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Hong Kong at the Pearl River Estuary: A hotspot of microplastic pollution

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ABSTRACT

Large plastic (>5 mm) and microplastic (0.315–5 mm) debris were collected from 25 beaches along the Hong Kong coastline. More than 90% consisted of microplastics. Among the three groups of microplastic debris, expanded polystyrene (EPS) represented 92%, fragments represented 5%, and pellets represented 3%. The mean microplastic abundance for Hong Kong was 5595 items/m^2. This number is higher than international averages, indicating that Hong Kong is a hotspot of marine plastic pollution. Microplastic abundance was significantly higher on the west coast than on the east coast, indicating that the Pearl River, which is west of Hong Kong, may be a potential source of plastic debris. The amounts of large plastic and microplastic debris of the same types (EPS and fragments) were positively correlated, suggesting that the fragmentation of large plastic material may increase the quantity of beach microplastic debris.

1. Introduction

Plastic is engineered to be durable and inexpensive, and approximately 50% of plastic products, including utensils, plastic bags and packaging, are designed to be disposable (Hopewell et al., 2009). Therefore, a large quantity of plastic waste is generated every year. In 2010, an estimated 275 million tonnes (MT) of plastic waste was generated by 192 coastal countries (Jambeck et al., 2015), which is nearly equivalent to the world production of plastic (265 MT) for the same year as reported by PlasticsEurope (2015). Of the 275 MT of plastic waste, up to 12.7 MT was eventually transported to the ocean because of inadequate waste disposal and littering (Jambeck et al., 2015). Plastic can persist in the marine environment because most plastic is not biodegradable (Andrady, 1994). However, plastic can be broken down into smaller pieces by wave action, hydrolysis and photodegradation in the marine environment (Andrady, 2011; Barnes et al., 2009). Plastic debris with a particle diameter of less than 5 mm is commonly referred to as 'microplastic' (Arthur et al., 2009; Moore, 2008). Although larger plastic debris (>5 mm) has a known impact on marine organisms (Derraik, 2002; Goldberg, 1995), microplastics have been gaining attention in the scientific community over the past decade because they pose a more pervasive threat to the marine environment (Barnes et al., 2009; Browne et al., 2007; Thompson et al., 2004).

Because microplastics are similar in size to sediment and certain plankton, they are harmful to a wide range of marine organisms as they may be mistaken as a food source (Wright et al., 2013). The ingestion of microplastics has been reported in various studies; one of the earliest studies reported the discovery of microplastics in wild fish in the North Atlantic Ocean at different life stages, namely, larvae, juveniles and adults (Carpenter et al., 1972). Under experimental conditions, the ingestion of microplastics has been reported for amphipods, lugworms and barnacles after exposure to microplastics for several days (Thompson et al., 2004). The direct ingestion and accumulation of microplastics in the gastrointestinal system can cause internal abrasions and blockages (Wright et al., 2013). Specific impacts were also identified in zooplankton, which showed a reduced consumption of algae after ingestion of polystyrene beads (Cole et al., 2013), and worms, which demonstrated an impaired ability to manage oxidative stress after ingesting polyvinyl chloride (PVC) (Browne et al., 2013). The possibility of microplastic transference from one organism to another has also been shown. In the Canary Islands, 38 Cory's shearwaters were found to contain an average of 8 plastic items in their guts, including large plastic and microplastic items (Rodríguez et al., 2012). Because their prey are usually 10 cm long and the mean length of plastic found in the shearwaters was only 8.7 mm, the plastic material appeared to have been transferred from their prey (Rodríguez et al., 2012). In the Goiana estuary of Brazil, 13.4% of Gerreidae ($N = 425$) examined in one study were found to contain nylon fragments ranging from 1 to 5 mm (Ramos et al., 2012). The preferred prey of Gerreidae include amphipods, barnacles and polychaetes (Teixeira and Helmer,

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1997), and these organisms have been shown to ingest microplastics (Thompson et al., 2004). Ramos et al. (2012) suggested that Gerreidae may have obtained nylon fragments from their prey at lower trophic levels. These studies exemplified the concerns expressed by scientists over the bioaccumulation and potential biomagnification of microplastics and associated pollutants in wild populations, which resembles the conditions associated with DDT in the 1940–1970s.

Hong Kong is a metropolis with a population of 7 million, and it is also a coastal city composed of a peninsula and adjacent archipelago of over 250 islands. Hong Kong's aquatic resources include numerous marine recreational zones and bathing beaches that attract millions of visitors every year. Over 20 fish culture zones are distributed in the New Territories and outlying islands, and they contribute to the seafood consumed in Hong Kong. In terms of ecological resources, Marine Parks, including Sha Chau and Lung Kwu Chau, Hoi Ha Wan, Yan Chau Tong and Tung Ping Chau, and the Cape D'Aguilar Marine Reserve were established by legislation in 1996 to protect the diverse marine life and habitats of the marine environment.

However, local and external sources of plastic contamination threaten the marine environment of Hong Kong. The daily amount of plastic waste generated in Hong Kong was 1866 tonnes in 2013, which represented approximately 20% of the locally generated municipal waste (HKEPD, 2015). The use of disposable plastic items, such as food packaging, plastic bags and polystyrene lunch boxes, is common in Hong Kong. Although the city's waste collection and management systems are relatively mature, plastic litter can enter Hong Kong waters directly by wind transport or indirectly through the storm water drainage system as well as through streams and rivers. In addition to local sources, the Pearl River northwest of Hong Kong may be a potential source of the city's plastic pollution. The Pearl River drains an area that includes more than 796,300 km^2 in eight provinces of China, including Guangdong Province (PRWRC, 2015). Nine densely populated cities of Guangdong Province, including Guangzhou, Shenzhen and Zhuhai, are situated in the Pearl River Delta region, which has a total population of close to 60 million. Because three quarters of the waste generated in China is estimated to be mismanaged (Jambeck et al., 2015) and Guangdong Province contributed 13.3% of the plastic production in China in 2014 (NBSC, 2015), the Pearl River is potentially a significant vector of plastic waste transport, particularly during the wet season (May–August), when most of the annual rainfall of approximately 2000 mm occurs (Lee et al., 2006).

To investigate the extent and severity of plastic pollution and provide guidance for remediation measures, the abundance and movement of plastics in the environment must be monitored. Beach surveys represent an indirect but cost-effective method of estimating the abundance and distribution of plastics in the marine environment. In this study, we collected plastic debris, including large plastic (>5 mm) and microplastic (0.315–5 mm) debris, from the beaches of Hong Kong and aimed to establish a baseline for the abundance and geographic distribution of various types of plastic debris, identify the plastic sources, and determine the quantitative relationships among the debris. The following hypotheses were tested in this study: (1) microplastics will be more abundant than large plastics in terms of counts; (2) microplastics will be more abundant on the west coast (consisting of four water control zones, namely Deep Bay, North Western, Southern and Victoria Harbour) than the east coast (consisting of three water control zones, namely Mirs Bay, Port Shelter and Tolo Harbour) of Hong Kong because of its proximity to the Pearl River; (3) microplastic abundance (in number) will be statistically correlated with large plastic debris because fragmentation on the beach is a potential source of microplastics; and (4) microplastic mean abundance in terms of counts per unit area will be higher than the international average because of proximity to urban centres and a large river estuary.

2. Materials and methods

2.1. Study area

More than 500 sandy beaches in Hong Kong were identified from topographic maps and Google Maps. Twenty-five beaches were selected on a stratified sampling basis from seven water control zones (WCZs) (Fig. 1), namely Deep Bay (DB), Mirs Bay (MB), North Western (NW), Port Shelter (PS), Southern (ST), Tolo Harbour (TH) and Victoria Harbour (VH). Each WCZ in Hong Kong has a similar hydrography and ability to assimilate water pollutants. All of the selected beaches were non-gazetted beaches, which means that shark prevention nets are not installed off the beach and beach maintenance does not occur frequently. Beach surveys were conducted between 7th July 2014 and 6th September 2014, a period when Hong Kong waters experienced a significant discharge from the Pearl River.

2.2. Sampling method

At each beach, the high strandline was identified, and four random locations were selected on a 30 m long transect. Sediment to a depth of 4 cm was excavated using a shovel at randomly selected locations from within a 50 $\times$ 50 cm quadrat, and the samples were subsequently transferred to a graduated bucket to a total volume of 10 L, thus producing four samples per beach. The sediment was then transferred to another empty bucket in small portions, and seawater was added and stirred gently for one minute so that large plastic was not broken into smaller pieces. The supernatant was filtered through a stainless-steel wire cloth with a 0.315 mm mesh size. This process was repeated until plastic was not found in the supernatant. All of the materials, including large plastic and microplastic items, retained by the wire cloth were transferred to a sealable, labelled plastic bag for further analysis in the laboratory.

2.3. Visual sorting

Each sample was resuspended in a beaker with tap water. The beaker was placed in an ultrasonic bath for five minutes to release plastics that were attached to other marine debris. The sample was then wet-sieved through a 0.315 mm sieve, and the beaker was rinsed with tap water thoroughly to ensure that plastics did not remain. The plastic items were visually sorted using pointed tweezers according to the criteria described by Norén (2007): (1) cellular or organic structures are not contained in the plastics; (2) plastic fibres are equally thick, capable of bending freely and do not taper at two ends; (3) plastic colours are homogeneous and clear; and (4) transparent and whitish items without typical plastic characteristics are examined under a microscope. The items that were identified as 'plastics' were sorted into five groups, with large plastic debris sorted into (1) expanded polystyrene (EPS) and (2) fragments and microplastic debris sorted into (3) EPS, (4) pellets and (5) fragments. All of the plastics were dried completely in an oven at 40 °C before weighing.

2.4. Statistical analysis

The Wilcoxon rank sum test was used to compare the mean and median of the west coast and east coast samples. The sites DB1, DB2 and MB4 (Fig. 1) were excluded from the test because the former two were sheltered by oyster farms and the latter was strongly

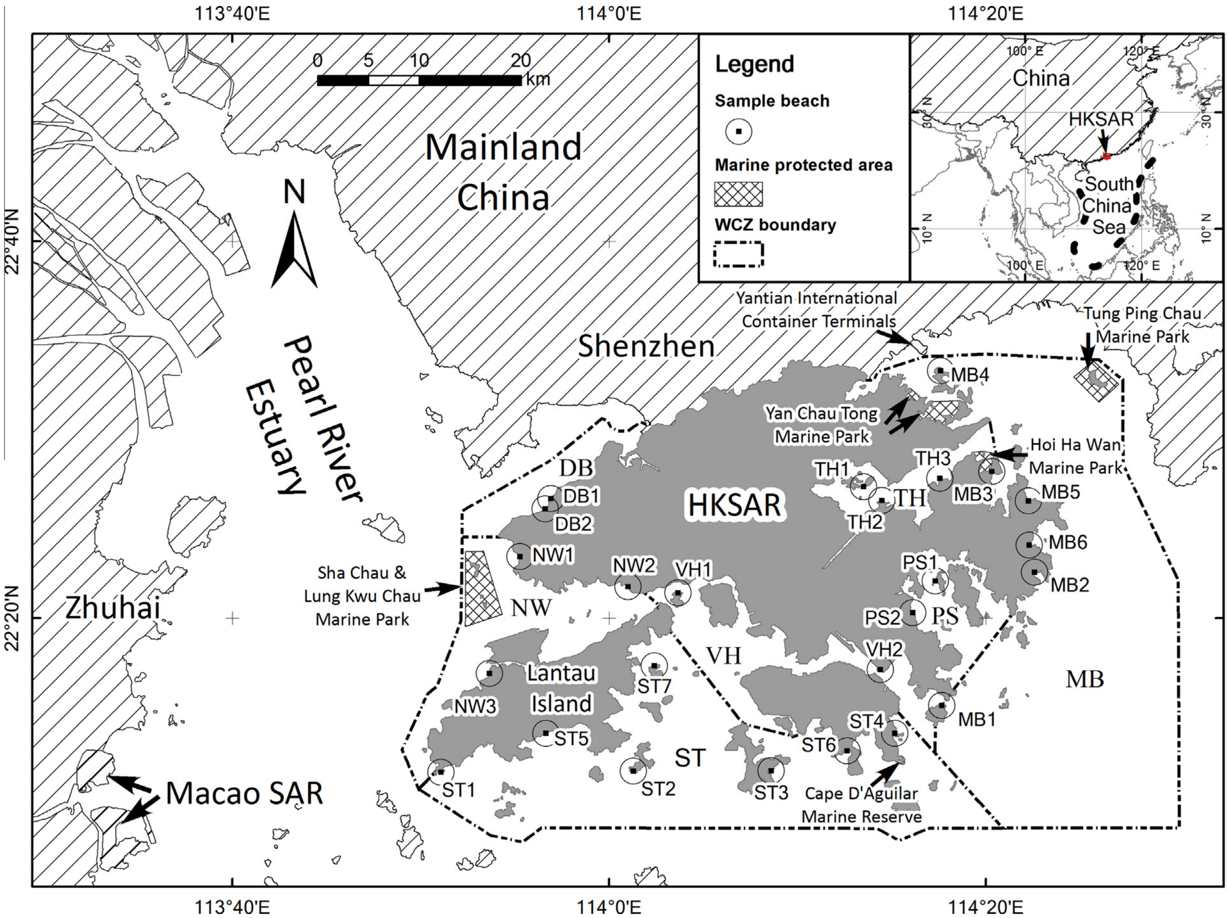

Fig. 1. Divisions of the seven simplified water control zones (WCZs) in Hong Kong and locations of the 25 sampled beaches. Two beaches were selected in Deep Bay (DB): Ap Tsai Hang (DB1) and Ha Pak Lai (DB2); six beaches were selected in Mirs Bay (MB): Tung Lung Chau (MB1), Long Ke Wan (MB2), Nam Fung Wan (MB3), Tung O Wan (MB4), Nam She Wan (MB5) and Tai Long Sai Wan (MB6); three beaches were selected in North Western (NW): Lung Kwu Tan (NW1), Tsing Lung Garden (NW2) and San Shek Wan (NW3); two beaches were selected in Port Shelter (PS): Sharp Island (PS1) and Pak Shui Wun (PS2); seven beaches were selected in Southern (ST): Fan Lau Tung Wan (ST1), Cheung Chau (ST2), Shek Pai Wan (ST3), Shek O Wan (ST4), Cheung Sha (ST5), Stanley Ma Hang (ST6) and Peng Chau (ST7); three beaches were selected in Tolo Harbour (TH): Ma Shi Chau (TH1), Pak Shek (TH2) and Lai Chi Chong (TH3); and two beaches were selected in Victoria Harbour (VH): Ma Wan Pak Wan (VH1) and Lei Yue Mun (VH2).

affected by a nearby land-based source, Yantian International Container Terminal in Shenzhen. A conservative level of significance (= 0.05) was selected for a one-tailed test with the following null hypothesis H_0 and alternative hypothesis H_1: microplastic median abundance on the west coast will be equal to or less than that of the east coast, and microplastic median abundance on the west coast will be greater than that of the east coast, respectively (two tailed, Hypothesis 2). If the results showed that the abundance is significantly higher on the west coast, then a Fisher's exact test would be performed to examine whether the three groups of microplastics differed significantly between the two coasts at the 0.05 level.

Spearman's rank correlation coefficients between all groups of microplastic and large plastic debris were determined. A 0.05 significance level was chosen (two tailed, Hypothesis 3).

2.5. Quantitative unit

At least four different units were used to report microplastic abundance in the sediment of the 22 studies reviewed by Hidalgo-Ruz et al. (2012), and a majority of these studies used 'items/m^2' or 'items/m^3' of sediment. Note that the sediment depths sampled in those 22 studies varied greatly and ranged from 0–5 cm to over 20 cm, and studies that reported microplastic abundance in items/m^2 resulted in a higher abundance per area when the sample volume was larger, because they failed to account for variation among the sample depths. Nonetheless, the current study reported microplastic abundance in items/m^2 to allow for maximal cross comparisons. Abundance reported in items/m^2 can be easily converted to 'items/L sediment' by dividing the former by a factor of 40. The weight of the microplastic debris was reported in 'g/m^2'.

Because the amount of microplastics on the same beach or between beaches just 2 km apart (McDermid and McMullen, 2004) can differ by up to 3 orders of magnitude (Heo et al., 2013), the authors employed non-parametric estimators, such as the median and median absolute deviation (MAD), to report abundance in the case of large inter- or intra-beach variability. Consequently, all analyses in this study employed both parametric (mean ± SD) and non-parametric estimators (median ± MAD).

3. Results

3.1. Overall abundance of microplastics in Hong Kong

A total of 154,227 plastic items were collected from 25 beaches in this study. Among these, large plastic debris constituted only a minor proportion (~9%), whereas microplastics represented the vast majority (91%, Hypothesis 1). Within the microplastic groups, EPS was the most abundant form (92%), followed by fragments (5%) and pellets (3%). Microplastics were found in all 100 quadrats sampled on 25 beaches. Among the large plastic debris, 9169 EPS (64%) and 5176 fragments (36%) were found.

The median number of microplastics found in Hong Kong was 520 ± 688 items/m^2 (±MAD; Table 1a). The WCZs with the highest and lowest median values were the NW (2098 ± 1705 items/m^2) and DB (94 ± 44 items/m^2), respectively. The overall mean abundance for Hong Kong was 5595 ± 27,417 items/m^2 (±SD; Table 1a), which is more than 10 times higher than the median value. The highest mean was found in the ST WCZ (15,554 ± 50,812 items/m^2), whereas the lowest was observed in the DB (106 ± 61 items/m^2). Although the DB WCZ was closest to the Pearl River, which is a potential source, the low abundance of plastic debris found in this area was expected because of the semi-enclosed hydrography of the bay. In addition, a number of offshore oyster farming platforms close to the two sampled beaches in DB were identified from satellite images. These platforms may also have sheltered most of the debris and kept it from depositing on the two beaches. If DB were excluded, the TH WCZ, which is also a semi-enclosed bay, would present the lowest median and mean microplastic abundance (262 ± 341 and 382 ± 344 items/m^2, respectively). The lowest number of microplastics in Hong Kong was 16 items/m^2 in MB1and MB5, and both sites lie along the east coast of Hong Kong. The highest abundance was 258,408 items/m^2 at ST1, which is located along the far southwest coast of Lantau Island.

The mean abundance was always higher than the equivalent median for all seven WCZs and Hong Kong as a whole because the data dispersion was large and the distribution of the data was positively skewed (skewness = 8.149). Large differences in microplastic abundance could occur at two nearby beaches. For example, although ST5 is only 10 km east of ST1 and both are in the ST WCZ with the same southeast-facing direction, the median abundance of microplastics at ST1 was approximately 350 times higher than that of ST5. A similar situation was observed in MB, where microplastics found at an enclosed beach, MB3, were 105 times more abundant (for median) than that at an open beach site, MB5, which is only 4 km away.

The non-parametric robust coefficient of variation (CVR%) is a more appropriate relative measure of dispersion than its parametric equivalent coefficient of variation (CV%). The CV% tends to increase significantly as the sample size becomes larger and presented values over 200% in the MB WCZ ($N = 24$) and over 300% in the ST WCZ ($N = 28$; see Table 1a). However, the CVR% was relatively stable across the seven WCZs with different sample sizes, which illustrates the strength of robust estimators in describing marine debris abundance.

In terms of the weight of microplastics collected, pellets accounted for 54%, EPS accounted for 29% and fragments accounted for 17%. Although EPS accounted for over 90% of the total number of microplastics, they only represented less than one-third of the total weight. In addition, EPS was usually highly fragmented, small in size and had a lower density, which explains why it contributed less to the total weight. In contrast, pellets had the lowest numbers but accounted for over half of the total weight. Pellets were rarely fragmented, and each intact pellet weighed up to 0.03 g; thus, they contributed significantly to the total weight of microplastics.

The median microplastics weight for Hong Kong was 0.4712 ± 0.6716 g/m^2 (Table 1b). If DB was excluded, the PS WCZ would present the lowest median (0.1164 ± 0.1417 g/m^2), whereas Victoria Harbour (VH) would present the highest (3.0774 ± 3.7960 g/m^2). The mean microplastics weight for Hong Kong was 5.5981 ± 25.8391 g/m^2, which is over 10 times higher than the median weight because of the influence of extremely large amounts of microplastics found at certain beaches, such as ST1, VH1 and MB4. If the DB WCZ was excluded, then the lowest and highest means were found in the TH WCZ (0.1588 ± 0.1663 g/m^2) and ST WCZ (14.1595 ± 47.8018 g/m^2).

3.2. Relative abundance of microplastics on the east and west coasts

Using the mean number of microplastics collected from each beach, the Wilcoxon rank-sum test revealed that the median of the 10 beaches on the west coast was significantly higher than that of the 12 beaches on the east coast ($p < 0.05$; Hypothesis 2), and this result is consistent with what was found when the medians were used instead of the means ($p < 0.05$) and indicates that the Pearl River may have been a potential source of microplastics found on the beaches of Hong Kong.

A Fisher's exact test revealed that the three groups of microplastics differed significantly between the east and west coasts ($p < 0.05$).

3.3. Statistical correlation between large plastic and microplastic debris

All of the Spearman's rank correlation coefficients shown in Table 2 were significant at the 0.05 level (two tailed), and high correlation coefficients were obtained between small and large plastic debris of the same types (Hypothesis 3). Both small EPS ($r = 0.843$) and small fragments ($r = 0.816$) were highly correlated with their large counterparts, and the highest correlation coefficient was found between small EPS and pellets ($r = 0.893$), whereas the lowest was found between large EPS and large fragments ($r = 0.656$).

4. Discussion

4.1. Overall abundance of microplastics in Hong Kong and comparisons with other regions

This study documented one of the highest abundances (5595 items/m^2) of microplastics found on beaches among studies of this type (Table 3). The microplastic mean abundance in Hong

Table 1a
Statistics of microplastic abundance in the seven WCZs and Hong Kong overall.

WCZ (W/E coast)	No. of quadrats (beaches)	Microplastics (0.315–5 mm) Abundance (items/m^2)			SD	CV%	MAD	CVR%
		Range	Median	Mean				
DB(W)	8 (2)	36–232	94	106	61	58	44	47
MB(E)	24 (6)	16–19,352	410	1834	3959	216	572	140
NW(W)	12 (3)	264–7288	2098	2349	1937	82	1705	81
PS(E)	8 (2)	56–1328	310	400	394	98	136	44
ST(W)	28 (7)	48–258,408	818	15,554	50,812	327	1112	136
TH(E)	12 (3)	24–1104	262	382	344	90	341	130
VH(W)	8 (2)	200–14,580	1736	5399	6297	117	2079	120
ALL	100 (25)	16–258,408	520	5595	27,417	490	688	132

Table 1b
Statistics of microplastic weight in the seven WCZs and Hong Kong overall.

WCZ (W/E coast)	No. of quadrats (beaches)	Microplastics (0.315–5 mm) Weight (g/m^2)			SD	CV%	MAD	CVR%
		Range	Median	Mean				
DB(W)	8 (2)	0.0080–0.2044	0.0398	0.0812	0.0793	98%	0.0436	110%
MB(E)	24 (6)	0.0028–15.4288	0.5552	1.9423	3.3520	173%	0.8137	147%
NW(W)	12 (3)	0.1928–8.8696	2.9038	3.5892	2.9210	81%	3.1603	109%
PS(E)	8 (2)	0.0044–1.1904	0.1164	0.2394	0.3952	165%	0.1417	122%
ST(W)	28 (7)	0.0168–249.1560	0.8000	14.1595	47.8018	338%	1.1001	138%
TH(E)	12 (3)	0.0008–0.5536	0.1624	0.1588	0.1663	105%	0.2046	126%
VH(W)	8 (2)	0.3024–25.7940	3.0774	8.6480	10.1758	118%	3.7960	123%
ALL	100 (25)	0.0008–249.1560	0.4712	5.5981	25.8391	462%	0.6716	143%

Table 2
Spearman's rank correlation coefficients between microplastic and large plastic groups. All of the correlation are significant at the 0.05 level (two tailed) with $N = 100$ for each group. EPS: expanded polystyrene.

	Small EPS	Small fragment	Pellet	Large EPS	Large fragment
Small EPS	1				
Small fragment	0.814	1			
Pellet	0.893	0.781	1		
Large EPS	0.843	0.687	0.856	1	
Large fragment	0.770	0.816	0.756	0.656	1

Kong is 50% higher than that of the South Korea, 7 times higher than that of Easter Island (Hypothesis 4). However, a consistent microplastic size classification has not been used among the cited studies because most did not collect plastics smaller than 1 mm, which might explain why our study recorded a higher number of microplastics. The sampling method also varied from one study to another, and these discrepancies highlight the importance of size and sampling procedure standardisation, which would allow comparisons across regions.

Microplastics were more abundant than large plastics on beaches (Hypothesis 1), which was expected because this situation is common in other regions, including South Korea (Heo et al., 2013), Brazil (Ivar do Sul et al., 2009), India (Jayasiri et al., 2013) and Portugal (Martins and Sobral, 2011). However, the relative abundance of the three groups of microplastics was different from the other compared regions except for that of Heungnam Beach, South Korea. Although fragments accounted for approximately 96.7% of the microplastics in Boa Viagem, Brazil (Costa et al., 2010) and 87% in the Hawaiian archipelago (McDermid and McMullen, 2004), 92% and 90.7% of the microplastics in Hong Kong and Heungnam Beach in South Korea (Heo et al., 2013), respectively, were EPS. The EPS spherules stranded on the Korean beach were believed to have originated from floating buoys that had fragmented (Heo et al., 2013). In the case of Hong Kong, the dominance of EPS microplastics was not surprising because EPS is widely used in insulated boxes for the transport of fresh food and take-away food in southern China and Hong Kong. When disposed of improperly, these boxes can easily enter rivers and storm water drainage systems, particular during rainstorms, and can be transported to the ocean and beach. Nevertheless, a recent study in the South China Sea observed that polypropylene and polyethylene in granule and fibre forms (Zhao et al., 2015) contributed to the majority of microplastics rather than EPS. The large sample size in this study provided a wider picture of the abundance and spatial distribution of plastic debris in Hong Kong and expands on the work of Zurcher (2009), who documented microplastics at only six beaches in Hong Kong. The median and mean (137 and 284 items/m^2, respectively) reported by Zurcher (2009) were lower than the results in our study (520 and 5595 items/m^2, respectively), which may have been because of the differences in the time of sampling. Zurcher (2009) collected a majority of samples during the dry season, whereas our samples were collected during the wet season. Because the Pearl River is believed to be the major source of plastic debris along Hong Kong beaches, the higher discharge

Table 3
Comparison of microplastic abundance (items/m^2) on beaches in different counties or regions. $N(n)^a$ = no. of quadrats (beaches).

Country/ Region	Site	$N(n)^a$	Abundance		Particle size (mm)	Method	Remark	Reference
			Range	Mean				
Hong Kong	25 beaches in 7 WCZs	100(25)	16–258,408	5595	0.315–5	Quadrat: 0.25 m^2; Depth: 4 cm; Sieve: 0.315 & 5 mm	N/A	This study
South Korea	Heungnam beach	10(1)	N/A	3652	2–10	Quadrat: 0.25 m^2; Depth: 5 cm; Sieve: 2 mm	N/A	Heo et al. (2013)
USA	Hawaiian archipelago	22(9)	5–23710	2333	1–15	Quadrat: 0.36 m^2; Depth: 5.5 cm; Sieve: 4.75, 2.8 & 1 mm	Abundance:mean/sum of two quadrats (high tide line and berm)	McDermid and McMullen (2004)
Chile	Easter Island	6(1)	N/A	805	1–4.75 & 4.75–10	Quadrat: 0.25 m^2; Depth: 2 cm; Sieve: 1 mm	N/A	Hidalgo-Ruz and Thiel (2013)
Greece	Kea Island	20(6)	Negligible–2195	725	1–2 & 2–4	Quadrat: 1 m^2; Depth: 3 cm; Sieve: 1, 2 & 4 mm	Range: all 20 samples; mean: 8 samples	Kaberi et al. (2013)
Hong Kong	6 beaches in 3 WCZs	42(6)	4–1400	284	2–5	Quadrat: 0.5 m^2; Depth: 2.5 cm; Sieve: 1 mm	N/A	Zurcher (2009)
Chile	Continental coast	228(38)	<1–169	27	1–4.75 & 4.75–10	Quadrat: 0.25 m^2; Depth: 2 cm; Sieve: 1 mm	Range is regional-based	Hidalgo-Ruz and Thiel (2013)
Portugal	Portuguese coastline	30(5)	1–137	153	≤5	Quadrat: (A) 0.25 and (B) 4 m^2; Depth: 2 cm; Filter/Sieve: (B) 2.5 × 3.5 mm	Range is a beach average	Martins and Sobral (2011)

of the Pearl River during the wet season would transport a greater amount of plastics to Hong Kong beaches compared with the amount transported in the dry season. Unpublished data by the authors of this study also support this temporal change in microplastic abundance on Hong Kong beaches.

Large variations were observed for beaches in the same WCZ. For example, the MB WCZ had the highest CVR% (140%) because it contained beaches at the higher end (e.g., MB4 and MB3) as well as beaches at the lower end (e.g., MB1 and MB5) in terms of the number of microplastics. Compared with other studies that reported a higher abundance of microplastics on windward beaches (Browne et al., 2010; Ivar do Sul et al., 2009), a clear pattern was not observed for the 25 beaches in Hong Kong with respect to prevailing wind direction. Other factors that are believed to affect the deposition and accumulation of plastic debris on Hong Kong beaches include the proximity to local sources, the surface current direction and beach maintenance activities. For instance, although MB4 is on the east coast (less affected by the Pearl River) and leeward side, as many as 6078 items/m^2 were observed at this site on average, and most were EPS. This beach appeared to be strongly affected by a densely populated urban area, Yantian, on the opposite coast. The direction of surface currents may also transport plastic debris to certain beaches where accumulation can occur. For example, the Hong Kong Tidal Stream Prediction System suggests that during spring-flood tides, fast surface currents (>1.5 m/s) flow directly towards ST1, which is located in a relatively exposed bay. These currents may have induced debris accumulation at ST1. The microplastic abundance at ST5 was unexpectedly low, and this may be due to the fact that the dominant flow in the bay where the beach is situated was predicted to be slow and diffuse (<0.5 m/s); thus, the flow conditions may not facilitate the accumulation of debris at this beach. Corcoran et al. (2009) suggested that plastics are particularly susceptible to fragmentation in the beach environment, which suggests that the frequency of beach maintenance can influence the number of secondary microplastic precursors, i.e., large plastic debris. The frequency of beach maintenance in Hong Kong varies depending on the beach's proximity to the city centre and recreational value. Certain beaches are cleaned more often (e.g., every day at MB6 and MB2), whereas others are cleaned less frequently (e.g., every week at MB3 and MB4). Cleaning is not performed on remote beaches such as ST1. Beach maintenance is conducted daily at MB6, which has high microplastic levels, and only once or twice per week at MB5, where microplastics were found at low concentrations. This contrast suggests that in Hong Kong, conventional beach maintenance may not directly reduce the amount of microplastics because it only targets larger debris.

4.2. Relative abundance of microplastics on the west and east coast of Hong Kong

The Wilcoxon rank sum test results revealed that microplastics were significantly more abundant at beaches on the west coast than on the east coast. This result suggests that the input of plastics from the Pearl River is an important factor in the geographic distribution of microplastics in Hong Kong. Although another study in the South China Sea (Zhao et al., 2015) did not find significant differences in microplastic abundance between beaches near the Pearl River Estuary and those away from the estuary, it is believed that the time of sampling (late April to May; a transition time between wet and dry seasons) did not match sufficient inputs of plastic debris from the Pearl River to cause a significant spatial difference. In contrast, all of the samples collected in this study were deposited on beaches during the wet season (May–August) when the Pearl River discharge is at its highest levels; therefore, a significant difference in microplastics was recorded.

A Fisher's exact test also suggested that the distribution of microplastic groups was significantly different between the east and west coasts of Hong Kong, which further confirmed that the two coasts may be subject to different sources of microplastics with different characteristics.

4.3. Statistical correlation between large plastics and microplastics

The high correlations between small and large EPS as well as fragments (Hypothesis 3) provided clear evidence in support of the plastic fragmentation process on the studied beaches. Microplastics are damaging to the environment because plastic debris never stops disintegrating into smaller pieces, even at scales invisible to the naked eye (Andrady, 2011). Although it is almost impossible to remove all microplastics from the environment, the high correlation between large and small plastics suggests that conventional beach maintenance can indirectly reduce microplastics by preventing large plastic fragmentation on the beach. However, fragmentation can still occur in the ocean; therefore, preventing the release or input of plastics to the environment is the most effective measure for minimising microplastic pollution.

Because of the potential benefit of maintenance activities and the finding that over 60% of the large plastics and over 90% of the microplastics were EPS, which is highly susceptible to fragmentation, beaches in Hong Kong that were cleaned with a higher frequency may be expected to have a much lower abundance of EPS compared with rarely cleaned beaches. The prolonged fragmentation of large plastics on beaches because of a lack of maintenance may have resulted in the sheer quantity of microplastics (258,408 items/m^2) found at the ST1 site. However, MB6, which is cleaned daily, has higher levels of microplastics (1138 items/m^2) than MB5 (43 items/m^2), which is cleaned only once or twice per week. The influence of beach cleaning on microplastics in Hong Kong is complex, and further research is required to develop a greater understanding of the process.

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