013.08.013

Vandenberg LN, Hauser R, Marcus M, Olea N, Welshons WV (2007) Human exposure to bisphenol A (BPA). Reprod Toxicol 24(2):139–177. https://doi.org/10.1016/j.reprotox.2007.07.010

Vaughan R, Turner SD, Rose NL (2017) Microplastics in the sediments of a UK urban lake. Environ Pollut 229:10–18. https://doi.org/10.1016/j.envpol.2017.05.057

Verster C, Minnaar K, Bouwman H (2017) Marine and freshwater microplastic research in South Africa. Integr Environ Assess Manag 13(3):533–535. https://doi.org/10.1002/ieam.1900

Vianello A, Boldrin A, Guerriero P et al (2013) Microplastic particles in sediments of a lagoon of Venice, Italy: first observations on occurrence, spatial patterns and identification. Estuar Coast Shelf Sci 130:54–61. https://doi.org/10.1016/j.ecss.2013.03.022

Wang W, Wang J (2018) Investigation of microplastics in aquatic environments: an overview of the methods used, from field sampling to laboratory analysis. TrAC 108:195–202. https://doi.org/10.1016/j.trac.2018.08.026

Wang J, Peng J, Tan Z et al (2017a) Microplastics in the surface sediments from the Beijiang River littoral zone: composition, abundance, surface textures and interaction with heavy metals. Chemosphere 171:248–258. https://doi.org/10.1016/j.chemosphere.2016.12.074

Wang W, Ndungu AW, Li Z et al (2017b) Microplastics pollution in inland freshwaters of China: a case study in urban surface waters of Wuhan, China. Sci Total Environ 575:1369–1374. https://doi.org/10.1016/j.scitotenv.2016.09.213

Wang F, Wong CS, Chen D, Lu X, Wang F, Zeng EY (2018a) Interaction of toxic chemicals with microplastics: a critical review. Water Res 139:208–219. https://doi.org/10.1016/j.watres.2018.04.003

Wang Z, Chen M, Zhang L, Wang K, Yu X, Zheng Z, Zheng R (2018b) Sorption behaviors of phenanthrene on the microplastics identified in a mariculture farm in Xiangshan Bay, southeastern China. Sci Total Environ 628–629:1617–1626. https://doi.org/10.1016/j.scitotenv.2018.02.146

Wessel CC, Lockridge GR, Battiste D et al (2016) Abundance and characteristics of microplastics in beach sediments: insights into microplastic accumulation in northern Gulf of Mexico estuaries. Mar Pollut Bull 109:178–183. https://doi.org/10.1016/j.marpolbul.2016.06.002

Woodall LC, Sanchez-Vidal A, Canals M, Paterson G, Coppock R et al (2014) The deep sea is a major sink for microplastic debris. R Soc Open Sci 1:140317. https://doi.org/10.1098/rsos.140317

Wright SL, Kelly FJ (2017) Plastic and human health: a micro issue? Environ Sci Technol 51:6634–6647. https://doi.org/10.1021/acs.est.7b00423

Wright SL, Thompson RC, Galloway TS (2013) The physical impacts of microplastics on marine organisms: a review. Environ Pollut 178:483–492. https://doi.org/10.1016/j.envpol.2013.02.031

Wu P, Cai Z, Jin H, Tang Y (2019) Adsorption mechanisms of five bisphenol analogues on polyvinyl chloride microplastics. Sci Total Environ 650:671–678. https://doi.org/10.1016/j.scitotenv.2018.09.049

Xiong X, Zhang K, Chen X, Shi H, Luo Z, Wu C (2018) Sources and distribution of microplastics in China's largest inland lake – Qinghai Lake. Environ Pollut 235:899. https://doi.org/10.1016/j.envpol.2017.12.081

Yu X, Ladewig S, Bao S et al (2018) Occurrence and distribution of microplastics at selected coastal sites along the southeastern United States. Sci Total Environ 613–614:298–305. https://doi.org/10.1016/j.scitotenv.2017.09.100

Zbyszewski M, Corcoran PL (2011) Distribution and degradation of fresh water plastic particles along the beaches of Lake Huron, Canada. Water Air Soil Pollut 220:365–372. https://doi.org/10.1007/s11270-011-0760-6

Zhang K, Su J, Xiong X et al (2016) Microplastic pollution of lakeshore sediments from remote lakes in Tibet plateau, China. Environ Pollut 219:450–455. https://doi.org/10.1016/j.envpol.2016.05.048

Zhao S, Zhu L, Wang T, Li D (2014) Suspended microplastics in the surface water of the Yangtze Estuary System, China: first observations on occurrence, distribution. Mar Pollut Bull 86:562–568. https://doi.org/10.1016/j.marpolbul.2014.06.032

Zhao S, Zhu L, Gao L, Li D (2017) Methodological limitations for microplastic quantification in the ocean: recommendations for overcoming the defects. WESTPAC Workshop for Marine MP. https://doi.org/10.1016/B978-0-12-813747-5.00002-3

Zhu L, Zhang K, Chen X, Shi H et al (2018) Microplastic pollution in North Yellow Sea, China: observations on occurrence, distribution and identification. Environ Pollut 636:20–29. https://doi.org/10.1016/j.scitotenv.2018.04.182

Ziajahromi S, Kumar A, Neale PA, Leusch FDL (2018) Environmentally relevant concentrations of polyethylene microplastics negatively impact the survival, growth and emergence of sediment-dwelling invertebrates. Environ Pollut 236:425–431. https://doi.org/10.1016/j.envpol.2018.01.094

Chapter 2
Identification and Remediation of Plastics as Water Contaminant

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Abstract Plastics are major assets for mankind due to their widespread applications in all spheres of life. The major drawbacks are their after-use handling, as it may take hundreds and thousands of years for its biodegradation. While major advancement has been made in the development of nontoxic and eco-friendly plastics, the accumulation of plastics in the environment has been a major concern in landfills, natural ecosystem, and oceans. The deleterious effects of plasticizers, additives, and dioxins from plastic pollutions on human health include endocrine disruption, reproductive disorders, and breast cancer. A well-managed plastic production, consumption, and disposal system must be put in place, to address this global problem. The development and application of biocompatible plastics and incentives on plastic reuse and recycle, within circular economy framework, must be implemented and enforced. This chapter will provide information about plastic; its types, nature and chemistry, consumption, and pollution impact; and the solutions and remedies. Different techniques to process various types of plastic wastes are discussed. Primary recycling of plastic wastes is a low-impact process. Mechanical recycling is widely used due to its effectiveness, where the waste is firstly converted into appropriate shapes and sizes through different processes. Chemical recycling involves the breakdown of polymers by heating in the absence of oxygen. Plastics are also degraded by means of ultraviolet light because these are not naturally degraded even by biotic means. The 3R scheme, which represents reduction, reusability, and recycling of plastic wastes, and the alternative measures through incentives to promote eco-friendly plastic products and a safer environment will be elaborated.

Keywords Plastics · Pollutions · Contaminants · Environmental impacts · Water pollution · Plastic degradation · Biodegradability · Additives · Remediation · Eco-friendly products

Abbreviations

ATR	Attenuated total reflectance
BBP	Butyl benzyl phthalate
BFR	Brominated flame retardants
BPA	Bisphenol A
BTBPE	1, 2-Bis(2,4,6-tribromophenoxy)ethane
CNS	Central nervous system
DBP	Dibutyl phthalate
DEHP	Diethylhexyl phthalate
DEP	Diethyl phthalate

DMP	Dimethyl phthalate
END	Endocrine disruption
EPS	Extended polystyrene
FTIR	Fourier transform infrared spectroscopy
GC/MS	Gas chromatograph/mass spectrometer
HBB	Hexabromobiphenyl
HDPE	High-density polyethylene plastic
LDPE	Low-density polyethylene plastic
MSW	Municipal solid waste
NaCl	Sodium chloride
NPE	Nonylphenol ethoxylates
PAE	Phthalic acid esters
PBDE	Polybrominated diphenyl ethers
PET	Polyethylene terephthalate
PSW	Plastic solid waste
PVC	Polyvinyl chloride
TBBPA	Tetrabromobisphenol A
WPO	Wet peroxide oxidation

2.1 Introduction

Before the discovery of plastics, elephant ivory (teeth and tusks) obtained from the remains of elephants have found applications in the manufacturing of billiard balls, combs, and many products. To meet the market demand for elephant ivory, the killing of the elephants has become widespread such as in the African continent that the elephant population has dramatically decreased. The ivory products consequently become prohibitively expensive. Thus, the alternative material was invented by J. W. Hyatt and his brother from cotton cellulose and named as "Celluloid" (National Museum of American History, Estate of Catherine Walden Myer). The word "Plastic" was coined from the Greek word "Plastikos" which means "moulded or shaped by heat" for the celluloid-like product easily moulded into different shapes. A big disadvantage in the preparation of the cellulose-based products is the exothermic reaction of the mixture which produces high energy and releases heat making it potentially highly flammable and risky.

An American chemist, L. Baekeland, considered as "the Father of the Plastic industry," has successfully synthesized bakelite, prepared using phenol from coal tar and formaldehyde and reacted together. Bakelite has a good property for insulation. The invention of bakelite opens up a new avenue for the development of plastics, its derivatives, and composite materials for specialized applications in most areas in the fields of material sciences. Plastics are durable and sometimes inert, which can withstand very harsh conditions of temperature and weathering. These properties of plastics make it a burden to the environment later, after use.

Plastics have become vital parts of human life and provide many advantages and ease the activities and the interactions with the surroundings and ecosystem (Hahladakis et al. 2018). These are due to the diverse properties of plastics which are easily incorporated into a wide range of applications, from domestic to major components in industries, as shown in Fig. 2.1. The production of plastic has increased from 2 to 382 metric tons between 1950 and 2015, with the total of 7800 metric tons in 65 years. Globally, 50% of the plastic manufacturers are located in the Asian region, while only 18–19% are in Europe and North America (Lam et al. 2018). The thermoplastics, which include polypropylene, polyvinyl chloride, and high-density polyethylene, have found diverse applications worldwide; but the thermosetting plastics, such as polystyrene and polyethylene terephthalate, receive higher demand. The plastic polymers are extensively used to make foams, synthetic fibers, adhesives, and coatings for different applications, resulting in increasing global plastic demand annually (Brems et al. 2012). However, plastics are resistance to decomposition and degradation, and can exist for a long time. As a consequence, plastic wastes are filling up the landfills and the municipal solid wastes, and may cause accidental fires and pollution. Made up of many different chemicals and additives, plastics can be the main source of cadmium and lead poisoning. The heterogeneity of the plastic composition may limit the recycling process as it may be costly to produce pure plastics or single polymer composites. Despite these limitations, the application of plastics in everyday human activities is set to continue. Plastics are less bulky and light and more suitable for use in transportation and automobiles as the load and fuel consumption are much

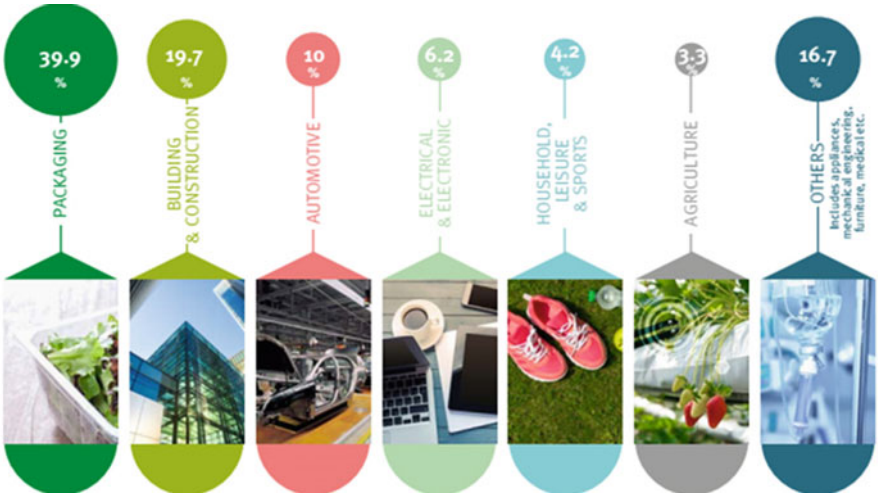

Fig. 2.1 The main market sectors of plastic. 39.9% of plastic is used in packaging; 19.7% in building and construction; 10% in automotive; 6.2% in electrical and electronics; 4.2% in household, leisure, and sports; 3.3% in agriculture; and 16.7% in various other sectors. (Reprinted with permission of [The history of plastics: from the Capitol to the Tarpeian Rock, Chalmin, Attribution 3.0 Unported (CC By 3.0)] from Chalmin 2019)

reduced (Clark et al. 1999). This chapter describes the different types of plastics, the sources and wastes generated, the impacts on human health, environment and marine life, and the different techniques used for the detection and removal of the plastic wastes and toxins.

2.1.1 The Plastic Consumption per Person

Figure 2.2 shows the total plastic production per person without taking into account the waste management and recycling. The figure represents the daily basis of plastic wastes generated by a person, measured in kilogram unit per individual. It can be seen that the plastic consumption per individual basis is ten times higher in countries including Guyana, Ireland, Kuwait, the Netherlands, and the United States (US) than other countries like India, Tanzania, and Bangladesh.

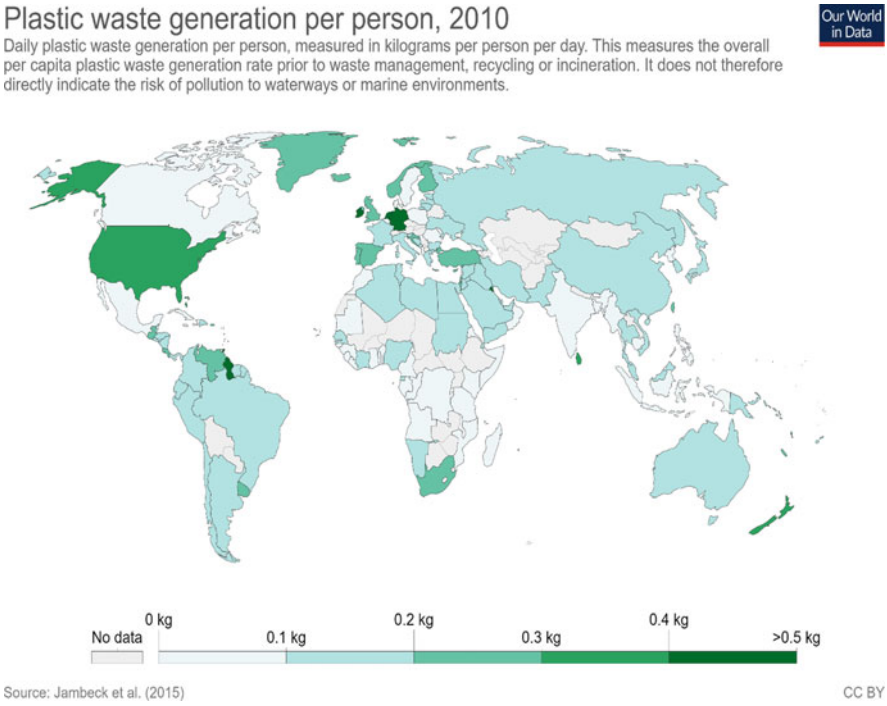

Fig. 2.2 The plastic waste production per person worldwide. The overall plastic waste generated per person before the waste management protocols, or recycling, but not indicating the effects of water pollution. (Reprinted with permission of [Plastic Pollution, Hannah Ritchie, Attribution 4.0 International (CC By 4.0)] from Hannah Ritchie 2018)

2.1.2 The Top 20 River Sources into the Oceans

The total production of plastics globally has been on the rise since the 1950s, with 311 million tons production in 2014, and predicted to be nearly 1800 million tons in 2050. Figure 2.3 illustrates the plastic production worldwide in million tons. China, North America, European Union, and Asia are the biggest cause of plastic pollution. Developed countries like the United States, Europe, Japan, Australia, and New Zealand are the top manufacturing and high consumption countries, but with

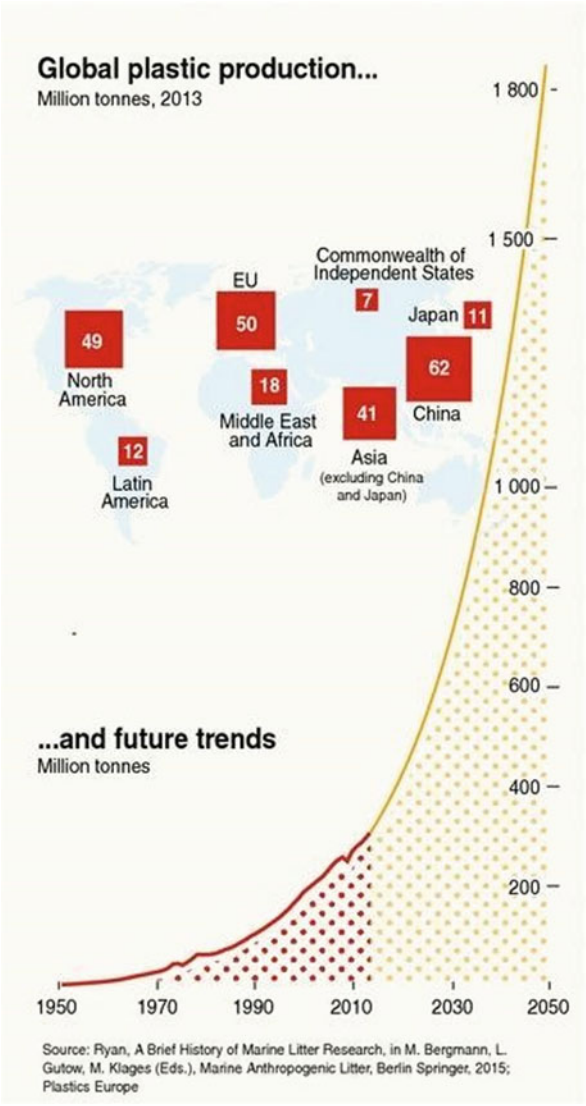

Fig. 2.3 The plastic production worldwide in million tons. China, North America, European Union, and Asia are the biggest cause of plastic pollution. (Reprinted with permission of [Marine litter plastics and microplastics and their toxic chemicals components: the need for urgent preventive measures, Gallo et al., Creative Common Attribution (CC by 4.0)] from Gallo et al. 2018)

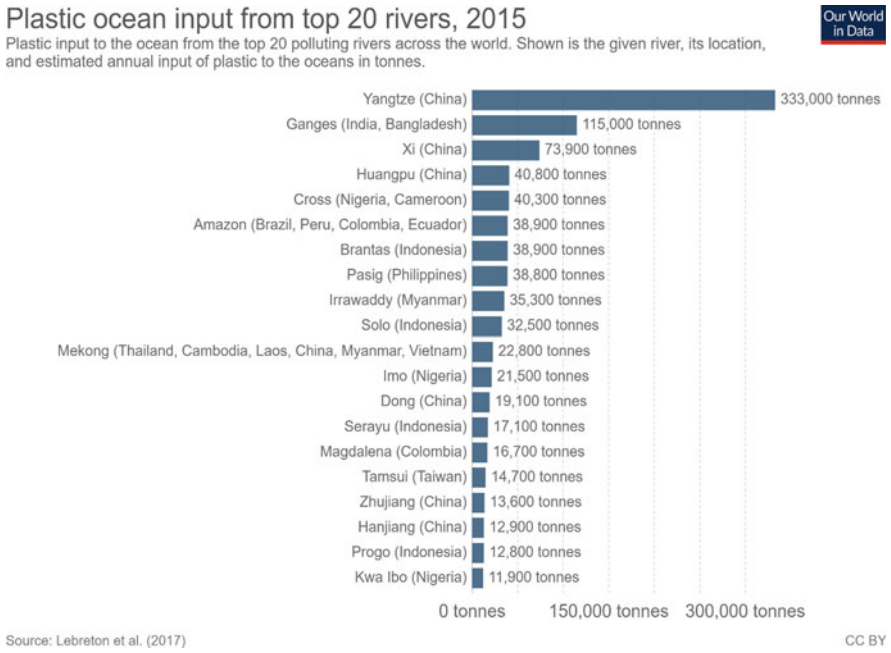

Fig. 2.4 Plastic input in the ocean of top 20 polluted rivers across the world. The river with its location and estimated annual input of plastics (in tons) to the oceans are shown. (Reprinted with permission of [Plastic Pollution, Hannah Ritchie, Creative Common Attribution (CC by 4.0)] from Hannah Ritchie 2018)

excellent waste disposal sytems in place. Many low- to middle-income countries in South Asia and sub-Saharan Africa are facing 80–90% of the plastic pollution with underdeveloped waste management system, resulting in high incidence of river and ocean pollution, and increasing water contamination. The top 20 polluted rivers contribute above 2/3 of the total river wastes and most of these are present in Asia. River Yangtze is at the top for causing pollution, with 333,000 tons of plastic in 2015, contributing up to 4% of the annual marine pollution, as shown in Fig. 2.4. There are different ways that contribute towards the entry of plastics into the aquatic ecosystem such as from the pollution on the beaches, plastic debris floating on the ocean surface, and deposition at the seabeds. One important source is the river that carries plastic effluents from the mainland to the offshore areas.

2.1.3 Classification of Plastics

Polymers are long-chained molecules, having unique structures and consisting of repeated subunits called monomers (“mer” means part). The single monomer structure is specifically used to identify chemically or specify any homopolymer. The

structure of single monomer $(-CH_2-CH_2-)_n$ describes polyethylene. When the number of repeated units "*n*" are in hundreds, its consistency becomes like a soft wax or a sticky fluid. When the repeated units are in thousands, it becomes the valuable solid plastic (Andrady 2017). In plastic polymer, the long hydrocarbon chains mainly consist of carbon and hydrogen atoms to form the basic structure. Carbon provides the main backbone of the polymer as it naturally has the ability to attach four other groups. Polymers such as polyethylene, polypropylene, polystyrene, and polymethyl pentane all have the carbon backbone, but there are some polymers that contain other than the carbon backbone including nylon which contains nitrogen atom, and polycarbonates and polyesters which mainly consist of oxygen atom. A few inorganic polymers contain silicon or phosphorus backbone (Vanapalli et al. 2019). The molecular arrangements of polymers can be in the form of amorphous or crystalline structure. The amorphous plastic does not have specific arrangements of atoms in the structure, and are randomly arranged. The amorphous polymer can be formed by controlling the polymerization process and quenching the molten polymer. They are generally transparent and have many applications in food wrappings, windows, contact lenses, and headlight lenses. The crystalline polymer has distinct pattern of atoms and molecules, and through quenching, the polymer structure is crystallized, and the degree of crystallinity controlled. Crystallinity provides strength, chemical resistance, stability, and stiffness. With increase in crystallinity, less light has the ability to pass through and this controls the degree of opaqueness. The work on polymers has increasingly shifted towards exploiting the unique properties for specific applications whilst making them more environmentally-friendly and less polluting to the environment.

Based on the applications, plastics can be classified into different classes:

Thermosetting Plastics

Thermoset plastics conserve their shapes when cooled and cannot be moulded back into their previous state. They are hard and long-lasting. The examples are polyurethanes and epoxy resins.

Thermoplastics

Thermoplastics are flexible as compared to thermosets and can be moulded back to its parent form. They are mostly used in packaging. The examples include polyethylene and polyvinyl chloride.

Plastic Composite

Polyethylene terephthalate or "stomach" plastics are used in the manufacturing of plastic bottles for juice, soft drinks, and liquids. These plastics can be made

phthalate free, soft and lightweight-carrying, transparent containers for packaging purposes. It is harmless but, after a long time and at high temperature, may produce carcinogens.

Plastic containers based on polyvinyl chloride are the flexible type of plastics. Phthalates used for its flexibility are harmful chemicals, in addition to bisphenol A, lead, and dioxin. High-density polyethylene plastic has high density and high tensile strength, suitable in the manufacturing of refrigerators and large containers and bags.

Low-density polyethylene plastic is heat resistant and highly brittle, has low tensile strength, may be transparent or opaque, and is used for packaging frozen foods. Polypropylene is a strong, semitransparent, and heat-resistant polymer, usually used for packaging of yogurt, and medicine. Polystyrene is a petroleum-based plastic polymer made from styrene monomer, and is also widely used for food packaging and insulation.

Long exposure to high temperature may produce neurotoxic, hematological, cytogenetic, and carcinogenic by-products.

The plastic material may be composed of different synthetic materials that are malleable when heated, and hardened upon cooling. These include various types of resins, polymer, derivatives, and proteins used instead of the traditional materials such as metals, wood, and glass. Because of this flexible characteristic, the use of plastics is ubiquitous. This has largely contributed to the plastic waste disposal problems seen today that have polluted the marine ecosystem, ocean and seabeds.

2.1.4 Types of Industrial Plastic Wastes

The different types of plastic wastes generated by the plastic industries include macroplastics, microplastics, nanoplastics, platic toxins, and the additives.

Macroplastics

Plastic particles with diameter ranging from 1 to 5 mm are defined as macroplastics. These plastics when ingested by marine animals get stuck in their guts and can be lethal. This type of plastic waste has contaminated the freshwater systems, shorelines, and oceans (Li et al. 2016).

Microplastics

These plastic particles are less than 1 mm. Because of smaller sizes, microplastics can penetrate the body of aquatic life or easily ingested and run through the digestive track, circulatory, or excretory system, and eventually interfere with the proper functioning of the body system. Once settled inside the body and not excreted out,

these particles start trickling down the food chain and entering the human body (Li et al. 2016).

Microplastics, though do not seem to be fatal to the livings organism, could still cause acute chronic toxicity. The toxic effects of microplastics can be a result of several mechanisms. Primarily, the toxicity can be caused by the polymeric materials used in the specific plastic goods. For example, polystyrene, commonly utilized as protective packaging, can easily circulate in the blood and induce chronic reproductive disorders in the suspension-feeding animals in the marine water. Microplastics can cause allergy and itchiness due to their tiny sizes with possibly the pointed ends as these materials penetrate into the body tissues. The intake may cause malnourishment and reproductive disruption (Sun et al. 2019). Microplastics are obtained from two different sources: primary and secondary sources. Primary microplastics are synthesized by industrial processes directly, while secondary microplastics are produced from primary microplastics by degradation under the extreme environment of moisture and heat (Li et al. 2016).

Primary Microplastics

This type of microplastic is manufactured on an industrial scale as microbeads of various sizes and shapes. They are mainly used in toiletries and commonly as "exfoliates" in sandblasting media, or as the "plastics pellets" or the raw materials for the manufacturing of these products. These pellets enter and pollute the ecosystem via industrial leakage, transportation, or during utilization. As illustrated in Fig. 2.5, there are different types of chemical structures present in the plastic wastes. Plastic resins are utilized mostly in the packaging, with short life span and found extensively as a part of litters or municipal solid wastes. The major types of thermoplastics that are commonly present in the microplastics are polyethylene,

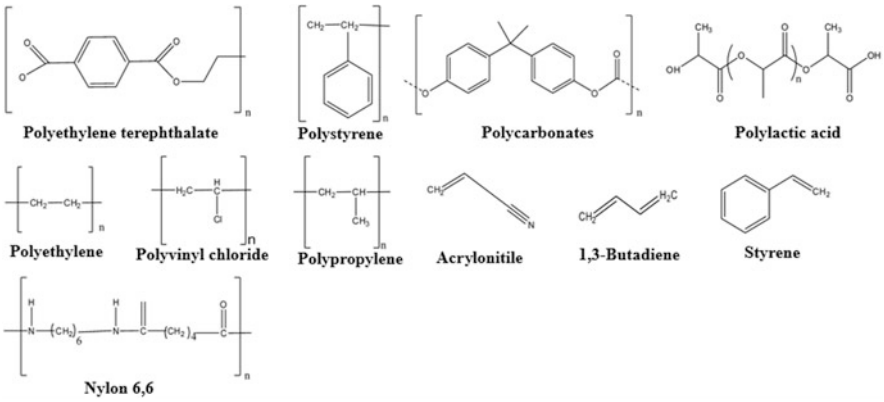

Fig. 2.5 Different types of structures present in the industrial plastic wastes. Carbon provides the backbone to nearly all plastic polymers (Modified from Vanapalli et al. 2019).