

Microplastics in the Marine Environment: A Review of the Methods Used for Identification and Quantification

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ABSTRACT: This review of 68 studies compares the methodologies used for the identification and quantification of microplastics from the marine environment. Three main sampling strategies were identified: selective, volume-reduced, and bulk sampling. Most sediment samples came from sandy beaches at the high tide line, and most seawater samples were taken at the sea surface using neuston nets. Four steps were distinguished during sample processing: density separation, filtration, sieving, and visual sorting of microplastics. Visual sorting was one of the most commonly used methods for the identification of microplastics (using type, shape, degradation stage, and color as criteria). Chemical and physical characteristics (e.g., specific density) were also used. The most reliable method to identify the chemical composition of microplastics is by infrared spectroscopy. Most studies reported that plastic fragments were polyethylene and polypropylene polymers. Units commonly used for abundance estimates are “items per m²” for sediment and sea surface studies and “items per m³” for water column studies. Mesh size of sieves and filters used during sampling or sample processing influence abundance estimates. Most studies reported two main size ranges of microplastics: (i) 500 μm –5 mm, which are retained by a 500 μm sieve/net, and (ii) 1–500 μm , or fractions thereof that are retained on filters. We recommend that future programs of monitoring continue to distinguish these size fractions, but we suggest standardized sampling procedures which allow the spatiotemporal comparison of microplastic abundance across marine environments.



INTRODUCTION

The worldwide production of plastics has increased considerably since the development of synthetic polymers in the middle of the 20th century.^{1,2} When discarded in the marine environment, plastics can become an environmental hazard.^{3,4} Plastic debris enters the marine environment in a wide range of sizes, in the micrometer to meter range.⁵ Microplastic particles comprise either manufactured plastics of microscopic size, such as scrubbers^{6,7} and industrial pellets that serve as precursors for manufactured plastic products (primary sources), or fragments or fibers of plastics derived from the breakdown of larger plastic products (secondary sources).^{4,8,9} Degradation processes of plastics are extremely slow,^{5,10} and thus microplastics potentially persist for very long time periods in the marine environment.^{11,12}

The presence and accumulation of microplastics in the ocean is of considerable concern for a variety of reasons, especially because they are ingested by marine biota.^{4,13} Microplastics can absorb persistent bioaccumulative and toxic compounds (PBT) from seawater,¹⁴ which include persistent organic pollutants (POPs)^{15–17} and metals.¹⁸ Once ingested, the absorbed pollutants may be transferred to the respective organisms.¹⁹ However, while microplastics have been reported in a wide variety of marine

organisms,^{20–24} the extent to which ingestion might present a toxicological hazard is not well-known.

In order to gain a better understanding of the impacts of microplastics, most studies have focused on quantifying their abundance in the marine environment. One of the main problems of large-scale spatial and temporal comparisons is the fact that a wide variety of approaches have been used to identify and quantify microplastics. Furthermore, microplastics comprise a very heterogeneous assemblage of pieces that vary in size, shape, color, specific density, chemical composition, and other characteristics. For meaningful comparisons and monitoring, it is thus important to define specific methodological criteria to estimate the abundances, distribution and composition of microplastics.²⁵ Future monitoring programs will benefit from standardized procedures for sampling and sorting of microplastics such as those proposed by the Marine Strategy Framework Directive of the EU.²⁶

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The main objective of the present review is to assess the different methods that have been employed for the identification and quantification of microplastics in marine environments. Based on the results, we recommend basic criteria and approaches to ensure that future quantitative estimates are comparable, providing standardized data of microplastics in the marine environment.

REVIEW OF METHODS

We conducted an extensive literature review using databases such as ISI Web of Knowledge, Science Direct, Google Scholar, and all published volumes of the journals *Marine Pollution Bulletin* and *Environmental Science & Technology*, for studies published up to December 2011. The term 'microplastics' was first used in 2004 to describe very small fragments of plastic (~50 μm) in the water column and in sediments.²¹ In 2009, Arthur et al. proposed that microplastics should include all fragments <5 mm.⁹ However, at present there is no universally adopted definition in terms of the size range for microplastics. In this review we take a broad, methodologically focused perspective dating back prior to 2004 and aim to include all studies describing small fragments of plastics in the environment, irrespective of whether the term 'microplastics' was specifically used. Keywords used in our searches were as follows: microplastics, microdebris, microlitter, plastic fragments, pellets, marine debris and plastics. We also examined the reference lists from the selected literature and back-tracked to other relevant papers until no new references came up.

A total of 68 research articles were found. From these we extracted information on (i) study objectives, (ii) sampling procedure, (iii) laboratory processing of samples, (iv) identification of microplastics, and (v) microplastics abundance. For the evaluation, we distinguished the main marine environments that were studied: sediment, water column, and sea surface.

OBJECTIVES OF STUDIES ON MARINE MICROPLASTICS

Small particles of plastic were first reported in the marine environment in the early 1970s.^{20,27} The objectives of subsequent studies were variable, with a majority of studies that examined the spatial distribution (abundance, mass, type, and/or size) of microplastics^{28–31} (Table 1). The objectives of

Table 1. Principal Objectives of the Examined Studies on Microplastics^a

objectives	<i>n</i> = 44 sediment	<i>n</i> = 30 sea surface	<i>n</i> = 7 water column	<i>n</i> = 68 total
methodology	2	2	-	3
presence/absence	4	2	1	5
spatial distribution	25	22	5	45
temporal variability	3	6	1	9
dispersal processes	1	-	-	1
physical properties and fragmentation processes	4	2	-	6
contaminants	12	3	1	13

^aNote that some studies have several objectives and thus the sum may exceed the total number of studies in each column.

other studies were to confirm the presence of microplastics in other locations,^{32,33} compare different sampling and sorting methods,^{34,35} and estimate proportions of microplastics versus macroplastics³⁶ or versus zooplankton.³⁷ A few studies also

examined temporal changes in microplastics abundance,^{21,38,39} dispersal,³⁶ and degradation rates.^{40–42}

Plastic pellets are also increasingly used as passive samplers for POPs^{12,43–46} and metals.¹⁸ Ingestion of microplastics by marine organisms and their physiological and ecological implications have also gained attention recently,^{47–49} but this topic is beyond the scope of this review.

SAMPLING

General Sampling Methods. Sampling of microplastics in the main marine environments (sea surface, water column, sediment) requires different approaches: samples can be selective, bulk, or volume-reduced. Selective sampling in the field consists of direct extraction from the environment of items that are recognizable by the naked eye, usually on the surface of sediments. This method was applied in 24 of the 44 sediment studies, 20 of which focused exclusively on plastic pellets. Sampling for plastic pellets is often selective, because their size range (1–6 mm diameter) makes them easily recognizable in the flotsam deposits of sandy beaches. However, when microplastics are mixed with other debris or have no characteristic shapes (i.e., irregular, rough, angular) there is a great risk of overlooking them,⁵⁰ and particular care needs to be taken when selectively sampling them in the field.

Bulk samples refer to samples where the entire volume of the sample is taken without reducing it during the sampling process (18 sediment studies and one seawater study). Bulk samples are most appropriate when microplastics cannot be easily identified visually because (i) they are covered by sediment particles, (ii) their abundance is small requiring sorting/filtering of large volumes of sediment/water, or (iii) they are too small to be identified with the naked eye.

Volume-reduced samples in both sediment and seawater samples refer to samples where the volume of the bulk sample is usually reduced during sampling, preserving only that portion of the sample that is of interest for further processing. Three sediment studies, 29 sea surface studies and six water column studies applied this method. For sedimentary environments, samples can be sieved directly on the beach or onboard the vessel⁴⁵ while for seawater samples, volume-reduced samples are usually obtained by filtering large volumes of water with nets. Bulk and volume-reduced samples require further processing in the laboratory.

Sediment Samples. Forty-four studies determined the densities of microplastics in sedimentary environments, mostly on sandy beaches. The number of beaches sampled in each study ranged from one^{33,42,43} to 300 beaches in a study from New Zealand.⁵¹ Most studies examined between 5 and 18 beaches (e.g., refs 40 and 52–54).

The specific tidal zone sampled on a beach varied considerably among studies; some covered the entire extent of the beach, from the intertidal to the supralittoral zone (Table 2). Some studies distinguished several littoral zones,²¹ while others pooled samples across different zones.^{40,55} The majority of studies, however, focused on the most recent flotsam deposited at the high tide line. A considerable number of studies (eight of 44 studies) did not explicitly mention the tidal zone where samples were taken.

This lack of uniformity across the reviewed studies shows the need to examine systematically where microplastics tend to accumulate across the beach zone. In a comparison of 10 different sampling methods, the highest amounts of macroplastic were usually found in the upper beach zones.⁵⁶ Pellets also

Table 2. Beach Zones Where Sediment Samples Were Taken^a

beach zones	no.
supralittoral	13
high tide line	28
high intertidal zone	14
mid intertidal zone	13
low intertidal zone	13
sublittoral	3
not specified	8

^aN = 44 studies; note that the sum of sampled zones exceeds the total number of studies, because several studies sampled more than one beach zone.

accumulate near the high tide line, but large quantities are also found in ditches and trenches on the back beach.⁵² In general, microplastics move differently than macroplastics in the sea: the distribution of macroplastics can often be explained by the prevailing currents and wind, while the mechanisms that drive the distribution of microplastics are less well-known and are possibly influenced by particle aggregation or animal activities.³⁶ Comparative studies should be conducted to determine the accumulation dynamics of microplastics along gradients of wave exposure and tidal height. Studies from the subtidal zone revealed that microplastics were more abundant in subtidal sediments than on sandy beaches and in estuarine habitats.^{8,21,57}

Sampling tools were reported in 31 of the 44 reviewed sediment studies. Selective sediment samples for plastic pellets and fragments were taken with tweezers,^{18,46} tablespoons,⁴² or picked up by hand.^{15,52,55} Twenty-eight studies sampled at the high tide line, using different approaches: (i) sampling a linear extension along the strandline with a spoon and/or a trowel (eight studies), (ii) sampling an areal extension using quadrats (13 studies), and (iii) sampling different depth strata using corers (two studies). Five studies did not report the exact sampling procedure. The three studies from the sublittoral zone^{8,21,57} sampled with Ekman and van Veen grabs.

Sampling units were directly related to the sampling instrument used. Studies that sampled a specific areal extension (from 0.0079 to 5 m²) employed quadrats and corers. Other sampling units were weight (from 0.15 to 10 kg) and volume of sediment (from 0.1 to 8 L).

Samples were taken to variable depths below the sediment surface. Twenty-seven studies did not mention the sampled depth. Reported sampling depths ranged from 0 to 32 cm (Table 3). Most studies sampled a single depth layer within the

Table 3. Depth Strata Sampled for Microplastic Abundance from Sediments^a

depths of samples	no.
0–5	16
5–10	4
10–20	6
>20	4
not described	27

^aN = 44 studies; note that the sum of sampled depth layers exceeds the total number of studies, because some studies sampled more than one layer.

top 5 cm of sediment.^{42,58,59} Two studies sampled a second layer at 10 cm depth, in addition to the sediment surface.^{32,40}

Two studies followed a stratified sampling scheme using a corer down to a depth of 25 cm, separating the core into five layers each of which had a thickness of 5 cm,⁶⁰ and to a depth of 28 and 32 cm, with four sediment layers of 7 and 8 cm, respectively.⁵⁷

Given that beaches and subtidal coastal habitats are dynamic systems with continuous and seasonal erosion of sediment^{61,62} microplastics may become buried in sediment during periods of accretion. Furthermore, beaches filter and retain particulate organic matter (POM) over a range of depths, and sediments between 0 and 5 cm depth are characterized by steep gradients and strong seasonal variation of more fine-grained particles and POM.⁶¹ In permeable sands, microplastics might accumulate in similar ways as sediment particles and POM, resulting in microplastics being trapped in deeper sediment layers;^{63,64} this should be examined with stratified samples using cores.^{59,60}

Sea Surface and Water Column Samples. Thirty-three studies investigated the abundance of pelagic microplastics (sea surface and water column). Twenty-six of these studies sampled exclusively at the sea surface. The depth of the surface layer sampled was not specified in most cases, with the exception of three studies that sampled neuston layers of 50–60 μ m (surface microlayer), 15 cm, and 25 cm thickness.^{32,65,66} Water column samples were taken from 1 to 212 m depth.^{32,65}

Sea surface samples were mostly taken by neuston nets (Table 4). The main advantage of using a net is that large

Table 4. Instruments Used for Sampling of Suspended Microplastics^a

instrument	sea surface	water column
bongo/zooplankton net	-	5
other plankton samplers	-	3
neuston net	28	-
other neuston samplers	1	-

^aN = 33 studies; note that the sum of studies using each instrument exceeds the total number of studies, because several studies took water column and sea surface samples.

volumes of water can be sampled quickly, only retaining the volume-reduced sample. There was only one study that collected bulk samples of 10 L using a rotating drum sampler.³² This sampler consists of a partly immersed rotating glass cylinder with a clean hydrophilic surface, using capillary force to sample water from the surface microlayer (1 to 1000 μ m thick).^{67–69} For water column samples, zooplankton nets were used most commonly (Table 4). Other instruments, such as the continuous plankton recorder (CPR)²¹ and an epibenthic sled,⁷⁰ were also used.

The most relevant characteristics of the sampling nets used are the mesh size and the opening area of the net. Mesh sizes ranged from 0.053 to 3 mm, with a majority of the studies (42%) ranging from 0.30 to 0.39 mm (Table 5). The net aperture for rectangular openings of neuston nets (sea surface) ranged from 0.03 to 2.0 m².^{31,37} For circular-bongo nets (water column) the net aperture ranged from 0.79 to 1.58 m².^{20,65} The length of the net for sea surface samples was mentioned in 14 studies, varying from 1.0 to 8.5 m, with most nets being 3.0 to 4.5 m long. The length of the net for water column samples was only specified in one study that used two different sampling devices: 3 m long bongo nets and an epibenthic sled with a net that was 1 m long.⁷⁰

Table 5. Different Mesh Sizes Used for Sampling of Suspended Microplastics^a

mesh size (μm)	sea surface	water column
50–290	2	2
300–390	13	2
400–505	5	1
600–1000	6	-
1500–3000	3	-
not specified	6	2

^aN = 33 studies; note that the sum of cases exceeds the total number of studies, because several studies took both water column and sea surface samples.

SAMPLE PROCESSING

Laboratory processing and subsequent sorting of microplastics is essential for bulk and volume-reduced samples. Four main steps can be distinguished during laboratory processing of samples: density separation, filtration, sieving, and visual sorting (Figure 1).

Density Separation. The specific density of plastic particles can vary considerably depending on the type of polymer and the manufacturing process. Density values for plastics range from 0.8 to 1.4 g cm⁻³, specifically for polypropylene from 0.85 to 0.94 g cm⁻³, polyethylene from 0.92 to 0.97 g cm⁻³, and for polystyrene from <0.05 to 1.00 g cm⁻³⁷¹ (for specific densities of plastic polymers see Table 7). These values refer to virgin resins, without taking into account the effect on density of various additives that might be added during product manufacturing. Typical densities for sand or other sediments are 2.65 g cm⁻³. This difference is exploited to separate the lighter plastic particles from the heavier sediment grains by mixing a sediment sample with a saturated solution and shaking it for a certain amount of time. After mixing,

the sediment is expected to rapidly settle to the bottom, while the low density particles remain in suspension or float to the surface of the solution. Subsequently, the supernatant with the plastic particles is extracted for further processing.

Ten of the 13 sediment studies that included density separation (Figure 1a–c,e) applied a concentrated saline NaCl solution (1.2 g cm⁻³). Other solutions applied were a sodium polytungstate solution with a density of 1.4 g cm⁻³,⁴⁰ tapwater,⁵⁰ and seawater.⁷² Plastics that float in fresh and seawater are polystyrene in foamed form, high and low density polyethylene, and polypropylene. Polystyrene in solid form also floats in a hypersaturated saline solution. Finally, the plastics that float in sodium polytungstate solution include flexible and rigid polyvinyl chloride (PVCs), polyethylene terephthalate (PETs), and nylon.^{1,50} A similar density separation procedure was used in two seawater studies, placing the sample in freshwater and removing floating particles from the supernatant.^{70,73}

Shaking time varied widely between studies, according to the size of the sediment sample: it ranged from 30 s²¹ up to 2 h.⁷⁴ The time used for the suspended particles to settle down after shaking ranged from 2 min^{21,36} up to 6 h.³² Recent studies explicitly mentioned a repetition of density separation of the sample remains.^{8,59} Unpublished work had shown that additional microplastic fragments can be recovered after an initial extraction (R. C. Thompson, personal communication). As a consequence three studies have since used several sequential extraction steps as being an efficient approach to maximize recovery in relation to sampling time.^{8,57,59}

Filtration. The plastic particles are separated from the supernatant obtained from the density separation by passing the solution that contains the plastic particles over a filter, usually aided by a vacuum.^{21,32} Filter papers had pore sizes of 1 to 1.6 μm (six studies) and 2 μm (one study).⁶⁶ In the study

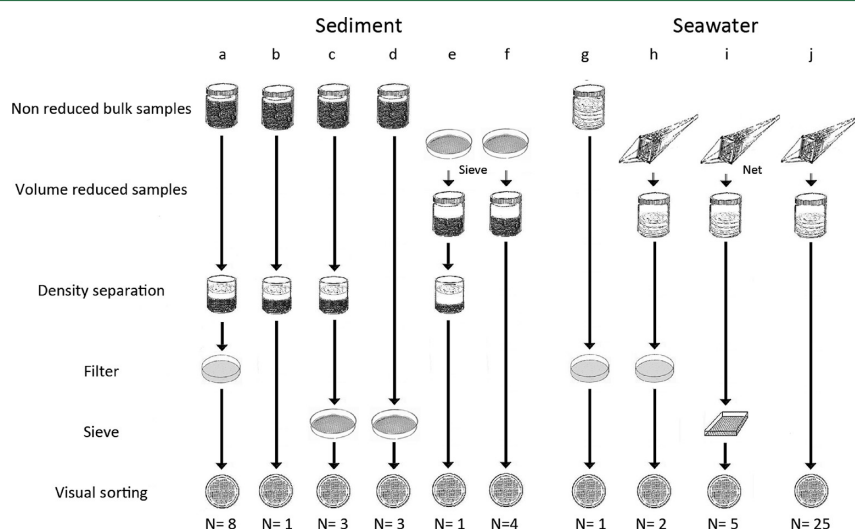


Figure 1. Steps for sample processing. (a) Bulk sediment sample separated by density difference and filtering; (b) Bulk sediment sample separated by density difference, where floating microplastics are picked up from the supernatant; (c) Bulk sediment sample separated by density difference and sieving; (d) Bulk sediment sample that is reduced by sieving; (e) Volume-reduced sediment sample separated by density difference, where floating microplastics are picked up from the supernatant; (f) Volume-reduced sediment samples where floating microplastics are picked up from the supernatant; (g) Bulk seawater sample passed through filter for microplastics separation; (h) Volume-reduced seawater sample passed through the filtration step; (i) Volume-reduced seawater sample passed through sieves; (j) Volume-reduced seawater sample passed straight through visual sorting. All methodologies included a final step of visual separation of microplastics; in some cases the identity of the pieces extracted was then confirmed by an additional step such as FT-IR spectroscopy ($n = 28$, see Figure 5B). N = 43 studies that employed the respective sequence of processing steps.

Table 6. Categories Used To Describe Microplastics

categories	
sources	consumer product fragments (e.g., fishing net) and raw industrial pellets
type	plastic fragments, pellets, filaments, plastic films, foamed plastic, granules, and styrofoam
shape	<i>for pellets:</i> cylindrical, disks, flat, ovoid, spheruloids <i>for fragments:</i> rounded, subrounded, subangular, angular <i>general:</i> irregular, elongated, degraded, rough, and broken edges
erosion	fresh, unweathered, incipient alteration, and level of crazing (conchoidal fractures), weathered, grooves, irregular surface, jagged fragments, linear fractures, subparallel ridges, and very degraded
color	transparent, crystalline, white, clear-white-cream, red, orange, blue, opaque, black, gray, brown, green, pink, tan, yellow, and pigmentation

Table 7. Number of Studies That Identified Polymer Type among the Sorted Microplastic Debris and Specific Densities of Different Polymer Types^a

polymer type	polymer density (g cm ⁻³)	no. of studies
polyethylene	0.917–0.965	33
polypropylene	0.9–0.91	27
polystyrene	1.04–1.1	17
polyamide (nylon)	1.02–1.05	7
polyester	1.24–2.3	4
acrylic	1.09–1.20	4
polyoximethylene	1.41–1.61	4
polyvinyl alcohol	1.19–1.31	3
polyvinylchloride	1.16–1.58	2
poly methylacrylate	1.17–1.20	2
polyethylene terephthalate	1.37–1.45	1
alkyd	1.24–2.10	1
polyurethane	1.2	1

^aData from a total of $N = 42$ studies.

where density separation was done with freshwater, the microplastics were picked up by tweezers from the surface of the aqueous supernatant.⁵⁰ In order to sort out larger particles before the filtration step, water samples can first be sieved over a sieve with 500 μm mesh size.¹

None of the reviewed studies specified in detail how the supernatant was extracted. Some fraction of the microplastics might stick to the wall of the receptacle that contains the solution, losing part of the sample during the procedure. Thus washing of the container walls onto the filter is recommended. Furthermore, samples can also become contaminated by particles present in the air of the laboratory, on the clothes of workers, in poorly cleaned instruments, by improperly sealed samples, by plaques of color scratched off the ship wall by the sampling gear, or by fibers broken off the plastic nets that are used for seawater sampling. For accurate results it is necessary to minimize sources of contamination, and avoid both loss of parts from the sample or overestimation of microplastics due to contamination. Control samples should always be used to confirm that there is no procedural sample contamination.⁶⁶ Several contamination prevention strategies (e.g., sealing of filters in Petri dishes during drying) have been specified.^{21,32,74} Some laboratories use the procedures described above (R. C. Thompson, personal communication), but it is recommended to standardize those and also run cross-calibrations among laboratories.

Sieving. Microplastics can be separated from samples using sieves of variable mesh sizes. Materials retained in the sieve are collected (and sorted), while those that pass through are usually discarded. The use of sieves with different mesh sizes allows distinguishing size categories of microplastics. Sieving was used by six sediment (Figure 1c–d) and five sea surface studies (Figure 1i). The sediment studies employed either one sieve^{57,72,75,76} or sieve cascades of two³³ and three sieves.²⁹ Sea surface studies used one,⁷⁷ five,^{37,78} and six sieves.^{70,79} The sieves had mesh sizes ranging from 0.038 to 4.75 mm. All studies included a sieve of 1 mm, except for the studies that used only one sieve with mesh sizes ranging from 0.038 mm,⁵⁷ to 0.33 mm^{72,77} and 2 mm,^{53,76} respectively.

Visual Sorting and Separation. In all reviewed studies, visual examination of the concentrated sample remains is an obligatory step. Careful visual sorting of residues is necessary to separate the plastics from other materials, such as organic debris (shell fragments, animals parts, dried algae, or seagrasses, etc.) and other items (metal paint coatings, tar, glass, etc.). This is done by direct examination of the sample by the naked eye or with the aid of a dissecting microscope.^{12,65,78–80} Most sea surface studies separated microplastics by visual sorting of the particles (Figure 1j) that were retained in the cod end of the net.^{28,30,81,82} The silk screen from the CPR is examined under the dissecting microscope for plastic particles.²¹

Previously isolated plastic fragments can also be washed for removing other substances that adhere to their surface (like sand and soil);²⁹ e.g. by ultrasonic cleaning in a liquid medium or deionized water.⁴² Samples can be preserved in their original form without initial sorting, or they can be immediately sorted to store only the plastics from the original sample. Plastics separated from the sample should be dried and kept in a dark and temperature-controlled environment (stable room temperature) to reduce degradation during storage.

To avoid misidentification and underestimation of microplastics it is necessary to standardize the plastic particle selection, following certain criteria to guarantee proper identification. This is particularly important when it is not possible to use more accurate methods, such as Fourier transform infrared spectroscopy (FT-IR). Pieces of microplastics toward the larger end of the size range (>1 mm) can to some extent be visually distinguished according to the following criteria: no cellular or organic structures are visible, fibers should be equally thick throughout their entire length, particles must present clear and homogeneous colors, and if they are transparent or white, they must be examined under high magnification and a fluorescence microscope.⁶⁶ New methods to separate microplastics from bulk samples or from samples with large amounts of organic debris need to be developed to improve the efficiency of sampling programs. Molecular mapping made by focal plane array (FPA)-based imaging has recently been examined to detect microplastics by scanning the surface of filters obtained from density separation and filtration of samples.⁸³ Enzymatic digestion of organic debris and other approaches could also be explored to facilitate the visual sorting of microplastics from large sample volumes. Electrostatic separation of plastics from sediments was extensively examined by one of us (R. C. Thompson, unpublished data), and while this proved efficient in separating known plastics spiked into specific sediments, it was not advantageous in the separation of mixtures of polymers from more diverse natural sediments and organic matter.

■ CHARACTERIZATION OF MICROPLASTICS

Due to the diversity of sources, there exists a wide variety of microplastics with multiple shapes, sizes, and origins (Table 6). The characteristics of microplastics determine their distribution and impact in the environment. For instance, dense plastic particles spend more time in contact and collide more forcefully with abrasive sediment particles than lighter microplastics do.³⁶ These differences are important because they can affect degradation rates, surface characteristics, and shapes of microplastic particles.

Size Fractions. The term “microplastics” was first used in the year 2004 and is associated with a classification based on size.²¹ There is no general consensus about a specific size nomenclature, although it has been suggested that microplastics should be defined as particles <5 mm.⁹ The studies reviewed here identified a wider range of sizes. Although not all studies referred exclusively to ‘microplastics’, they nonetheless classified micro- and small plastics, generally items <20 mm.

The minimum size of the collected microplastics directly depends on the sampling and processing methods. For sediment samples that were sieved, the minimum sizes of

collected microplastics ranged from 0.5 to 2 mm.^{33,84} Similarly, the minimum size of microplastics collected from seawater samples is determined by the mesh size of the net. Mesh sizes varied from 53 μm to 3 mm for seawater samples (Table 5). During sample processing, the sizes of microplastics obtained from bulk seawater and sediment samples are limited by the pore size of the filters (1.6 to 2 μm).^{21,66}

The size ranges of the collected microplastics varied widely among the reviewed studies. Forty-seven studies reported values for minimum and maximum sizes of microplastics; 16 of these studies were related to pellets. Plastic preproduction pellets have a reference diameter of 1 to 5 mm¹⁵ with a typical diameter of 3.5 mm.³⁸ The values obtained by the reviewed studies were close to these reference values, with a range of 1 to 6 mm. Fifteen sediment studies reported the size range for plastic fragments, with size ranges of 1 μm to 20 mm (Figure 2a).

The size ranges of microplastics in sea surface samples were reported in 17 studies (Figure 2b). The widest size range from sea surface studies was from 0.5 to 29 mm.³⁸ Eight studies were consistent with upper size recommendations in Arthur et al. (2009)⁹ and classified the plastic particles with a maximum

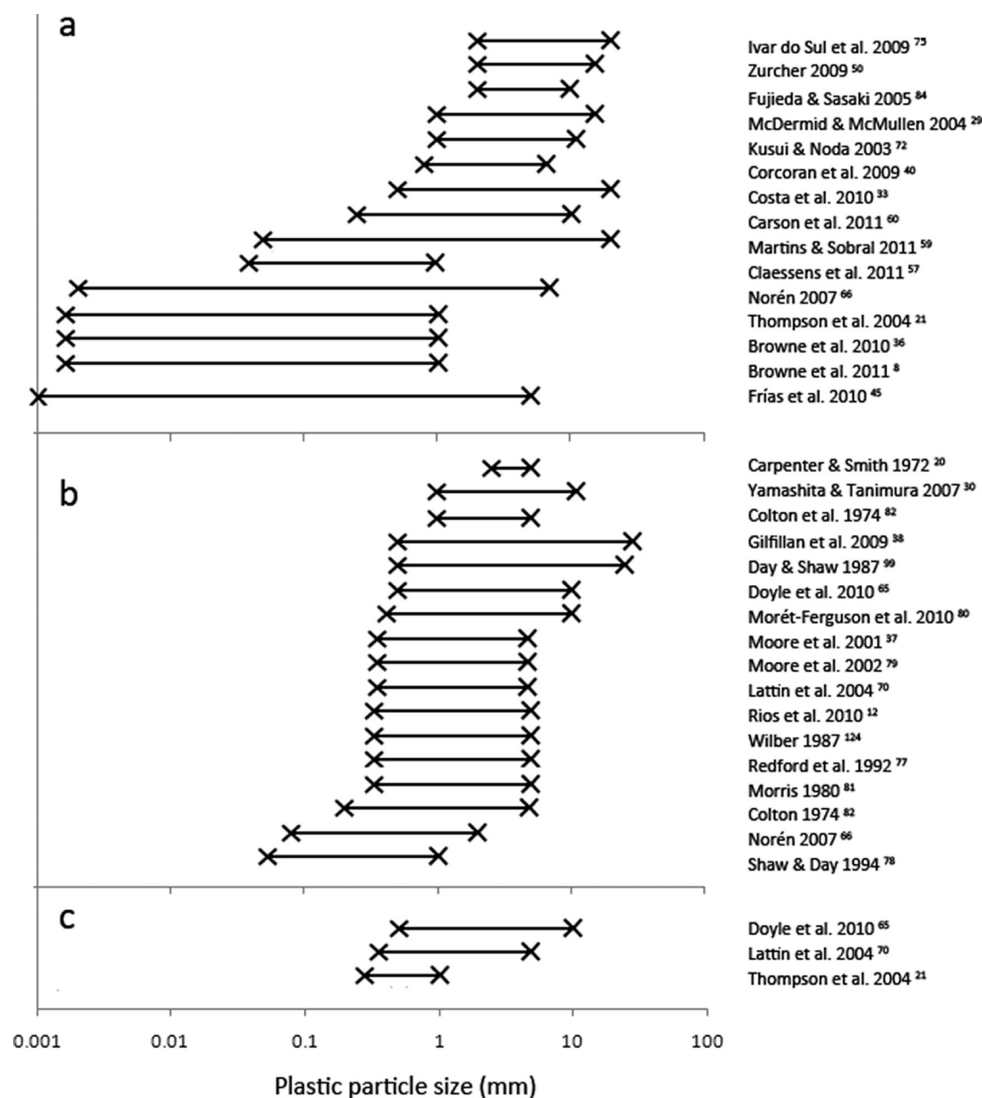


Figure 2. Size ranges for microplastics from (a) sediment, (b) sea surface, and (c) water column studies. Only those studies that provided the lower and upper size limits of microplastics are shown (excluding studies of plastic pellets because here size limits are dictated by pellet sizes).

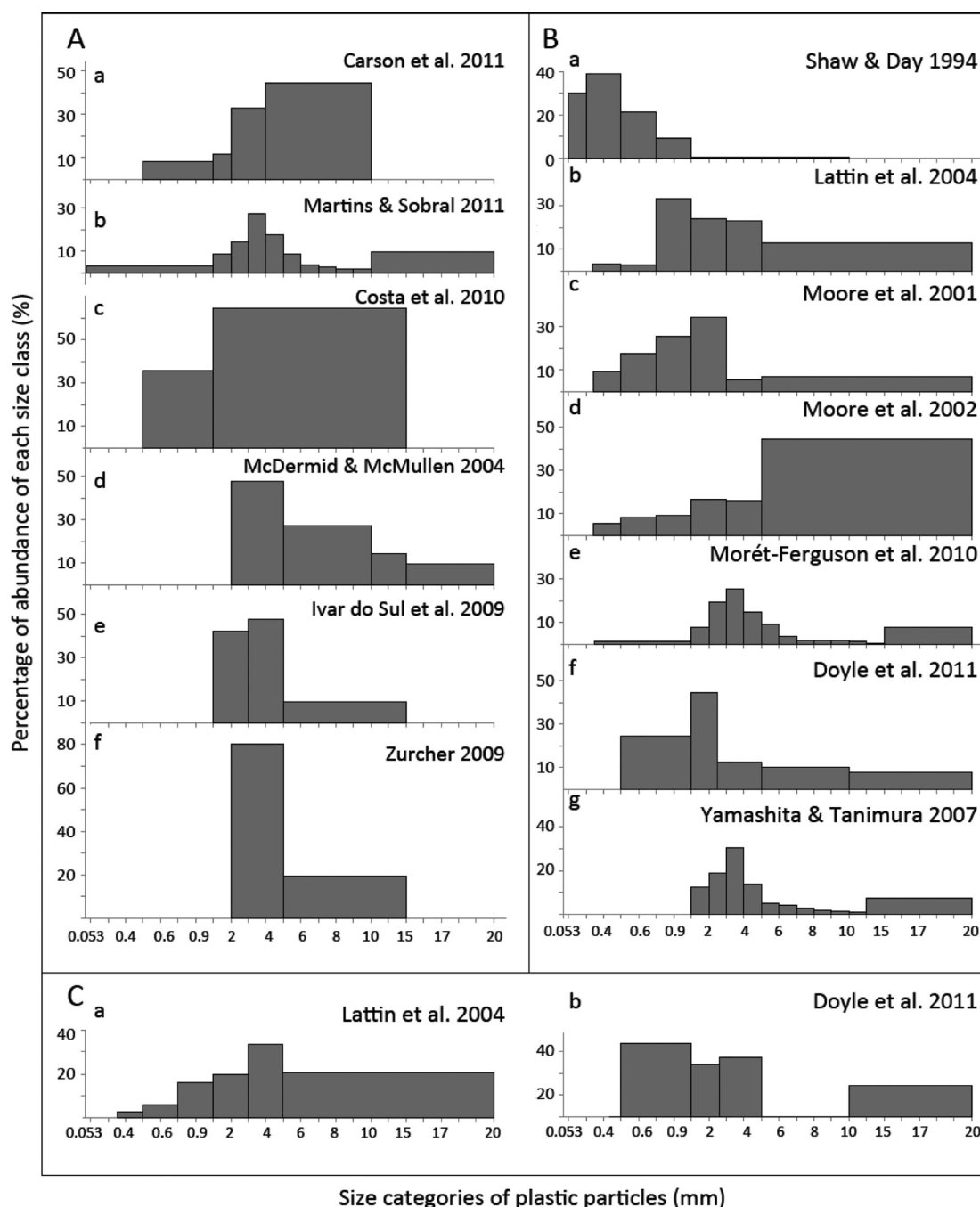


Figure 3. Distribution of plastic particles among size categories. (A) Sediment studies: (a) ref 60, (b) ref 59, (c) ref 33, (d) ref 29, (e) ref 75, (f) ref 50. (B) Sea surface studies: (a) ref 78, (b) ref 70 (c), ref 37, (d) ref 79, (e) ref 80, (f) ref 65, (g) ref 30. (C) Water column studies: (a) ref 70, (b) ref 65.

value of 5 mm and a minimum value according to the mesh size of the nets (ranging from 0.335 to 5 mm).⁷⁹

Three of the seven water column studies presented size range values. The maximum value reported was 10 mm⁶⁵ (Figure 2c). The minimum value for microplastics in water samples (sea surface and water column) was 1.6 μm ⁴ although this study did not mention the maximum value of the collected plastic fragments.

Some of the reviewed studies also distinguished different size classes of microplastics (Figure 3). Size categories were given in six sediment studies (Figure 3A), mostly in those that used

sieve cascades during sample processing. The largest proportion of plastic fragments was obtained in the size classes of 1 to 5 mm.^{29,33,75} One study that used an “*in situ*” sieving step (1 mm) and density separation (Figure 1e) also presented size categories. Here, plastic pellets represented 58.3% of all microplastics.⁵⁰

Seven sea surface studies reported size categories (Figure 3B). Studies with a sieving step retained smaller particles than studies that only used visual sorting. Most plastic items identified in these studies were between 0.25 to 5 mm in diameter,^{30,37,65,70,78} but many were also >4.8 mm.⁷⁹ Only two water column studies

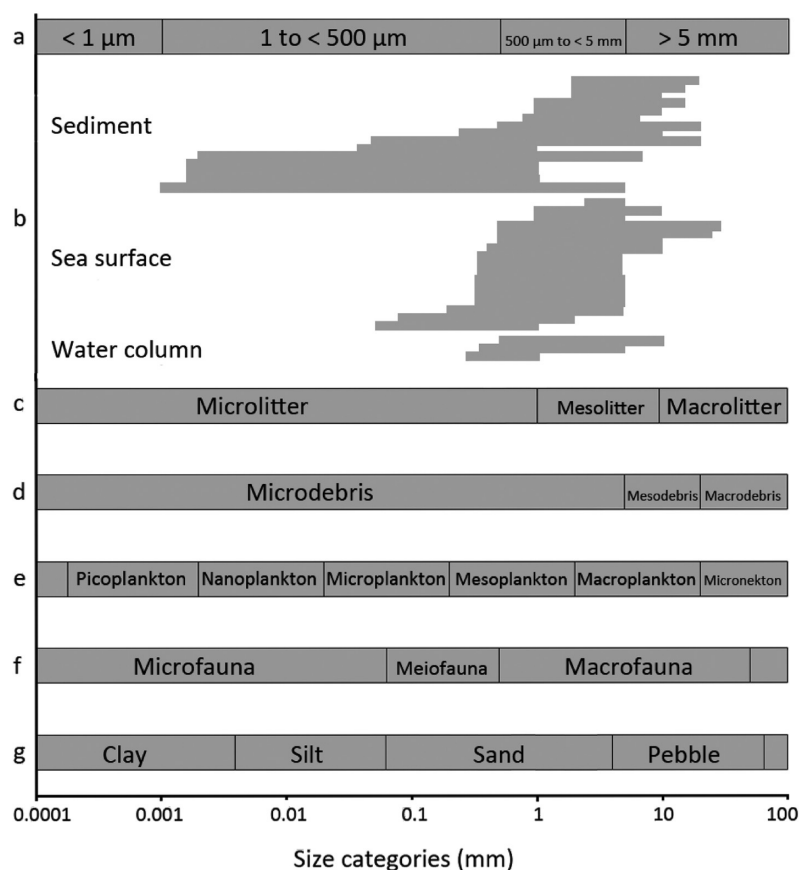


Figure 4. Categories of particle sizes. (a) Suggested methods-oriented categories of microplastics based on this review: 1 to <500 and 500 μm to 5 mm, (b) size range of microplastics given by the reviewed studies (based on Figure 2), (c) litter,¹²⁰ (d) debris,⁵ (e) plankton,^{121,122} (f) benthos,¹²³ (g) geology.⁸⁵

distinguished size classes (Figure 3C), based on sieving and visual sorting. Most microplastics were found in the size classes 0.5 to 1 mm⁶⁵ and 2.8 to 4.75 mm.⁷⁰

No minimum size has been defined for microplastics. The smallest reported size was 1 μm diameter and 20 μm length in sediment samples.⁴⁵ Most studies presented values above 500 μm for sediment samples and 300 μm for seawater samples. This differentiation depended directly on two main factors: the tools used during sampling and the processing steps. Particles >500 μm are retained in standard sieves and can then be sorted using a dissecting microscope. Particles <500 μm were usually only obtained by studies with density separation and filtration, and particles <2 μm are unlikely to be sampled representatively.³⁶

Microplastics occur in size ranges that are similar to many organisms from benthos and plankton communities. The same applies to geological sediment categories, which are mobilized in similar ways as microplastics. Size ranges of microplastics can be related to the geological categories of silt and sand,⁸⁵ micro-, meio-, and macrofauna for benthos, and micro- and macroplankton (Figure 4). Due to these overlaps, microplastics are frequently obtained in studies targeting specific benthos or plankton size categories.^{37,79} The strong overlap between important size categories of benthic and planktonic organisms also highlights the potential for microplastic ingestion by a wide variety of organisms.

Based on the preceding comparison and on presently employed methods to quantify microplastics in the environment, it may be useful methodologically to distinguish two

main size categories of microplastics: (i) < 500 μm (with the lower size limit, which should be stated, being restricted by technological constraints of identification equipment), and (ii) 500 μm to 5 mm (Figure 4a). In the future, samples could be sieved over a 500 μm mesh, and the fraction passing through the sieve should then be analyzed by density separation and filtering. This would ensure that those studies that use the density separation and filtration technique to quantify the smaller size fractions of microplastics (<500 μm) can also be compared with other studies that only employ sieves to quantify the large fraction of microplastics (500 μm to 5 mm). Beyond those fractions it is very likely that there are even smaller fragments that are in the range of nanoparticles. Identifying and quantifying those nanoplastics will require new and innovative methods.¹

Morphology and Physical Characterization of Microplastics. The number of categories used to classify microplastics depends on the criteria of the respective authors, which can vary widely. Fifty-four of the 68 reviewed studies offered morphological descriptions of microplastics, referring to origin, type, shape, color, and/or degradation stage of the particles (Table 6). Eighteen of these studies corresponded exclusively to studies on plastic pellets. The variation in sizes, shapes, and colors of microplastics is of particular concern since they could easily be mistaken for food by marine organisms and seabirds.^{21,22,86}

Sources and Types of Microplastics. Sources of plastic pellets were mainly associated to plastic-processing plants close to study sites.^{76,87} However, plastic pellets have also been found on urban beaches distant from potential sources, implying

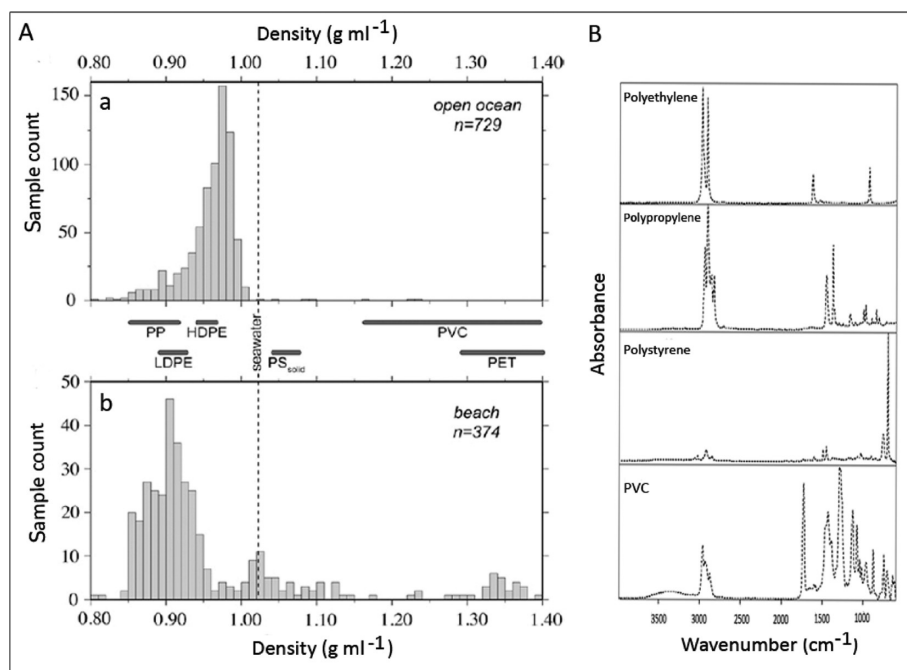


Figure 5. (A) Frequency of microplastics of different specific densities found (a) at the sea surface and (b) in beach sediments. Broken vertical line indicates the specific density of seawater and bold horizontal lines show the specific densities of particular polymers (based on ref 80); PP: Polypropylene, HDPE: High density polyethylene, LDPE: Low density polyethylene, PS: Polystyrene, PVC: Polyvinyl chloride, PET: Polyethylene terephthalate. Reprinted from Morét-Ferguson et al. The size, mass, and composition of plastic debris in the western North Atlantic Ocean. *Mar. Pollut. Bull.* **2010**, 60, 1873–1878 (ref 80), with permission from Elsevier. (B) Fourier transform infrared spectroscopy (FT-IR) spectra of some common plastic polymers. Spectra obtained from Bruker Optics ATR-Polymer Library, A Collection of Synthetic Fibres, Copyright 2004 Bruker Optic GmbH.

long-distance marine transport.³³ Some properties of plastic pellets may change during residence at sea. For example, the specific density of pellets decreased during prolonged exposure to the marine environment, from 0.85 to 0.81 g cm⁻³ for high density polyethylene (HDPE) and from 1.41 to 1.24 g cm⁻³ for polystyrene (PS).⁸⁰ Buoyancy and density of plastics may change during their residence at sea due to weathering and bio-fouling.^{80,88} This can be seen in the fact that the specific densities of many pelagic microplastics do not coincide with that of primary polymers (Figure 5). In the open ocean microplastics with high specific density (negative buoyancy) will quickly sink and are thus absent from neuston samples (Figure 5).

Fragments from plastic consumer products were of variable types and diverse origins. These particles have been described as “embrittled and weathered, irregularly shaped and sized degradational chunks of plastic”,⁵¹ with sharp, broken edges.⁷⁸ The origin of these fragments can be fishing nets, line fibers (polypropylene strands), thin plastic films, industrial raw material (e.g., from ship breaking industry), pellets or polymer fragments of oxo-biodegradable plastic.^{65,70,74,89} Other particular sources of microplastics are facial cleansers⁷ and small polyethylene microplastics or polyester fibers of low density which escape from treatment screens at wastewater plants and eventually arrive in the ocean.⁸

Shape and Erosion of Microplastics. Microplastics vary in shape from irregular to spherical and long-thin fibers. Plastic pellets can have tablet-like, oblong, cylindrical, spherical, and disk shapes, mostly spherical to ovoid with rounded ends.⁵² Most fragments found in subtidal and estuarine sediments were fibers.^{8,21,36} The shape of plastic fragments depends on the fragmentation process as well as residence time in the environment. Sharp edges might indicate either recent introduction into the

sea or the recent break-up of larger pieces, while smooth edges are often associated with older fragments that have been continuously polished by other particles or sediment.^{27,65} Circularity varied inversely with particle size. Larger particles had more elongate shapes and/or irregular surfaces, while progressively smaller particles were consistently more circular.³⁸ Likely, particles continue to fragment and degrade to ever smaller particles over time.^{1,65}

Degradation and erosion of the particle surface are caused by biological breakdown, photodegradation, chemical weathering, or physical forces (wave action, wind, sand-blasting).¹ This can cause visible cracks on the plastic surface, producing a wide variety of different particle shapes.⁷⁸ Scanning electron microscopy revealed that angular and subangular particles featured conchoidal fractures, while rounded particles had linear fractures and adhering particles.⁴⁰ Numerous surface scratches on predominantly eroded angular plastic fragments (<1 cm²) may be caused by continuous particle–particle collision.⁴² Pellets that presented a degree of weathering have been termed eroded or weathered plastic pellets.^{76,90,91} Many of the plastic pellets found in a study on New Zealand beaches were fresh but some showed degradation and embrittlement.⁵¹ Surface abrasion is also caused by physical degradation and oxidative aging of plastic particles in response to ultraviolet and infrared components from solar radiation.^{1,73} Plastic fragments found in scats of fur seals *Arctocephalus* spp. also had clear abrasion marks, presumably generated either in the digestive tract of the seals or during physical breakdown on nearby cobble beaches.⁹²

The surface texture of microplastics may affect the concentrations of sorbed chemicals. Pollutant sorption to plastic pellets increases with the surface area as a result of weathering,

Table 8. Various Quantitative Units Used in the Reviewed Studies^a

results units	N = 22 sediment	N = 21 sea surface	N = 5 water column
Abundance (N = 39)			
items per m ²	13	13	-
items per m ³	5	6	5
items per m strandline	3	-	-
items per kg sediment	1	-	-
Mass (N = 13)			
grams per m ²	2	6	-
grams per m ³	-	2	1
grams per gram sediment	3	-	-

^aN = 43 studies; note that the number of studies with the respective units exceeds the total number of studies.

which enhances the sorbate's effective diffusivity.¹⁵ Although plastics undergo various physical and chemical changes as they age, no method exists at present that allows for determining how long the particles have been in the marine environment (unless they have characteristics that can be traced to a specific point source such as a ship or container wreck). However, this information would be invaluable to estimate drift trajectories of floating microplastics and, thus, potential source regions.

Color of Microplastics. The colors of microplastics were characterized in 24 of the 68 reviewed studies, revealing a diverse range of colors (Table 6). The most common colors found were white or related (e.g., discolored yellow, clear-white-cream). Color can facilitate separation in situations where microplastics are scattered among large quantities of other debris. Particles with eye-catching colors have a high probability of being isolated for subsequent identification as microplastics, while those with dull colors are easily overlooked, thus potentially introducing bias.

Colors have been used for a preliminary identification of the chemical composition of the most common pellets.⁵² Clear and transparent plastic pellets have been ascribed to polypropylene (PP), and white plastic pellets to polyethylene (PE),⁵⁸ but for conclusive identification further analyses are required (see below). Low density PE has opaque colors, while ethyl vinyl acetate corresponds to clear and almost transparent pellets.⁹³ Color has also been used as an index of photodegradation and residence time at the sea surface^{17,94} and the degree of tarring or weathering.⁵⁵ It has been suggested that discolored PE pellets may contain higher amounts of PCBs than non-discolored pellets, because the discoloration process (yellowing) is indicative of longer exposure time to seawater, which enhances the chances of the polymers becoming oxidized.⁴³ Black and aged pellets, essentially those composed of polystyrene (PS) and PP, presented the highest diversity of adsorbed pollutants for both PAHs and PCBs.⁴⁵

Identifying the Chemical Composition of Microplastics. Plastics are synthetic polymers made from a wide range of chemical compounds with different characteristics each. Forty-two of the reviewed studies described the chemical composition of microplastics, although not all of them conducted rigorous chemical analyses. The most common polymers identified in the reviewed studies were PE, PP, and polystyrene (Table 7), which is commonly used for packaging.³⁶

Several methods have been employed to identify microplastic polymers. Identification based on infrared (IR) spectroscopy was used in 28 studies. This method compares the IR spectrum

of an unknown plastic sample with spectra of known polymers (Figure 5B). The different types of spectroscopy applied for microplastics identification were infrared spectrophotometer,⁵¹ Fourier transform infrared spectroscopy (FT-IR),^{21,45,74} and near-infrared spectrometer.⁴⁶ A range of common polymers like PP, PE, and polyester can be identified by these techniques.⁸ Another chemical analysis is the Raman spectroscopy²³ which also gives information about the crystalline structure of the polymer.⁹⁵ Also, a differential scanning calorimeter was used in one study,⁹⁶ where temperature is applied simultaneously to an unknown sample and a reference material.

Characteristic smoke during combustion and solvent assays have also been used to determine the polymers that microplastics are made of.^{27,51,73,97} Synthetic polymers can also be identified using the specific density of the particles (see also Figure 5A) and to a lesser extent other characteristics such as color. The density-based identification method has been applied in two studies,^{80,98} in which a sample is placed in distilled water and ethanol or concentrated solutions of calcium or strontium chloride are titrated until the plastic piece is neutrally buoyant.

The use of certain characteristics, such as specific density and color, seem useful methods for rapid and economic polymer identification of plastic pellets, because those characteristics have been described for virgin pellets.^{80,93} Nonetheless, for plastic fragments this method cannot be applied, because their shape (an indicator for recent fragmentation or prolonged persistence and erosion along the edges) and color are more variable and are unlikely associated with a specific polymer type. Microparticles of unknown origin might also be erroneously characterized as microplastics, a problem that increases considerably with decreasing particle size. For that reason, the use of spectroscopy (FT-IR spectroscopy, near-infrared spectroscopy, and Raman spectroscopy) is strongly recommended for small plastic fragments, because it can determine the chemical composition of unknown plastic fragments with high reliability. This step is critical since up to 70% of particles that visually resemble microplastics are not confirmed as plastics by FT-IR spectroscopy (R. C. Thompson, personal communication). Alternative spectroscopic techniques, like attenuated total reflectance (ATR) FT-IR spectroscopy, could also facilitate the identification of irregularly shaped microplastics that cannot be identified by FT-IR spectroscopy,⁸³ but the main disadvantage is the high cost of this instrument.⁹⁵

■ QUANTIFICATION OF MICROPLASTICS

Quantitative data were reported in 60 of the 68 reviewed studies, which (i) examined the spatial and temporal distribution of microplastics, (ii) analyzed methodological aspects, (iii) quantified organic pollutants and metals, and (iv) determined rates of accumulation of microplastics on beaches. Mass and abundance of microplastics was determined in 13 and 39 studies, respectively (Table 8). For sediment samples the most commonly used units for mass were "grams of microplastics per m²" and for abundance "microplastic items per m²" (or items cm⁻²). For sea surface samples, "grams per m²" and "items per m²" were the most commonly used values for mass and abundance, respectively, although a considerable number of studies also reported "items per volume" (items m⁻³). Only one study for water column samples quantified mass values in "milligrams per m³", while abundance was mostly reported as "items per m³". The value of "pieces per day", the plastic

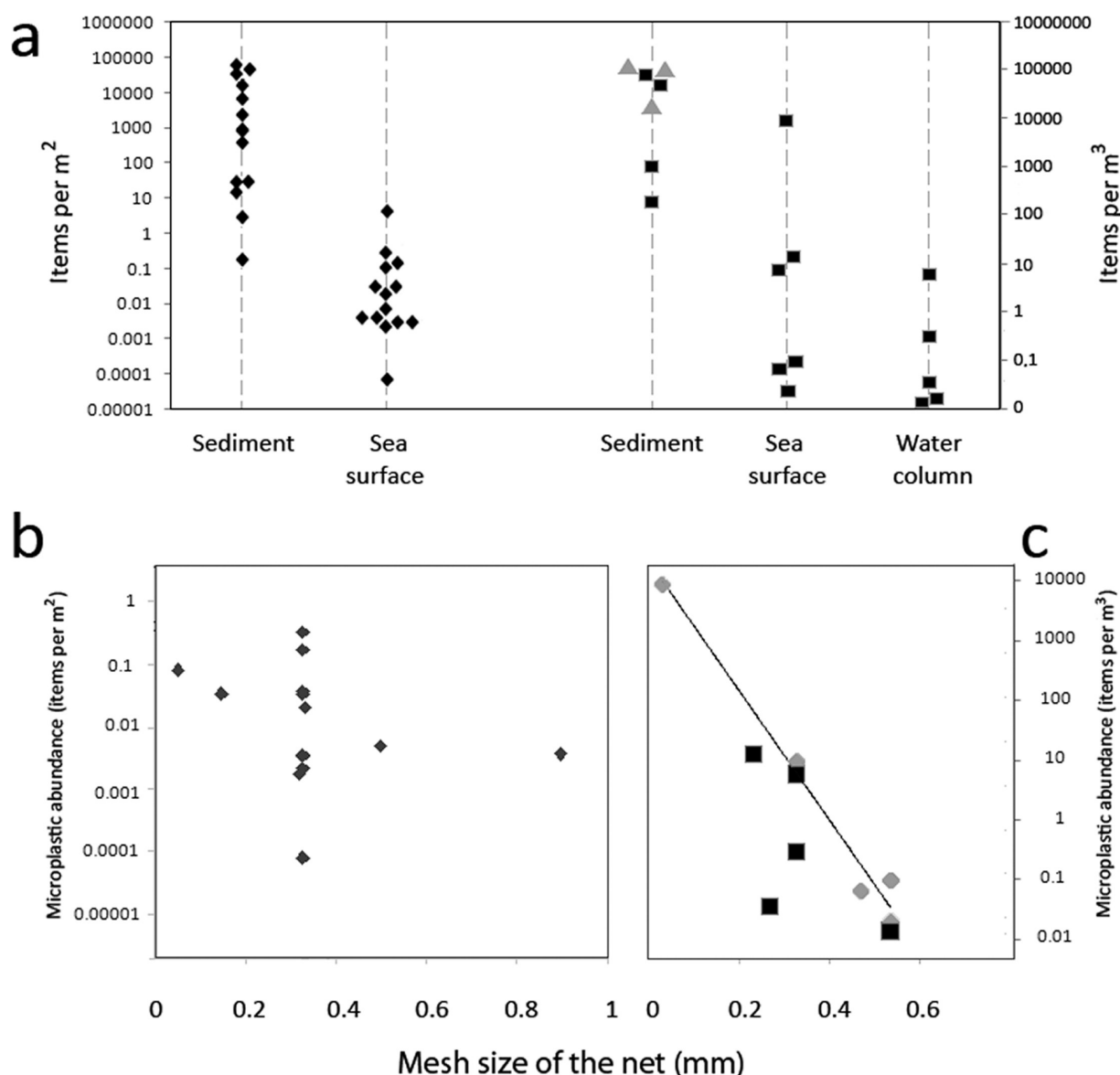


Figure 6. (a) Comparison of microplastic abundance in sediment, sea surface, and water column environments. The units are expressed on a logarithmic scale for items m^{-2} (left axis, diamonds) and items m^{-3} (right axis, squares and triangles). Values for subtidal sediments are highlighted by gray triangles. Note that values were scaled up for sediment samples (areas or volumes of replicates generally comprise 10–100 cm^2 or 10–100 cm^3 , respectively), while values for seawater samples were scaled down (replicates generally sample areas/volumes 10–1000 m^2 or 10–100 m^3 , respectively). Overlapping dots were separated to show all data points. (b) Relationship between the mesh size of the nets and abundance (logarithmic scale) of microplastics in sea surface samples as items per m^2 . (c) Relationship between the mesh size of the nets and abundance (logarithmic scale) of microplastics in sea surface (gray diamonds) and water column (black squares) samples as items per m^3 . Line shows significant relationship ($p < 0.05$) for sea surface samples. Each data point represents one study; if several values were provided for a particular study, we calculated the mean value.

replenishment rate on Hawaiian beaches, was estimated by one study.⁴²

Values for abundances ranged from 0.21 to more than 77,000 items m^{-2} in sediment samples.^{52,72} These values are substantially higher than those from sea surface samples, which ranged from 8×10^{-5} to 5 items m^{-2} ,^{76,99} i.e. there were several orders of magnitude difference between the two environments (Figure 6a). Abundance values per volume ranged from 0.022 to 8,654 items m^{-3} at the sea surface^{38,66} and from 0.014 to 12.51 items m^{-3} in the water column.^{65,81} Also in this case, sediment samples contained substantially higher amounts of microplastics, ranging from 185 to 80,000 items m^{-3} .^{36,59} The three studies that obtained subtidal sediments

reported abundances of ~ 5 synthetic fibers 50 mL^{-1} sediment,²¹ ~ 0.8 synthetic fibers 50 mL^{-1} sediment,⁸ and 97 particles kg^{-1} dry sediment,⁵⁷ which scales up to $\sim 115,000$, $\sim 18,000$, and $\sim 125,000$ items m^{-3} , respectively (Figure 6a).

The fact that seawater samples correspond to volume-reduced samples taken with nets might explain the lower abundances of microplastics in these environments, compared to sediments (Figure 6a). Abundances of microplastics are likely directly related to the mesh size of the net. A possible loss of particles $< 1 \text{ mm}$ passing through a mesh size of 0.95 mm has been suggested to impede the comparison with other studies that used a net with smaller mesh size.⁸⁷ The retention efficiency differs substantially between an 80 μm mesh and a

450 μm mesh, with an up to 100,000 times higher concentration of small plastic fibers in the former.⁶⁶

When comparing among the reviewed studies, there was indeed a tendency of a negative exponential relationship between mesh size and abundance for sea surface samples measured as items per m^3 ($p = 0.024$) but not for sea surface measured as items per m^2 ($p = 0.54$) or water column samples ($p = 0.35$) measured as items per m^3 (Figure 6b,c). The lack of a correlation for some of the examined relationships is probably due to fundamental variations in microplastic abundances between the locations where samples were taken, e.g. the open ocean in the South Atlantic⁹⁸ or coastal waters near Cape Province, South Africa.²⁸ Most likely, abundances of microplastics also depend on distances from sources and human population centers, similar as reported for macroplastics.^{100,101} Furthermore, ocean currents can play an important role in transporting and accumulating microplastics on the shore or in oceanic gyres.^{28,36,102}

The variable units in which abundance and mass of microplastics are reported become problematic when different studies are compared, even though units can be transformed in some cases. The choice of a specific unit to quantify microplastics is a very relevant topic. We suggest the use of convertible units whenever possible. For example, if sediment

samples are taken in a standardized manner in a specific surface area and from a specified depth layer, per-area data (items m^{-2}) can be easily converted to per-volume data (items m^{-3}) and both should be reported.

Also, the classification of microplastics is important for determining abundances and source pathways. Fragments from plastic products were often numerically dominant, followed by plastic pellets^{28,36,37,65,78,80} and styrofoam as the second most abundant material.³⁰ This suggests that at present most microplastics originate from secondary rather than primary sources.^{38,78,80} While plastic pellets were very abundant between the 1970s and 1990s,^{51,73} their proportions seem to have decreased in recent years,²⁵ possibly due to better practices during pellet transport. Reference collections have proven to be of extraordinary importance in order to analyze short- and long-term temporal trends.^{21,38,39}

A solid analysis of long-term trends requires standardized procedures in sampling and sample processing. This review on methods applied in research on microplastics in the marine environment indicates the importance of standardized procedures that will maximize comparability of past and future investigations in pelagic and sedimentary marine environments (Figure 7). All of these procedures include sieving of bulk or

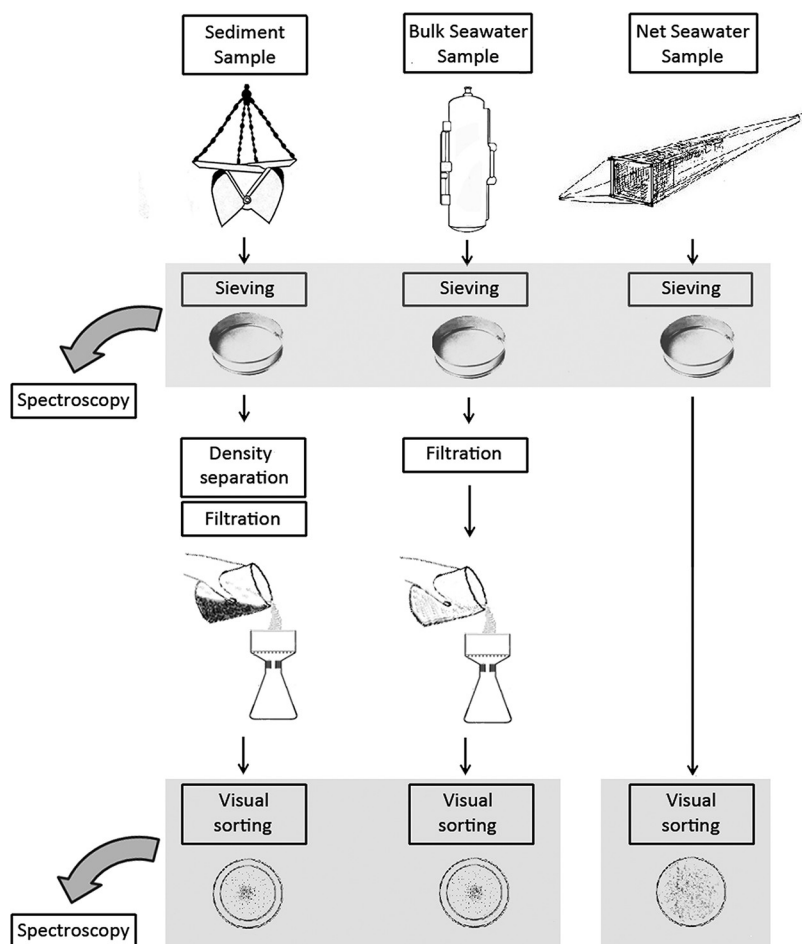


Figure 7. Suggested sampling schemes for different types of samples to achieve maximum comparability among results from past and future sampling programs on marine microplastics. All samples should be sieved over a standard mesh, ideally of 500 μm , or alternatively 1000 μm . The material retained in the sieve should then be identified by Fourier transform infrared spectroscopy (FT-IR). Sieved sediment samples should then be processed by the density separation and followed by the filtration over a fine filter of about 1 μm . Bulk water samples can be filtered directly after sieving. Samples taken with nets (sea surface or water column) should also be sieved over a 500 μm mesh; microplastics can then directly be sorted from the sieve and separately from the sieved water.

volume-reduced samples to cover the full size range of marine microplastics adequately and an obligate visual sorting step. Whenever possible, a stratified sampling strategy should be applied for sediment samples (seafloor, beaches) to determine the dynamics of microplastics within marine sediments.

OUTLOOK

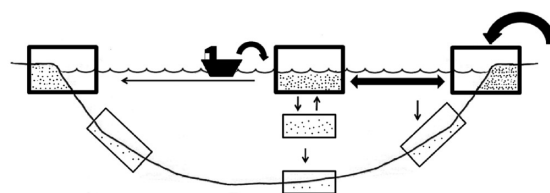
The observed differences between types and amounts of microplastics in the main marine habitat compartments (shore sediments, sea surface, water column, and seafloor) indicate that import, export, and residence times of microplastics may vary depending on their characteristics, mostly size and the specific density of the polymers.

Microplastics of low specific density are positively buoyant and thus likely spend a long time at the sea surface (or in the water column), where they can potentially be transported over long distances. They can thus be found in remote places, e.g. on sandy beaches, distant from their sources (Figure 8). However, particles with low specific density have also been found in subtidal sediments.^{8,21,57} CHN elemental analysis revealed relatively high contents of nitrogen (N) on microplastics, which suggested abundant epibiont overgrowth, because N is not a component of synthetic polymers.⁸⁰ Overgrowth by micro- and macro-organisms causes an increase in specific density and thus contributes to a loss in buoyancy and sinking of microplastics^{86,103} (Figure 8a). In contrast, erosion may lead to decreases in specific density, thereby enhancing buoyancy.⁸⁰ Biofouling and erosion thus cause changes in specific density, affecting exchange processes between different compartments. Due to complex interactions between fouling, erosion, and surface-volume ratios of particles, it can be hypothesized that temporal changes in buoyancy of microplastics depend on particle sizes. More research is needed to understand the interaction between epibionts and microplastics and their effects on particle buoyancy.¹⁰⁴

While positively buoyant microplastics are widely dispersed across the world's oceans, microplastics of high specific density are negatively buoyant and thus sink more rapidly to the seafloor; consequently they are expected to accumulate in subtidal sediments near their sources (Figure 8b). Interestingly, microplastics appear to be rare in deep sea sediment traps,³⁹ but more deep sea studies are needed as macroplastic debris is now relatively common in these habitats.⁵

The transfer of microplastics between compartments (shore, sea surface, water column, seafloor) is likely to vary, and there are particular areas where these particles have been shown to accumulate: on the shores,⁷⁵ on the seafloor,^{105,106} and in the oceanic gyres.^{37,107,108} Given the lack of samples from subtidal and deep sea sediments, future studies should examine these marine environments. Also rocky shore samples are markedly absent from studies on microplastics. This is surprising because exposed rocky shores should enhance fragmentation of macroplastics that are battered against rocks and subsequently ground down further by large moving boulders.^{92,109} Due to the high hydrodynamic energy, it is likely that rocky shores export ground-up microplastics. In contrast, salt marshes with low hydrodynamic energy probably are retention systems for microplastics (e.g., particle retention in salt marshes).¹¹⁰ Quantitative sampling on complex rocky shores and in salt marshes is challenging but given the above considerations, it appears important to estimate plastic fragmentation, transfer, and accumulation in these habitats.

A (Buoyant microplastics)



B (Non buoyant microplastics)

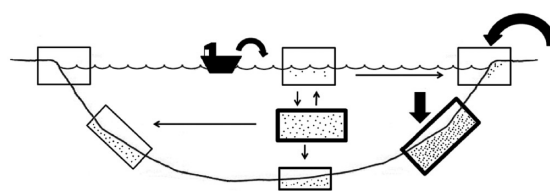


Figure 8. Schematic figure indicating standing stocks in different habitat compartments and flux pathways of (a) positively buoyant and (b) negatively buoyant microplastics in the marine environment: sandy beaches, subtidal sediments, sea surface, water column, and ocean floor. Curved black arrows indicate the inputs of microplastics into the environment, straight black arrows show the fluxes between different habitat compartments, bold borders around larger boxes highlight the most likely compartments for accumulation of microplastics (tiny dots).

Smaller plastic pieces are likely to mix with food items⁴⁹ and hence organisms may transport them into other (including nonmarine) compartments.⁹² Seabirds selectively feed on plastics from the sea surface,^{99,111} which can be deposited in terrestrial habitats by regurgitation, defecation, or decomposition after death.¹¹² The types of plastics most commonly ingested by seabirds are plastic pellets and user plastics, such as fragments and monofilament lines.^{13,113–116} For these reasons seabirds have been used as indicators of changes in the amount and composition of plastic debris in certain regions.^{25,114,117} Stomachs of different seabird species contained plastic particles mostly between 2 and 8 mm.^{118,119} Thus, stomach contents can only be used to monitor particles in this size range; other organisms such as invertebrate suspension- and deposit-feeders may provide opportunities to sample smaller pieces of debris.

Considering that microplastics cannot be effectively removed from the ocean, future studies are necessary to understand how biological agents (such as epibionts or seabirds) and abiotic factors (UV radiation, wave action, currents) affect the transfer, accumulation, and further breakdown of microplastics and to describe the potential impacts of this debris. More work is also needed to identify and reduce/eliminate the sources of microplastics in the environment. Hopefully, this review will contribute toward establishing standardized sampling programs and hence to a more comprehensive understanding of the sources, sinks, and fluxes of microplastics in the marine environment.

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Notes

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