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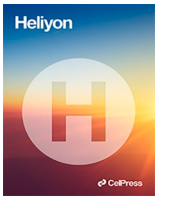

Research article

Spatiotemporal characterisation of microplastics in the coastal regions of Singapore

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ABSTRACT

In the 21st century, plastic production continues to increase at an unprecedented rate, leading to the global issue of plastic pollution. In marine environments, a significant fraction of plastic litter are microplastics, which have a wide range of effects in marine ecosystems. Here, we examine the spatiotemporal distribution of microplastics along the Johor and Singapore Straits, at surface and at depth. Generally, more microplastics were recorded from the surface waters across both Straits. Fragments were the dominant microplastic type (70%), followed by film (25%) and fiber (5%). A total of seven colours of microplastics were identified, with clear microplastics as the most abundant (64.9%), followed by black (25.1%) and blue (5.5%). Microplastics under 500 μm in size accounted for 98.9%, followed by particles 500–1000 μm (1%) and 1–5 mm (0.1%). During the monsoon season, the abundance of microplastics across various sites were observed to be > 1.1 times when compared to the inter-monsoon period. Rainfall was a closely related to the increased microplastic abundance across various sites in the Singapore Strait. This suggests that weather variations during climate change can play critical roles in modulating microplastic availability. Beach sediments facing the Singapore Strait recorded an abundance of 13.1 particles/kg, with polypropylene fragments, polyethylene pellets and thermoplastic polyester foam identified via Fourier transform infrared spectroscopy. Hence, it is crucial to profile the spatiotemporal variation of microplastic abundance in both the surface and in the water column to gain a better understanding of the threat caused by microplastic pollution in the coastal regions of Singapore.

1. Introduction

Plastic pollution is a pertinent problem of the 21st century. This issue has gained significant attention in the recent decade among scientists and the public as plastic litter is increasingly abundant in many terrestrial and aquatic ecosystems. To date, there are an estimated 296, 000 tonnes of plastic that exist in the oceans. This number is expected to increase, with hotspots of microplastics around the world with abundances of 30, 000–38, 000 particles/kg in marine sand sediments [1]. Approximately 11% of total ocean plastics are microplastics [2]. Microplastics are small plastic particles of less than 5 mm in length and exist in two forms-primary and secondary [3]. Primary microplastics are small plastic pieces designed for various uses, such as cosmetics, clothing and plastic production [4]. Resin pellet beads and facial microbeads are some examples of primary microplastics. Secondary microplastics originate from the

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breakdown of larger plastic pieces, such as styrofoam buoys, derelict fishing gear, due to physical and biological processes over time [5]. The rate and extent of plastic degradation depends on various physical (age and type of polymer) and environmental (surrounding temperature and pH) factors [6].

Microplastics enter the marine environment through various ways. Urban sources such as agricultural [7] and stormwater runoff [8] are pathways where terrestrial microplastics enter the oceans. In addition, synthetic textiles release microfibers during washing processes and these are not fully eliminated by filtration systems in wastewater treatments plants. As a result, they are released into marine waters [9]. A study by Ref. [10] showed that an average wash load of 6 kg released approximately 700 000 acrylic fibers from domestic washing machines. Sea-based industries such as shipping and fishing also contribute to microplastic pollution [11]. Gray water (wastewater) from showers, basins and laundry of ships have recorded a high abundance of 2000–50 000 microplastics/L [12].

Due to the small size of these particles, microplastics are easily mistaken as food by marine animals. This has been clearly observed in pelagic and benthic organisms such as bivalve mollusks [13] and shrimp [14]. Although some microplastics will be egested by these organisms, many plastic particles are still retained for an extended period. Microplastic particles have been observed in organs such as gills and stomach and are found to remain in the hemolymph for as long as 48 days [15]. Larger marine animals such as the common mink and sei whales are also recorded to ingest microplastics through their prey species [16]. These whales commonly feed on fish species from the Scombridae and Gadidae families, which contain large amounts of microplastics [16].

Microplastics have a large surface area to volume ratio, which enhances their capacity to adsorb harmful pollutants in marine waters [17]. Studies have examined how microplastics can accumulate and release harmful compounds such as polybrominated diphenyl ethers and dichlorodiphenyltrichloroethane (DDT; [18,19]. Microplastics are known to be biologically inert. However, once these particles are ingested, pollutants that have been adsorbed onto their surfaces can enter the cells of organisms and disrupt their physiological processes. Ingestion of DDT-treated microspheres has resulted in poorer growth in larval fish *Menidia beryllina* [20]. Exposure of the Japanese medaka fish (*Oryzias latipes*) to microplastics and its associated chemicals have disrupted endocrine genes [21].

In marine environments, microplastics can exist for hundreds of years [22]. As a result, they form a suitable habitat for the colonization of many microorganisms, including harmful or non-native ones. A wide range of phyla have been found colonizing the surfaces of microplastics, including Annelida, Bryozoa, Cnidaria and Mollusca [23]. Pathogens such as *Vibrio parahaemolyticus* and *Vibrio vulnificus* have been identified from polyethylene (PE) fragment and fibers from the Baltic Sea [24]. [25] identified the toxic bacterium *Photobacterium rosenbergii* from beach sediment microplastics located near coral reefs. This bacterium is associated with coral bleaching and its proliferation can be detrimental to existing coral reef ecosystems [26]. The bloom-forming dinoflagellate *Pfiesteria piscicida* was also identified on microplastics from the Baltic Sea [27]. This dinoflagellate *P. piscicida* is known to be toxic and has caused major fish kills in previous blooms [28,29]. The long-range transport of these harmful organisms can be damaging to marine ecosystems. Although the numbers of these organisms may be few on these microplastics, blooms of these organisms in new locations can be triggered with suitable nutrient and environmental conditions [30].

In Southeast Asia, the problem of plastic pollution in marine environments is highly pertinent, with concentrations of microplastics ranging from 0.1 to 1.1 $\times$ 10^4 pieces/L [31]. However, there have only been 36 studies in this region investigating microplastic pollution across various matrices such as beach and marine sediments, seawater, and marine organisms [31]. In Singapore, studies related to marine microplastics are relatively limited, with a few reports of microplastic pollution in mangroves [32], seagrasses [33] and beach sediments [25]. The Johor Strait is known to be eutrophic and highly polluted, with high inputs of nitrogen sources, ranging from 2.04 to 6.47 μM-N for nitrate and nitrite [34]. The Johor Strait is also characterized by many aquaculture fisheries carrying seafood from farm to table. Various beaches in the Johor and Singapore Straits were previously found to contain high levels of sand sediment microplastics (9.2–59.9 pieces/kg; [25]. Hence, it is important to elucidate the presence of microplastics in seawater as a high level of microplastics in seawater could be assimilated in seafood and be transferred to the consumer. This will in turn harm human health and threaten food security. In this study, we aimed to characterize the spatial and temporal distribution of microplastics isolated from the Johor and Singapore Straits. Surface and depth samples were obtained to examine for any differences in microplastic

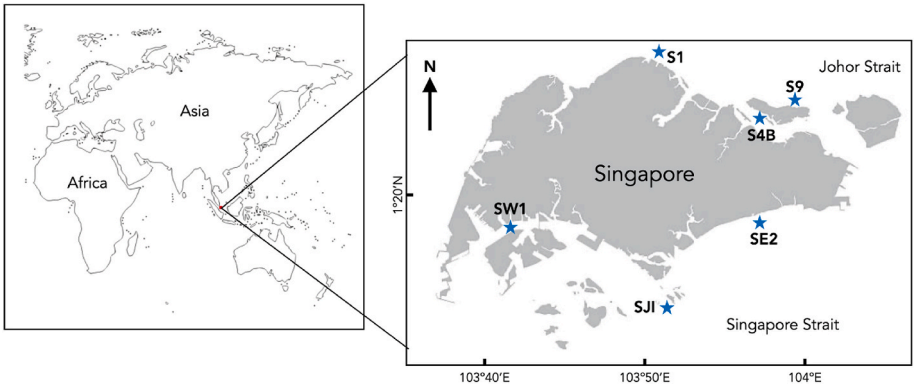

Fig. 1. Sampling area and stations for microplastics in the Johor and Singapore Straits in this study. A total of six stations were evaluated. The stars indicate the sampling points.

abundance. Environmental variables such as temperature, rainfall and wind speed were also collected to explore any association with microplastic abundance at various sampling sites.

2. Materials and methods

2.1. Sampling stations and collection

In this study, sampling was conducted within the Johor and Singapore Straits from 2021 to 2022. Monthly seawater sampling was conducted across six stations around Singapore from August 2021 to January 2022 (Fig. 1). A bucket was used to collect surface seawater samples and a Niskin bottle was used to collect seawater at 5 m depth. A single beach sediment sample was collected at Se2 in April 2022 for comparison purposes (Fig. 1). Singapore is a tropical island nation (728 km^2) located in Southeast Asia. The country is characterized by a wet equatorial climate with relatively high rainfall (~2200 mm) and annual average temperatures around 27.5 °C. The Johor Strait is a 50 km-long narrow international strait that separates Singapore and Peninsular Malaysia. This strait connects to the Singapore Strait on the southeast and to the Straits of Malacca on the western side. Sampling stations S1, S9 and S4B were facing the Johor Strait. The Singapore Strait is a channel that lies between Singapore and Riau Islands, Indonesia. This Strait is also an international commercial shipping route. The remaining sampling stations, SW1, SJI and Se2 were located on the Singapore Strait. Sampling of microplastics were conducted in the Johor due to the high abundance of microplastics observed in beach sediments of these areas [25]. Furthermore, the Johor Strait is characterized by multiple aquaculture farms which increases the level of anthropogenicity in the region. Commercial shipping routes are known to be hotspots of microplastic pollution, with container ships being great microplastic contributors [35] and hence the Singapore Strait was chosen for sampling purposes. The western part of the country was not sampled due to restricted access. Surface seawater samples were collected using a large bucket and sealed in 500 mL collection bottles for further analysis. At 5 m depth, seawater samples were obtained using Niskin bottles. A 100 m stretch of beach was chosen for sand sediment collection at site Se2 to provide a basis of comparison against seawater microplastic samples. Sampling was done on the high-strand line, at the zone of vegetation, 3 m from the shoreline. Beach samples were collected according to the protocol of Curren et al. (2018). For sand sediment samples, collected microplastics were resuspended in a sterile filtered 1.2 g/cm^3 sodium chloride solution to separate microplastics from the sand particles. Sterile stainless-steel tweezers were used to obtain microplastic samples for microscopy.

Microplastics from seawater samples were analysed by pipetting 1 mL of seawater onto a Sedgewick rafter slide and viewed under the inverted microscope (Nikon, Ti–S). Microplastics were separated from organic matter using the hot-needle test according to the protocol by Ref. [36]. Microplastic abundances were determined from triplicate counts. A blank control was conducted before analysing each seawater sample to ensure that no microplastics were present before examination. All microplastics were characterized and recorded according to size (<500 μm, 500–1000 μm and 1–5 mm), colour and type (fiber, foam, pellet, fragment or film).

2.2. Quality control

In this study, glass and metal labware were used wherever possible. All labware (forceps, glass bottles, petri dishes, metal sieve) were sterilized and pre-rinsed with milliQ water twice. During analysis, all containers were covered with aluminum foil or glass lids to prevent microplastic contamination from the air. Microplastic particles identified for spectroscopy were individually rinsed with milliQ water and dried at room temperature before analysis. Contamination protocols follow that of Curren et al. (2018).

2.3. Collection of meteorological variables

Meteorological variables such as average temperature, rainfall and wind speed for water samples were obtained from the Meteorological Service Singapore (MSS) (http://www.weather.gov.sg/home/) from various weather stations around Singapore.

2.4. Fourier Transform Infrared spectrometer (FTIR)

Beach sediment microplastics were analysed using an Alpha II Fourier Transform Infrared spectrometer (FTIR) equipped with a diamond ATR crystal (Bruker, Germany). Individual microplastic samples were transferred to the diamond using sterilized forceps. IR spectral data were collected across a wavelength of 4000 cm^{-1} to 450 cm^{-1} with an interval of 1 cm^{-1}, with reference to Bruker's material database.

2.5. Data analysis

The differences in microplastic abundances across sampling stations were tested using one-way analysis of variance (ANOVA) and Tukey's Honestly Significant Difference (HSD) *post hoc* pairwise comparisons. For all statistical tests, a significance level of 0.05 was chosen. The 'multcomp' package in R studio (version 4.1.3) was used to run various statistical analyses. Principal component analysis (PCA) was used to analyse the clustering between various sampling sites and environmental variables in R. Reported results were given as means ± SD and corrected to three significant figures wherever required.

3. Results

Microplastics were detected in both surface and seawater samples at 5 m depth across all sampling stations in both the Johor and Singapore Straits. The concentration of microplastics ranged from 106 to 238 particles/mL in the Johor Strait and 143–196 particles/mL in the Singapore Strait (Table 1). During the monsoon season, many sites recorded an increase in microplastic abundance across the Johor and Singapore Straits. Sites S1, S9, SW1 and SE2 had 1.1–1.7 times more microplastics during the monsoon season compared to the inter-monsoon period. Site SE2 had the greatest increase observed (1.7×) during the monsoon season. In December, the microplastic abundance at site S9 was almost three times that of the average abundance in the Johor Strait across the sampling months. Similarly, sites SW1 and SE2 had 1.3 and 1.8 times more microplastics than the average abundance in the Singapore Strait across the sampling months.

Overall, microplastic fragments, film and fibers were observed (Fig. 2). Fragments accounted for the majority of the microplastics, at 70%, followed by film and fiber at 25% and 5%, respectively (Fig. 2). Fragments were the most dominant at each sampling location, with site SJI recording the most fragments of 100% at depth (Fig. 3). However, at surface, site SJI had film pieces being the most dominant at 34% (Fig. 3). The three types of microplastics-fragments, film and fibers were detected at all sites, except for site SJI, where only fragments were detected at depth (Fig. 3). Microplastic types were significantly different within each site across both the Johor and Singapore Straits (Table 2; $p < 0.05$). Across all the sites, there were significant differences in the microplastic abundances for fragments and fibers (Table 3; $p < 0.05$). At sites S4B and SW1, microplastic abundances were significantly different between the three comparison categories (film vs fragment, film vs fiber and fragment vs fiber; Table 3; $p < 0.05$).

Generally, the abundance of microplastics were greater at the surface in the Johor Straits (sites S1 and S9), compared to the Singapore Strait (sites SJI, SW1 and SE2), where the abundance of microplastics was greater at depth (Table 1). Across the sites at both surface and depth, the abundance of microplastics were not significantly different (ANOVA, Tukey's HSD, $p > 0.05$). Between surface and depth samples, there were significant differences observed between microplastic film collected across sites (Table 4; ANOVA, $p = 4.75 \times 10^{-2}$ and 1.55×10^{-2}, respectively). The abundance of film collected at the surface waters of site SJI and SE2 were significantly different (Tukey's HSD, $Q = 4.51$, $p = 3.78 \times 10^{-2}$). At depth, the abundance of film microplastics were significantly different across site S1 and SJI (Tukey's HSD, $Q = 5.53$, $p = 6.68 \times 10^{-3}$).

Besides accounting for microplastic type, the colour of plastic particles were also recorded. Across the various microplastics, a total of seven colours were observed from all sites (Fig. 4). From all microplastic types, clear microplastics were the most abundant (64.9%), followed by black (25.1%), blue (5.5%), purple (2.3%), pink (1.7%), red (0.5%) and brown (0.04%). For fragments, black was the dominant fragment colour (75%) and 12% were transparent (Fig. 4A). Other colours, purple (7%), blue (5%) and red (1%) were recorded (Fig. 4A). For microplastic film, 89% were transparent, 9% were blue and 2% were red (Fig. 4B). The majority of microplastic fibers were transparent (94%), 3% red and 3% were blue (Fig. 4C).

Microplastics in this study were categorised into three size fractions-smaller than 500 μm, 500–1000 μm and 1–5 mm (Fig. 5). Across the stations, microplastics smaller than 500 μm were the most abundant, at 98.9%, followed by pieces of size 500–1000 μm and 1–5 mm at 1% and 0.1% respectively (Fig. 5). Microplastics of size 1–5 mm were only observed from the surface waters of S1 (Fig. 5). In this study, 42% of sites only recorded microplastics smaller than 500 μm in size. Across all sites, the size of microplastics were significantly different (ANOVA, $p < 0.0001$). The abundance of microplastics were significantly different across pairs <500 μm and 500–1000 μm and <500 μm and 1–5 mm (Tukey's HSD, $Q = 321$ and 324, respectively $p < 0.0001$).

Patterns of microplastic composition across sites against environmental variables such as rainfall, temperature, salinity and windspeed were visualized through a PCA plot (Fig. 6). The first two axes amount to 49.4% of the variation between the stations (Fig. 6). Rainfall was closely associated with surface and depth samples of sites SJI and SE2 during the month of November (Fig. 6).

A single beach sediment sample was obtained at site SE2, where the microplastic abundance recorded was a total of 13.1 particles/kg. Microplastic fragments, foam, pellets, film and fibers were observed with the abundance of 3.27, 4.58, 3.27, 0.654 and 1.31 particles/kg of sand, respectively. Fragment microplastics were identified to be polypropylene (PP; Fig. 7). Microplastic foam pieces were identified to be thermoplastic copolyester (TPC; Fig. 7) and pellets were identified to be polyethylene (PE; Fig. 7). Fragments were observed to be green (40%), white (40%) and blue (20%). Foam microplastics were white (85.7%) and pink (14.3%). The remaining pellet, film, and fiber microplastic particles were all white in colour. On the same day, the surface waters of SE2 were sampled and were

Table 1
Microplastic abundance and type at surface and depth seawater of various locations of the Johor and Singapore Straits.

	S1		S9		S4B		SJI		SW1		SE2	
	S	D	S	D	S	D	S	D	S	D	S	D
Film/mL	21.2 ± 28.2	32.2 ± 33.5	28.8 ± 25.1	17.9 ± 14.4	24.1 ± 5.85	19.6 ± 14.6	50.7 ± 16.7	0	34.1 ± 19.3	19.1 ± 11.6	15.2 ± 11.5	96.7 ± 14.4
Fragment/mL	66.2 ± 79.8	58.6 ± 24.6	83.8 ± 47.0	97.8 ± 48.7	46.3 ± 22.7	49.8 ± 36.2	44.4 ± 19.2	62.5 ± 28.5	41.2 ± 24.7	43.6 ± 30.8	86.0 ± 58.4	76.7 ± 18.7
Fiber/mL	8.15 ± 7.66	12.4 ± 19.1	5.97 ± 7.83	4.03 ± 4.90	0.925 ± 2.27	0.556 ± 1.36	5.66 ± 9.62	0	0.833 ± 1.67	3.74 ± 4.36	6.11± 6.50	2.15 ± 4.81
Total across types/mL	95.5	10.3	119	120	71.4	70.0	101	62.5	76.2	66.5	107	88.5
Total per site/mL	106		238		141		163		143		196	

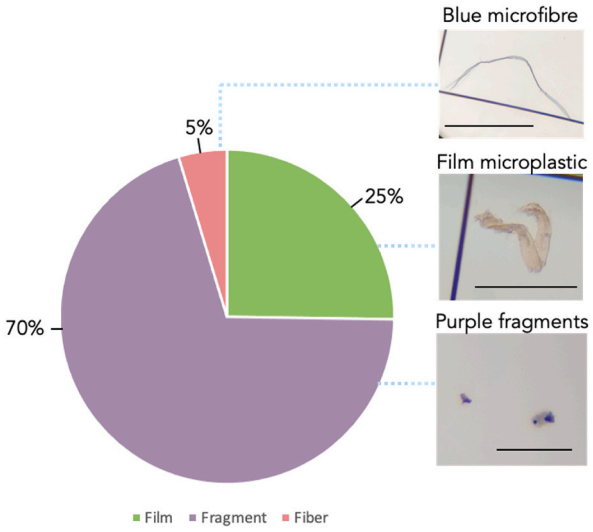

Fig. 2. Composition of microplastic types found in this study. Three types of microplastics were observed: film, fragment and fiber. Examples of blue microfibers, film microplastics and purple microplastic fragments were shown on the right of the pie chart. The scale bars on each picture indicate 5 μm.

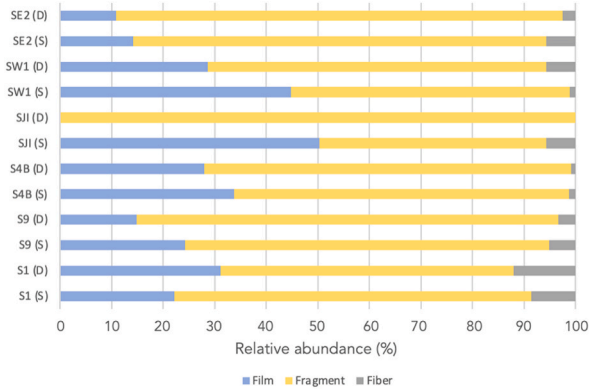

Fig. 3. Composition of each microplastic type recorded from surface and depth samples of sampling sites. The colours in the chart correspond to the legend above.

Table 2
One-way ANOVA test results showing the differences in composition of microplastic types within each sampling site.

	SS	df	MS	*F* statistic	*P*-value
S1	17.1	2	8.53	5.96	0.00615*
S9	49	2	24.5	28.3	<0.0001*
S4B	13.8	2	6.74	21.2	<0.0001*
SJI	5.92	2	2.96	7.56	0.00537*
SW1	6.53	2	3.27	10.2	0.000815*
SE2	35.9	2	18.0	28.5	<0.0001*

The * indicates significant differences ($p < 0.01$).

recorded to have 206 microplastic particles/mL, consisting of fragments (84%), film (8%) and fiber (8%). Majority of the microplastic fragments were black (74.2%) and the remaining transparent (12.9%), pink (6.45%) and blue (6.45%). Fibers observed were blue (66.7%) and transparent (33.3%). At depth, microplastic abundance was observed to be 22.2 particles/mL and consisted of fragments (50%) and film (50%). At this site, all the fragment and film microplastics collected were recorded to be black and pink, respectively.

Table 3
Output of Tukey's HSD *Post hoc* test on the composition of microplastic types found within each site.

	S1		S9		S4B		SJI		SW1		SE2	
	Q-statistic	*P*-value	Q-statistic	*P*-value	Q-statistic	*P*-value	Q-statistic	*P*-value	Q-statistic	*P*-value	Q-statistic	*P*-value
Film vs. fragment	3.27	0.0680	7.95	0.0001*	5.08	0.00294*	2.75	0.161	2.49	0.206*	8.68	<0.0001*
Film vs fiber	1.51	0.542	2.16	0.292	4.11	0.0175*	2.75	0.161	3.84	0.0334*	1.05	0.742
Fragment vs fiber	4.78	0.00522*	10.11	<0.0001*	9.19	<0.0001*	5.50	0.00391*	6.33	0.00058*	9.73	<0.0001*

The * indicates significant differences ($p < 0.01$).

Table 4
One-way ANOVA test results showing the differences in composition of microplastic types between surface and depth samples.

Surface	SS	df	MS	*F* statistic	*P*-value
Film	4.04	5	0.808	2.61	0.0475*
Fragment	9.56	5	1.91	0.880	0.508
Fiber	0.184	5	36.8	1.22	0.325
Depth					
Film	5.05	5	1.01	3.45	0.0155*
Fragment	10.6	5	2.13	2.05	0.102
Fiber	0.533	5	107	1.37	0.267

The * indicates significant differences ($p < 0.01$).

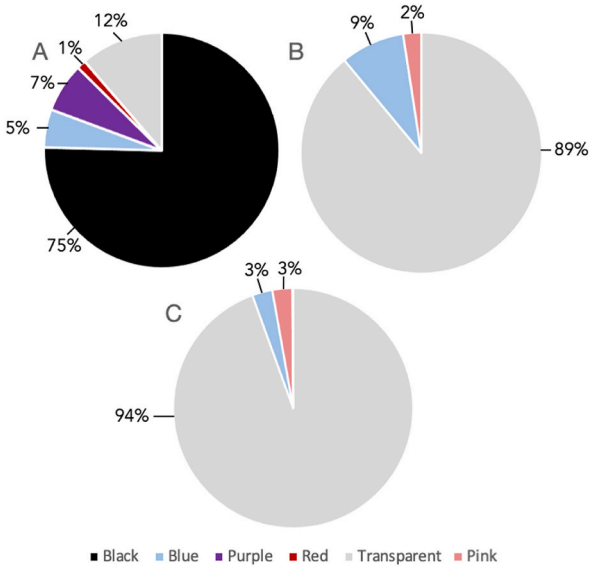

Fig. 4. Colour composition of microplastic fragments, fiber and film across sites. A total of seven colours were observed. (A) Colour composition of microplastic fragments. (B) Colour composition of microplastic fiber. (C) Colour composition of microplastic film. The colours in the chart correspond to the legend above.

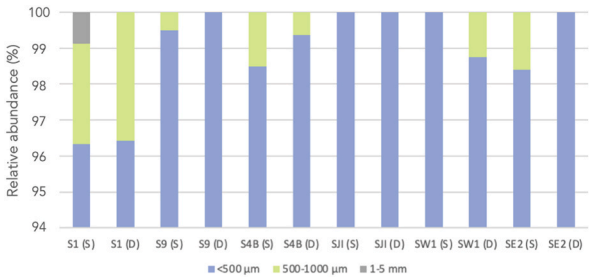

Fig. 5. Size distribution of microplastics across sampling locations. The colours in the chart correspond to the legend above.

4. Discussion

In this study, it is evident that microplastic pollution is present in the coastal waters of Singapore. The microplastic concentration in the Johor and Singapore Straits is comparable to that of the Northeastern Pacific Ocean (Table 5 [17,19,37–39], [37]; and is higher than that of the Northeastern Atlantic Ocean (Table 5; Lusher et al., 2014) and the coastal waters of Tarragona, Spain [39]; Table 5). Microplastic abundances across both straits were lower than that in the neighbouring region of the Terrenganu estuary, Malaysia (Table 5; [38]. From the Johor Strait, site S9 recorded the highest microplastic abundance from surface and depth samples (Table 1). This site is the closest to the mouth of the Johor River, which is highly polluted due to agricultural activities [40] and waste from plastic and rubber industries [41]. It is generally observed that more polluted waters result in higher microplastic abundances in various locations [42,43]. For beach sediments, it was also observed that sites in the Johor Strait recorded a higher microplastic abundance

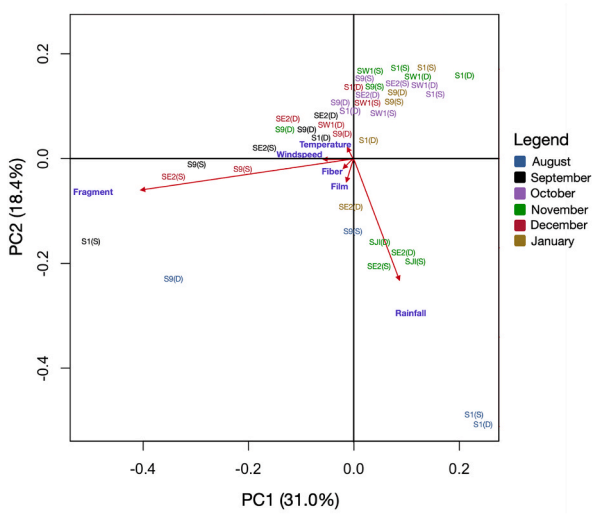

Fig. 6. Principal component analysis displaying the variation in microplastic composition across the sites in relation to environmental variables: temperature, salinity, rainfall and windspeed. The (S) and (D) in site labels correspond to surface and depth, respectively. Colours in the chart refer to the months of sampling according to the legend on the right.

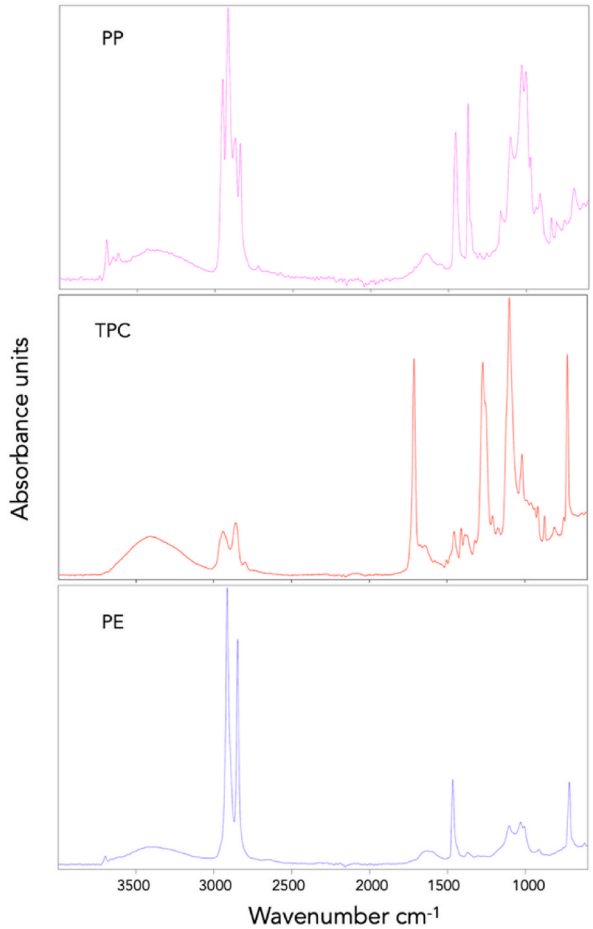

Fig. 7. FTIR spectra of different microplastic polymer types isolated from beach sediments.

Table 5
Comparison of seawater microplastic abundance across various regions around the world.

Region	Microplastic abundance (particles/L)	Reference
Hangzhou Bay, China	1.4×10^{-3}	[19]
Northeastern Atlantic Ocean	2.4×10^{3}	Lusher et al. (2014)
Northeastern Pacific Ocean	27.9×10^{4}	[37]
Arrábida, Portugal	450	[17]
Terengganu estuary, Malaysia	5.46×10^{5}	[38]
Tarragona, Spain	1.3×10^{3}	[39]
Johor Strait	$14.3–19.6 \times 10^{4}$	This study
Singapore Strait	$10.6–23.8 \times 10^{4}$	

(31.1–59.9 particles/kg of sand sediment) compared to sites in the Singapore Strait (9.2 particles/kg of sand sediment; [25]. From surface waters, the Johor Strait had a higher average concentration of microplastics compared to the Singapore Strait. This could also be due to the lower flow of water in the Johor Strait, because of the causeway which separates Singapore and Johor Bahru, Malaysia [44]. A lower water flow would mean a greater accumulation of microplastics, resulting in a higher abundance observed in the Johor Strait. Across the sites, the average microplastic concentrations were about 1.4 times greater at surface waters (95 pieces/mL) compared to at depth (69.6 pieces/mL). This concurs with other reports which showed a decrease in microplastic abundance with depth of sampling [45,46]. Many studies have investigated the presence of microplastics from surface seawater [47,48] or sediments [49]. However, there are few reports on the vertical distribution of microplastics along the water column. This distribution can be altered by various physical and environmental factors such as particle size, density and water flow [50,51].

Microplastic distribution along the water column is known to be inhomogeneous [52]. Hence in this study, the concentration of microplastics were measured in milliliters instead of liters, to prevent overestimation of the results. In this study, surface, and water at depth of 5 m were examined and provided evidence about the variation in microplastics at two different depths. However, more layers along the water column could be sampled to provide a greater resolution of microplastic distribution in the water column. This is especially so for microplastics of smaller sizes (10 μm), which were found to be more abundant in the water column and more easily transported vertically, due to the pycnocline [53]. The improved depth profiling will allow better understanding of vertical migration of microplastics, regarding upwelling events [37]. In this study, the sediment concentration of microplastics were not examined in both Straits. The understanding of sediment microplastic concentration will provide a better understanding of the vertical gradient, from surface to water column and sediment [52].

Across the sites, microplastic film, fragments and fibers were identified, with fragments being the dominant microplastic type. This is similar to other works conducted in the Baltic Sea [54], the Mediterranean [55] and Korea [56], which had microplastic fragments as the major fraction. Overall, black was the main colour identified for microplastic fragments in this study. Along the Johor Strait, many aquaculture farms were observed to use black plastic drums and carboys as floatation devices. Over time, exposure to high temperatures and light intensities can result in physical degradation of these large items, releasing microplastic particles into the marine environment. In addition, given that Singapore is a busy shipping port, it is likely that many of these black fragments are paint particles from ships and boats [57]. The weathering of the ships' hulls and flaking of anti-fouling coatings are known to be significant sources of marine microplastic fragments [58].

At site SE2, beach sediment and seawater samples were taken on the same day to examine the differences in microplastic abundances and types. As both measurement units were different (particles/kg and particles/mL), their abundances cannot be directly compared. However, the microplastic composition for beach and seawater samples were different. TPC foam microplastics were the dominant microplastic type present and is commonly used in tubing and insulation [59]. Fragments were still the dominant microplastic type from seawater. White polyester pellets present on the beach could have been part of the plastic pre-production process and originate from spillages from container ships carrying these items. As site SE2 is a popular recreation beach, brightly coloured propylene fragments from beach sediments could have come from the degradation of larger items such as toys and plastic bottles.

Studies in other locations have reported rainfall to be a significant environmental contributor to microplastic pollution [60,61]. Greater rainfall has resulted in a larger surface runoff from terrestrial sources, which ultimately enter marine environments. Furthermore, microplastics floating in the atmosphere can adhere to raindrops and be transferred to marine waters during periods of heavy rain [62]. Besides rainfall, other environmental variables such as temperature have also been studied to determine its impact on microplastic pollution. The formation of specific bacterial assemblages on microplastics in the Baltic Sea have been shaped by temperature [63]. Furthermore, temperature changes have also increased the toxicity of microplastics to *Daphnia magna* and *Daphnia pulex* [64].

Biofilms naturally develop on the surfaces of microplastics after long periods of time in the marine environment. This 'conditioning film' further enables the attachment of larger organisms such as mussels, algae and barnacles [65]. As a result, their densities increase, exceeding that of the surrounding seawater and they descend the water column [66]. The seafloor is thought to be the ultimate sink for most microplastics in oceans [67]. Many of these particles settle in marine sediments and become more available to benthic organisms such as jellyfish [68], starfish and bivalves [66]. Furthermore, benthic organisms such as shrimp and mussels are popular seafood consumed by man and are reported to contain microplastics across various studies [69,70]. In the Singapore Straits, pathogenic bacteria have been found colonizing the surfaces of microplastics [25]. The genus *Photobacterium rosenbergii* was identified and this species can cause coral bleaching [26]. As the Singapore Strait is characterized by many coral reefs in marine parks, proliferation of this species on microplastics can hamper conservation efforts.

In recent years, the presence of microplastic contaminants in seafood has been heavily discussed as a route of exposure to humans [71]. This is especially so if the organism is consumed whole, without removing the digestive organs. Previous studies have detailed the egestion of some microplastics from marine organisms during depuration [72]. However, selective accumulation of microplastics still exists and is dependent on many factors such as the microplastic type and feeding characteristic of the organism [73]. Contaminated seafood adds to the existing ways which microplastics can enter the human body. To date, microplastics have been found in bottled [74] and tap water [75], tea bags [76] and even air [62]. It is for a fact that microplastics enter and are present in the human body, as these particles have been found in human placenta [77], lung [78] and stool samples [79]. However, the long-term effects of these contaminants on the human body are yet to be fully understood.

Microplastics not only threaten human health and food security, but has other effects on coastal water quality, potentially reducing the aesthetic value of recreational areas. The socio-economic impact of microplastic pollution has been studied in various locations [80,81]. Given the multi-faceted implications of microplastic pollution, a greater call is needed to manage this issue on an individual and regional scale.

5. Conclusion

In this study, the spatiotemporal variation of marine microplastics from the Johor and Singapore Straits were examined at surface and at depth. The Johor Strait had a higher abundance of microplastics compared to the Singapore Strait. This is likely due to the Johor Strait being more polluted and having a lower water flow. There were no significant differences observed in average microplastic abundances across surface and depth seawater samples. However, it is still critical to elucidate the vertical distribution of microplastics as only sampling the surface waters could result in an over-or underestimation of true microplastic quantities. From seawater samples, microplastic fragments, fibers and film particles were observed, with black microplastic fragments being the most dominant. From the beach sediment, TPC foam, PP fragments and PE pellets were recorded. Rainfall was closely associated with increased microplastic abundances across some sites during the Northeast monsoon season. This suggests that weather variations during climate change can play critical roles in modulating the microplastic availability in marine environments and should continue to be explored in future studies. Efforts to combat plastic pollution should continue, starting from individuals to national policies, to reduce plastic waste and hence microplastic pollution as a whole.

Author contribution statement

Emily Curren: Wrote the paper, analysed and interpreted the data.
Sandric Chee Yew Leong: Supervised data analysis and interpretation of data. Contributed data analysis tools.

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Data availability statement

Data is all included or referenced in the article.

Declaration of interest's statement

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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