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Commercially important mangrove crabs are more susceptible to microplastic contamination than other brachyuran species

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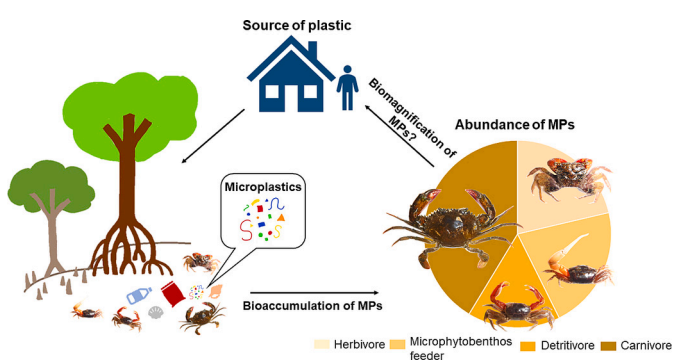
HIGHLIGHTS

- Brachyuran crabs are good indicator for identifying the pollution including microplastics (MPs).
- Fibre and fragment types were abundant in the crab specimens collected from Setiu Wetlands.
- Abundance of MPs significantly varied in relation to the crab's feeding guilds.
- The commercially important *Scylla olivacea* was found to have both direct and indirect modes of MPs ingestion.
- Domestic waste, along with subdued water circulation are responsible for plastic contamination in the study sites.

GRAPHICAL ABSTRACT



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ABSTRACT

Brachyuran crabs are ecologically and economically important macrofauna in mangrove habitats. However, they are exposed to various contaminants, including plastics, which bioaccumulate in relation to their feeding modes. Setiu Wetlands is a unique place on the east coast of Peninsular Malaysia where different ecosystems such as mangroves, lagoon, beaches, etc., are duly connected and influencing each other. In recent years, the shifted river mouth has threatened these wetlands, causing severe hydrodynamic changes in the lagoon, especially in the core mangrove zone. The present study tested microplastics (MPs) contamination in the mangroves through brachyuran crabs as indicators. Three sampling sites, namely Pulau Layat, Kampung Pengkalan Gelap, and Pulau Sutung were chosen. The four abundant crab species *Parasesarma eumolpe*, *Metaplax elegans*, *Austruca annulipes*, and *Scylla olivacea*, which display different feeding behaviours were collected from all sites covering the dry (Feb–Mar 2021) and the wet (Dec 2021–Jan 2022) seasonal periods. There were significant differences in the seasonal abundance of MPs among crab species. The highest accumulation of MPs in the crab stomachs in the dry season could be linked to subdued water circulation and poor material dispersion. Besides the lower MPs in the wet period due to improved water exchange conditions, its significant presence in the stomachs of *S. olivacea* indicates the role of its feeding behaviour as a carnivore. In addition, the micro-Fourier transform infrared spectroscopy (micro-FTIR) revealed the widespread occurrence of polymers such as rayon and polyester in all species across the sites. Given the fact that crabs like *S. olivacea* are commercially important and the ones contaminated with MPs can cause detrimental effects on the local community's health, further managerial actions are needed to assure sustainable management of the Setiu Wetlands.

1. Introduction

Plastic contamination, caused by extensive usage and inefficient waste management of plastic items, has become a serious environmental threat in the recent years (Shahul Hamid et al., 2018). About 6.3 billion tonnes of cumulative primary and secondary (recycled) plastic waste was generated around the globe in 2015 (Geyer et al., 2017). The current trends of plastic production and mismanagement are indicating at least 33,000 million metric tonnes of waste by 2050 (John et al., 2022). Meanwhile, the COVID-19 pandemic has brought additional loads of plastic waste all over the world, including for Malaysia, through several single-use items such as hand gloves, personal protective equipment, hand sanitizer bottles, and medical test kits (Peng et al., 2021).

The mismanaged plastics usually end up in landfills and enter the marine environment via streams or rivers as its major pathway (Lebreton et al., 2017; Schmidt et al., 2017; Kabir et al., 2023). The marine debris of such land origin causes adverse impacts on the biota and proved to be life-threatening to many organisms like fish, turtles, dolphins, and various invertebrate species (Waite et al., 2018; Watts et al., 2015; Ouyang et al., 2022). Prior reaching to the open waters, a significant amount of plastic waste is trapped within the mangrove habitats by their extensive root systems like pneumatophores (Luo et al., 2021, 2022; Martin et al., 2019; Ouyang et al., 2022). Due to UV radiation, tidal/wave action, bacterial degradation and macrofaunal activities the large plastic wastes or macroplastics are fragmented into small plastic or microplastics (MPs) sized <5 mm (Lujan-Vega et al., 2021; Andrady et al., 2022). Accumulation of MPs in the mangrove areas also takes place through daily tides and water current transporting the land-derived materials from one location to another (Kukulka et al., 2012).

Mangrove fauna, especially benthic invertebrates (mainly mussels, oysters, gastropods and crabs), are strongly affected by the plastic waste and the MPs ingestion (Mearns et al., 2015; Waite et al., 2018; Ouyang et al., 2022). The ingested MPs may block the digestive tract and impair gills in some cases (Mearns et al., 2015), while reduces the foraging capacity, energy uptake, and growth in others (Watts et al., 2015). Similarly, the toxicants leached from plastic might disrupt the endocrine function of the invertebrates (Rochman et al., 2014). The activities such as feeding and burrowing of the invertebrates also increase plastic fragmentation and MPs in the environment (So et al., 2018, 2022, 2023). Under these circumstances, a decline in invertebrates' populations was observed in coastal wetlands (Ouyang et al., 2022). This ecological impact strongly affects brachyuran crabs, which are the dominant resident fauna in mangroves, both in terms of abundance, taxonomic diversity and functional roles (Cannicci et al., 2008, 2021). Some of the significant roles played by the mangrove crabs include soil oxygenation (Koch and Nordhaus, 2010), sediment nutrients transfer/turnover (Gao and Lee, 2022), microbial community enrichment (Booth et al., 2019) and net carbon sequestration (Andreetta et al., 2014) remain crucial for the health of mangrove social-ecological systems (Dahdouh-Guebas et al., 2021). The species of the genus *Scylla*, namely *Scylla serrata* (Forskål, 1775), *S. olivacea* (Herbst, 1796), and *S. tranquebarica* (Fabricius, 1798) are also well recognized for their commercial and aquaculture production values (Fazhan et al., 2022). Mangrove crabs, moreover, proved to be affected by a vast array of anthropogenic factors, including climate change and various sources of pollutants, and have been proposed as indicator species for different ecosystem changes (Cannicci et al., 2009; Bartolini et al., 2011; Yando et al., 2021). In addition, they have been suggested as a priority for further research to estimate the health of natural mangrove forests and to assess mangrove degradation (Dahdouh-Guebas et al., 2022).

Setiu Wetlands in State Terengganu on the east coast of Peninsular Malaysia is represented by several coastal ecosystems including mangroves, seagrass beds, mudflats, beaches, lagoon and estuary forming an interconnected seascape (Ruwaimana et al., 2018). The local people depend on these wetlands for their livelihood through, among other activities, finfish and shellfish collection, cage culture, non-timber forest products and handicrafts making (Mohd Azmi, 2014). Setiu Wetlands are indeed considered as a fisheries hub of Terengganu (Mohd Salim et al., 2015). However, since 2015, an array of anthropogenic factors, such as shifting of Setiu river mouth, a reduced freshwater discharge due to oil palm plantations and increased settlements, brought considerable changes to the hydrodynamics of the lagoon (Zainol et al., 2022). The reduced water circulation, due to high sedimentation and decreasing depth, is likely to increase the retention of plastic waste in the mangrove sediment (Dalvand and Hamidian, 2023; Li et al., 2018). Besides the mismanaged plastics from elsewhere, the local aquaculture, agriculture, and household activities could raise the deposition of MPs in the mangroves (Mearns et al., 2015). Given the status of Setiu Wetlands as a State Park frequented by local and non-local visitors (Alipiah et al., 2020), further loads of plastic wastes could be expected (Giurea et al., 2018).

The presence of MPs in the surface water, sediment, polychaetes, bivalves, and fishes collected from Setiu Wetlands was already reported by Ibrahim et al. (2016, 2017, 2021) and Hamzah et al. (2021), but no information is available at present on the ingestion of MPs by the mangrove crab populations. The present study aimed to bridge this gap of knowledge by studying the amount of MPs ingested by the most abundant brachyuran crabs species. The objectives were (i) to analyse

the abundance/composition of MPs in the stomachs of the crab species with different feeding behaviours and, (ii) to assess site-wise and season-based variations in the MPs ingestion by the selected crabs. The findings of this research are expected to evaluate the possible use of mangrove crabs as indicators for MPs contamination, to raise awareness on the intensity of plastic wastes locally and to inform the need of plastic waste management policies and future mitigation measures.

2. Materials and methods

2.1. Study area and sampling sites

Setiu Wetlands, connected to the South China Sea (Fig. 1), are strongly influenced by the daily flood/ebb conditions. The hydrodynamics in the lagoon are further governed by both wet and dry seasons of the year (Zainol et al., 2022). Three sampling sites, namely Pulau Layat (close to the core mangrove i.e., the largest patch with rich species diversity), Kampung Pengkalan Gelap (between the core mangrove and the shifted river mouth), and Pulau Sutung (close to the shifted river mouth) were chosen for their different spatial and ecological characteristics (Fig. 1). Along with the chances of having different deposition rates of MPs at the sampling sites due to changed local environmental conditions (cf. Weinstein et al., 2016), we hypothesised the presence of different sources of plastic wastes at each site, due to their proximity to different land-use and land-cover. For instance, the upstream Pulau Layat is located close to an aquaculture and fishing jetty, while Kampung Pengkalan Gelap is placed near the ecotourism boardwalk and an inland housing area. The downstream Pulau Sutung is next to the river mouth where seawater and freshwater exchange take place continuously.

2.2. Collection of crabs

Four abundantly distributed mangrove crab species with distinct feeding modes, namely *Parasesarma eumolpe* (De Man, 1895) (Sesarmidae), *Metaplax elegans* De Man, 1888 (Varunidae), *Austruca annulipes* (Milne-Edwards, 1837) (Ocypodidae), and *Scylla olivacea* (Herbst, 1796) (Portunidae), were collected at each sampling site during both the dry (Feb-Mar 2021) and the wet (Dec 2021-Jan 2022) seasons (Fig. 2). These species were selected to represent four different feeding guilds,

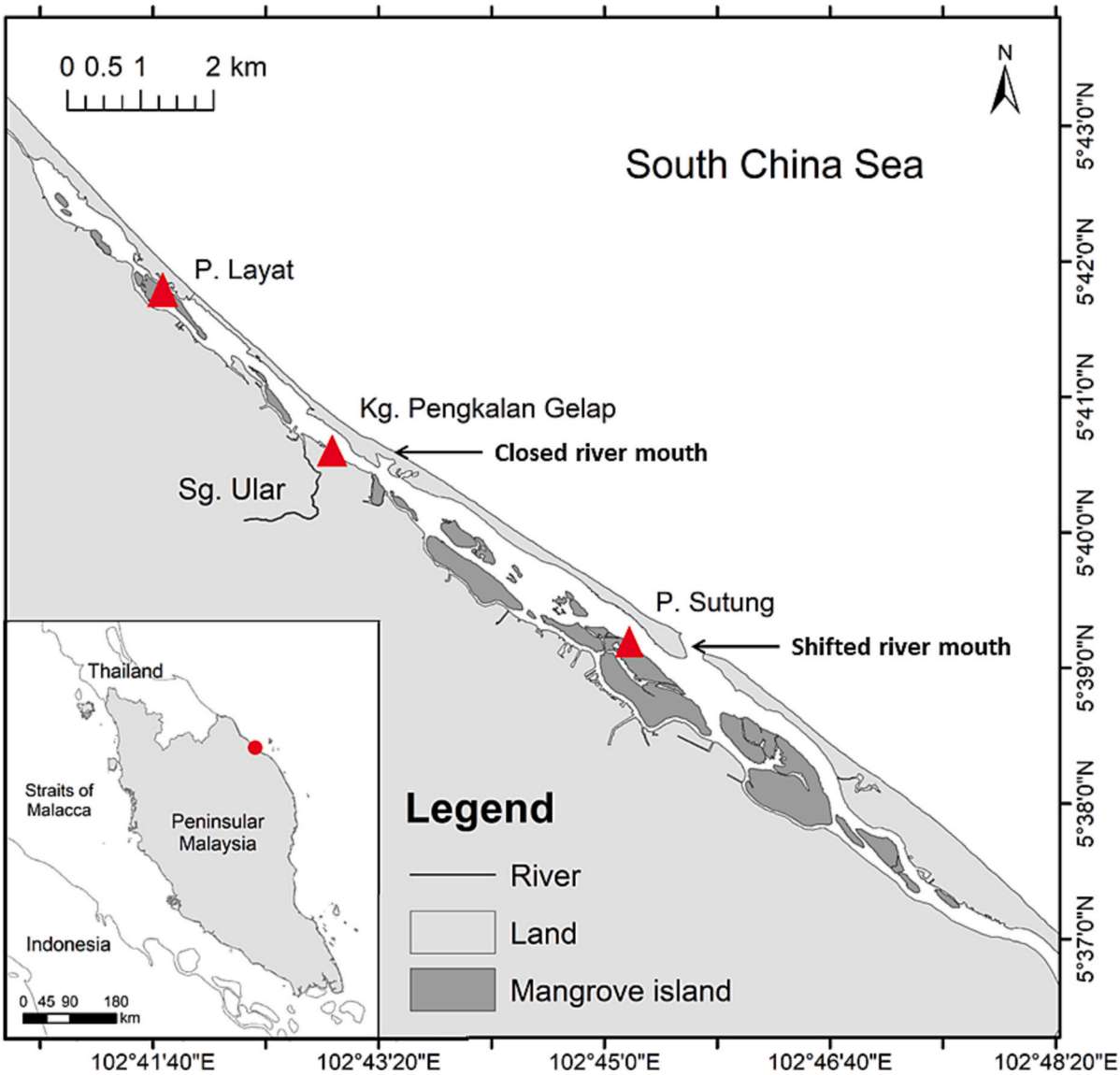

Fig. 1. Study area showing the three sampling sites namely, Pulau Layat, Kampung Pengkalan Gelap, and Pulau Sutung for the collection of mangrove brachyuran crabs at Setiu Wetlands on the east coast of Peninsular Malaysia.

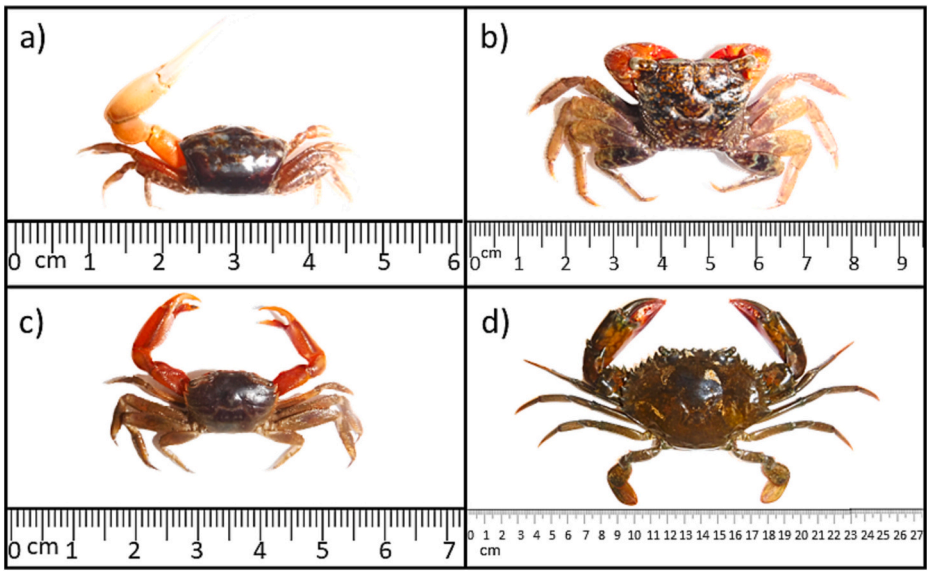

Fig. 2. The four abundantly distributed mangrove brachyuran crabs at the Setiu Wetlands - a) *Austruca annulipes*, b) *Parasesarma eumolpe*, c) *Metaplax elegans* and, d) *Scylla olivacea*.

since feeding habits of mangrove crabs can affect both the abundance and the composition of the ingested MPs (Not et al., 2020; Liu et al., 2023). Commonly to all *Parasesarma* species, *P. eumolpe* is known to be an opportunistic feeder with a wide range of food sources, but its diet mainly consists of mangrove litter (herbivore) (Ashton, 2002; Zakirah et al., 2022). *Metaplax elegans* also feeds on a wide range of sources, but it mainly relies on mangrove detritus (detritivorous) (Nordhaus et al., 2011). The fiddler crab *A. annulipes* filters the surface of the sediment to feed on the film of microalgae (microphytobenthos feeder) (Bartolini et al., 2009; Peer et al., 2016), whereas *S. olivacea* has an animal diet (carnivore) (Hidir et al., 2018). Identification of the crabs was done meticulously based on relevant taxonomic keys and literature (Crane, 1975; Fazhan et al., 2020; Keenan et al., 1998; Shahdadi and Schubart, 2015; Shih et al., 2019).

The above crab species were the only representative of their feeding guilds found at all the selected sampling sites. We choose to focus our analyses only on those species present at all sites to avoid a spatially unbalanced sampling design and consequent reduction of statistical power. In fact, a sampling design with different species from different sites would not have been able to disentangle the effects of the terms site and species, respectively, on the possible differences in MPs ingestion. The other frequently seen intertidal crabs at Setiu Wetlands include *Parasesarma plicatum* (Latreille, 1803), *Clistocoeloma merguiense* De Man, 1888, *Haberma* sp., *Gelasimus vocans* (Linnaeus, 1758), and *Moguai aloutos* Tan & Ng, 1999 (Zakirah et al., 2022).

All specimens, except *S. olivacea*, were collected by hand catch method at low tide (Ashton, 2002). *P. eumolpe* was mostly found in the vegetated areas, while *A. annulipes* were collected at the sandy waterfronts (Mokhtari et al., 2016), and *M. elegans* on the exposed mudflats. For *S. olivacea*, the traditional crab traps called "bubu" in Malay language were placed nearby the waterfront and/or *Rhizopora* spp. roots. The commercially important *S. olivacea* is regularly caught by the local fishermen for their livelihood. A total of ten individuals per species from each sampling site per season was targeted. However, the lower catch of some individuals in the wet period, especially *S. olivacea*, limited the sample size to 233 (seven specimens less than the target). The crab samples were transferred to the laboratory on the same day of collection (2 h to reach by car), rinsed with ultra-pure deionised water (MiliQ), and then preserved in the glass beakers (covered with aluminium foil) at −18 °C until further processing.

2.3. Sample preparation

Each crab was weighed (g) using a micro balance (Sartorius Ag Goettingen #CP224S, Canada), while its carapace width and length were measured (cm) using a vernier calipers (Mitutoyo Corp., #33375714, Japan), before dissecting the cardiac stomach. The stomachs were then digested with the potassium hydroxide (KOH) in separate glass vials, covered by aluminium foil, and placed in an oscillation water bath at 60 °C for 48–72 h at 240 rpm. The digested solution in each vial was filtered through a 1.6 μm pore size glass filter, using vacuum pump (Rocker 300, #167300-22, Taiwan), and the filter papers were dried in a desiccator for at least 24 h. The MPs left on each filter paper were carefully observed, identified, grouped, counted, and measured under a stereomicroscope (Carl Zeiss Stemi 508, China) attached to the digital camera (Axiocam 208 colour). The MPs were also categorized into bead, fibre, fragment, and pellet types along with their colour variations by following Hidalgo-Ruz et al. (2012). A hot needle test was used to separate the MPs from the other particles on the filter paper (Beckingham et al., 2023). Further examination of the MPs was done using a Scanning Electron Microscope (SEM) with Energy Dispersive X-Ray Analyzer (Tesca-Vegan 5, Czech Republic) for the physical characteristics and micro-Fourier transform infrared spectroscopy (micro-FTIR) (ThermoFisher Scientific, USA) for the polymer detection, respectively.

2.4. Data analyses

The abundance of MPs was represented by box plots (IBM SPSS v.28, Academic licence, UMT). The total number of MPs and the abundance of particle types found were analysed through univariate and multivariate Permutational Analysis of Variance (PERMANOVA) designs (Anderson et al., 2008), respectively. Both analyses were applied to test for differences in the MPs ingested between seasons (2 levels, fixed and orthogonal), across sampling sites (3 levels, fixed and orthogonal) and species (4 levels, fixed and orthogonal). Due to their heteroscedasticity, assessed using a Levene's test, we used a logarithmic transformation and a square-root transformation for the total amount and the overall composition of MPs, respectively, and the Euclidean distance was used to calculate the dissimilarity matrix. When appropriate, post-hoc pairwise tests were performed to examine the significant differences among levels of factors and their interactions. A Principal Component Analysis

(PCA) on previously normalised data was performed as an unconstrained ordination, to visualise patterns of MPs composition found in the stomachs. To further analyse the differences in the amount of MP categories in the different species, we performed a Canonical Analysis of Principal Coordinates (CAP). All analyses were based on 9999 permutations and were carried out using the software PRIMER *v*.7 and its add-on package PERMANOVA+ (Academic licence, Serial #3234) (Anderson et al., 2008). Spearman's correlation coefficient (R_s) was used to find the relationship between the abundance of MPs and the crab's body weight (SPSS *v*.20). Due to the significantly weak correlation between these two variables ($r^2 = 0.23$), the number of MPs were presented per individual.

2.5. Contamination control

Several precautions were taken to ensure the accuracy of the present results. All lab apparatus were rinsed by using the filtered (with 1.6 μm pore size glass filter) ethanol and ultra-pure MiliQ deionised water. Other precautionary measures include the usage of a closed and clean chamber to run the experiments, avoiding unnecessary opening of the filtration setup, covering the petri dishes and other containers with an aluminium foil, wearing the nitrile rubber gloves and a cotton lab coat. In addition, the procedural blanks, without biological tissue, and the blank filter papers in petri dishes exposed to ambient workplace chambers and field were tested to assess the background contamination (cf. Ibrahim et al., 2021).

3. Results

3.1. Morphometric measurements

Among the four brachyuran crabs, *S. olivacea* with a maximum carapace width and length had the highest body weight (Table 1). The other species, *P. eumolpe*, *M. elegans*, and *A. annulipes* were rather smaller with a significant variation among them, except for carapace width between *M. elegans* and *A. annulipes* (PERMANOVA Post-hoc, $t = 0.083$, $p > 0.001$).

3.2. Microplastics in crabs

A total of 633 MP particles were found in the 184 crab stomachs, accounting for 79 % of the total (233) samples collected for dry and wet seasons. The number of MPs per individual ranged from 0 to 24 items with a size of 0.01–5 mm. *Scylla olivacea* had the highest number of MPs (289), followed by *A. annulipes* (156), *P. eumolpe* (101), and *M. elegans* (87) in the order. The background contamination in the blank samples was small with only 0–2 MPs.

The three-way univariate PERMANOVA detected a significant difference in the total abundance of MPs ingested by the different species (Table 2). The test also found a strong impact on the MP content of the stomachs due to second and third term interactions, showing significant differences across sites and between seasons (Table 2).

The Post-hoc tests showed that *S. olivacea* ingested significantly more MPs than many of the other species across three sampling sites and during the two seasons, although some variability in the amount of MPs was evident (Table 3, Fig. 3). Differences in the number of MPs ingested by the species were significant for the wet season, except for *P. eumolpe* vs *M. elegans* (Table 3, Fig. 3).

Table 2
Results of the univariate three-way PERMANOVA test on the abundance of microplastics found in the stomachs of the brachyuran crabs collected from Setiu Wetlands. For each factor, the degrees of freedom (df), the value of the Mean Squares (MS) of the Pseudo-F parameter and its probability level (P) are given. Significant values where $P < 0.05$ are highlighted in bold.

Factors	df	MS	Pseudo-F	P
Season	1	0.36634	1.0772	0.2967
Site	2	0.57866	1.7015	0.1826
Species	**3**	**8.1526**	**23.972**	**0.0001**
Season × site	**2**	**1.0564**	**3.1062**	**0.0437**
Season × species	**3**	**3.0721**	**9.0331**	**0.0001**
Site × species	**6**	**0.86091**	**2.5314**	**0.0237**
Season × site × species	**6**	**1.4146**	**4.1594**	**0.0005**
Res	209	0.34009		
Total	232			

3.3. Microplastic types and crab's ingestion

Fibre was the most dominant type of MPs found in all species, while fragments were found in *S. olivacea* only. In relation to the colour, blue fibre constituted ca. 45 % of the total MPs in all crabs, followed by black fibre (21 %) and the rest of the colours found (with <5 % each). The green fragments in *S. olivacea* constituted 21 % of the total MPs in this species.

The three-way multivariate PERMANOVA detected significant difference in the amount of different types of MPs ingested by the different species across sites and between seasons (Table 4).

These results show a high variability of the ingested MPs with no seasonal or site-specific patterns that confirmed by the PCA ordination (Fig. 4A). The CAP analyses could, however, show that most of the variability in the ingested MPs was due to the ample range of items found in the stomach of the carnivorous *S. olivacea* (Fig. 4B).

3.4. Physical and chemical characteristics of microplastics

The morphology of fibre and fragments showed two distinct conditions, described as smooth and rough surfaces (Fig. 5), where the latter could represent the effect of weathering.

In total, 13 types of plastic polymers were detected (Table 5). Among others, rayon, polyester, and polytetrafluoroethylene (PTFE) were widespread and commonly found in all brachyuran crab species across the sampling sites (Fig. 6). Kampung Pengkalan Gelap showed the highest diversity of polymers, with polyacrylate, melamine-formaldehyde, and fluorocarbon types only found at this site. Also, PTFE was found in all four crab species collected from this sampling site. In terms of the variability among species, polyethylene was noticed only in *S. olivacea* collected from all three sampling sites (Table 5).

Table 1
Carapace and body weight measurements of the mangrove brachyuran crabs collected from Setiu Wetlands (range, mean ± SD) (genus names: P = *Parasesarma*, M = *Metaplax*, A = *Austruca*, and S = *Scylla*).

	P. eumolpe (Herbivore) (*n* = 59)	*M. elegans* (Detritivore) (n = 59)	*A. annulipes* (Microphytobenthos feeder) (*n* = 60)	*S. olivacea* (Carnivore) (*n* = 55)
Carapace width (cm)	0.93–2.37	0.82–1.68	0.77–1.84	6.83–11.59
	(1.60 ± 0.30)	(1.23 ± 0.21)	(1.23 ± 0.25)	(8.69 ± 1.05)
Carapace length (cm)	0.75–1.84	0.50–1.12	0.47–1.23	4.63–8.97
	(1.29 ± 0.24)	(0.84 ± 0.13)	(0.74 ± 0.16)	(5.96 ± 0.87)
Body weight (g)	0.27–5.72	0.11–1.51	0.10–1.35	40.09–296.19
	(2.06 ± 1.28)	(0.69 ± 0.04)	(0.55 ± 0.32)	(113.35 ± 42.97)

Table 3
Results of the PERMANOVA Post-hoc tests for the interactions - site × species and season × species. For each test, the value of the t parameter and its probability, P, are given.

Site: Pulau Layat			Dry season		
Groups	t	P	Groups	t	P
P. eumolpe, *A. annulipes*	1.2282	0.2236	*P. eumolpe*, *A. annulipes*	0.75666	0.4549
P. eumolpe, *M. elegans*	1.0261	0.3209	*P. eumolpe*, *M. elegans*	1.3843	0.1652
P. eumolpe, *S. olivacea*	1.4539	0.1543	*P. eumolpe*, *S. olivacea*	1.762	0.0806
A. annulipes, *M. elegans*	2.1737	0.0385	*A. annulipes*, *M. elegans*	0.64875	0.5189
A. annulipes, *S. olivacea*	0.66817	0.5007	*A. annulipes*, *S. olivacea*	2.4263	0.0185
M. elegans, *S. olivacea*	2.1378	0.0388	*M. elegans*, *S. olivacea*	2.9468	0.0048

Site: Kampung Pengkalan Gelap			Wet season		
Groups	t	P	Groups	t	P
P. eumolpe, *A. annulipes*	2.6168	0.0132	*P. eumolpe*, *A. annulipes*	5.662	0.0001
P. eumolpe, *M. elegans*	0.8213	0.4089	*P. eumolpe*, *M. elegans*	0.24465	0.8041
P. eumolpe, *S. olivacea*	3.6928	0.001	*P. eumolpe*, *S. olivacea*	7.1756	0.0001
A. annulipes, *M. elegans*	3.9194	0.0003	*A. annulipes*, *M. elegans*	5.6524	0.0001
A. annulipes, *S. olivacea*	1.1341	0.268	*A. annulipes*, *S. olivacea*	2.9527	0.0048
M. elegans, *S. olivacea*	5.1824	0.0001	*M. elegans*, *S. olivacea*	7.2134	0.0001

Site: Pulau Sutung		
Groups	t	P
P. eumolpe, *A. annulipes*	1.8253	0.0747
P. eumolpe, *M. elegans*	0.4012	0.6852
P. eumolpe, *S. olivacea*	6.5807	0.0001
A. annulipes, *M. elegans*	1.3545	0.1783
A. annulipes, *S. olivacea*	5.2499	0.0001
M. elegans, *S. olivacea*	6.0339	0.0001

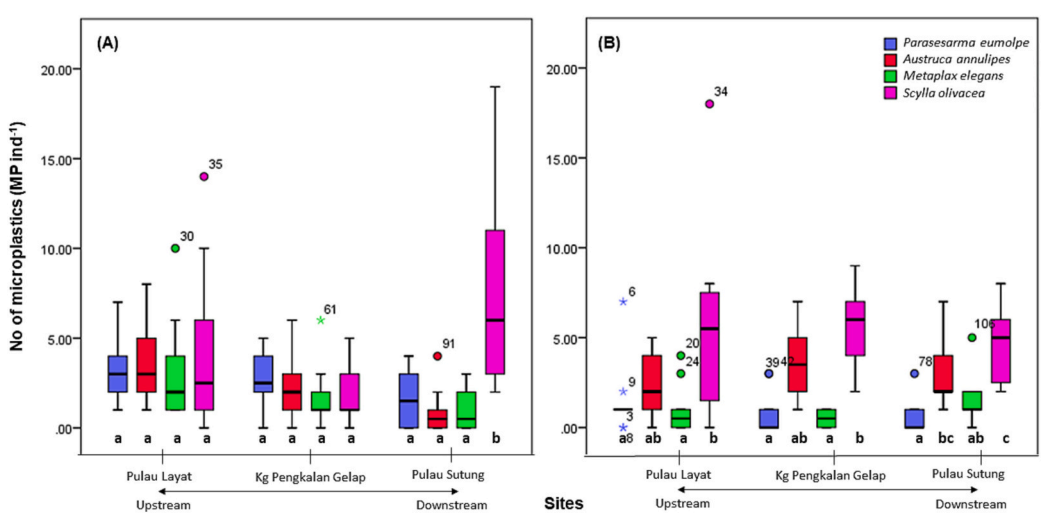

Fig. 3. Number of microplastics in different brachyuran crab species across three sampling sites at the Setiu Wetlands for (A) dry and, (B) wet seasonal periods – median, range (min. and max. value marks at the end of whiskers), standard error (box), standard deviation (whiskers). Circles and stars are the data outliers (Kg = Kampung = village in official Malay language). The lower-case letters indicate statistical differences ($p < 0.05$) between the species at each sampling site.

Table 4
Results of the multivariate three-way PERMANOVA on the types of MPs found in the stomachs of the brachyuran crabs collected from Setiu Wetlands. For each factor, the degrees of freedom (df), the value of the Mean Squares (MS) of the Pseudo-F parameter and its probability level (P) are given. Significant values where $P < 0.05$ are highlighted in bold.

Factors	df	MS	Pseudo-F	P
Season	**1**	**13.227**	**8.9647**	**0.0001**
Site	**2**	**4.483**	**3.0385**	**0.0031**
Species	**3**	**16.475**	**11.166**	**0.0001**
Season × site	2	2.9242	1.982	0.0424
Season × species	**3**	**3.8866**	**2.6342**	**0.0023**
Site × species	**6**	**2.9121**	**1.9737**	**0.0034**
Season × site × species	**6**	**3.1215**	**2.1157**	**0.0015**
Res	209	1.4754		
Total	232			

4. Discussion

4.1. Brachyuran crabs as indicators for microplastics contamination

Southeast Asian countries, namely Indonesia, Philippines, Vietnam, Thailand, and Malaysia are hotspots for mismanaged plastics (Jambeck et al., 2015), and significantly contributing to the amount of plastic debris in the oceans (Lebreton et al., 2017). Some of these nations also hold a luxuriant mangrove cover, where ~24 % of the global mangrove extent is represented by Indonesia and Malaysia alone (Bunting et al., 2022). Besides the provisioning, regulating, supporting, and cultural service values of the mangrove ecosystems (Dahdouh-Guebas et al., 2020, 2021; Osland et al., 2020; Satyanarayana et al., 2021), they are acting as a medium to trap plastic wastes and become reservoirs of MPs (Martin et al., 2019; Luo et al., 2021; Ouyang et al., 2022; Kwan So et al., 2022). Plastic contamination in the mangroves can inhibit gas exchange and release harmful chemicals that lethal to both vegetation and surrounding fauna (Martin et al., 2019).

Although the abundance of MPs found in the stomachs of brachyuran crabs of Setiu Wetlands (0–24 items per individual) was less than the earlier reports elsewhere (60–375 items per individual) (Not et al., 2020; Patria et al., 2020), the current trends of plastic usage and mismanagement warrant further precautionary measures and regular monitoring. A possible reason for such lowered counts of MPs in the crabs from Setiu could be linked to less plastic debris within the premises of the sampling sites. The recent findings of Ibrahim et al. (2021) also found rather a lower abundance of MPs in the water (0.36 items/L) and the sediment (5.97 items/g) here compared to similar investigations at Hong Kong, China, and Vietnam (Ho and Not, 2019; Zhang et al., 2019; Kieu-Le et al., 2023). On the other hand, mangrove sediments of Qinzhou Bay and Maowei Sea in China, Mahebourg and Ferney in Mauritius, and along the coast of Singapore (Mohamed Nor and Obbard, 2014; Li et al., 2018, 2019; Seeruttun et al., 2023) showed less MPs contamination than at Setiu Wetlands. In this context, along with real differences in plastic abundance at different locations, characterised by varied nature of tides, water current, wind and geometry (Safak et al., 2015), possible dissimilarities in the methodological approaches (including filter paper pore size) should be taken into account. For instance, Patria et al. (2020) analysed the entire soft tissue of *Metopograpsus quadridentatus* (Grapsidae), unlike the present study analysed only the stomach part. The research on MPs is an emerging field with several limitations all over (Provencher et al., 2020; Hernández-Sánchez et al., 2021). Therefore, estimation of the MPs in the organisms as well as the surrounding environment require standard uniform protocols starting from the sample collection to preservation and analyses (Hidalgo-Ruz et al., 2012; Lenz et al., 2016; Pfeiffer and Fischer, 2020; Provencher et al., 2020; Ibrahim et al., 2021).

Besides the higher variability of MPs abundance across species, sites and seasons, we constantly recorded a significantly higher number of MPs in the stomachs of *S. olivacea*. Although, the highest number of MPs in *S. olivacea* (up to 24 MPs/ind) can indeed be dependent on their size, but we found a significantly weak correlation between the amount of MPs and the body weight of the crabs. The MP types in the gut of these predators were also more diverse, with the fragments found only in this species. These results suggest that the predatory behaviour of this species is the major source of MPs in its stomachs. The lowest number of MPs in *M. elegans* (up to 10 MPs/ind) is perhaps due to its restricted detritus diet in the mangroves (Nordhaus et al., 2011).

The findings of this study also raise concerns over public health due to the existing demand for *S. olivacea* in the local markets. The green fragments, with polyethylene, in *S. olivacea* were found to have originated from the fishing net and/or bubu traps as confirmed by the FT-IR. Nylon is used in making the fish nets, while bubu traps and cage culture units are prepared by polyethylene mesh. As the diet of *S. olivacea* is mainly composed of crustaceans, molluscs, with a small contribution of algal materials (Hidir et al., 2018), they could have been erroneously consumed the green fragments as one of those animal's or plant-based products. On the other hand, the fragments may also be ingested via its prey such as fishes, gastropods, bivalves, which can be an indirect source of ingestion for the carnivores. Based on the abundance of MPs in the present study as well as the chances of direct and indirect modes of MPs ingestion, it was possible to conclude that in Setiu the only marketable crab species is more susceptible to plastic contamination, followed by microphytobenthos feeders, herbivores, and detritivores.

The abundance of blue and black fibres in *P. eumolpe*, *M. elegans*, and *A. annulipes* at Setiu Wetlands also coincides with the other studies encompassing fishes, polychaetes, and green crabs collected from the same location and elsewhere (Piarulli et al., 2019; Garcés-Ordóñez et al., 2020; Hamzah et al., 2021; Jiang et al., 2022). This would confirm the tendency of consuming bright coloured MPs by the marine organisms due to its attractive nature or similar colour with their preys (Ryan, 2016; Jiang et al., 2022; Li et al., 2019; Ma et al., 2020; John et al., 2022). The bioaccumulation leads to the spread of MPs across a range of habitats and diverse organisms in low to higher trophic levels (including humans) and show possible toxicity effects (Hantoro et al., 2019; Campanale et al., 2020; Ajith et al., 2020; Bhuyan, 2022; Li et al., 2023; Alberghini et al., 2023). Overall, the mangrove crabs, with their higher bioavailability to MPs (Zhang et al., 2021), were found to be good indicators of the plastic contamination at Setiu Wetlands and also warrant further attention towards the public health.

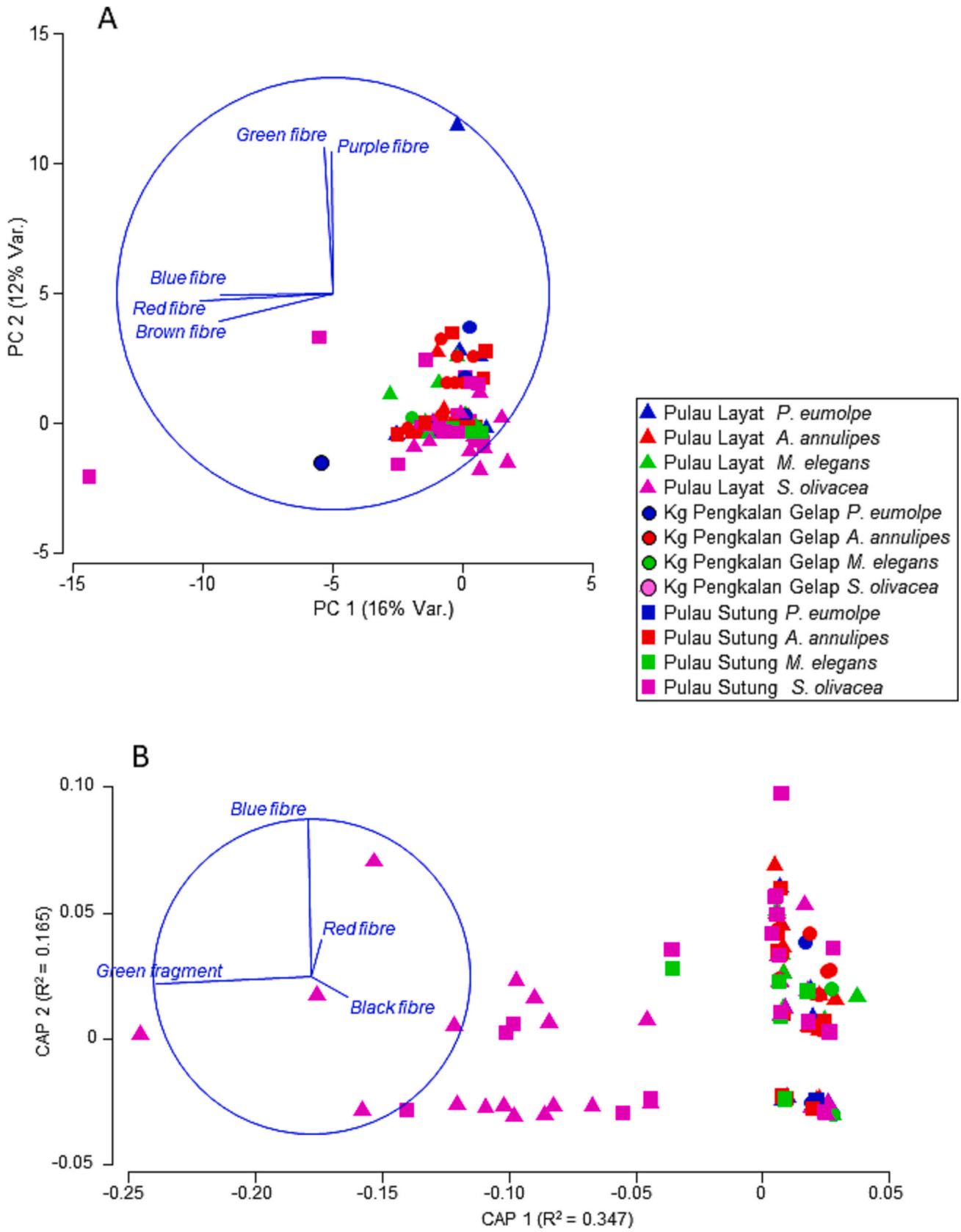

Fig. 4. Two-dimensional scatter plots of the first and second principal components (A) and of the first and second canonical axes (B) of MPs type compositions found in the stomach of four mangrove crab species from Setiu Wetlands. Vectors of the linear correlations between individual variables are superimposed on the graph (sampling sites: P = Pulau, Kg = Kampung) (genus names: P = *Parasesarma*, M = *Metaplax*, A = *Austruca*, and S = *Scylla*). The circle in each panel represents correlation circle and the orientation of fibre/fragment vector lines approximate their correlation to the ordination axes. The angle of separation between the vector lines can represent a positive or negative correlation between them.

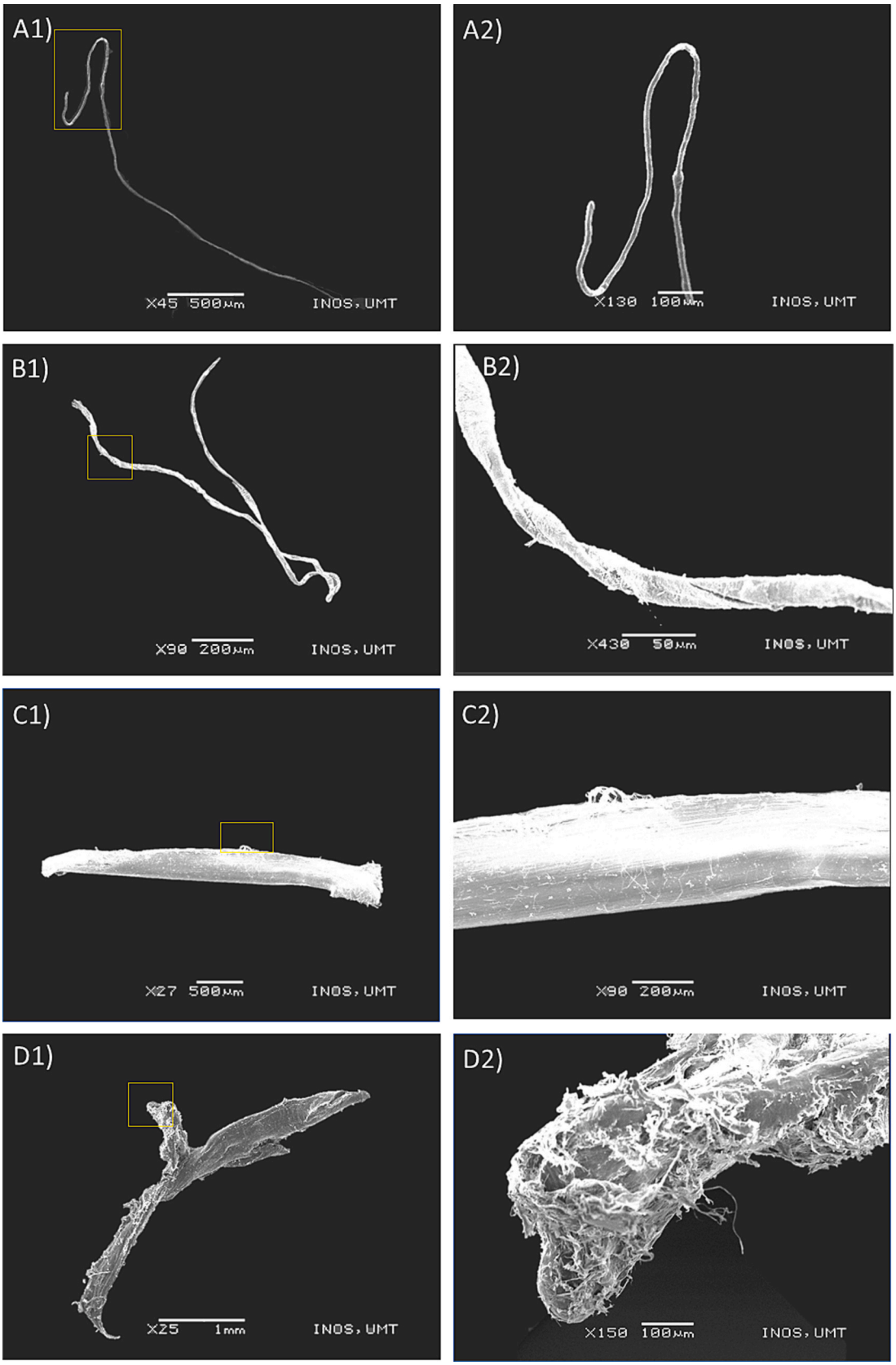

Fig. 5. Scanning Electron Microscope images of the microplastics found in mangrove brachyuran crabs of the Setiu Wetlands (1) and their enlarged view (2): (A) smooth fibre (B) weathered filament, (C) smooth fragment; (D) weathered fragment (fibre forming fragment).

Table 5
Different types of polymers – polyethylene (PE), polyester (PET), polyamide (PolyA), polyacrylate (PolyAc), polytetrafluoroethylene (PTFE), polystyrene (PS), polyvinyl alcohol (PVA), ethylene vinyl alcohol copolymer (EVOH), rayon (R), polymethyl methacrylate (PMMA), melamine-formaldehyde (MF), fluorocarbon polymer (FP), and phenoxy resin (PR), found in the brachyuran crab samples collected from Setiu Wetlands ('+' shows presence, '–' shows absence) (sampling sites: P = Pulau; Kg. P. = Kampung Pengkalan).

Site	Species	PE	PET	PolyA	PolAc	PTFE	PS	PVA	EVOH	R	PMMA	MF	FP	PR
P. Layat	*P. eumolpe*	–	+	–	–	–	–	–	–	–	–	–	–	–
	A. annulipes	–	–	–	–	–	–	–	+	+	–	–	–	–
	M. elegans	–	+	+	–	+	–	–	–	–	+	–	–	–
	S. olivacea	+	–	–	–	–	–	+	–	–	–	–	–	–
Kg. P. Gelap	*P. eumolpe*	–	–	+	–	+	–	–	+	+	–	–	–	–
	A. annulipes	–	+	–	–	+	+	–	–	–	–	–	+	–
	M. elegans	–	+	–	–	+	–	+	–	+	–	–	–	–
	S. olivacea	+	–	–	+	+	–	–	–	+	–	+	+	–
P. Sutung	*P. eumolpe*	–	–	–	–	+	–	–	–	+	–	–	–	–
	A. annulipes	–	+	–	–	+	–	–	–	–	–	–	–	+
	M. elegans	–	–	–	–	–	–	–	–	+	–	–	–	–
	S. olivacea	+	–	–	–	–	–	–	–	+	–	–	–	–

4.2. Site and seasonal impacts on the microplastics

The current observations indicate that both the geographic location of sampling sites and the seasonal hydrodynamics play a strong role for the extent of MPs contamination in Setiu Wetlands. Besides the core mangroves at Pulau Layat, which able to trap significant plastic waste (cf. van Bijsterveldt et al., 2021; Rahim et al., 2020), the poor material dispersion/longer resident time of the particle in the upstream (Rynne et al., 2016; Zainol et al., 2022) are responsible for a higher abundance/ingestion of MPs at this site. In this context, the reduced freshwater input from River Ular, along with the consequences of the shifted (Setiu) river mouth like sediment (sand) deposition, increased elevation, and infrequent tidal inundation (personal observation), are practically influencing the accumulation and the distribution of MPs locally. Earlier, Ibrahim et al. (2016, 2017) and Hamzah et al. (2021) also found a drastic decrease in the MPs between the northern (upstream) and the southern (downstream) sectors of the Setiu lagoon in relation to the mangrove bivalve, *Anadara cornea* (Reeve, 1844); estuarine fish, *Lates calcarifer* (Bloch, 1790), and a polychaete, *Namalycastis* sp. On the other hand, less MPs across the sampling sites in the wet season are attributable to the improved water exchange conditions through precipitation/floods. The flushing rate of the particles in the closed Setiu lagoon is considerably high for the wet periods (John et al., 2020; Zainol et al., 2021).

The widespread occurrence of polymers like rayon, polytetrafluoroethylene (PTFE), and polyester at the sampling sites, especially Pulau Layat and Kampung Pengkalan Gelap, is largely associated with domestic waste, fishing gear, and boat paint activities (cf. John et al., 2022). Household laundry is one of the main sources of MPs as clothes contain synthetic and semi-synthetic fibres like polyester, nylon, and rayon (Browne et al., 2011). PTFE is typically present in the paints and coatings used for boats and home appliances (Lee et al., 2022). Also, the nylon fishing nets contain polyester (Nor and Obbard, 2014). While domestic sewage enters the wetlands through upstream channels, the old fishing nets in and around the ecosystem are discarded by local fishermen. Exclusive presence of the diverse polymers at Kampung Pengkalan Gelap was due to different plastic sources (e.g., plastic covers, bags, drink bottles, polystyrene/styrofoam boxes) landed from the adjacent housing areas, local and non-local visitors at the ecotourism boardwalk. Importantly, the garbage dumped close to mangrove areas by the surrounding population is entering wetlands through the rain and tidal actions. The rough and weathered MPs due to photooxidation by UV radiation and mechanical abrasion by wave action (Song et al., 2017) not only leach harmful chemical additives and raise plastic contamination in the environment, but also increase the chances of MPs ingestion by organisms (Ibrahim et al., 2016).

5. Conclusions

The potential of brachyuran crabs as indicators of the contamination of MPs at Setiu Wetlands was evident. Although characterised by a rather high variability among sites and between seasons, the presence of MPs in the crabs' stomachs was ubiquitous across all sites, which showed differences in the composition of such MPs. Further managerial actions are required not only to reduce plastic waste but also for its appropriate recycling/disposal measures. With respect to the analysed species with different feeding guilds, the only commercially important *Scylla* spp. are more susceptible to the contamination of MPs than all other species, suggesting that MPs can enter the human food chain by this source. The present findings serve as baseline for future studies and be able to assist in sustainable conservation and management of the Setiu Wetlands and their products.

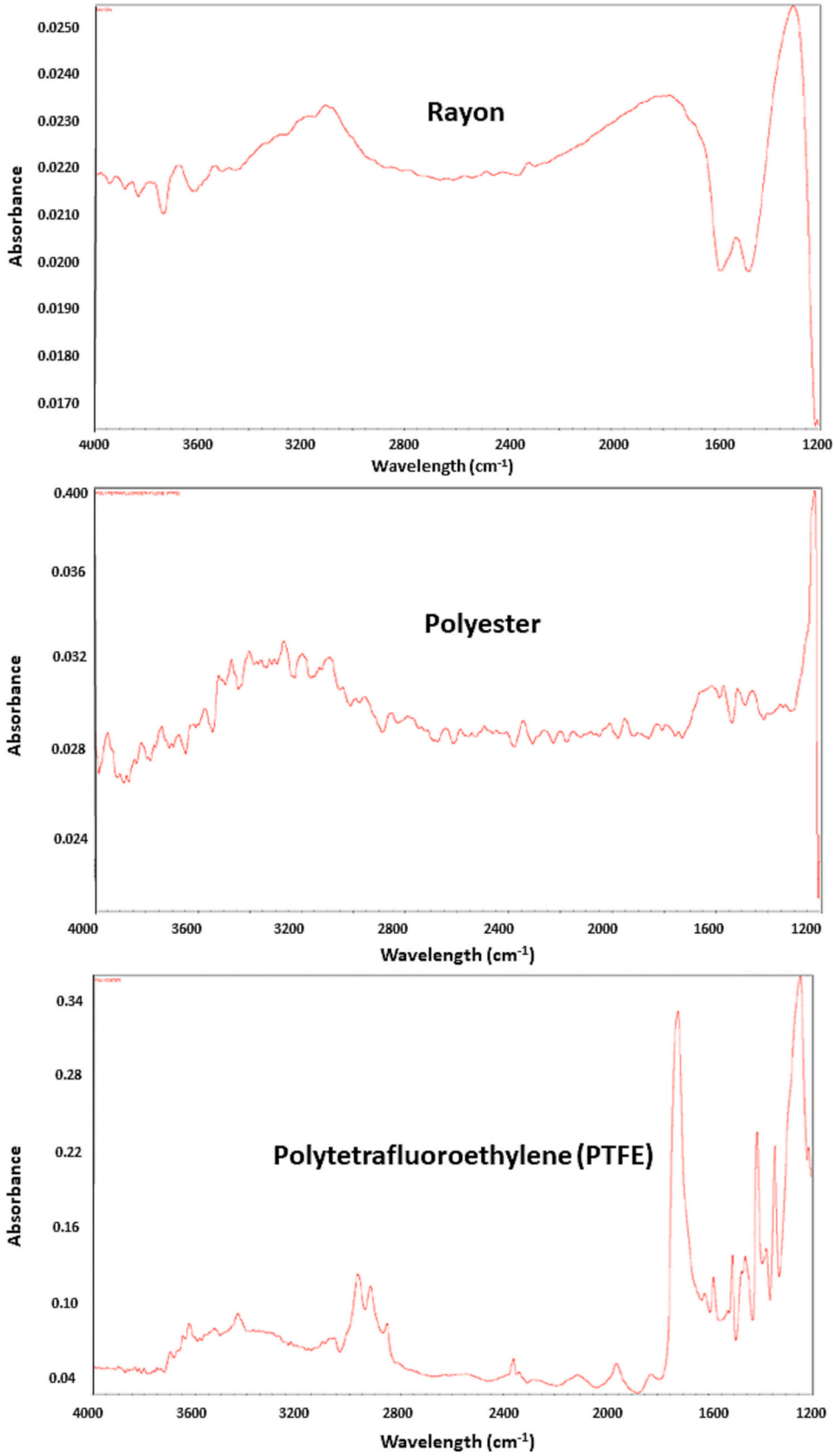

Fig. 6. Absorption spectra of the commonly found plastic polymers in the mangrove brachyuran crabs of Setiu Wetlands - a) rayon, b) polyester, and c) polytetrafluoroethylene.

CRediT authorship contribution statement

Conceptualisation: NHAR, BS, II, JMJ, SC and FD-G; Methodology: NHAR, BS, YSI, CN, SC and FD-G; Software: NHAR, BS and SC; Validation: NHAR, BS, YSI, CN, II, JMJ, SC and FD-G; Formal analysis: NHAR, BS and SC; Investigation: NHAR; Resources: NHAR, BS, YSI and SC; Data Curation: NHAR, BS and SC; Writing - Original Draft: NHAR and BS; Writing - Review & Editing: NHAR, BS, YSI, CN, II, JMJ, SC and FD-G; Visualisation: NHAR, BS, SC and FD-G; Supervision: BS, II, JMJ, SC and FD-G; Project administration: BS; Funding acquisition: BS and JMJ.

Declaration of competing interest

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

Data availability

Data is available at https://doi.org/10.1016/j.dib.2023.109420.

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