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Oceanic microplastics in Japan: A brief review on research protocol and present pollution

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ABSTRACT

Microplastics (MPs) are considered a global threat due to their adverse effects on biota. Although there have been many studies of MPs in the environment and experimental studies of their effects on living organisms, insufficient data is available to assess their pollution. Therefore, we have compiled a research protocol for MP and the current status of their pollution in Japan. This review reports MPs in three locations as sea surface water, seafloor sediments, and coastal sediments. Because mesh size of the nets and location of stations relate to the result, this review highlights the importance of survey designs. Shapes, colors, lengths (size), and polymer type of MPs are related to their distribution and abundance and reveal the origination of MPs, so this review recommends reporting baseline data. Eventually, this review organized future issues.

1. Introduction

The development of synthetic polymers called plastics starts in the 1950s, and total annual production had reached 350 million tons in 2015 (PlasticEurope, 2018). Most waste plastic products are discarded in landfills or recycled (Geyer et al., 2017), but mismanagement or accidents cause the transfer of a proportion of them into the environment. Since the amount of such transferred plastic, especially in the ocean, is enormous 4.8–12.7 million tons y^{-1} (Jambeck et al., 2015); 1.15–2.41 million tons y^{-1} (Lebreton et al., 2017); 0.4–4 million tons y^{-1} (Schmidt et al., 2017), reduction of marine debris is one of the targets of the Sustainable Development Goals, specifically SDGs 14-1. However, since we had found only a portion of marine plastic debris, we need to clarify the fate of missing plastics to achieve such a reduction (Cózar et al., 2014).

Previous studies lined up fragmentation, sedimentation on the seafloor, and migration to living organisms as the destination candidates of missing plastics (e.g., Brandon et al., 2019; Cole et al., 2013). In particular, fragmentation gets attention, and plastic pieces with practically a major diameter of 5000 μm or less (microplastics, MPs; GESAMP, 2019) are a critical topic in the debris fields (Andrady, 2011). MPs exist in the various ocean environments, such as seafloor sediments and even though fish digestive tract (e.g., Bergmann et al., 2017; Cole et al., 2013; Matsuguma et al., 2017; Tanaka and Takada, 2016). Since additives in plastics and persistent organic pollutants adsorbed on plastics are harmful to organisms (e.g., Moore et al., 2001; Yamashita et al., 2016; Yeo et al., 2019), there are concerns about adverse biological effects of MPs.

However, because the knowledge on MPs is insufficient, the widely ranged estimation of the waste plastic transported into the ocean (Jambeck et al., 2015; Lebreton et al., 2017; Schmidt et al., 2017). Pathway of MPs is one of the crucial factors to reveal the fate of MPs, but most surveys had focused on floating MPs on the sea surface; the number of research on MPs in seafloor sediments related to the pathway is still tiny (Andrady, 2011; Cole et al., 2011; Cózar et al., 2014; Uddin et al., 2021). Furthermore, in 2020, although a numerical model simulated efficient transportation of MPs from the surface layers to deeper layers (500 m) by feeding and agglutination by zooplankton, Kvale et al. (2020) could not decide optimum parameters for operating this model because of lack of data.

Although the need for more knowledge of oceanic MPs was highlighted, we faced huge challenges to achieve it. One of the challenges is the lack of data coming from no standardized protocol. Although several institutes have proposed guidelines to harmonize the protocols and many related papers have been published every year, it needs a close examination of protocols used in previous studies to harmonize the protocols. Not only the protocols, but the data handling is also a vital issue for the assessment of MP pollution. Therefore, we review the research protocols for studying marine MPs and the present state of MP

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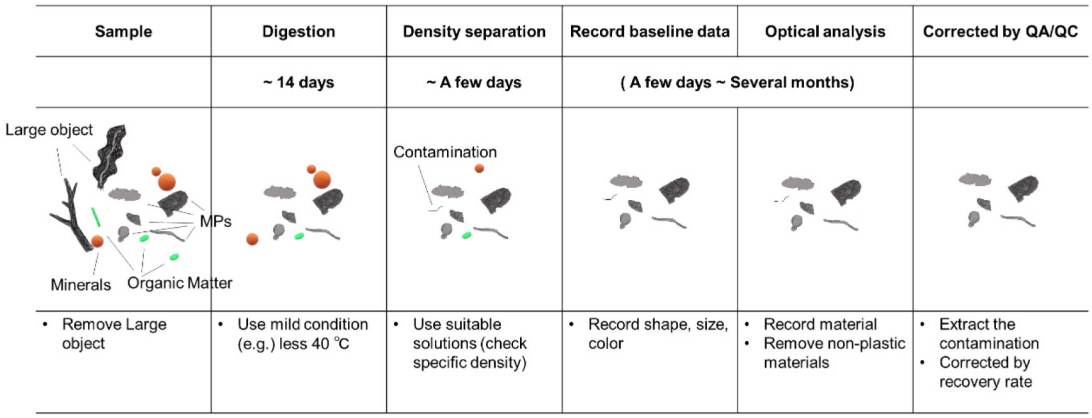

Fig. 1. Schematic diagram showing the process of analyzing microplastics (MPs).

pollution in Japan to rearrange recent achievements. This review contributes to assess of MPs to summarize necessary information on protocols, baseline data.

2. Standardized protocols

Before explaining the fields survey, we should mention the standardized protocol of MP research since crowded methods hinder comparisons among studies (e.g., Frias et al., 2019; Frias and Nash, 2020; GESAMP, 2019; Masura et al., 2015; Michida et al., 2019).

Standardized protocols include pretreatments such as chemical digestion to remove biological particles and density separation to remove denser particles than plastic (e.g., Masura et al., 2015; Muuno et al., 2018; Fig. 1). Chemical digestion methods risk damaging MPs; therefore, some researchers recommend moderate experimental conditions (e.g., lower than 40 degrees by Karami et al. (2017); low concentration of H_2O_2 by Uddin et al. (2020)). Multiple digestion technique was also recommended (Alfonso et al., 2021). In addition, we should attend to the scope of the method because plastic particles may be overlooked during density separation if plastics are denser than the chemical solutions. After pretreatments, standard protocols recommend using optical instruments to identify materials (Isobe et al., 2019; Nakano et al., 2021b).

Here we summarize the optical analysis of MPs by using the Fourier-Transform Infrared spectroscopy (FTIR) procedure, which is popular in Japan (Tables 1–3). Other optical instruments used for identifying MPs, such as the Raman microscope, are summarized in GESAMP (2019) and Nakajima and Yamashita (2020).

The FTIR can measure the Infrared absorption spectrum (IR spectrum). Several ways for operating FTIR exist, and the choice of which one to use depends on the size of the MPs to be analyzed. In the case of visible MPs (>300 µm), the total attenuated reflection method (ATR) is the standard. The measurement condition is 650–4000 cm^{-1} of the wavenumber range, eight cm^{-1} of the resolution, and the number of spectra to estimate the ensemble averaging is preferably four or more.

The analytes are then identified based on the match of their IR spectra to reference spectra in a database (commonly called a library), by the Hit Quality Index (HQI), where a higher value indicates a closer match (e.g., Ushijima et al., 2018). According to previous reports, if the HQI exceeds a threshold, the candidate material is accepted as a match to the material in the library (e.g., Hanke et al., 2013). However, if a biofilm covers the surface of the particle, the IR spectrum of biofilm contaminates. This contamination leads to low HQI. Hence, removing inhibitors by the digestion described above or by cutting the candidate and measuring the cut surfaces is necessary.

After subtracting non-plastic particles by optical identification, we should mention quality assurance/quality control (QA/QC); best practice based on a blank experiment and a recovery test contributes is required (e.g., Rochman et al., 2019). In addition, some researchers proposed a new device to obtain best practices (Nakajima et al., 2019; Tsuchiya et al., 2019). For example, we should prevent the contamination of plastic particles while observation, it was difficult to prevent it because polycarbonate tube was often used in core sampling, in this perspective, Tsuchiya et al. (2019) proposed a core sampling with aluminum tubes.

In any case, since the methods for analyzing MPs are still under development, it is necessary to consider the advantages and disadvantages of different analysis methods and to carefully examine which MPs can be detected by the method before starting a study.

3. Microplastics in the oceanic environment

As was mentioned in the previous section, although protocols are still under development, it is necessary to clarify the fate of MPs in the environment and their effects on organisms. This section summarizes the recommended survey methods and data organization methods for surface water, seafloor sediments, and coastal sediments, and introduces some of the recent research on MPs in the marine environment in Japan.

3.1. Surface water

3.1.1. Sample collection

Surveys of MPs in the surface waters around Japan are summarized in Table 1. Frias et al. (2019) recommended using neuston nets or manta nets for the MP sampling floating on the sea surface with towing speeds of 2–3 knots and towing time of 10–20 min. Since almost all Japanese studies use a neuston net with a mesh size of 350 µm (Isobe et al., 2015; Isobe, 2016; Matsuguma et al., 2017; Nakano et al., 2021a; Sagawa et al., 2018), except for Ripken et al. (2021), who used a manta net with a 300 µm mesh (Table 1), mesh selectivity proposed by Tokai et al. (2021) may not be a problem in intercomparisons of these studies.

Mesh selectivity is described as a function $r\,(l, m)$ of particle size passing a net having a certain mesh size, which is described below

$$l, m\,(l) = \frac{\exp\,(a + bl/m)}{1 + \exp\,(a + bl/m)}, \quad (1)$$

Table 1
Summary of surveys on floating microplastics in surface waters around Japan.

Location	Equipment	Mesh size (μm)	Towing time or sample amount (min or L)	Sieve (μm)	Digestion	Density separation (g/cm^3)	Spectroscopy	Length	Shape					Optical identification	Polymer type	Abundance[b]	Reference
									Fragment	Lines	Film	Foam	Pellet				
East Asian Seas	NN	350	20	–	–	1.0 (Water)	○	MD	○	–	–	○FPS	–	ATR-FTIR	PE, PP	0.03–491.0 (3.74, pcs/m^3)	Isobe et al. (2015)
Seto Inland Sea, Tokyo Bay, Ise Bay, Suruga Bay	NN	350	20	–	–	–	○	MD	○	–	–	–	○ Microbeads	ATR-FTIR	UnKnown	0–11.1 (–, pcs/m^3)	Isobe (2016)
Tokyo Bay	NN	315	20	315, 1000, 5000	○	–	○	–	○	○ Fibers	○ Film, Sheet	–	○ Microbeads	ATR-FTIR	PE, PP	–	Matsuguma et al. (2017)
Hiroshima Bay (Seto Inland Sea)	NN	350	10–15	355, 5600	Not used	1.4 (Unknown)	○	MD	–	–	–	○FPS	–	ATR-FTIR	PE, PP, FPS, PS, Other	0.03–0.24 (–, pcs/m^2)	Sagawa et al. (2018)
Around Yamaguchi (Seto Inland Sea)	G	–	1	1[a]	H_2O_2 + Fenton reaction + 70 °C	1.5 ($ZnCl_2$)	○	–	○ Fragments, Granules	○ Fibers	–	–	–	ATR-FTIR	PE, PP, PET	33.22–77.50 (–, items/L)	Kabir et al. (2020)
Tokyo Bay	NN	350	10–20	100	30% H_2O_2 + Fenton reaction + 40–70°C	1.6 (NaI)	○	MD	○	○Line	○	○ Foam	○ Pellet, Microbeads	ATR-FTIR	PE, PP, PEP, PS, Others	0–17.75 (0.55 or 3.98[c], pcs/m^3)	Nakano et al. (2021a)
Around Okinawa	MN	300	15	300	–	–	○	unknown	–	–	–	–	–	Micro-Raman spectroscopy	PE, PP, PEP, PS, Others	–	Ripken et al. (2021)
Off Nagasaki	NN	350	∼10	–	30% H_2O_2	–	○	MD	○	○Fibers	○	○ Foam	–	ATR-FTIR	PE, PP, PS, Others	0.04–1.71 (0.49, pcs/m^3)	Kobayashi et al. (2021)

NN: Neuston net, G: Grab sampler, MN: Manta net, FPS: Foamed polystyrene, MD: major diameter (longest axis), ATR-FTIR: Fourier Transform Infrared Spectroscopy with attenuated total reflection method, FPS: foamed polystyrene, PE: polyethylene, PP: polypropylene, PS: polystyrene, PET: polyethylene terephthalate, Others: other polymer types were recorded in the paper.

[a] Using PTFE filter with pore size of 1 μm.

[b] Values in a blanket is average.

[c] The first value is January, and the second is May.

Table 2
Summary of surveys on microplastic s in seafloor sediments around Japan.

Location	Equipment	Depth (cm)	Sample amount (g)	Sieve (μm)	Digestion	Density separation (g/cm^3)	Spectroscopy	Length	Shape					Optical identification	Polymer type	Abundance (pcs/kg)	Reference
									Fragment	Lines	Film	Foam	Pellet				
Tokyo Bay	GC	50 or 100	10 (freeze-dried)	315, 1000, 5000	○	1.6 NaI	–	–	○	○ Fibers	○ Film, Sheet	–	○ Microbeads	ATR-FTIR	PE, PP, PEP, PS, PET, PVC, PA, EVA, PAK, PCL	1845–5385	Matsuguma et al. (2017)
Beppu Bay	GC	50	–	355	–	–	○	–	–	–	–	–	–	ATR-FTIR	PE, PP, PS	89	Masumoto et al. (2018)
Hiroshima Bay (Seto Inland Sea)	S. M grab sampler	0–11	–	355, 5600	–	1.7 Unknown	○	MD	○	–	–	○ FPS	–	ATR-FTIR	FPS, PE, PP, PS	24–253	Sagawa et al. (2018)
Tokyo Bay	E.B. grab sampler	0–5	10 (wet)	15	H_2O_2	1.6	○	MD	–	–	–	–	–	μ FTIR	PE, PP, PS, PET, PA, PVC, Others	53,300–145,000	Wang et al. (2021)

GC: gravity corers, E.B.: Ekman Berge bottom sampler, S.M.: Smith-McIntire's bottom sampler, MD: major diameter (longest axis), ATR-FTIR: Fourier Transform Infrared Spectroscopy with attenuated total reflection method FPS: foamed polystyrene, PE: polyethylene, PP: polypropylene, PS: polystyrene, PET: polyethylene terephthalate, PEP: polyethylene polypropylene copolymer, PVC: polyvinyl chloride, PA: polyamide, EVA: Ethylene-Vinyl Acetate, PAK: polyacrylate, PCL: polycaprolactone.

Table 3
Summary of surveys on microplastics in beach sediment in Japan.

Location	Equipment	Depth (cm)	Sample amount (g)	Sieve (μm)	Dry (degree/h)	Digestion	Density separation (g/cm^3)	Spectroscopy	Length	Shape					Optical identification	Polymer-type	Reference
										Fragment	Lines	Film	Foam	Pellet			
Sagami Bay, Tokyo Bay	40 × 40 × 3	3	–	2000, 4750	–	Not used	Not used	○	–	○	–	–	–	○ Pellet	ATR-FTIR	PE, PP, PS, Other	Ikegai et al. (2018)
Seto Inland Sea	25 × 25 × 5	5	500 (dry)	50, 150, 250, 500, 1000, 2000, 5000	90/ 24	H_2O_2 + Fenton reaction +70 °C	1.5 $ZnCl_2$	○	–	○ Fragment, Granules,	○ Fibers	○	–	○ Microbeads	ATR-FTIR	PE, PP, PS, PET, PVA	Kabir et al. (2020)
Hiroshima Bay (Seto Inland Sea)	40 × 40 × 2	1	–	355	–	–	1.7 (Unknown)	○	MD	○	○ Fibers	○ Film, Sheet	–	○ Microbeads	ATR-FTIR	FPS, PE, PP, PS	Sagawa et al. (2018)
Tokyo Bay	100 × 50 × unknown	–	–	1000	–	Formic acid → H_2O_2 → NaOH	–	○	MD etc...	○	○	○	○	○	ATR-FTIR	PE, PP, PS, and others	Tanoiri et al. (2021)

MD: major diameter (longest axis), ATR-FTIR: Fourier Transform Infrared Spectroscopy with attenuated total reflection method, FPS: foamed polystyrene, PE: polyethylene, PP: polypropylene, PS: polystyrene, PET: polyethylene terephthalate, PVA: polyvinyl alcohol.

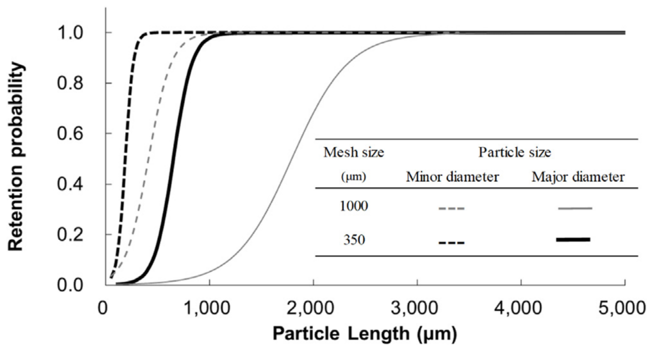

Fig. 2. Retention probability of microplastics (MPs) of varying sizes (particle length) depending on the mesh size, 350 μm (black lines) and 1000 μm (gray lines). Solid lines indicate the predicted probability when considering the major diameter of MPs; dashed lines indicate the predicted probability when considering MPs' minor diameter (shortest length).

where l is the length of MPs and a, b and p are obtained by the maximum likelihood method applied to Eq. (2):

$$L(a, b, p) = \sum \left[N_L \ln \phi(l) + N_S \ln(1 - \phi(l))\right] \quad (2)$$

where $\phi(l) = \frac{p\exp(a+bl)}{1-p\exp(a+bl)}$.
N_L and N_S are the particle numbers collected by a test and control net, respectively. If we use a major diameter φ as 1000 μm, the optimized values of a, b and p are −7.27, 3.67, and 0.5, respectively. This selection curve shows that almost all particles with a φ of more than 3000 (1000) μm are recovered using a net with a mesh size of 1000 μm (350 μm), whereas smaller particles are not recovered (Fig. 2). If we use a minor diameter instead of φ, the length of mesh size matched to a minor diameter of collected MPs. This implies that the number of elongated MPs such as lines/fibers would underestimate compared with spherical MPs; hence, baseline data of MPs required shape information.

Such discrepancy in the number of MPs is also found in grab sampling (Kabir et al., 2020). Their filtration amount was obviously small, but the abundance of fiber was large (several hundred times as in other studies) and that of fragment was small.

3.1.2. MPs in the surface water

We now summarize the main findings of some of the recent studies of MPs in surface water around the coast of Japan and some of the problems that can arise when trying to compare studies.

The average concentration of MPs in the open ocean surrounding Japan was estimated to be 3.74 pcs m^{-3} (Isobe et al., 2015), whereas off the coast of Nagasaki, the concentration was 0.49 pcs m^{-3}; in Tokyo Bay concentrations varied temporally, with 0.55 pcs m^{-3} in January and 3.98 pcs m^{-3} in May (Kobayashi et al., 2021; Nakano et al., 2021a). Although these values are based on the number of MPs sampled by neuston nets and do not consider the proportion of MPs that sink due to the disturbance of the sea surface by winds (Kukulka et al., 2012), the abundance of floating MPs around Japan is likely to be on the order of 10^{-1} to 10 pcs m^{-3}. In addition, the values were converted to area abundance, the amount was 34,000–422,000 pcs/km^2 in Tokyo Bay (Nakano et al., 2021a) and 1,720,000 pcs/km^2 (Isobe et al., 2015). Since higher abundance of MPs have been observed near the coast during high precipitation periods (Kobayashi et al., 2021; Nakano et al., 2021a), it is recommended to monitor floating MPs across seasons.

The type of data recorded in studies of MPs differs depending on the purpose of the study (Table 1), making some comparisons difficult. For example, since some studies do not record MP shapes such as film, line, or pellet, it is difficult to judge whether these shapes are prevalent in the environment or make interregional comparisons. Nevertheless, one interesting observation about foam MPs can be made by comparing the studies in Table 1. Isobe et al. (2015) and Sagawa et al. (2018) described foam particles as foamed polystyrene (FPS) because almost all of them were polystyrene (PS), whereas Nakano et al. (2021a) found foamed MPs made not only of PS but also PP and PE, and thus described them as foam. These studies' main composition of foamed plastics varied depending on the region from which they were sampled, such as the open sea, Hiroshima Bay, or Tokyo Bay. Thus, these differences may be due to regional differences in the use of foamed plastics. In fact, in Hiroshima Bay, it has been pointed out that many MPs originate from the Styrofoam buoys used in oyster farming.

An example highlighting the importance of recording consistent data is the studies of Nakano et al. (2021a) and Tanoiri et al. (2021), who found many green flat particles not recorded in other published studies on suspended MPs. Since Ikegai et al. (2018) found MPs having same characteristics as them in coastal sediment and pointed out the original commercial goods, we could point out the obvious contamination of green flat particles from the land source.

Although PE and PP were the major types of plastic found in most studies in Japan (e.g., Hiroshima Bay; Sagawa et al., 2018), copolymer of them was not negligible in Tokyo Bay (Matsuguma et al., 2017; Nakano et al., 2021a); several possible reasons for this difference exist. The first one is the difference of the spectral libraries used for material determination. To help prevent this problem, it is recommended to describing which library used for material determination. The second reason is the variation in the person's skill level judging the match between sample and library spectra. The last reason is that copolymer might be significantly major used around Tokyo Bay; to point out this, more monitoring is required.

One point to note when comparing studies is the reported length of MP. The 'longest length' is often recorded, but Ripken et al. (2021) did not show the kinds of length. If they use other definition of the length as an average etc…, their reported size of MPs might be small compared to that reported in other studies. Therefore, the size definition should be expressed in a paper. In addition to the length, note that the size distribution of MPs depends on the net's mesh size as was mentioned above. Thus, to compare the size of MPs reported in published studies, we should also consider mesh selectivity.

3.2. Seafloor sediments

3.2.1. Sample collection

Samplings of MPs in seafloor sediments have been carried out by using gravity corers and grab samplers (Masumoto et al., 2018; Matsuguma et al., 2017; Sagawa et al., 2018; Wang et al., 2021); Table 2. Globally, only a few studies have focused on the vertical profile or depositional flux of MPs in sediment (Ballent et al., 2016; Brandon et al., 2019; Chen et al., 2020; Courtene-Jones et al., 2020; Li et al., 2020; Masumoto et al., 2018; Uddin et al., 2021), despite this information being needed to help reveal the pathways by which plastic goes missing in the environment. Therefore, more surveys using core samplers are required.

3.2.2. MP Contamination in the seafloor sediment

Several studies recognized MP contamination in the seafloor sediment (Masumoto et al., 2018; Matsuguma et al., 2017; Wang et al., 2021). The abundance of MP was 89 pcs kg^{-1}-dry weight in Ohita Bay, 24–253 pcs kg^{-1}-dry weight in Hiroshima Bay and

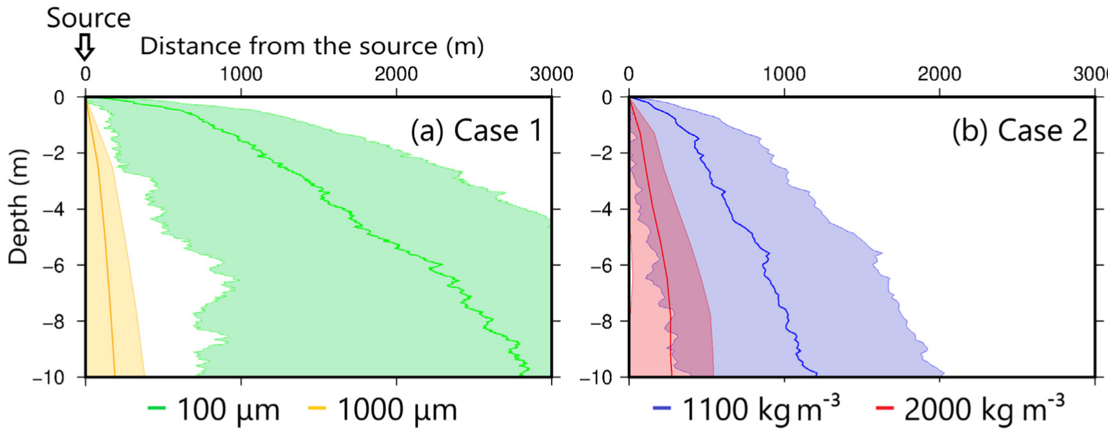

Fig. 3. Schematics of the simulated sinking behavior of MPs; (a) case 1: different particle sizes with the same density (1500 kg m^{-3}) and (b) case 2: particles with different densities but constant sizes (500 µm). Horizontal distance was computed by random fluctuation from the source. The thick lines show the average position calculated from 100 particles and the shaded areas indicate the standard deviation of the particle location.

53,300–145,000 pcs kg^{-1}-dry weight in Tokyo Bay. The abundance in Tokyo Bay seems to be high compared to other reports, but this is because the measurable size range of the micro-FTIR method used by Wang et al. (2021). Since micro-FTIR can measure the range of 20–5000 µm, Wang et al. (2021) included smaller particles compared to other studies.

In Tokyo Bay, Wang et al. (2021) did not find any large MPs but Matsuguma et al. (2017) did it. Such difference is expressed by a vertical two-dimensional numerical analysis using random horizontal motion, Stokes drift, and Stokes' equation (modified from Isobe et al., 2014). In this model, the horizontal velocity, u, is expressed by the following equation:

$$u = \frac{-a^2 \sigma k \cosh\{2k(h+z)\}}{2\left\{\cosh^2(kh)\right\}} + \frac{R\sqrt{2K_h \Delta t}}{\Delta t}, \quad (3)$$

where for the sea surface wave, a is the amplitude, σ is the wavelength, k is the wavenumber, R is a random number between -1 and 1, K_h is the horizontal diffusivity and Δt is the time step. For the vertical velocity, w, the equation used depends on the Reynolds number, Re:

$$w = d^2\left(\rho - \rho'\right) g/18\eta + R\sqrt{2K_z \Delta t}/\Delta t, Re < 1, \quad (4)$$

$$w = 0.223d\{\left(\rho - \rho'\right)^2 g^2/(\rho\eta)\}^{1/3} + R\sqrt{2K_z \Delta t}/\Delta t, 1 \leqslant Re \leqslant 100, \quad (5)$$

$$w = 1.82\left\{\frac{\left(\rho - \rho'\right) gd}{\rho}\right\}^{1/2} + R\sqrt{2K_z \Delta t}/\Delta t, 100 < Re, \quad (6)$$

where d is the particle size, h is the water depth, ρ is the density of seawater, ρ' is the density of the particles, g is the acceleration of gravity, η is the viscosity coefficient, and Kz is the vertical eddy diffusivity.

When the particle setting of different sizes (100, 500, and 1000 µm) was simulated in this numerical model, it was found that the larger a particle's size, the faster it sank (Fig. 3, left). In addition, the results of simulations using particles of different densities (1100, 2000 kg m^{-3}) showed that the denser the particle, the faster it sank (Fig. 3, right). Taken together, the deposit flux (number of particles) of MPs and the sediments polymer characteristics (size and composition) depend on the distance of the sampling location from the MP source. Therefore, this review recommends deploying several observed points following the currents' direction of the coastal region (river or landside to open ocean), if we survey the MPs contamination in the seafloor sediments.

The depositional flux to the seafloor has increased exponentially since the 1950s (e.g., Martin et al., 2020), and its value in recent years are 2.17 pcs m^{-2} y^{-1} in Ohita Bay, 6 × 10^{12} pcs m^{-2} y^{-1} in Tokyo Bay (Masumoto et al., 2018; Wang et al., 2021). The flux range was large because of the difference in the size of MPs that could be detected by them. Therefore, we should carefully consider the values and size which can be detected.

3.3. Coastal sediments

3.3.1. Sample collection

Microplastics in coastal sediments are collected by scooping up the surface sediment from inside a quadrat (Table 3; Ikegai et al., 2018; Kabir et al., 2020; Sagawa et al., 2018; Tanoiri et al., 2021). Of the four studies conducted in Japan, two used a 40 cm × 40 cm quadrat (Ikegai et al., 2018; Sagawa et al., 2018), one used a 25 cm × 25 cm quadrat (Kabir et al., 2020), and one used a 100 cm × 50 cm quadrat (Tanoiri et al., 2021). Every study collected the surface sediments (2–5 cm). Ikegai et al. (2018) collected samples from the intertidal zone, while Tanoiri et al. (2021) focused on the tidal flat. Because Frias et al. (2018) recommend at least three subsamples and three locations per beach (one at the highest tide line, one at the lowest tide line, and one in the intertidal zone) and collecting samples once in each season, we should conduct such observation in Japan.

After collecting, candidate particles are processed in the same way as those collected from surface water or seafloor sediments, i.e., they are treated by oxidation and specific gravity separation and then identified by optical analysis.

3.3.2. MP Contamination in coastal sediment

Only three studies have assessed MPs in coastal sediments in Japan (although Tanoiri et al. (2021) collected samples of coastal sediments, they did not characterize the nature of MPs in the environment). In addition, two of the three studies did not report baseline data of MPs; rather, they focused on the presence of location-specific MPs, which could be useful in determining the commercial goods from which MP particles originated. For example, Sagawa et al. (2018) reported MP concentrations of 5–1245 pcs kg^{-1}-dry sediments on a beach facing Hiroshima Bay. Most of them were FPS (5–1206 pcs kg^{-1}-dry sediments). Since FPS is frequently used for oyster farming in Hiroshima Bay, Sagawa et al. (2018) assumed that the MPs found in their study originated from oyster farming. Ikegai et al. (2018) summarized the MPs that had drifted ashore in Sagami Bay, and showed that pellets, capsule-like particles, and green flat particles were predominant.

The capsule-like particles are thought to be the shells of coated fertilizers used in agriculture (Katsumi et al., 2020, 2021); The green flat particles were thought to be the same as those observed by Nakano et al. (2021a) and Tanoiri et al. (2021) and were assumed to come from artificial grass.

However, no reports are summarizing the data on coastal sediment MPs in a unified manner, and comparison among published studies is not easy. Therefore, it is recommended to conduct surveys following the experimental design guidelines of Frias et al. (2018) and to analyze the data by using the methods described in Section 2.

4. Future remarks

Elucidating the fate of MPs in the marine environment requires the examination of the history of MP deposition, MP degradation, the alteration of MP sinking velocity due to biofilms, and MP resuspension (Ye and Andrady, 1991; Rummel et al., 2017). While research in these fields is ongoing, much remains unknown. For example, in the case of photodegradation, there is a gap between the rates of degradation observed in experiments and those stated in the literature (Nelson et al., 2021). In addition, it is known that bio-fouling times depend on the shape of particles (Chubarenko et al., 2016), so it has been suggested that the fate of MP differs depending on its shape; however, no studies have tested this hypothesis. Another area that needs further investigation is MP deposition and resuspension. As disturbance processes near the seafloor redistribute MPs to both the deeper sediments and the overlying water (Xia et al., 2021), MP deposition's effects on organisms are complex.

In the case of large plastic debris, the effects of ingestion and chemicals derived from plastics are known (Yamashita et al., 2016), and similar effects are feared for MPs. In fact, in a laboratory experiment in which terrestrial snails were exposed to fibers, a concentration of 0.01% MPs in the sediment was reported to induce reduced feeding and to damage chorionic villi (Song et al., 2019). In addition, research on MPs in marine organisms continues to expand (Nakao et al., 2019; Ushijima et al., 2018) following the initial discovery of microbeads in the digestive tracks of anchovies in Tokyo Bay (Tanaka and Takada, 2016). It has been pointed out that differences in the feeding methods of various marine organisms are related to the number of MPs that are ingested (Ushijima et al., 2018). Thus, both laboratory experiments and environmental studies have been conducted to evaluate the effects of MPs on ecosystems and understand their transfer pathways. Unfortunately, however, previous reports are insufficient to clarify the concentrations and characteristics of MPs transferred to the environment, and domestic data that can be used to assess the effects of MPs on organisms do not exist as of 2021. For example, in most cases, MPs in the experimental environment are expressed in terms of the mass concentration, whereas MPs in sediments are often expressed in terms of the number of particles, thereby hindering direct comparison with the experimental environment (e.g., Tanoiri et al., 2021). Therefore, it is necessary to accumulate baseline data on the nature of MPs (shapes, colors, lengths, polymer type, mass) in the marine environment by following the survey design introduced in this review and subsequently evaluate MP impacts on organisms.

CRediT authorship contribution statement

Haruka Nakano: Conceptualization, Writing – original draft. **Hisayuki Arakawa:** Project administration, Resources, Validation, Writing – review & editing.

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.

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