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Factors Influencing the Spatial Variation of Microplastics on High-Tidal Coastal Beaches in Korea

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Abstract The presence and distribution characteristics of microplastics become a big issue due to the adverse effects on marine organisms caused by not only microplastics but any incorporated and/or adsorbed pollutants. Distribution of microplastics (50- to 5000-μm size) was determined for three sandy beaches on an isolated island in a high-tidal costal region to elucidate spatial distributions in relation to beach locations. The abundances of microplastics ($n = 21$) measured were 56–285,673 (46,334 ± 71,291) particles/m^2 corresponding to the highest level globally. Out of observed polymer types, expanded polystyrene was overwhelmingly dominant. Although lying toward the estuary of the largest river in the country, the north-side beach contained a 100-fold lower abundance than two south-side beaches that faced southerly wind and currents that were prevalent throughout the study season. In addition, distinct differences between the beaches on either side were also present in terms of size distribution and spatial homogeneity of microplastics on the same beach. Winds and currents are therefore considered to be the driving forces in the distribution of microplastics.

The commercial manufacture of plastics has increased rapidly in recent years and is estimated to be 308 million tons annually (Andrady and Neal 2009). Approximately 10 % of total plastics produced in the world are estimated to reach and end up in marine environment with no removal or reuse (Thompson 2006). According to previous studies (Derraik 2002; Barnes et al. 2009), plastic debris accounts for 60–80 % of marine litters.

Macrosized plastics in marine environments are physically, biologically, or chemically degraded and broken down into nanosized and microsized particles (Andrady 2011; Hidalgo-Ruz et al. 2012). These weathered particles, with size smaller than a few millimeters, are categorized as "microplastics" (Cole et al. 2011; Hidalgo-Ruz et al. 2012) together with primary plastic particles, which are manufactured to be of a microsize for products such as cosmetics, air-blasting media, and medicines (Moore 2008; Cole et al. 2011).

Due to the small size of microplastics, a variety of marine organisms are reported to mistake microplastics for prey and to ingest the particles (Browne et al. 2008; Lee et al. 2013a; Wright et al. 2013). The microplastics in the marine environment is of considerable concern not only because various hazardous chemicals are used as additives to achieve softness, resistance to degradation, and/or durability (Browne et al. 2007; Thompson et al. 2009), but

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because microplastics can accumulate hydrophobic pollutants by 10^5 times more times than the surrounding seawater (Van et al. 2012). Therefore, microplastics are suspected to be a vector transferring incorporated or adsorbed harmful chemicals into the marine food chain (Teuten et al. 2007; Tanaka et al. 2013).

The levels and kinds of incorporated additives and/or adsorbed pollutants differ with the size, polymer type, and weathering extent of microplastic (Endo et al. 2005; Teuten et al. 2007). Thus, determining the occurrence and distribution characteristics of microplastics in a qualitative and quantitative manner is a prerequisite for the further risk assessment of microplastics and microplastic-derived pollutants. However, no global consensus on the cut-off size and sampling methods used for investigating "microplastics" has been agreed upon (Hidalgo-Ruz et al. 2012). Recently, dramatic discrepancies caused by the different sampling methods used in analyzing seawater (Chae et al. 2014; Song et al. 2014), or different sampling stations on beach sediment (Heo et al. 2013), have been observed in the recorded abundance and composition pattern of microplastics. It is therefore considered that a standard sampling protocol is required to make an accurate representation of the distribution of microplastics.

It is also evident that the wind, currents, and waves transporting the floating plastics are driving forces influencing the abundance and distribution of microplastics, and to the authors' knowledge, little has been reported about the importance of these factors. Therefore, this study aimed to elucidate (1) the effect of location of sandy beaches in relation to the variation in abundance and distribution of microplastics in high-tidal coastal region and (2) whether this is an indirect indicator of the influence of physical driving forces such as the wind, current, or tide.

Materials and Methods

Sampling

Study Area

Incheon–Kyeonggi coastal sea, which is located in the mid-west of the Korean peninsula, is considered to be a representative coastal region, where various terrestrial and marine human activities are concentrated and an extreme tidal range (on average approximately 9 m) is formed (Fig. 1). Large coastal cities are developed along the shoreline of this region, including Incheon city (population of approximately 3 million) and Ansan/Shiheung city (population of approximately 1 million). Incheon harbor, the second largest international harbor in Korea, is located to the west of Incheon city and hosts >17,000 vessels/ships annually. The estuary of the Han River, a direct input pathway of terrestrial materials, lies the northern part of the Incheon–Kyeonggi coastal sea. The Han River flows across the largest watershed in Korea (approximately 26,000 km^2) through the most populated city [Seoul (population of 40 million)] and discharges approximately 4 million tons/day of freshwater to the estuary (Kim 2012).

In addition to terrestrial inputs, marine activities (including those of fisheries and aquaculture) contribute to the input of marine litter and/or microplastics in the sea. A number of small-size piers used by fisheries are located along the shoreline, as well as sea-farms for seaweed, shellfish, and fish, are ubiquitously distributed offshore.

Soya Island (area 3.03 km^2; shoreline length 13 km) was selected as the study area. It is located approximately 68 km southwest of the Han River estuary and approximately 48 km southwest of the Incheon city/harbor and faces the Yellow sea to the west (Fig. 1). A majority of terrestrial input sources are located at the northeast region of the island. The Island was selected for the following reasons:

- It has several sandy beaches that lie in varying directions. Therefore, this study was able to investigate the distribution characteristics of microplastics on each beach and evaluate the effect of currents and/or the wind in delivering the plastic litters and/or microplastics.
- It lies at an adequate distance from the inland shoreline to directly reflect semidiurnal or seasonal changes in the direction of the wind or the tidal/sea current. As shown in Fig. 1, a semidiurnal tide flowing northeasterly at the ebb tide and southwesterly at the flood tide passes different sides of the island, respectively. Under the monsoon, the wind (and sea current) blows southerly in summer and northerly in winter in this region. These changes can cause seasonal changes in the input pathway of microplastics to this island.
- The beaches on this small-sized and distantly located island experience only minimal disturbance from tourists (<several tens people/day in the summer season) compared with most of the beaches along the inland shoreline which are disturbed extensively by large numbers of tourists.

Three beaches (SID, SIT, and SIB) out of a total six beaches on the island were selected in relation to their direction, accessibility, existence of high strandline (some beaches where breakwaters were built were excluded), and minimal disturbance by human activities. Within 1 month before sampling, there were no human disturbances for SID and SIB, but residents performed a beach-clearing activity on SIT to clear off any visible macro-marine litters. Two islands (SID and SIT) are situated in the south (SID in the southwest; SIT in the south), and one island (SIB) is located in the north (the northeast).

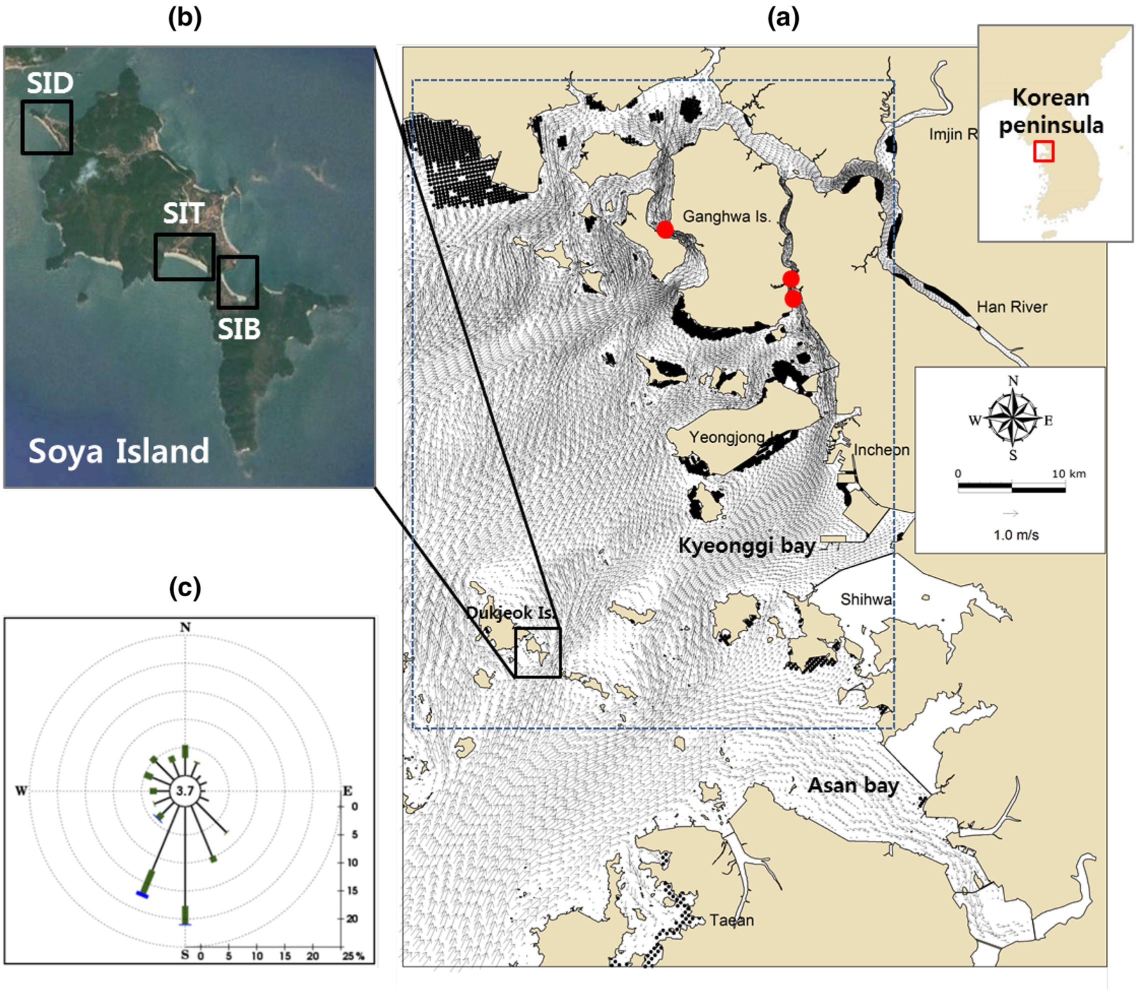


Fig. 1 **a** Study area and location map: The *small arrows* on the coastal seas indicate the directions and maximum velocities of the flood tidal current during spring period in July to August 2013 (the model used is the so-called Environmental Fluid Dynamics Code, and it showed good model performance for simulating tidal currents in Kyeonggi bay (Yoon and Woo 2013). The *dotted quadrangle* and *three red-filled circles* indicate the area of the Incheon–Kyeonggi coastal region and marine litter–clearing spots, respectively. **b** The location of three beaches in Soya Island (SID, SIT, and SIB), situated in a southwest (SW), south (S), and northeast (NS) direction, respectively. **c** Wind-rose measured by a marine buoy observatory at Dukjeok Island (August 2013), which is located near Soya Island [quoted from the Korea Meteorological Administration report (2013)] (Color figure online)

Sample Collection

Microplastics on three sandy beaches were collected from 26 to 27 July 2013. The distribution of microplastics can vary in relation to the action of waves in foreshore and from the action of wind on the backshore over a high strandline (Heo et al. 2013). Therefore, the high strandlines represent the microplastic distribution on each beach (McDermid and McMullen 2004; Lee et al. 2013b). In this study, every high strandline was divided into 9–14 districts using the same interval spacing (approximately 30 m) from the far-right to the far-left side. Sampling stations ($n = 8$–13) for sediments were then assigned at the boundaries of the individual districts (Fig. S1).

The whole surface sediment in a grid of 50 cm (length) × 50 cm (width) × 2 cm (depth) at each station was skimmed off and was sequentially sieved through stainless steel sieves with a nominal pore sizes of 5000 and 1000 µm. Total samples of >5000 and 1000–5000 µm, and 1 mL of homogenized samples <1000 µm, were each stored in a polyethylene bag and transported to the laboratory.

Qualitative and Quantitative Determination of Microplastics

Size Separation

First, microplastics 1000- to 5000-μm in size in samples were floated in saturated NaCl solution (specific density 2.16 g/cm^3) to separate them from any interfering particles. All floating materials in NaCl solution were picked out using a 1000-μm pore-sized sieve and then dried for 24 h at room temperature (or 60 °C). Dried 1000- to 5000-μm particles were sequentially sieved through 4000-, 2800-, 2000-, and 1000-μm pore-sized sieves, and thereafter all of the plastic-like particles in each size category (i.e., 4000–5000, 2800–4000, 2000–2800, and 1000–2000 μm) were picked out by the naked eye. Plastic-like particles in each size category were again separated into expanded polystyrene (EPS) (which is fragmented from Styrofoam products) and non-EPS particles.

For plastics <1000 μm in size, the supernatant of saturated NaCl solution passing through a 1000-μm pore-sized sieve was filtered sequentially through 500- and 300-μm pore-sized sieves and finally a glass fiber filter (0.75 μm, 47 mm Ø; Whatman). After drying at 60 °C, the plastic-like particles in the 500- to 1000- and 300- to 500-μm categories were sorted visually using a microscope (Stemi DV/4; Carl Ziess, Germany).

After visual sorting, spectroscopic analysis was performed to confirm the presence of plastic particles and to identify their polymer type. For all of the size categories up to >300 μm, the total number of plastic-like particles sorted visually was perfectly reproduced using spectroscopic analysis (slope >0.99 and $r^2 = 1$ on 1:1 linear regression line), thus indicating no significant errors in visually sorting plastics from the sample mixture. The smallest plastic particles (50–300 μm) were directly counted and identified on dried filter paper using a Fourier transform–infrared spectroscopy (FT-IR) miscroscope as described in our previous study (Chae et al. 2014).

Synthetic Polymer Identification

Spectroscopic analysis was performed using FT-IR as described in detail in our previous study (Chae et al. 2014). In brief, plastic-like particles >300 and <300 μm in size were analyzed using a vacuum FT-IR spectroscope (VERTEX 80 V; Bruker, Germany) and an FT-IR microscope (HYPERION 2000; Bruker, Germany), respectively. Synthetic polymers of the plastic-like particles were identified and confirmed by matching with a FT-IR polymer spectrum library. All spectra were recorded as 20 scans in the spectral range of 8000–650 cm^{-1} at a resolution of 4 cm^{-1}.

Synthetic polymers identified in this study were polypropylene (PP), polyethylene (PE), polystyrene (PS), polyvinyl sulfate, polyurethane foam (PUF), EPS, paraffin, polyamide, ethylene–vinyl acetate, and acrylonitrile butadiene styrene. Microplastics were classified into seven size categories (4000–5000, 2800–4000, 2000–2800, 1000–2000, 500–1000, 300–500, and 50–300 μm), and all concentrations (particles/m^2) were based on FT-IR analysis.

Statistical Analysis

Nonparametric statistical analyses were performed using software [SPSS IBM Statistics, version 21 (Chicago, IL)]. Krusakal–Wallis test and Mann–Whitney rank-sum test were used to test the differences in abundances of EPS or non-EPS polymers among the three beaches and between any two beaches, respectively. Spearman's rank correlation coefficients were determined for correlations among EPS, non-EPS, PP, and PE and among size classes of EPS or non-EPS.

Results

Comparison of Mean Distribution Among Beaches

Mean Abundance

The mean abundance (±SD) of the entire microplastics (<5000 μm) found on three sandy beaches, expressed as the number of particles per square meter (particles/m^2), was 119,182 ± 96,885 at SID, 46,669 ± 44,614 at SIT, and 1247 ± 918 at SIB (Table 1). The SIB beach, which is situated on the northeastern side of the island and is therefore expected to receive more abundant plastic litter and particles originating from the Han River, had a microplastic abundance between 40 and 100 times lower than that of SID and SIT, which are located in the south or southwest of the island, respectively.

Significant differences in the standing stocks of EPS and non-EPS particles were exhibited among the three beaches (Kruskal–Wallis test; $p < 0.01$ for EPS and $p = 0.017$ for non-EPS). This was ascribed to differences between the two south-side beaches (i.e., SID and SIT) and the north-side beach (i.e., SIB) ($p < 0.01$ for EPS and $p < 0.05$ for non-EPS) but not between the two south-side beaches ($p = 0.062$ for EPS and $p = 0.859$ for non-EPS) according to the Mann–Whitney test.

Composition of Polymer Type

The most abundant microplastic particle found on all of three beaches was EPS, which was fragmented from

Table 1 Abundances of EPS and non-EPS plastic particles found in three beaches

Size (μm)	EPS (particles/m^2)			Non-EPS (particles/m^2)		
	SID ($n = 8$)	SIT ($n = 10$)	SIB ($n = 13$)	SID ($n = 8$)	SIT ($n = 10$)	SIB ($n = 13$)
>5000	2287 ± 2387 (8)	286 ± 280 (10)	4 ± 6 (5)	108 ± 88 (8)	42 ± 44 (9)	1 ± 2 (2)
4000–5000	2638 ± 2622 (8)	281 ± 217 (10)	2 ± 5 (4)	45 ± 39 (8)	36 ± 51 (6)	1 ± 2 (3)
2800–4000	23,200 ± 21,671 (8)	3614 ± 2261 (10)	35 ± 63 (9)	99 ± 99 (8)	147 ± 234 (9)	2 ± 3 (5)
2000–2800	31,573 ± 29,459 (8)	7593 ± 4831 (10)	49 ± 76 (12)	54 ± 50 (8)	134 ± 145 (8)	2 ± 4 (4)
1000–2000	38,076 ± 31,866 (8)	17,324 ± 17,996 (10)	147 ± 217 (13)	47 ± 48 (8)	88 ± 120 (7)	6 ± 9 (6)
500–1000	18,533 ± 12,993 (8)	13,739 ± 22,112 (10)	346 ± 495 (13)	58 ± 33 (8)	134 ± 207 (7)	12 ± 17 (6)
300–500	2175 ± 1716	1534 ± 1986 (10)	91 ± 138 (11)	0	12 ± 28 (2)	3 ± 8 (2)
50–300	2688 ± 1621 (8)	2031 ± 2024 (10)	463 ± 543 (8)	0	0 (0)	88 ± 181 (3)
Total[a]	118,168 ± 96,688	46,118 ± 44,017	1133 ± 938	301 ± 227	551 ± 621	114 ± 180

Styrofoam (Table 1; Fig. 2). On average, EPS particles accounted for >99 % of total microplastics on both SID and SIT and 87 % on SIB of total microplastics. The dominance of EPS particles (>90 %) was also observed in all size categories and at all stations of three beaches except for within some size groups and stations of SIB.

The second-most abundant polymer-types were PP and PE, and their abundances were 135 ± 112 particles/m^2 (0.13 ± 0.09 % of total microplastics) and 96 ± 74 particles/m^2 (0.10 ± 0.05 %), respectively, in SID; 236 ± 305 particles/m^2 (0.43 ± 0.53 %) and 244 ± 276 particles/m^2 (0.32 ± 0.29 %), respectively, in SIT; and 108 ± 188 particles/m^2 (12.2 ± 25.2 %) and 7 ± 10 particles/m^2 (0.48 ± 0.79 %), respectively, in SIB. Among the abundance of total non-EPS plastic particles, PP and PE accounted for 75 ± 13 % in SID, 59 ± 37 % in SIT, and 85 ± 33 % in SIB followed by PUF and PS, which accounted for on average 5–34 % and 3–9 %, respectively. Other polymer types were rarely found with an average abundance of <5 particles/m^2.

Mean Size Distribution

For EPS particles, the 1000- to 2000-μm size class was the most abundant on both SID and SIT beaches accounting for 33 ± 6 % and 32 ± 15 % of the total EPS particles, respectively (Fig. 2). With a decrease in the size class, the abundance of EPS increased exponentially to 1000–2000 μm and thereafter decreased exponentially. Unlike the bell-shaped size distribution observed in these two beaches, the abundance of EPS on SIB increased exponentially with a decrease in size class to the smallest size class of 50–300 μm.

Mean size distributions of non-EPS particles also exhibited a distinct difference between the two beaches on the southern side (i.e., SID and SIT) and the beach on the northern side (i.e., SIB) (Table 1; Fig. 2). On the two southern-side beaches, the size class of <1000 μm was rarely found and abundance of the >1000-μm size class was distributed uniformly with no significant difference among the size classes (Kruskal–Wallis test; $p > 0.05$). In contrast, the most abundant size class on the northern side beach was 50–300 μm. However, it is necessary to note that non-EPS particles were rarely observed on SIB (as discussed later in the text). The mean size distributions of non-EPS particles were different to those of EPS particles on the same beach.

Spatial Distribution on Each Beach

Abundance

The abundance of EPS particles in individual stations ranged from 27,749 to 285,221 particles/m^2 on SID, from 5667 to 137,860 particles/m^2 on SIT, and from 56 to 3260 particles/m^2 on SIB. Despite of the differences (a maximum 10- to 60-fold among the stations on the same beach), the abundance of EPS was found in a longitudinal gradient along the high strandline from one end of the beach to the other end, particularly on SID and SIT (Fig. 3). Similarly, the abundance of non-EPS differed by a maximum factor of several tens among the stations but was also spatially distributed on a gradient according to the distribution of EPS. Good correlations in abundance were observed between EPS and non-EPS on SID or SIT (Fig. 4a). However, unlike the strong correlations found on southern-side beaches (Spearman rho = 0.71; $p < 0.05$ for SID; Spearman rho = 0.93; $p < 0.001$ for SIT), the non-EPS abundance on SIB was not correlated with the EPS abundance (spearman rho = 0.061; $p > 0.05$). The abundance of PP and PE, two major non-EPS polymer types found, also showed strong correlations on SID (spearman

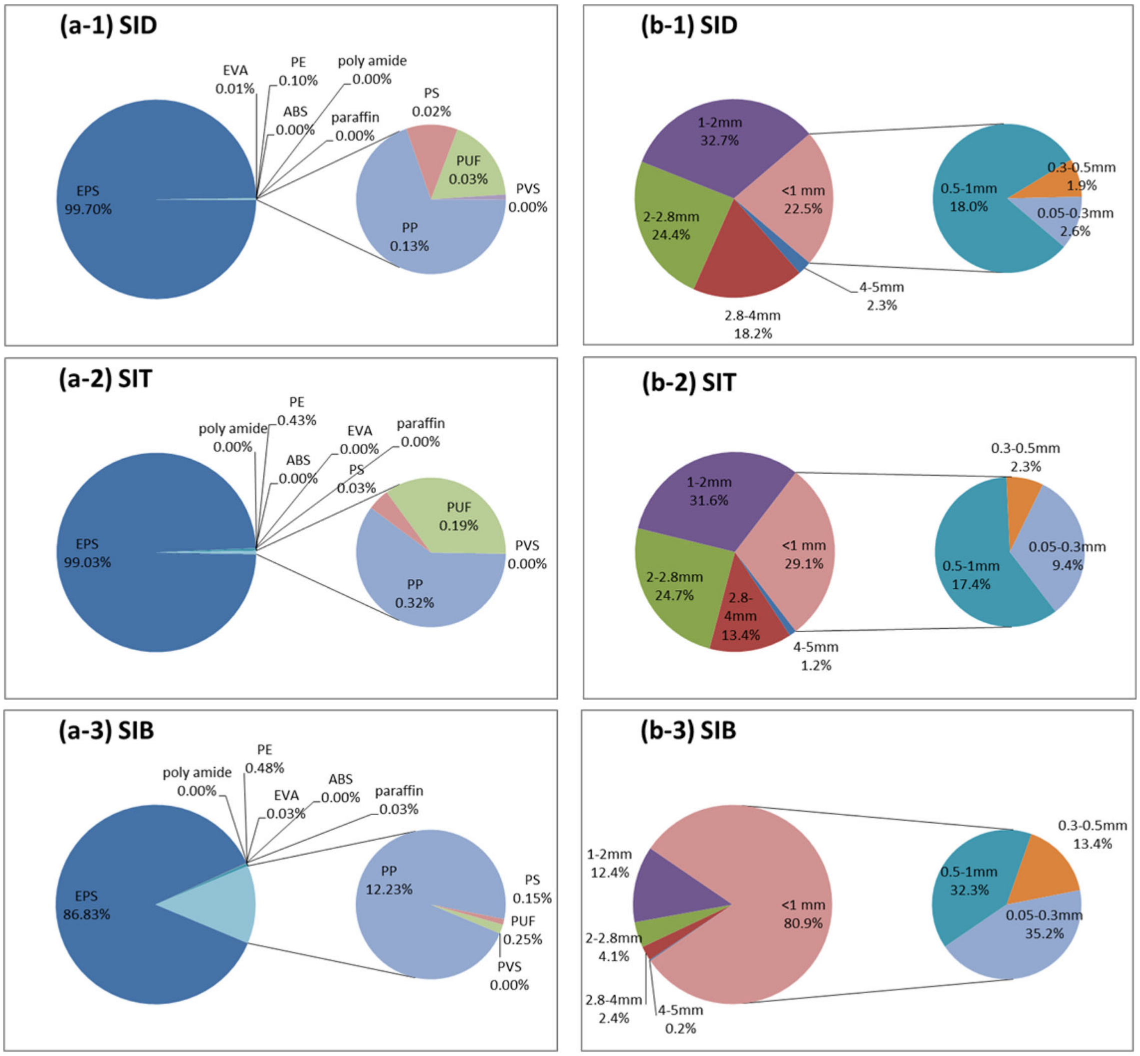


Fig. 2 Mean composition pattern of microplastics in three beaches: **a** polymer types and **b** size classes (Color figure online)

rho = 0.88; $p < 0.01$) and SIT (spearman rho = 0.84; $p < 0.01$), but no correlation was found on SIB (spearman rho = 0.23; $p > 0.05$) (Fig. 4b).

Size Distribution

The relative compositions of the size distributions of microplastic particles were compared between the stations (Fig. 5). The spatial homogeneity of EPS size distribution was strongly established for stations on SID and SIT and, to a lesser extent, on SIB. Consequently, there were significant correlations among all size classes on SID, between most size classes on SIT, and some size classes on SIB ($p < 0.05$, Table 1 and Table S1). The size distribution of non-EPS particles was heterogeneous in space. Nevertheless, significant correlations were present among some size classes on SID and SIT, but there were no correlations on SIB (Table 1 and Table S2).

Discussion

Source of EPS

The type of microplastic found in this study was overwhelmingly represented by EPS, similar with those observed in south coasts of Korean peninsula (Lee et al. 2013b; Heo et al. 2013). EPS produced in Korea accounts for 2.7 % of global production, and the country produces 200,000 tons annually including 2500 tons for marine floating-buoys (Hong et al. 2013). In 2012, fishes, shellfishes, and seaweeds were harvested in the area of 500 ha within the Incheon–Kyeonggi coastal sea and a total of 4100 hectares (if Chungnam Province's coastal sea is included) (south of Kyeonggi coastal region) [Korea Statistical Information Service (http://kosis.kr)]. Styrofoam buoys without covers are used to float marine gear for aquaculture or catching fish in these coastal regions (see

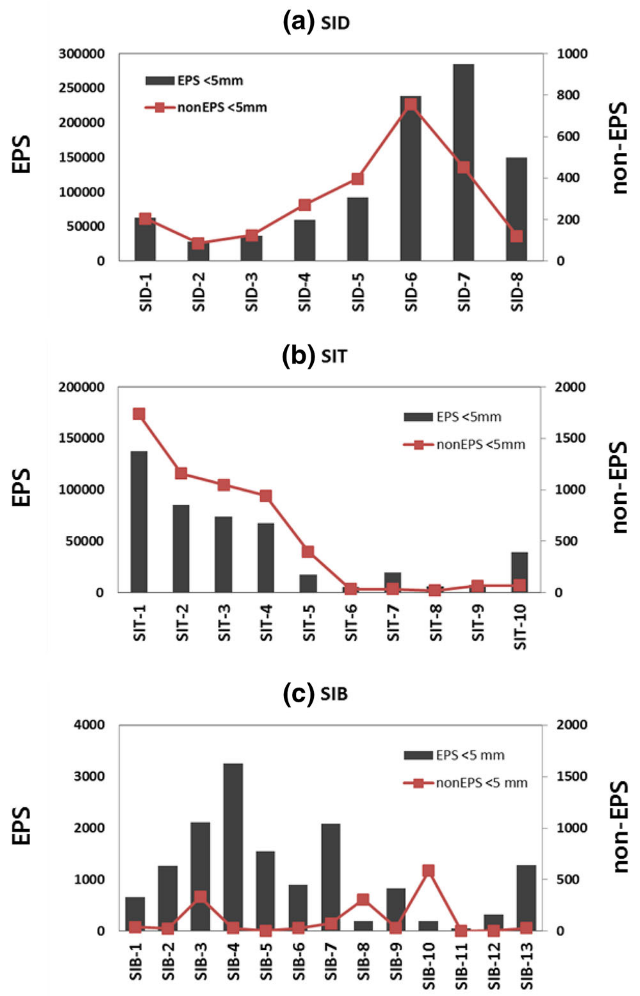


Fig. 3 Spatial distribution of the abundances of EPS and non-EPS (≤5000 μm particles/m^2) on the same beach (Color figure online)

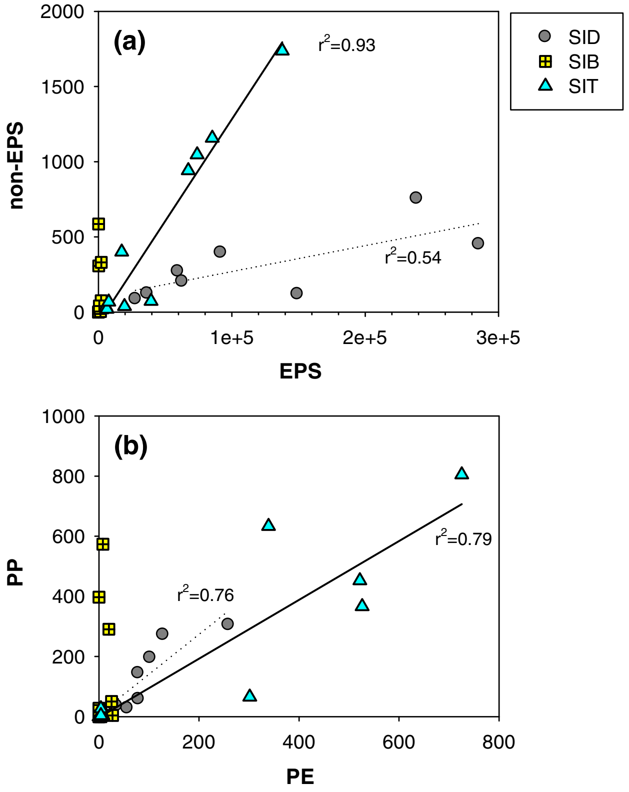


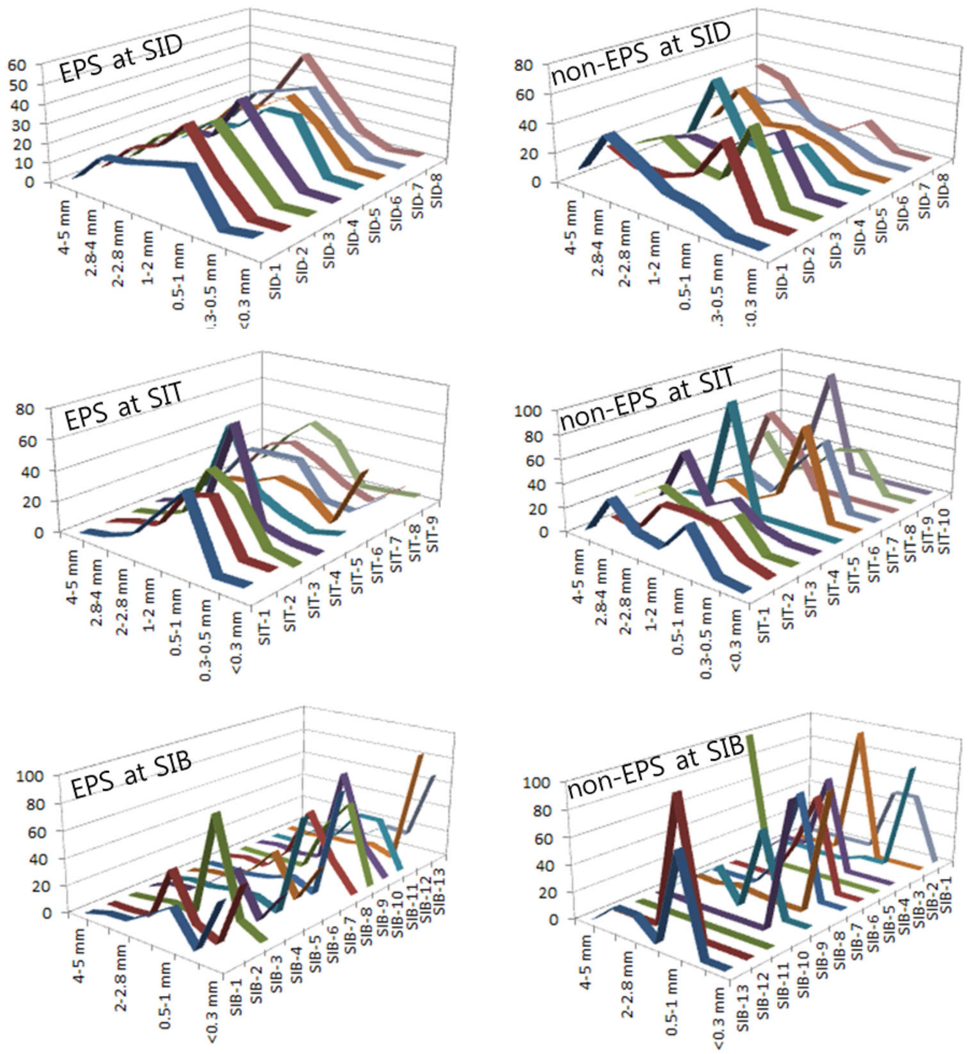
Fig. 4 Correlation between abundances of non-EPS versus EPS (**a**) and PP versus PE (**b**) (Color figure online)

Fig. S2). For example, in this region, one line suspends sixteen 62-L and four 100-L Styrofoam buoys for laver culture and at least 30,000 × 62-L and 8,000 × 100-L Styrofoam buoys are used at two laver-culturing spots approximately 30 km northeast and west off the Soya Island, respectively. Several thousands of 200- and 400-L Styrofoam buoys are additionally used in this region with mostly concentrated to the north of the study island (if buoys used to float fish-catching nets in the Incheon–Kyeonggi near- and off-shore are included).

Based on an obligatory recovery rate of 10 % in Korea, most Styrofoam buoys used are not recovered, and they end up in the marine environment (Hong et al. 2013). According to national marine debris monitoring, EPS debris amounts to 30 % (v/v) of marine litter collected on the Korean coastal shoreline (Lee et al. 2013b), and this substantial amount is attributed to aquaculture industries (Cho 2005). Most of the macro-plastic litter observed on the study beaches (mostly on SID and SIT) was obtained from Styrofoam-made marine gear (mostly Styrofoam buoys) (Fig. S2).

It was considered likely that abundant standing stock and distribution of EPS particles found on this study beaches (particularly on SID and SIT) originated from the successive fragmentation of macro-Styrofoam litter after it landed ashore or from the accumulative deposition of fragmented particles floating on the seawater surface, although their relative contributions could not be quantified. Styrofoam buoys are fragmented on the shore by photo-thermal oxidation, ultraviolet irradiation, and physical weathering (Andrady 2011). Meanwhile, the faster decomposition of EPS in seawater than in air is possibly caused by constant exposure to sunlight after the removal by seawater of an embrittled layer (Gregory and Andrady 2003). Substantial quantities of EPS particles (11 and 15 particles/m^2 with size range of 50–5000 μm) were measured in two seawater surface microlayer samples collected near Soya Island in August 2013 (unpublished). These EPS particles in surface seawater would be expected to eventually be deposited on the shore by wind- and/or current-driven transport. Because a buoy is composed of spherules with a mean diameter of 2.94 ± 0.33 mm, one 62-L standard Styrofoam buoy is estimated to generate millions of spherules (Heo et al. 2013). Buoy litter collected on the backshores of the study beaches

Fig. 5 Spatial variation in size distribution of EPS and non-EPS (Color figure online)



was observed to contain EPS spherules measuring 5.89 ± 0.93 mm ($n = 40$). Therefore, if all of the Styrofoam buoys in the region were to be fragmented to spherules (and not yet to smaller particles), approximately 10^{11} EPS spherules would be produced.

The amount of land-based marine debris discharged from the Han River to this coastal region is estimated to be approximately 191,000 m^3/year; of this, vinyl and plastic comprise 27.2 % (Cho 2005). However, no data relating to Styrofoam-based litter inland-based debris was provided. Nevertheless, the contribution of the land-based debris to standing stocks of EPS in the study area is likely to be negligible when considering the predominance of sea-based buoy wastes found on the study beaches.

Effect of Wind and Tide on Spatial Distribution

Both EPS and non-EPS particles were observed more frequently and abundantly on the two south-side beaches than on the north-side beach, although the SIB beach faces the northeastern sea where Styrofoam buoy–based catching and culturing activities are practiced and where Han River freshwater flows in.

The seasonal wind and current can be considered possible reasons for dramatically lower microplastic abundance on SIB. Wind can be an efficient driving force transporting the materials, such as EPS, floating on the sea surface. According to a marine buoy observatory near Soya Island that provides daily meteorological data (Korea Meteorological Administration 2013), southerly winds accounted for 68 % of winds >0.5 m/s in June and 69 % in August 2013 (Fig. S3). In July of the same year, for which most of the data related to marine buoys are missing, the nearest inland meteorological stations (Incheon stations) reported a predominantly southerly wind (84 %). A prevalent southerly winds in this region could deliver litters and particles of plastics from the southern near- and/or off-shore areas (i.e., Chungnam province) where coastal aquaculture is extensively distributed. Second, the flow direction of tidal current could represent another driving force that differentiates the distribution of marine debris among beaches. According to our numerical-simulation results, in this region the ebb tide flows from the northeast to the southwest, and the flood tide vice versa, at a maximum speed of 0.5 m/s (see Fig. 1 and Fig. S4). Thus, plastic litter/particles from northern off-shore and near-shore areas, including the Han River estuary, cannot directly deposit on the high strandline of SIB beach because the water-line retreats from the shoreline when marine debris in the northern area is moved in the direction of Soya Island by way of the ebb tidal current. The high strandlines on all three beaches, directly for south-side beaches and indirectly for north-side beach, receive marine debris delivered by a flood tidal current that inflows from the southwest area. Third, the regional current in the western sea of Korean peninsula, which is a branch of the Taiwan Current and the Kurushio Current, flows from south to north along the coastal line (Kim et al. 2013). This normal current transports marine materials to the northern region on a long-term scale. Last, marine litter–clearance activities can be considered a causal factor in the spatial distribution of microplastic. Marine litter weighting hundreds of tons, the composition of which has not been recorded, is known to have been cleared during every rainy season (June to October) at three stations on the Han River estuary. Such a regular clearance activity might efficiently decrease the introduction of inland-discharged plastic litter to the northeastern area of the study island. However, land-based litter and microplastics, even if any exist, are unlikely to accumulate to a substantial extent on the study island when considering the wind and currents already discussed herein.

A similarity in the spatial distribution of EPS and non-EPS was observed along the high strandline of both south-side beaches. This indicates that the two groups of plastic landed ashore together with a spatially similar gradient in abundance. The mean abundances of each EPS size class were strongly correlated between SID and SIT (Spearman rho = 0.86 at $p < 0.01$ for EPS; Spearman rho = 0.96 at $p < 0.01$ for non-EPS), and the size distribution was also homogeneous in space on both beaches (Fig. 5). In addition, the two beaches exhibited a similar composition profile of non-EPS particles (Fig. 2). Therefore, the two south-side beaches appear to experience the same input pathway of microplastics (i.e., delivery by way of southerly winds and currents) in addition to negligible disturbance on both beaches.

The north-side beach, SIB, exhibited outstanding differences compared with the other two beaches in terms of its standing stock of microplastics and the composition profile of non-EPS particles as mentioned previously. No correlation existed in the mean abundances of each size class between SID (or SIT) and SIB (>0.05 for both EPS and non-EPS). In contrast, to the other two beaches, macrosized marine debris, including Styrofoam buoys, were rarely present, even in the upper littoral zone and backshore of SIB. This supports the notion that the occurrence of microplastics in SIB, whether related to wind/currents or the weathering of existing macro-debris, is trivial. The numbers of items counted from each sampling grid (0.25 m^2) on SIB were <30 for EPS and five for non-EPS in most of the size classes. This might be ascribed to the small amounts of standing stocks that no significant patterns in spatial distribution and size distribution was not observed for SIB beach.

Implications for Coastal Environment

It is difficult to directly compare the abundance and distribution of microplastics among worldwide beaches owing to the different sampling method and size categorizations applied. However, the outstanding predominance of EPS particles present is in agreement with results from the south coast of Korea (Heo et al. 2013), and the southern and western coasts of Japan (Kusui and Noda 2003; Fujieda and Sasaki 2005), where aquaculture activities are extensively present. From the high strandlines of six beaches on the Korean south coast, where approximately 90 % of oysters produced in the country are harvested, 14,230 ± 23,571 EPS particles/m^2 (1- to 5-mm size) were measured, and >95 % of total microplastics observed was EPS (Heo et al. 2013). The Japanese coast exhibited 35,000 particles/m^2 (98 % of total particles) of 2- to 4-mm foamed plastic fragments on the southern coast and 2205 particles/m^2 (84 % of total particles) of Styrofoam >0.3 mm on the western coast (Kusui and Noda 2003). The mean abundances (particles/m^2) of total plastic particles found on the coast of other countries were 76 (0.5–20 mm) in Boa Viagem, Brazil (Costa et al. 2010); 132 (0.001–5 mm) on the western coast of Portugal (Martins and Sobral 2011); 55 (>0.001 mm) in the Tarmar estuary, USA (Browne et al. 2010); and 4666 (1–15 mm) on the Hawaiian archipelago, United States (McDermid and McMullen 2004). Compared with those global abundances, our study beaches (particularly, SID and SIT) showed the highest ranking levels by several orders of magnitude.

In an accelerated mechanical abrasion experiment using advanced techniques, such as Nile Red straining and fluorescence microscope, Shim et al. (2014) showed the presence of a number of nano- to tens of micrometer-sized EPS particles, most of which could not be identified by FT-IR microscope alone. This implies that there is likely to be a number of uncounted smaller EPS particles present, or still to be generated, within the sands of the study beaches.

These nanosized to microsized EPS particles can be ingested not only by plankton or nekton while floating on the sea surface but also by epi-fauna and in-fauna inhabiting the beaches when ashore.

Hexabromocyclododecane (HBCD), which has been used as an additive to meet fire safety standards, is most commonly used in EPS and extruded polystyrene foam (Alaee et al. 2003). In 2013, this compound was newly added as to the substance list compiled in the Stockholm Convention on Persistent Organic Pollutants. Recently, Rani et al. (2014) detected great concentrations of HBCD in a variety of polystyrene products used in Korea, including a mean concentration of 53,500 ng/g in white-colored aquaculture Styrofoam buoys. Based on their buoy-based HBCD content and the estimated number of Styrofoam buoys in use for fisheries and aquaculture in the Incheon–Kyeonggi coastal sea, it is estimated that at least approximately 100 kg of HBCD could be introduced to this marine environment by the Styrofoam buoys. Because substantial amounts of HBCD can be released when EPS is weathered and fragmented, it is necessary to regard EPS as an important source of HBCD contamination and exposure in this coastal environment.

Conclusions

Three sandy beaches on the same island, each lying in a different direction, were investigated to elucidate the effect of beach location on spatial variability of the composition and occurrence of microplastics in coastal beach sediments under a semidiurnal tidal cycle.

A majority of microplastics observed in this study originated from Styrofoam buoys. The abundance of microplastics found is considered to be at the upper bound of global levels. The abundances varied by as much as 100 times between the different beaches with the highest level found on the south-side beach. Southerly winds and currents, which were prevalent in the study season, are considered to have delivered the microplastics and Styrofoam buoys directly to the southern side beaches where they accumulated, and such factors are considered to be the driving forces behind beach-to-beach variations.

The abundance of microplastics was found to be horizontally graded along the high strandline from the far-left to the far-right side of the beach (or vice versa). Despite differences in standing stocks by a factor of 50 between the stations on the same beach, spatial similarities among the stations were observed in not only the size distribution of EPS but also a relationship between the abundances of EPS and non-EPS. This implied that microplastics (whether EPS or non-EPS) within a beach could distribute not randomly but with a gradient pattern (particularly, for abundance), which may be caused by spatially gradual difference in current and/or wind energies transporting microplastics to a beach. T therefore, to understand variations in the average abundance and distribution of microplastics, we suggest that any sampling stations used should be situated on at least the center and both sides of the beach. In addition, our findings indicate that the placement of the beach could be a critical factor in representing or assessing microplastic contamination in any coastal region.

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