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Review

Toward a long-term monitoring program for seawater plastic pollution in the north Pacific Ocean: Review and global comparison☆

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ABSTRACT

Through a literature survey and meta-data analysis, monitoring methods and contamination levels of marine micro- and macroplastics in seawater were compared between the North Pacific and the world's other ocean basins. The minimum cut-off size in sampling and/or analysis of microplastics was crucial to the comparison of monitoring data. The North Pacific was most actively monitored for microplastics and showed comparatively high levels in the global context, while the Mediterranean Sea was most frequently monitored for macroplastics. Of the 65 extracted mean abundances of microplastics in seawater from the North Pacific, two (3.1%) exceeded the lowest predicted no-effect concentration (PNEC) proposed thus far. However, in the context of business-as-usual conditions, the PNEC exceedance probability may be expected to reach 27.7% in the North Pacific in 2100. The abundance of marine plastics in seawater, which reflects the current pollution status and marine organisms' waterborne exposure levels, is a useful indicator for marine plastic pollution. For regional and global assessments of pollution status across space and time, as well as assessment of ecological risk, two microplastic monitoring approaches are recommended along with their key aspects. Although microplastic pollution is closely linked with macroplastics, the monitoring data available for floating macroplastics and more extent to mesoplastics in most ocean basins are limited. A more specific framework for visual macroplastic survey (e.g. fixed minimum cut-off size, along with survey transect width and length according to survey vessel class) is required to facilitate data comparison. With the implementation of standardised methods, increased efforts are required to gather monitoring data for microplastics and—more importantly—floating macroplastics in seawater worldwide.

1. Introduction

Plastic pollution has been ubiquitously observed in seawater worldwide (Shim and Thompson, 2015) since the occurrence of both micro- and macroplastics in seawater was first reported in the early 1970s (Carpenter et al., 1972; Venrick et al., 1973). Both macro- and microplastic pollution levels have increased in tandem with global plastic production (Brandon et al., 2019; Ostle et al., 2019). Several recent studies have predicted that future plastic pollution levels will continue to increase in the context of business-as-usual conditions (Everaert et al., 2018; Isobe et al., 2019; Lau et al., 2020). Microplastic contamination levels in various marine compartments have been reported worldwide (Lusher, 2015; Shim et al., 2018); the North Pacific and its surrounding marginal seas are more polluted than other oceans, with the exception of the Mediterranean Sea, which is an almost enclosed sea (Cózar et al., 2014; Isobe et al., 2015; Kim et al., 2018; Shim et al., 2018). Sixteen of the twenty rivers with the highest estimated terrestrial plastic debris discharge levels are located in Asia, and the region contributes approximately 67% of the world's riverine plastic debris input (Lebreton et al., 2017). Asian countries contribute more

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than 50% to global plastic demand (Plastics Europe, 2020). The ocean current system ultimately conveys floating marine plastic debris originating on the Asian continent and from maritime activities in its marginal seas to the North Pacific Ocean (Maximenko et al., 2012).

Assessment of the status and trend of plastic pollution with appropriate space and time resolution is essential for the management and mitigation of marine plastic pollution. Among the various abiotic environmental matrices, seawater is an important monitoring matrix to assess floating and suspended plastic pollution. Some types of plastic debris, including microplastics introduced into the marine environment, may be floating or suspended depending on their density, shape, and size (Song et al., 2018; Eo et al., 2021). Marine organisms and seabirds may ingest or become entangled in floating and suspended debris (Secretariat of the Convention on Biological Diversity and the Scientific and Technical Advisory Panel—GEF, 2012; Hong et al., 2013; Nelms et al., 2016; Ryan, 2018; Curtis et al., 2021). Moreover, such debris may pose navigational hazards through entangling of ships' propellers or blocking of engine cooling systems (Hong et al., 2017). They can also function as mediators for the transport of non-indigenous species and pathogens (Zettler et al., 2013) and can provide new habitats for organisms (Goldstein et al., 2012; Haram et al., 2021). Therefore, plastic pollution levels and characteristics in surface water and water columns constitute useful information for evaluating and comparing the degree of pollution among sites, basins, regions, and global oceans; they also aid in assessing ecological risk when combined with waterborne toxicity data (Jung et al., 2021) or geographic seabird population data (Wilcox et al., 2015).

Floating and suspended microplastics in marine water are generally collected in towed nets or by grab (or point) sampling using a bucket or submersible pump at a fixed station (Burns and Boxall, 2018; Shim et al., 2018). The collected samples are transported to laboratories and analysed using various methods, which include extraction, organic matter removal, filtration, and/or identification steps (Shim et al., 2017). Macroplastic debris in water has been directly quantified on board through visual surveys or collected in trawl net tows and then analysed on board or in a laboratory (Cheshire et al., 2009; GESAMP, 2019). Different sampling and analytical methods produce non-comparable datasets, which reduces data usability and prevents the integration of monitoring data at both national and international levels. For example, differing minimum cut-off sizes for microplastics applied in sampling and analytical methods can produce differences of orders of magnitude in abundance, thereby changing the overall shape and polymer composition and particle size distribution (Song et al., 2014; Zheng et al., 2021). Various sampling and analytical methods may be adopted to suit the specific purposes of studies and monitoring programs. However, long-term regional and global assessment of plastic pollution requires a reliable and comparable monitoring dataset, which may be obtained via standardised monitoring methodology. Various monitoring methods for micro- and macroplastics in seawater were summarised by the Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP, 2019). Gago et al. (2018) and Mochida et al. (2019) proposed guidelines for monitoring microplastics in surface waters using neuston net tows. Two monitoring methods for microplastics (net tows and large-volume pump sampling) and visual surveying of macroplastics were recommended by the Arctic Monitoring and Assessment Program (AMAP, 2021).

As one of five companion articles by a working group of the North Pacific Marine Science Organization (PICES), this review focuses on plastic pollution in seawater in the North Pacific Ocean. We reviewed monitoring methods and plastic pollution levels in the surface waters and water column of the North Pacific Ocean and its marginal seas, as well as other ocean basins, with the aim of identifying and recommending appropriate plastic pollution indicators. Through a literature survey, we evaluated the abundance and geographic coverage of data, monitoring methodologies, and plastic pollution levels and characteristics. Based on the level of complexity, popularity, and reliability, a surface seawater plastic pollution indicator was recommended for the North Pacific and its marginal seas.

2. Materials and methods

2.1. Microplastic data collection and screening

Data about microplastics in seawater published in peer-reviewed scientific journals listed in Web of Science between 1972 and 2020 were searched on 31 May 2021. The search keywords were as follows: [(microplastic) + (marine, coastal, or ocean) + (water, saltwater, seawater, or water column) + (occurrence, distribution, accumulation, pollution, monitoring, or characteristics)]. An additional report of large-scale monitoring studies in the North Pacific (Day et al., 1990) was added to fill the data gap in the 1990s. In total 1178 papers were searched, and 204 datasets from 175 papers that included seawater microplastic abundance data were extracted from the searched data (Table S1). Among these papers, datasets were further selected based on study area (e.g. saltwater areas excluding the Caspian Sea and Black Sea), availability of information regarding the mean abundance of microplastics, sampling and analytical methods, and detailed data quality assurance and control. Some papers contained data concerning multiple methods or multiple regions. Microplastic abundances were reported with mean, median, and/or range values with different units of number, mass, or both per unit area, volume, or weight of seawater. For data consistency, literature was only selected for which mean values based on the numbers of items per unit volume or per unit area were available. Papers were included for which the mean microplastic abundance could be calculated from raw data provided in the text, table, or supplementary information. When the microplastic abundances were reported as particles/km^2 or particles/m^2, they were converted to particles/m^3 by using the provided net-mouth and sampling area. Microplastic data were excluded if they had been exclusively measured in sea surface microlayers. Consequently, 161 mean values for microplastic abundance were compiled from 129 papers in the present study (references in Supplementary Information).

Among those 129 papers, 52 reported the abundances of plastics >5 mm (upper size limit of microplastics) in size, and 21 reported the upper size limit of sampled or analysed plastics. Only 8 papers separately categorised mesoplastics in the size range of 5 mm to 20–25 mm, and another 6 papers provided plastic abundance graphs including a size interval similar to the mesoplastic range. Although the mesoplastic papers described in the following section were combined with the papers noted above, data on mean mesoplastic abundance were available from only seven studies (Table S2). Thus, no further analysis of mesoplastics was conducted.

2.2. Macroplastic data collection and screening

Mesoplastic (5–25 mm) and macroplastic (>25 mm) data in seawater published in the peer-reviewed scientific journals listed in SCOPUS were searched from 1972 through December 31, 2020. The database search keywords were "marine floating macro debris, -litter, or -plastic" and "marine floating meso-debris, -litter, or -plastic." In total, 60 papers were extracted for further screening with respect to the methodology and abundance of meso- and macroplastic debris (Table S3). We included one paper published in 2021 (Pogojeva et al., 2021) because it was the only study that reported macroplastic debris abundance in Arctic waters. Some papers reported both microplastic and mesoplastic abundance. However, if they did not report mesoplastic abundance separately, they were excluded from further analysis. Several researchers employed aerial surveys using airplanes for macroplastic debris detection, then reported the distribution and estimated abundance of such debris (Lecke-Mitchell and Mullin, 1992; Lecke-Mitchell and Mullin, 1997). These works were not considered in this review because of the different methodologies applied to estimate abundance, as well as the difficulties of comparison with other datasets. Finally, 49 papers were selected that provided the sampling method and abundance data in detail (references in Supplementary Information). Among them, 47 papers reported macroplastic abundance; 3 papers reported micro-, meso-, and macroplastic abundances together (Ruiz-Orejón et al., 2018, 2019; Suaria et al., 2020b). Four papers reported micro- and mesoplastic levels (Collignon et al., 2014; Faure et al., 2015; Suaria et al., 2016; Fossi et al., 2017). All but two papers used visual survey methods from ships for macro debris detection. Observers recorded all materials (e.g. plastics, wood, metal, and fibre/clothes) via visual survey for macro debris; plastics constituted most of the floating macro debris. In this review, we attempted to extract plastic items only. When only the percentage of plastic items (rather than actual abundance) was provided separately, the abundance was calculated from the data provided in the paper and its supplementary information. Most papers reported macroplastics based on visual survey assessments; we focused on those papers in this review. In the final selected publications, we attempted to find the major criteria that most publications adopted to report macroplastic abundances which included debris size, transect width, detecting instrument, and parameters of vessel operation (e.g. speed and elevation of the observation platform). The reporting unit is also a major component that affects comparison of the data; most macroplastic levels were reported as items/km^2. The term "abundance" rather than "density" was used for macroplastic contamination levels to ensure consistency with microplastics; it also avoided confusion with the physical density used to explain microplastic fate.

3. Results

3.1. Seawater microplastic sampling methods

The extracted microplastic papers were sorted according to the investigated region (Fig. S1) and the minimum cut-off size in terms of the mesh size of nets, sieves, or filters (hereafter, minimum size) used for microplastic particle sampling (Table 1). The minimum size varied widely from 0.45 μm to 1000 μm, which inevitably affected microplastic abundance (*see the following section*). The present study arbitrarily divided the mesh size into seven size ranges to evaluate the relationship between mesh size and mean abundance: < 10 μm, 10–100 μm, 101–200 μm, 201–300 μm, 301–400 μm, 401–500 μm, and 501–1000 μm. Most data obtained were in the 301–400 μm size range (n = 72; 44.4%), followed by 10–100 μm (n = 35; 23.3%), 101–200 μm (n = 18; 11.7%), 201–300 μm (n = 16; 9.9%), and others (<5.6% each). Thus, direct comparison without consideration of minimum size may lead to serious errors concerning assessment of geographic differences in microplastic pollution. This limitation applies to any comparison of microplastic abundances.

The methods used to collect microplastics in seawater may be broadly classified into three categories: net tows, pumping, and grab sampling (Table 2). Net tows are the most common and conventional method used to collect suspended microplastic particles in a surface or water column by towing horizontally or vertically. The nets used in the literature included manta nets, neuston nets, continuous plankton recorders for horizontal towing, while bongo nets, WP2 nets, vertical nets, plankton nets, and cylindrical-conical nets were used for vertical towing. Some studies employed bongo nets to collect microplastics in surface waters. Most net types used for vertical towing were similar in their dimensions and had mesh sizes of 120–500 μm, although phytoplankton nets typically had mesh sizes of 50–77 μm. The data collected using the net tow method constituted 75.9% (n = 123) of all collected data; most such data (58.5%; n = 72) were collected using nets with a 301–400 μm mesh size range in most regions, followed by 101–200 μm (16.0%), 201–300 μm (10.6%), and others (<10.0% each) (Table 2). Therefore, net tow-based data generally represent the abundance of microplastics over hundreds of micrometres in size across large spatial areas (>1 km) representing large volumes (approximately 10–50 m^3). In contrast, pumping and grab sampling can collect microplastics in comparatively small volumes (approximately 100–500 L) at one specific sampling location. Both methods have advantages in measuring microplastics down to approximately 10–50 μm because they are sequentially connected to micrometre-sized filters or nets. In addition to grab (stationary) pumping, several studies applied a ship-based underway water pumping system as a continuous pumping method that allowed the collection of water samples across a large area several meters below the sea surface during the ship's voyage (Desforges et al., 2014; Lusher et al., 2014; Enders et al., 2015; Lusher et al., 2015; Cincinelli et al., 2017). The pumping method-based data contributed 12.3% (n = 20) of the total data, 65% (n = 13) of which was obtained from the 10–100-μm minimum size. Grab sampling directly collects bulk water using bottles, buckets, or the Niskin, Jussi, Van Dorn, Hydrosphere, or McLane Large Volume Water Transfer System. Grab sampling contributed 11.7% (n = 19) of the data. Similar to the pumping method, the data collected by grab sampling were mostly filtered through micrometre-sized nets or filters: 78.9% (n = 15) in 10–100 μm and 15.8% (n = 3) in <10 μm. These findings indicate that the sampling method and size of collected microplastics are closely related, with the pumping and grab sampling methods capable of quantifying smaller particles compared with typical the net tow method.

Accurate measurement of sampling volume is critical for calculating microplastic abundance. Pumping and grab sampling using a bucket or bottle allow for more accurate measurement of water volume compared with net tows. Thus, installation of a flow meter in the mouth of neuston and manta nets has been recommended to measure the filtered water volume more accurately (Suaria et al., 2016). Among 122 studies using net tows, only 58 (47.5%) used a flow meter to calculate the filtered volume, while 43 (35.2%) calculated the volume according to the towing distance and area of the net opening; the remaining 21 studies did not mention how the filtered water volume was measured or calculated.

3.2. Effects of sampling method and location on seawater microplastic abundance

Microplastics, by definition, have a wide size spectrum from 0.001 to 5 mm (GESAMP, 2016). Microplastic abundances in environmental

Table 1
Number of collected microplastic mean abundance datasets in seawater according to sampling region and minimum cut-off size by sampling or analysis.

Region	Mesh, sieve, or filter size (μm)							
	<10	10–100	101–200	201–300	301–400	401–500	501–1000	Total
N Pacific	3	20	1	–	31	7	3	65
S Pacific	1	–		1	2	–	–	4
N Atlantic	1	9	8	4	19	–	1	42
S Atlantic	1	–	2	5	1	–	1	10
Indian Ocean	–	–	3	2	4	–	–	9
Mediterranean	–	2	3	1	10	1	0	17
Arctic	–	3	–	2	3	1	–	9
Antarctic	–	1	1	1	2	–	–	5
Total	6	35	18	16	72	9	5	161

Table 2
Number of collected microplastic mean abundance datasets in seawater of the world ocean according to sampling method and minimum cut-off size by sampling or analysis.

Sampling method	Mesh, sieve, or filter size (μm)							
	<10	10–100	101–200	201–300	301–400	401–500	501–1000	Total
Net tows	1	7	15	13	72	9	5	122
Pumping	1	13	2	3	–	–	–	20
Grab sampling	3	15	1	–	–	–	–	19

samples strongly depend on the minimum size collected by the sampling device (e.g. net mesh size) and the instruments used for identification (e.g. microscopy versus vibrational spectroscopy). It is critical to compare microplastic abundances at different sampling sites and regions within the same microplastic size range. All microplastic data extracted from the literature survey were plotted according to minimum size and are presented in Fig. S2. The mean value of microplastic abundance retrieved from the literature showed a 10 orders of magnitude difference between the minimum value (4.80×10^{-6} particles/m^3) in the North Pacific's South Equatorial Countercurrent (Spear et al., 1995) and the maximum value (3.31×10^4 particles/m^3) in Küçükçekmece Lagoon, Marmara Sea (Turkey) (Çullu et al., 2021), with a mean (± standard deviation) of 653 (±29,271) particles/m^3 and a median of 0.42 particles/m^3. The two extreme values were obtained using neuston net tows (mesh size, 1000 μm) and a grab-pumping method (filter pore size, 50 μm), respectively. The mean microplastic abundances clearly increased as the minimum size decreased (Fig. 1a). The logarithm-transformed mean microplastic abundances and the mid-size of minimum size interval showed a significant negative linear relationship ($p < 0.05$; $r^2 = 0.88$), when microplastic abundances were averaged according to the grouped minimum size intervals (Fig. 1b and Table S4). The regression equation [log (microplastic abundance) = −0.0082 × minimum size + 3.4017) showed that each 121-μm minimum size increment was associated with a tenfold increase in microplastic abundance. These results indicate that microplastic abundances in seawater strongly depend on the minimum size range, regardless of sampling region and time.

The difference in sampling method was related to the minimum size of the collected microplastics, which determined microplastic abundance. A significant difference was observed in microplastic abundances among the three water collecting methods (analysis of variance; $p < 0.01$), mostly because of the net tow method's particularly low values compared with the other two methods (t-test; $p < 0.05$ for each pair): 1569 ± 2306 particles/m^3 (median = 690 particles/m^3) for grab sampling versus 3417 ± 7393 particles/m^3 (median = 575 particles/m^3) for the pumping method versus 62 ± 524 particles/m^3 (median = 0.22 particles/m^3) for the net tow method (Fig. S3). No significant difference was observed in microplastic abundance between the pumping and grab sampling methods (t-test; $p > 0.05$) in this review. The mean mesh sizes used for microplastic collection or measurement were 47 ± 46 μm for grab sampling, 86 ± 86 μm for pumping, and 326 ± 154 μm for net tows. These demonstrated significant differences between the net tow and other two methods (t-test; $p < 0.001$ for each), but not between pumping and grab sampling.

Regarding the sampling depth of microplastics, surface waters within the top 1 m accounted for 85.1% (n = 137) of all the datasets, followed by the water column from 1 m below the surface to thousands of meters in depth in 11.8% (n = 19) of the datasets, with the remainder of the datasets (3.1% (n = 5)) covering both the surface water and water column. Comparing microplastic abundances between the surface and water column among studies was difficult due to the limited amount of data obtained using the same mesh size (e.g. 300–350 μm) for sampling. Many water column studies used net mesh sizes smaller than 300 μm. Among the water column studies, a few involved multi-depth layer sampling to reveal vertical profiles of microplastic abundances (Lattin et al., 2004; Dai et al., 2018; Song et al., 2018; Zobkov et al., 2019; Tekman et al., 2020; Uurasjärvi et al., 2021). Four studies reported a general decrease in microplastic abundance with sampling depth (Dai et al., 2018; Song et al., 2018; Tekman et al., 2020; Uurasjärvi et al., 2021), while two studies showed complex vertical profiles of microplastic abundance (Lattin et al., 2004; Zobkov et al., 2019).

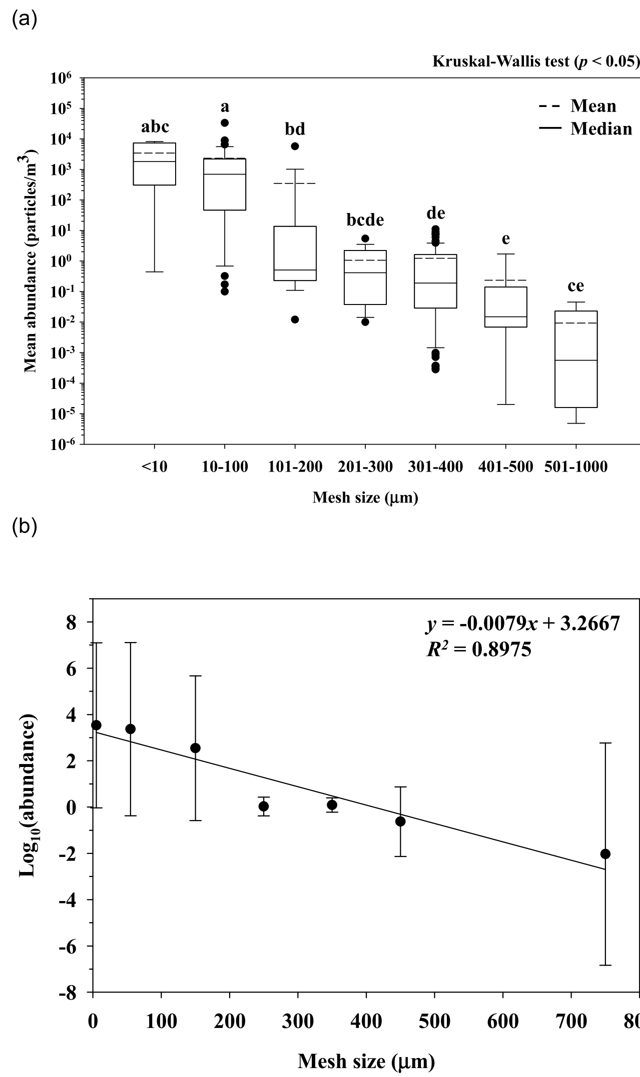

Fig. 1. Average abundance of (a) microplastics in seawater of the world ocean according to the minimum cut-off size range in sampling or analysis and (b) relationship between logarithmically transformed average abundance and the minimum cut-off size. Mean values with the same letter designation in boxplot (a) are not significantly different (Kruskal-Wallis test; $p < 0.05$ and subsequent Mann-Whitney U test; $p < 0.002$).

3.3. Geographic difference in seawater microplastic abundance

The world's oceans were categorised into eight geographic ocean regimes according to the investigated location: the North Pacific, South

Pacific, North Atlantic, South Atlantic, Indian Ocean, Mediterranean Sea, Arctic, and Antarctic regions. Most microplastic abundances were collected in the North Pacific (n = 65; 40.1%) (Fig. S4), followed by the North Atlantic (n = 42; 25.9%), Mediterranean Sea (n = 17; 11.1%), South Atlantic (n = 10; 6.2%), Arctic (n = 9; 5.6%), Indian Ocean (n = 9; 5.6%), Antarctic (n = 5; 3.1%), and South Pacific (n = 4; 2.5%). This geographic data distribution indicates that most microplastic surveys (77.2%) have been concentrated in three ocean regimes surrounding the mid-latitude countries of the northern hemisphere.

The above analysis demonstrates the dependency of microplastic abundance on the measured minimum size of microplastics, indicating that there is a need to standardise data according to microplastic size to identify the geographic distribution of microplastic pollution levels. As mentioned above, data collected using the pumping and grab sampling methods—most of which originated from mesh sizes of 10–100 μm—contributed a small portion of all data points (25%) and were obtained in specific regions, rather than all ocean realms (Tables 1 and 2). Most data were obtained using the net tow method, which was also the most frequently used method in all ocean region expeditions; a mesh size of 301–400 μm was most frequently applied. Despite the arbitrary assignment of the interval 301–400 μm, all data in the minimum size range were obtained within a narrow mesh size range (320–355 μm). Most data in the 100–200-μm and 201–300-μm ranges were also obtained in 200 μm mesh (68.4%) and 300 μm mesh (81.3%), respectively. Thus, we identified geographic differences in microplastic pollution levels with data obtained using only 300–355-μm mesh-sized nets to prevent data distortion associated with mesh size. Data points in this mesh size range (n = 85) constitute 69.1% of the net-based data points and at least three microplastic abundance data points from each of the eight ocean realms.

The geographic distribution of mean (± standard deviation and median) microplastic abundances collected using the 300–355 μm mesh size and all mesh sizes is shown in Fig. 2. In the 300–355 μm mesh size, the mean microplastic abundance level was 1.16 (±2.16) particles/m^3, with a median of 0.17 particles/m^3 across all regions; the highest level was found in the Mediterranean Sea (1.50 ± 2.58 and 0.27 particles/m^3; n = 11), followed by the North Pacific (1.49 ± 2.22 and 0.33 particles/m^3; n = 31), North Atlantic (1.23 ± 2.69 and 0.15 particles/m^3; n = 22), Indian Ocean (0.67 ± 0.85 and 0.29 particles/m^3; n = 6), Arctic (0.60 ± 0.56 and 0.34 particles/m^3; n = 3), South Atlantic (0.46 ± 0.98 and 0.03 particles/m^3; n = 6), Antarctic (0.10 ± 0.14 and 0.03 particles/m^3; n = 3), and South Pacific (0.01 ± 0.008 and 0.005 particles/m^3; n = 3) (Fig. 2). However, microplastic abundance in the North Pacific did not significantly differ from microplastic abundances in other northern hemisphere regions (the North Atlantic, the Mediterranean Sea, and the Indian Ocean) (*t*-test; $p > 0.05$ for each pair); it significantly differed from the southern hemisphere regions (the South Pacific and the South Atlantic) and the polar regions (*t*-test; $p < 0.05$ for each pair). This finding implies a correlation between microplastic pollution in the global oceans and population density, which reflects the pattern of plastic usage. The median values of microplastic abundance were generally one order of magnitude lower than their mean values.

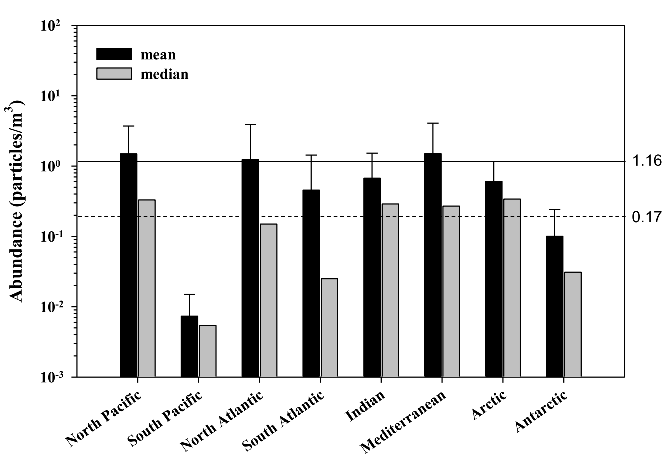

Fig. 2. Geographical distribution of average microplastic abundances in seawater. Datasets were filtered by only 300–355 μm mesh sizes. Solid line is the average of mean values and dotted line is the average of median values.

Seawater microplastic monitoring was conducted most often in marginal seas including coastal areas (n = 118; 73.3%), followed by the open ocean (n = 41; 25.5%) and both marginal seas and the open ocean (n = 2; 1.2%). The geographic differences in microplastic abundance among marginal seas, ocean gyres, and the open ocean were compared using only data from 300 to 355-μm mesh-sized nets (Fig. 3). The mean abundance in marginal seas (1.38 ± 2.46 and median 0.27 particles/m^3) was significantly ($p < 0.05$) higher than that in the open ocean (0.23 ± 0.43 and median 0.06 particles/m^3), excluding ocean gyres, but was not significantly ($p > 0.05$) different from that in ocean gyres (0.45 ± 0.99 and median 0.02 particles/m^3).

3.4. Ecological risk of waterborne microplastics in the North Pacific

Ecological risk assessment of microplastics can be achieved by the integration of water exposure data (i.e. abundance in water) and effect data (i.e. bioassay on aquatic organisms by waterborne exposure) (Jung et al., 2021), in accordance with the ecological risk assessment framework (ECHA, 2008). During the earliest period in microplastic research, a significant mismatch in the size and shape of microplastics between exposure and effect data impeded the assessment of ecological risk caused by waterborne microplastics (Shim and Thompson, 2015). As noted above, the exposure data with a minimum size of 10–20 μm have rapidly increased. Moreover, reported effect data for various aquatic taxonomic groups with test microplastic sizes of approximately 10–1000 μm have recently become more abundant. Five studies have attempted to derive hazard concentration 5% (HC_5) values, and three studies derived predicted no-effect concentration (PNEC) values for waterborne microplastics based on the species sensitivity distribution (Burns and Boxall, 2018; Everaert et al., 2018; Besseling et al., 2019; Everaert et al., 2020; Jung et al., 2021) (Table S5). The PNEC value represents the concentration of microplastics below which adverse effects in seawater are not expected to occur (ECHA, 2008). Three PNEC values (6.65 particles/L without size consideration (Everaert et al., 2018), 121 particles/L for microplastics >1 μm (Everaert et al., 2020),

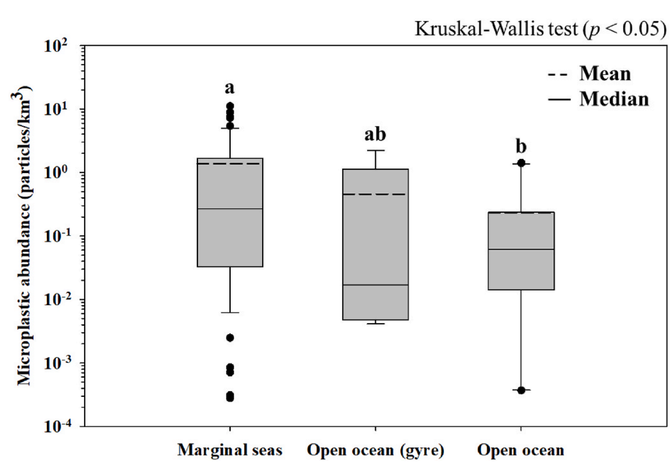

Fig. 3. Comparison of distribution of average microplastic abundances in seawater among marginal sea, ocean gyre, and open ocean. Datasets were filtered by only 300–355 μm mesh sizes. Solid line is the average of mean values and dotted line is the average of median values. Mean values with the same letter designation in boxplot (a) are not significantly different (Kruskal-Wallis test; $p < 0.05$).

and 12 particles/L for non-spherical microplastics within the size range of 20–300 μm (Jung et al., 2021)) were used for comparison with the microplastic abundance data extracted from the literature survey in this study (Fig. 4). Of the 65 mean abundance datasets for the North Pacific extracted from the literature, 2 (3.1%) showed exceeding the lowest PNEC of 6.65 particles/L. Microplastics in areas along the east coast of Guangdong, China (8.9 particles/L) (Zhang et al., 2020) and Long Beach Harbor, USA (8.1 particles/L) (Wiggin and Holland, 2019) were above one PNEC of 6.65 particles/L. Microplastic abundance above PNEC values indicates the potential for adverse biological effects in a particular body of water. The microplastic contamination level in global seawater has been projected to increase 50-fold in 2100, assuming that the current plastic emission scenario does not improve (i.e. "business-as-usual scenario") (Everaert et al., 2018). When this increment is applied to the microplastic mean abundances for the North Pacific retrieved in this study, 12.3% (n = 8), 27.7% (n = 18), and 27.7% (n = 18) of the predicted mean abundances of microplastics in North Pacific waters may exceed the PNECs of 121, 12, and 6.65 particles/L in 2100, respectively. Of 18 predicted mean microplastic abundances in 2100 exceeding the PNECs of 12 and 6.65 particles/L in the North Pacific, 14 are located in East Asian coastal areas and the rest in coastal areas of the northeastern Pacific.

3.5. Seawater macroplastic visual survey methods

For macro debris quantification, all but two reports used a visual survey method. Two investigations in the west Mediterranean Sea (Ruiz-Orejón et al., 2018, 2019) were conducted using manta nets and included micro- and mesoplastics, with a maximum debris cut-off size of 100 mm. Despite the persistent lack of standardised size classification for marine plastics (Hartmann et al., 2019), most monitoring guides adopted 5–25 mm for mesoplastics and >25 mm for macroplastics (GESAMP, 2019). However, visual survey reports did not follow the widely recognised size classification. The most frequently adopted lower size limit for macro debris detection was > 2–2.5 cm (42.9% of the literature), followed by 1–2 cm (14.3%) (Table S6). Nine studies (18.4%) reported no lower size limit.

Transect width in visual surveys may significantly influence the survey results of floating macroplastics because most studies simply assume that all floating debris within a fixed distance of the ship was detected. However, only 11 studies provided detection widths of transects, which were in the range of 10–600 m. Ryan (2013) applied a correction factor for the loss of items because of detectability according to distance from the vessel and debris size. Additionally, most studies did not correct the count according to the distance or plastic size; they adopted a width of sight ranging from 10 m to 300 m.

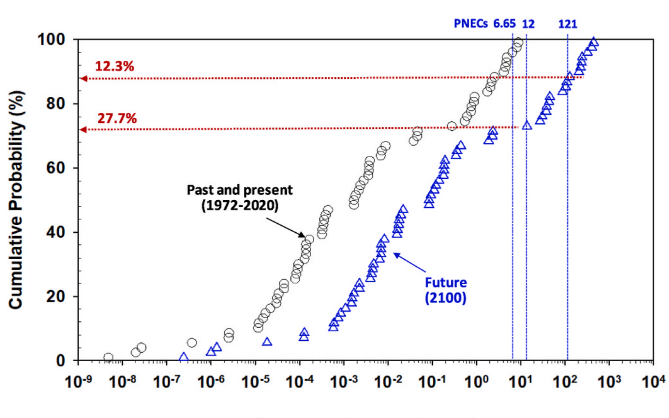

Fig. 4. Cumulative probability of seawater microplastic levels reported in the North Pacific Ocean from 1972 to 2020 and predicted in 2100 (calculated from Everaert et al., 2018). The blue dotted lines and numbers indicate predicted no effect concentration (PNEC) levels (6.65, 12, and 121 particles/L) suggested by Everaert et al. (2018), Jung et al. (2021), and Everaert et al. (2020), respectively. The red dotted lines and numbers indicate the percentage of future concentration data exceed the highest and lowest PNEC level, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Approximately two-thirds of the studies reported the vessel speed of their research vessels (Table S7). Forty-four per cent of the vessels used a speed of <10 knots, 22% used a speed of 10–20 knots, and 2% used a speed of >20 knots; speeds were not reported for 32% of the vessels. Observation height for the observer to detect floating plastic debris varied from <5 m to 35 m (Table S8).

Observation heights from sea level of <5 m constituted the largest proportion (18.5%) of the data, followed by heights of 10–15 m (11.1%); almost half of the studies did not report observation heights (Table S8). The observation methods, such as naked eye or binocular usage, are provided in Table S9.

In addition to the individual differences among observers, macroplastic abundances reported in visual surveys may vary considerably due to predetermined variables such as the lower size limit of observed plastics, effective detection distance from the vessel, vessel speed, observation height, and survey area (or effort). Furthermore, surrounding conditions (e.g. sea state and weather-related visibility) differed for each cruise. The mean macroplastic abundances with lower size limits of 2–2.5 cm (n = 36; 528 ± 2126 items/km^2; median = 44 items/km^2) and 5–10 cm (n = 4; 1055 ± 1967 items/km^2; median = 111 items/km^2) were much greater than the abundance with a limit of >20 cm (n = 20; 11 ± 18 items/km^2; median = 2 items/km^2), but the difference was not significant ($p > 0.05$) due to high variability (Fig. 5a). The mean abundance of macroplastics surveyed at an observation height above sea level of <10 m (n = 14; 169 ± 146 items/km^2; median = 171 items/km^2) was significantly ($p < 0.05$) greater than the abundance obtained at an observation height of >15 m (n = 19; 26 ± 55 items/km^2; median = 3 items/km^2) but not significantly different from the abundance obtained at 10–15 m height (n = 8; 356 ± 694 items/km^2; median = 21 items/km^2) (Fig. 5b). Most data (31 of 33) for the two observation heights (<10 m and >15 m) were obtained from the Mediterranean Sea. Therefore, further geographic comparisons with respect to observation height could not be conducted.

3.6. Geographic differences in seawater macroplastic abundance

The area most studied with respect to floating macroplastics was the Mediterranean Sea, which was the focus of 20 studies (42.6%), followed by the North Pacific (n = 9; 19.1%), North Atlantic (n = 7; 14.8%), and South Pacific (n = 5; 10.6%) (Fig. S5). More studies of floating macroplastics were conducted in the northern hemisphere than in the southern hemisphere. Each study adopted its own strategies; in this review, we selected abundance data with similar minimum sizes (approximately >1 cm) for generally acceptable comparison. The mean and median values were calculated according to geographic region; if the data were reported by several sectors, each abundance was regarded as an individual value.

Plastics were the predominant item among floating macro debris (Table S10). The mean abundance of macroplastics from all regions was 125 items/km^2. The highest abundance was observed in the Mediterranean Sea (213 items/km^2, n = 17), followed by the Indian Ocean (200 items/km^2, n = 5), the North Pacific (48 items/km^2, n = 13), the South Pacific (18 items/km^2, n = 1), the North Atlantic (14 items/km^2, n = 2), the South Atlantic (3.2 items/km^2, n = 3), the Antarctic (0.2 items/km^2, n = 2), and the Arctic (0.004 items/km^2, n = 2) (Fig. 6). The statistical differences (Kruskal–Wallis test) were tested using mean values from the three top regions. The abundances were significantly ($p < 0.05$) different between the Mediterranean Sea and the North Pacific, confirming that the Mediterranean Sea is the most affected region and has the highest abundance of floating macroplastics.

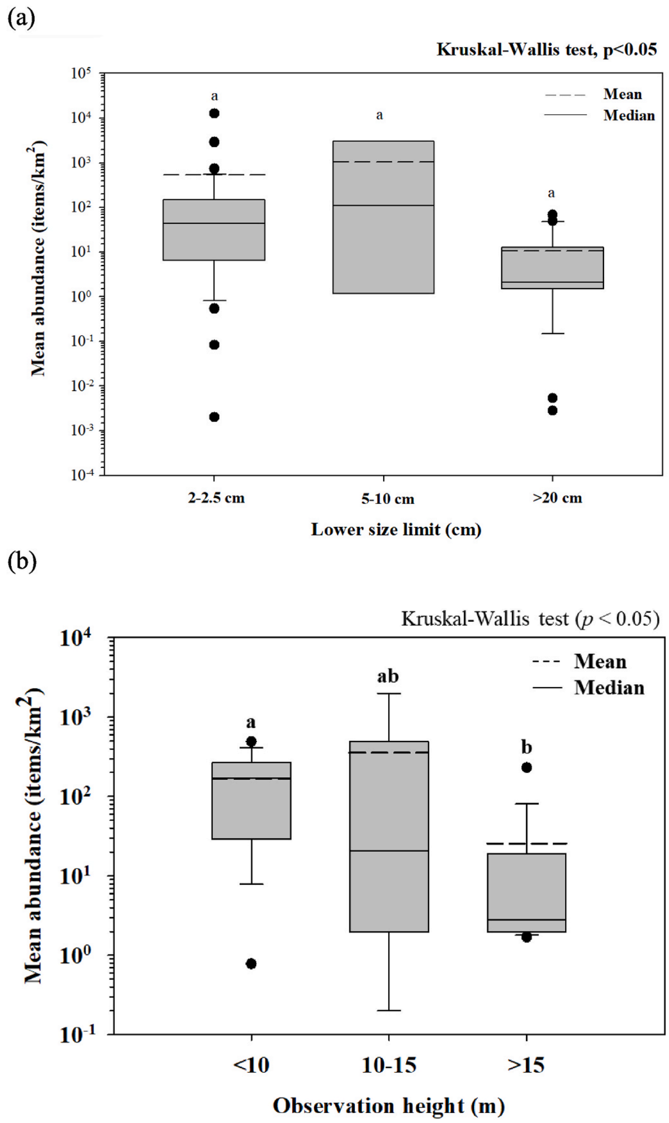

Fig. 5. Relationship (a) between the mean abundances of macroplastics in seawater and lower size limit of detection or (b) observation height of visual survey. Mean values with the same letter designation in boxplots are not significantly different (Kruskal-Wallis test; $p < 0.05$).

4. Discussion

4.1. Sampling and monitoring methodologies for plastics in seawater

Monitoring of marine plastic debris has become a top priority worldwide and has been recommended or carried out at the national, regional, and global scales. Monitoring studies may be categorised into shoreline, seawater, and seafloor studies based on their spatial location in the marine environment. Among these types, analysis of shoreline plastic debris generally has standardised monitoring protocols for macroplastics (OSPAR, 2010; NOAA, 2013) and microplastics (Frias et al., 2018); monitoring protocols are undergoing discussion and validation for floating macroplastics (Arcangeli et al., 2020) as well as microplastics in seawater (Mochida et al., 2019; AMAP, 2021) and seafloor macroplastics (OSPAR; https://www.ospar.org/work-areas/eiha/marine-litter/assessment-of-marine-litter/seabed-litter) due to intrinsic constraints related to their position or (for microplastics) the relative novelty of their description (Arcangeli et al., 2020).

As described previously, microplastic abundance is strongly related to sampling net or sieve mesh size, which also depends on the sampling method (Song et al., 2014; Lindeque et al., 2020; Tokai et al., 2021). This means that the use of different sampling methods can undermine the inter-comparison of data to explore pollution levels in different regions and temporal changes in microplastic pollution levels. Thus, a standardised method is needed to facilitate the use of seawater microplastic abundance and characteristics as pollution indicators. According to this review of seawater, the net tow method (with manta or neuston nets for surface analysis and bongo for subsurface sampling) with a mesh size of 300–355 μm was most popular, has produced datasets for many geographic regions, and shows reasonable results concerning geographic comparison of microplastic pollution levels. Unlike other methods, this net tow method can also represent the microplastic pollution level in the investigated region because it samples a large volume of water (e.g. several tons) across a large area (e.g. several square kilometres). Sampling large volumes of water is important because it ensures that large-sized microplastic particles (>1 mm), which are relatively low in number but have considerable mass, are not missed (Song et al., 2020; Kim et al., 2021). Therefore, this net tow method with a mesh size range of 300–355 μm can be strongly recommended as an appropriate Tier I sampling method for the long-term monitoring and inter-comparison of surface water. Three guidelines (Gago et al., 2018; Mochida et al., 2019; AMAP, 2021) recommend net tows with a mesh size of 300–333 μm for surface water microplastic sampling. The detailed sampling and sample processing procedures required for this method have been adequately described (GESAMP, 2019). The basic information required includes the trawled area, depth, and filtered water volume to produce debris abundances per unit area and unit volume. For reliable information regarding microplastic polymer composition, the instrumental analysis of collected samples should be based on vibrational spectroscopy or a comparable chemical confirmation method, considering the limitations of other techniques (Song et al., 2015; Shim et al., 2017; Lee et al., 2021). Additionally, there is increasing need for the acquisition of small-sized (<300 μm) microplastic abundance data because smaller particles are considerably more abundant in environmental samples with greater bioavailability to various aquatic organisms (e.g. zooplanktons and bivalves) (Sun et al., 2017; Cho et al., 2021). In that regard, the recommended net tow method cannot fully evaluate the ecological risk; microplastics smaller than the mesh size could be missed. Two previously derived PNEC values considered microplastic size >1 μm (Everaert et al., 2020) and >20 μm (Jung et al., 2021). Therefore, large-volume (>100 L) grab or pump sampling can be recommended as an appropriate Tier II sampling method that covers microplastics <300 μm in size for ecological risk assessment of waterborne microplastics. In addition, inclusion of water column sampling, at least in the middle depths and above the seafloor, is strongly recommended for Tier II sampling to obtain more accurate estimates of microplastic pollution levels and standing stock. Monitoring of only surface water may lead to overestimation of microplastic abundance in seawater due to the relatively high levels in surface water compared with the rest of the water column (Song et al., 2018). The microplastic standing stock in seawater could be strongly underestimated when microplastics in the water column are not considered. Two monitoring methods (Tier I and Tier II or size range selection) should be carefully considered for each nation's or authority's purpose. Alternatively, the relationship between size and abundance observed in this study and proposed by another study (Kooi and Koelmans, 2019) could be used to predict the abundance of smaller sized microplastics in the same sample (or region), where microplastic particles larger than 300–355 μm were assessed using the recommended net tow method. Such an extrapolation method may be helpful for estimating the abundance of smaller microplastic particles until their actual abundance is measured for environmental and/or human health risk assessment (Kim and Song, 2021; Lee et al., 2021).

Floating macroplastics may serve as a timely indicator of the marine plastic burden because they reveal the primary form of debris entering the sea before fragmentation, submersion, or being washed ashore

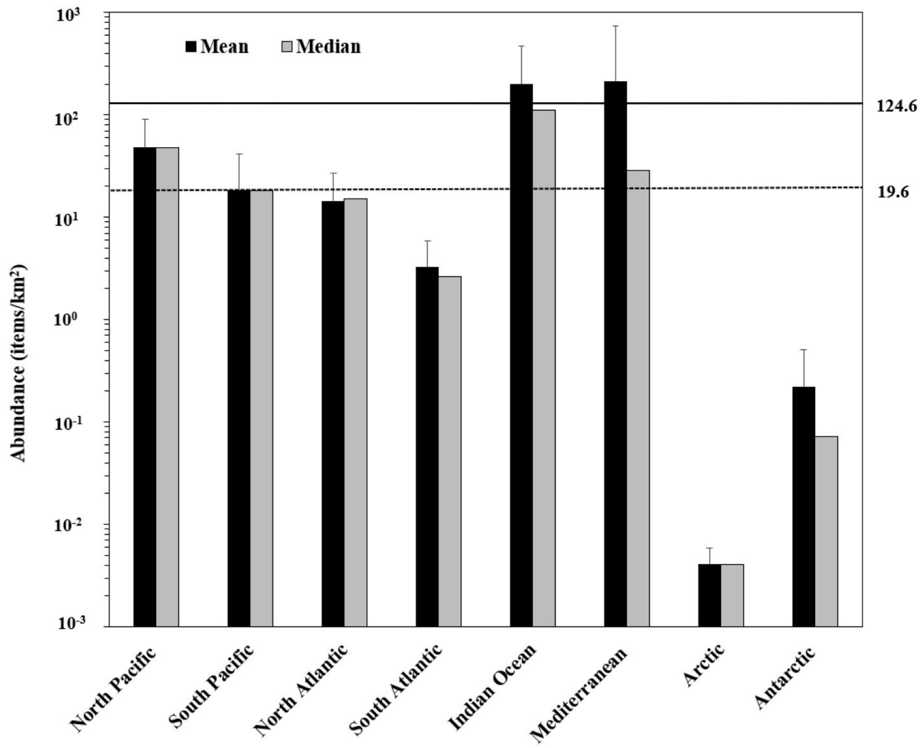

Fig. 6. Geographic distribution of average floating macroplastic abundance across the world ocean monitored by visual surveys (mean: black bars; median: gray bars). The solid horizontal line is the average of mean values and the dotted horizontal line is the average of median values. The abundances were significantly (Kruskal–Wallis test; $p < 0.05$) different between the Mediterranean Sea and the North Pacific.

(Arcangeli et al., 2020). These macroplastics can also be used to identify the main sources and pathways of plastic contamination, thereby contributing to assessments of mitigation effectiveness (Thiel et al., 2011). Macroplastic surveys are typically undertaken using visual methods. Two monitoring guides, the National Oceanic and Atmospheric Administration Marine Debris Program (Lippiatt et al., 2013) and United Nations Environment Programme/Intergovernmental Oceanographic Commission guidelines on Survey and Monitoring of Marine Litter (Cheshire et al., 2009), describe the components of visual surveys and methods for floating macro debris analysis. These guides are useful for initiating visual surveys, but many critical factors (e.g. effective detection distance according to the vessel used) are not clearly described. Nearly all reviewed publications employed the visual survey method. Debris size, detection width, and parameters of vessel operation (e.g. speed and observation height) varied among the studies included in this review; these factors can affect debris detectability and produce differences in abundance, item composition, and size. The absence of standardised monitoring guidelines hampers the assessment of floating macroplastic debris and the progress in cooperative efforts to address floating marine debris at both national and international levels. The vessel size used (observation height), vessel speed, survey transect width, strip length, and observer experience influenced macroplastic abundance and composition in a systematic comparison (Arcangeli et al., 2020); these findings indicate poor data compatibility among monitoring studies. For example, fixed vessel speed, minimum cut-off size, and strip width and length according to vessel size or class are essential considerations. Although the minimum cut-off size of debris differs between small/medium vessels (2.5 cm) and large vessels (20 cm), use of a size threshold of 20 cm for small and medium vessels will support comparison of data from two different vessels via data truncation (Arcangeli et al., 2020).

Abundance differences may also be associated with proximity to land. Some papers reviewed in this study (Thiel et al., 2013; Díaz-Torres et al., 2017; Ruiz-Orejón et al., 2018) and other studies from the Mediterranean Sea, the North Pacific, and the South Pacific demonstrated greater abundances in waters close to the land (Law and Thompson, 2014). Population centres and industrial sources (e.g. aquaculture facilities) could contribute to higher abundances in particular areas, as demonstrated for shoreline debris (Rech et al., 2014; Hardesty et al., 2017; Eo et al., 2018). Source-related research or studies should focus on key items that indicate debris origin to clarify the distribution characteristics of macroplastics in seawater. Plastic debris remains afloat for long periods and can travel far from its original source; therefore, less industrialised areas or remote waters should be investigated to understand distribution and transport characteristics. Arctic and Antarctic waters, in particular, merit additional attention because the ice barrier can no longer be expected to serve as a sink of plastic debris in the context of global warming; debris kept in ice is also likely to be released into the surrounding waters (Pogojeva et al., 2021).

Interestingly, mesoplastics in the size range of 5–25 mm (GESAMP, 2019) are not intentionally targeted in either micro- or macroplastic studies. Particles in this size range can be sampled during microplastic surveys using net tows. Although many microplastic studies reported the abundances of plastic particles >5 mm, the size ranges for reporting particles >5 mm varied widely. Few studies clearly designated the 5–25 mm range as 'mesoplastics'. Therefore, additional efforts are required, if possible, to classify the mesoplastic size range in plastic particle counts clearly and to report mesoplastic abundance separately.

4.2. Global distribution of plastics in seawater

Plastic litter in seawater is a trans-boundary pollutant that can travel around the world until being washed ashore or removed through sinking. The global distribution of plastics in seawater should be assessed using *in situ* observations combined with ocean circulation models to identify pollution hot spots. When the mean microplastic abundance data were compared with consideration of the sampling mesh size (300–355 μm), the Mediterranean Sea and North Pacific Ocean (including its marginal seas) were the most polluted basins worldwide. Two global microplastic monitoring studies of surface water using net tows conducted during the 2010s reported slightly discrepant results. In the report by Cózar et al. (2014), the South Atlantic and North Atlantic showed higher microplastic abundances in both the non-accumulation and accumulation zones produced by subtropical gyres compared with the North Pacific, while Eriksen et al. (2014) reported that microplastic abundance was twofold higher in the North Pacific than in the North Atlantic. Differences in sampling stations, times, and methods likely contributed to these discrepant results; another factor may have been the presence (Eriksen et al., 2014) or absence (Cózar et al., 2014) of data from the Northwest Pacific. Tanhua et al. (2020) described a recent exploration of global surface water microplastic monitoring and reported that relatively high microplastic (100–500 μm) abundances in surface water were found off southwestern Europe and in the southwestern Pacific. Another large-scale monitoring study of microfibres in surface water covering portions of the Mediterranean, Atlantic, Indian, and Antarctic regions revealed that the Mediterranean Sea was highly contaminated with microfibres (Suaria et al., 2020a). Our review found that high microplastic abundances were generally reported in Asian marginal seas and the Western Pacific Ocean. East Asian seas showed 16- and 26-fold higher surface water microplastic abundances compared with the greater North Pacific and other ocean basins worldwide, respectively (Isobe et al., 2015). The North Pacific was ranked first in terms of the total mass of microplastics and second (after the Mediterranean Sea) in terms of the total amount of microplastics in model-based predictions (van Sebille et al., 2015). The North Pacific Ocean, particularly Asian marginal seas, clearly constitutes a global hot spot of microplastic pollution. Considering the high contribution of land-based plastic inputs to the North Pacific from Asia (Lebreton et al., 2017; Borrelle et al., 2020), implementation of mitigation measures must be prioritised throughout the North Pacific region.

The North Pacific Ocean, including its marginal seas, was represented in 65 (40.1%) of the 161 datasets assessed in this review. Among these 65 datasets, the Northwest Pacific, mostly Asian marginal seas, contributed to 46 datasets (70.8%), followed by the Northeast Pacific including the Northeast Pacific gyre (n = 14; 21.5%) and the Central/subarctic North Pacific (n = 5; 7.76%). In the Northwest Pacific, most monitoring studies were performed in Chinese waters (n = 29), followed by Korean (n = 8) and Japanese waters (n = 3). Although more seawater microplastic abundance data are available for the North Pacific region than other ocean basins, the existing data are insufficient for assessing the spatial distribution due to bias in the monitoring station locations around the East Asian Seas and Northeast Pacific region, including the subtropical gyre. Additional monitoring studies are strongly recommended in Southeast Asian Seas, the Northwest Pacific open ocean, and the Central North Pacific to increase the spatial coverage of waterborne microplastic pollution data. Although the Indian Ocean and polar regions (i.e. "dead ends" of global ocean currents) receive large amounts of mismanaged plastic waste (Jambeck et al., 2015; Lebreton et al., 2017) and high concentrations of microplastic particles (Cózar et al., 2017; Kim et al., 2021), investigations in those areas have been scarce.

The mean abundance of macroplastics was highest in the Mediterranean Sea and was significantly greater than those in the North Pacific and North Atlantic. This is in contrast to the abundances of microplastics reported in this review, which were highest in the North Pacific. To address this discrepancy, we suggest that changes in survey methods in each region are needed. The Mediterranean Sea was the region most intensively surveyed for floating macroplastics; the surveys covered a wider area in this region than other regions. A few studies covered either the entire Mediterranean Sea (Arcangeli et al., 2018; Arcangeli et al., 2020) or most of the western Mediterranean Sea (Campana et al., 2018). In contrast, floating macroplastic monitoring data in the North Pacific Ocean were limited and were particularly scarce in the East Asian seas and the Northwest Pacific, where microplastic levels are generally high and where major rivers introduce land-based plastic waste (Lebreton et al., 2017). Floating macroplastics were investigated only once in the entire Pacific Ocean during the 1990s, with detailed surveys performed around Taiwan and Mexico (Díaz-Torres et al., 2017; Chiu et al., 2020). The difficulty of sampling floating marine plastics across broad areas of open ocean other than the Mediterranean Sea may impede the collection of monitoring data. The sampling cost associated with the use of ships for visual surveys represents an additional obstacle. Domestic and international ship of opportunity programs for gathering oceanographic data or joint research among countries may provide useful survey tools to address this lack of data. In addition, some monitoring efforts have focused exclusively on microplastics, leading to biases, particularly in East Asian seas and the Northwest Pacific Ocean. Extensive research funding has become available for emerging issues such as microplastics, whereas macroplastic pollution is a neglected research topic. The abundances of surface water mesoplastics and microplastics showed a significantly positive relationship (Ruiz-Orejón et al., 2019). Upon entering the environment, plastic debris breaks into smaller pieces via photo-oxidation due to sunlight exposure, followed by mechanical breakdown within months or years according to polymer type (Song et al., 2017, 2020). However, a large portion of the microplastic pollution problem can be solved by addressing macroplastic littering, and this relationship has largely been ignored. To properly assess pollution status and support subsequent management efforts, the spatiotemporal distribution and characteristics of plastic pollution in global ocean waters must be investigated via more intensive surveys that are balanced in terms of geography and plastic particle size, particularly in the North Pacific.

4.3. Plastic in seawater as a pollution indicator

Microplastics vary widely in terms of size, shape, and polymer type. Thus, it is substantially more time-intensive to collect toxic effect data through laboratory bioassays that involve various microplastics, taxa, and toxic endpoints, rather than a single toxic chemical; it is also difficult to collect field exposure data that match each other. To our knowledge, none of the environmental criteria and standards for protection of marine life from waterborne microplastics are yet available at the national or international levels. With exponentially increasing research regarding microplastic pollution and efforts to match the sizes and shapes of microplastics used in bioassays, exposure and effect data publication have greatly increased during the past 5 years. Several studies have attempted to derive HC_5 and/or PNEC values that do not harm marine organisms and ecosystems. Despite considerable uncertainty associated with the lack of data regarding chronic toxic effects of non-spherical microplastics on some essential taxa (Jung et al., 2021), the PNEC could be recommended as a tentative target for the maximum concentration. The three PNEC values (6.65, 12, and 121 particles/L) identified in this review covered a range of approximately one order of magnitude. The proposed PNECs should be updated in the future with additional microplastic toxic effect data that reflect more environmentally relevant conditions over time.

When the mean abundance data in North Pacific Ocean waters extracted from the literature were compared with the three PNECs, two values (3.1% of all data) exceeded the lowest PNEC (6.65 particles/L). In this meta-analysis, only mean abundance data were used because raw abundance data were not entirely available and accessible throughout the published literature. If all raw abundance data from oceans worldwide were used for ecological risk assessment, at least four of the mean abundances extracted from the literature would exceed the PNECs. However, abundances >6.65 particles/L (6650 particles/m^3) or higher PNECs (12,000 and 121,000 particles/m^3) have seldom been reported in marine environments. Therefore, if all raw data were available, the percentage of data exceeding the PNEC would have been lower than the percentage based on mean abundance data. Generally, current seawater microplastic levels in the North Pacific and the world's other oceans presumably pose no great ecological risk to marine environments.

However, several studies have indicated a clear increasing trend in terms of marine microplastic pollution in recent decades (Thompson et al., 2004; Claessens et al., 2011; Brandon et al., 2019). The increase in future pollution levels was also predicted in the context of business-as-usual conditions (Everaert et al., 2018; Isobe et al., 2019; Lau et al., 2020). Based on this scenario, a large proportion of future seawater microplastic levels in the North Pacific are expected to significantly exceed the proposed PNECs in 2100, according to data from the present meta-analysis and the study by Jung et al. (2021). Therefore, the proposed PNECs (6650–121,000 particles/m^3) may be a reasonable initial management goal for microplastic pollution in North Pacific seawater. Future monitoring of microplastics in seawater should be planned and conducted in a manner that is compatible with PNECs by considering the sizes and shapes of microplastics to be analysed. Therefore, microplastic data could be used as pollution indicators to assess spatial and temporal distribution, as well as ecological risk, along with management target goals or objectives.

Marine floating macroplastics have had tangible detrimental impacts on marine ecosystems via entanglement, ingestion, harmful organism dispersion, and habitat destruction. Economic damage has also ensued from impacts on tourism, fishing industries, and navigational hazards. Such damage has been reported worldwide, and intensive research has been conducted to estimate economic losses associated with floating marine debris in some regions (Good et al., 2010; McIlgorm et al., 2011; Hong et al., 2017). Despite the well-known environmental and economic threats posed by floating macroplastic debris, its distribution has not yet been investigated comprehensively. Furthermore, the relationship between floating macroplastic abundance and ecological impacts has not been assessed fully. The spatial overlap of the model-based global distributions of floating plastics and the number of seabird species was used to assess seabird plastic-ingestion risk (Wilcox et al., 2015). However, the floating macroplastic abundance that harms marine organisms has not been established.

In this regard, the “good environmental status” (GES) within the Marine Strategies Framework Directive (MSFD) may serve as an example to help improve the pollution status associated with plastic pollution. Marine debris is one of the MSFD descriptors used to evaluate and monitor the ecological status of European marine waters (MSFD, EC, 2008); the MSFD aims to achieve GES in these waters. To assess the achievement of GES, the European countries adjacent to the Mediterranean Sea carefully evaluated floating marine debris levels. Similar efforts should address marine debris in other oceans, including the Pacific and Indian Oceans. To adopt this approach for application to other regions (e.g. the North Pacific), GES or other goals should be defined explicitly and in a sophisticated manner based on comprehensive monitoring surveys. Before the establishment of adverse effect levels for floating macroplastics, such as microplastic PNECs, a target goal should be set to reduce or (at least) maintain current abundance levels in each monitoring region. Practically, it is unrealistic to expect plastic free oceans at present and in the near future. Increased efforts should be invested in measuring marine floating macroplastic abundance levels, which may derive acceptable risk or impacts on marine ecosystems and economies. To achieve this, the development of a standardised monitoring methodology and expansion of the monitoring program are critical considerations. Without these measures, it will remain difficult to compare the levels of floating macroplastics, set mitigation goals, and establish management policies.

5. Conclusion

The monitoring methods and contamination levels of plastics in seawater were reviewed with respect to the North Pacific and the world’s other ocean basins. Larger monitoring efforts of microplastics have been undertaken in the North Pacific compared with other ocean regions, but these surveys were spatially biased toward marginal seas in the Northwest Pacific region. In addition, biased monitoring efforts focusing exclusively on microplastics have frequently been reported, even though macroplastics are a source of microplastics, and monitoring of macroplastics can be conducted using the ship of opportunity program at a lower cost compared with microplastic surveys. Mesoplastics of 5–25 mm in size were often excluded from both micro- and macroplastic monitoring studies, resulting in a missing component of plastic pollution in standing stock assessments.

Methodological factors such as the minimum size, sampling depth, and location of microplastics and the observation height of macroplastics affected plastic particle abundances, hampering data usability and comparability. In this study, we recommend a tiered approach to long-term monitoring of seawater plastic pollution in the North Pacific, covering a wide microplastic size range and addressing the purposes of pollution monitoring and risk assessment, with emphasis on the key aspects that should be maintained.

The North Pacific Ocean is one of the most highly contaminated regions worldwide in terms of microplastic abundance. The present seawater microplastic levels in the North Pacific Ocean presumably pose no great ecological risk to the marine environment, but a large proportion of future seawater microplastic concentrations may significantly exceed the threshold for adverse biological effects. The abundance of plastics in seawater is a useful plastic pollution indicator that provides exposure levels for assessment of ecological risk. Increased effort should be invested in research to determine the pollution levels and characteristics of marine floating plastics associated with risks or impacts on the marine ecosystem and economy.

Credit author statement

W.J.S, S.-K.K and J.L conceptualized this study. J.L, S.E and J.-S.K. collected and compiled data from the literature under the supervision of W.J.S. and S.-K.K.. W.J.S., S.-K.K. and J.L. wrote the original draft, and C.S. contributed to the critical review of the paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2022.119911.

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