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Marine microplastics in the ASEAN region: A review of the current state of knowledge☆

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ABSTRACT

Microplastic pollution is a prevalent and serious problem in marine environments. These particles have a detrimental impact on marine ecosystems. They are harmful to marine organisms and are known to be a habitat for toxic microorganisms. Marine microplastics have been identified in beach sand, the seafloor and also in marine biota. Although research investigating the presence of microplastics in various marine environments have increased across the years, studies in Southeast Asia are still relatively limited. In this paper, 36 studies on marine microplastic pollution in Southeast Asia were reviewed and discussed, focusing on microplastics in beach and benthic sediments, seawater and marine organisms. These studies have shown that the presence of fishing harbours, aquaculture farms, and tourism result in an increased abundance of microplastics. The illegal and improper disposal of waste from village settlements and factories also contribute to the high abundance of microplastics observed. Hence, it is crucial to identify the hotspots of microplastic pollution, for assessment and mitigation purposes. Future studies should aim to standardize protocols and quantification, to allow for better quantification and assessment of the levels of microplastic contamination for monitoring purposes.

1. Introduction

Plastic pollution is a growing global environmental issue that has greatly impacted aquatic ecosystems. Since the 1950s, there is an exponential growth in global plastic production, resulting in over 335 million tonnes of plastic being produced in 2016 (Wang et al., 2019). Currently, the majority of plastics produced are low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET) and polyvinyl chloride (PVC). Combined, these plastics constitute approximately 90% of worldwide plastic production (Andrady and Neal, 2009). Microplastics are known as synthetic plastic particles which are smaller than 5 mm in diameter (Rochman et al., 2019). The first mention of microplastic contamination was by Carpenter and Smith (1972), and only in recent decades has this issue been studied in greater detail in various environments (Castillo et al., 2016). Microplastics are classified into two main forms-primary and secondary microplastics (Lehtiniemi et al., 2018). Primary microplastics refer to plastic particles which are manufactured at a small size for specific applications-such as resin beads for plastic production, and microbeads for facewashes or toothpastes. Although plastics are durable, larger plastic particles such as styrofoam buoys and plastic bottles can fragment to give secondary microplastics due to weathering caused by prolonged exposure to ultraviolet radiation (Julienne et al., 2019) or physical impact (Efimova et al., 2018; Guo & Wang, 2019c). The extent of microplastic pollution in the environment is ubiquitous. To date, microplastics have been identified in lakes (Sighicelli et al., 2018), mangroves (Li et al., 2020), oceans (Zarfl et al., 2011), even in air (Gasperi et al., 2018) and ice sheets (Geilfus et al., 2019).

In marine environments, microplastics have been observed along coastal beaches (Karthik et al., 2018), in the water column (Cincinelli et al., 2019) and benthic sediments (Pagter et al., 2020). Eight percent of these microplastics have land-based origins from coastal, industrial and domestic activities (Sharma & Chatterjee, 2017; Derraik, 2002). Unlike macroplastics, microplastics escape wastewater treatment plants and enter into the marine environment as domestic effluents (Carr et al., 2016).

Due to the small size and ubiquity of these microplastics, these

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particles are a threat to marine organisms as they fall in the same size range as their prey and often mistaken by food (Roch et al., 2020). Marine organisms which are commonly consumed by humans such as crabs (Watts et al., 2014), shrimp (Carreras-Colom et al., 2018), mussels (Li et al., 2016), oysters (Li et al., 2018) and fish (Jovanović, 2017) have been reported to ingest microplastics. For instance, polystyrene (PS) microplastics greater than 150 μm were observed to be translocated within the gills, hepatopancreas and stomach of the mudflat fiddler crab, *Uca rapax* (Brennecke et al., 2015). In *Mytilus edulis,* Kolandhasamy et al. (2018) observed the adherence of microfibers to its soft tissues. In another study, Browne et al. (2008) noted a translocation of PS microspheres of 3–9.6 μm in diameter from the digestive tract to the circulatory system in *M. edulis.* The presence of microplastics has resulted in detrimental effects in these organisms. Exposure of *Mytilus* sp. individuals for 2 months to PS microbeads resulted in the increased production of reactive oxygen species and increased haemocyte mortality (Paul-Pont et al., 2016). This has implications on food safety as these organisms are often eaten whole without the removal of their guts and could possibly transfer their ingested microplastics to the human body.

Microplastic particles are evident along many shorelines around the world. These plastics are washed up on beaches and can accumulate especially along the high-strand vegetation lines, as they are trapped between plant material (Curren and Leong, 2019). The presence of microplastics on coastal beaches has been investigated in countries such as Slovenia (Laglbauer et al., 2014), Portugal (Frias et al., 2010), Thailand (Bissen & Chawchai, 2020) and Singapore (Curren and Leong, 2019). While these plastic particles may be small, their existence on beaches can pose a threat to human health as they are shown to be a vector for the transport of harmful microorganisms such as bacteria and viruses (Zettler et al., 2013). The attachment of the harmful virus *Vibrio* spp. has been observed marine microplastics in the Baltic sea (Kirstein et al., 2016), France (Frère et al., 2018), Scotland and China (Xu et al., 2019; Zhang et al., 2020). Other harmful bacteria such as *Pseudomonas alcaligenes* and *Escherichia coli* have been identified from microplastics along the coastlines of Singapore and the United Kingdom, respectively (Curren and Leong, 2019; Harrison et al., 2014). Furthermore, the biofilms that arise on microplastic surfaces drive the growth of pathogenic microbes, causing these organisms to be more infectious as compared to their free-living state (Bowley et al., 2020).

Over long periods of time, the surfaces of microplastics can be colonized by microorganisms, resulting in an increased density. Particles that become denser than seawater will sink from the water surface the benthic sediment. This is an issue as the size fractions of microplastics are very similar to the granules found in benthic sediments. This makes microplastics more available to sediment-dwelling biota (Wright et al., 2013; Van Cauwenberghe et al., 2015). This could lead to a higher intake of microplastics by organisms such as shrimp and clams (Wang et al., 2019).

Asia is the largest continent in the world, covering about 30% of the total area on Earth (Mattern, 2002). The Association of Southeast Asian Nations (ASEAN) region consists of the ten countries: Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand and Vietnam. The east Asian seas are known to have one of the greatest levels of plastic pollution in the world (Walther et al., 2020). However, in Southeast Asia, the issue of microplastic pollution has only been gaining awareness in the past few years, with microplastics research emerging from countries such as Brunei (Qaisrani et al., 2020), Malaysia (Barasarathi et al., 2014; Karbalaei et al., 2019), Indonesia (Syakti et al., 2018; Firdaus et al., 2020), Thailand (Thushari et al., 2017), Singapore (Curren and Leong, 2019), Philippines (Paler et al., 2019; Kalnasa et al., 2019), Myanmar (Mon & Nakata, 2020) and Vietnam (Phuong et al., 2019). To date, there are no published reports from the remaining southeast Asian nations such as Cambodia, East Timor and Laos.

Hence, the objectives of this review were to: (1) summarise the current state of knowledge of marine microplastic research from various ASEAN nations; and to (2) discuss the possible implications of microplastic pollution on the environment and human health. A schematic diagram has been drawn to give an overview of the presence of marine microplastics in the different matrices (Fig. 1).

2. Methods

We used the following phrases related to marine microplastic contamination as keyword searches: "marine microplastics, microplastic beach sediment, microplastic benthic sediments, microplastics in seawater, microplastics in marine biota" across indexed journal databases.

Relevant data regarding microplastic abundances across different matrices from countries in Southeast Asia were extracted and tabulated. The percentages of the microplastic types and polymers were recorded, where possible and used for further calculation. Differences in microplastic abundance across the various matrices were tested using one-way analysis of variance (ANOVA), followed by Tukey's HSD *post hoc* pairwise comparisons. A significance level of 0.05 was chosen. The 'multcomp' package (Hothorn et al., 2016) in R studio (version 1.301073) was used to conduct the statistical analysis. F-ratio and p-values were reported to two decimal places.

3. Results and discussion

The contamination of microplastics in the marine environment is an emerging issue that has gained increasing attention in the past few years. From Southeast Asia, a total of 36 studies were conducted to analyse the presence of microplastics across beach sediments, seawater, benthic sediments and in marine organisms. Where possible, the percentages of each microplastic type and polymer were displayed (Tables 1–4). The distribution of the studies together with a summary of the microplastic concentrations analyzed in this survey were visualized in a map (Fig. 2).

3.1. Microplastics from beach sediments

Sediments from two beaches in Kuching, Sarawak, Malaysia, were examined for the presence of microplastics. Kampung Santubong was once a popular fishing village and Kampong Trombol is a place with sparse human population and some coastal agriculture. Across both stations, the dominant plastic polymer was PP (Table 1). Although the two locations were different, there was no significant difference in the abundance of microplastics observed. For this study, the authors

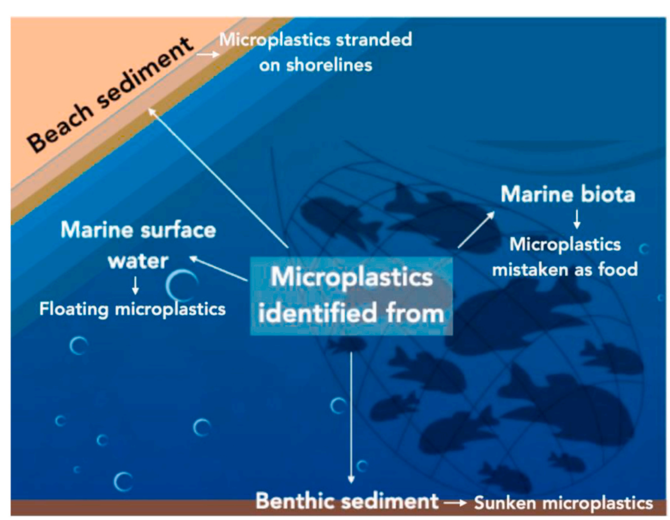

Fig. 1. Schematic diagram representing the presence of microplastics in the marine environment: in beach sediments, water column, benthic sediments and marine biota.

Table 1
Microplastics recorded from beach sediments of southeast Asia.

Location	Location	Sampling period	Microplastic concentration	Size range	Microplastic category	Polymer type	Reference
Malaysia							
Sarawak, Kuching	Santubong Beach	Aug 2014	0.0358–0.411 g (in total)	>1 mm	Fragment	PE (31%), PP (28%), PS (19%), PET (13%), others (9%)	Noik and Tuah (2015)
	Trombol Beach		1.54–1.73 g (in total)		Fragment	PP (37%), PE (30%), PS (17%), PET (11%), others (5%)	
Philippines							
Luzon	Talim Bay	NA	260 pieces/kg	>0.7 μm	Fragment (52%), Film (29%), Granules (19%)	NA	Paler et al. (2019)
Misamis Oriental, Macajalar Bay	Opol	April 2018	400 pieces/kg	>400 μm	Fragment (33%), Filament (33%), Fibers (17%), Others (17%)	NA	Kalnasa et al. (2019)
	El Salvador City		340 pieces/kg				
	Alubijid		380 pieces/kg				
Singapore							
Johor Strait	Sembawang beach	Apr-Jul 2018	31.1 pieces/kg	>1 mm	Fragment (33%), Fiber (4%), Foam (57%), Granule (4%), Film (4%)	NA	Curren and Leong (2019)
	Changi beach		599 pieces/kg		Fragment (62%), Foam (28%), Film (10%)		
Singapore Strait	Lazarus Island		9.16 pieces/kg		Fragment (33%), Fiber (8%), Foam (33%), Granule (26%)		
Vietnam							
Tien Giang Province	Estuary	NA	42.5 pieces/kg	500 μm-5mm	Fragment (60%), fiber (14%), granules (26%)	PP (47%), PE (44%), PS (5%), PVC (4%)	To et al. (2020)
	Tan Thanh		44.6 pieces/kg		Fragment (74%), fiber (15%), granules (11%)	NA	
Vung Tau City	Pineapple beach		2.5 pieces/kg		Fragment (52%), fiber (16%), granules (32%)		
	Back beach		4 pieces/kg		Fragment (20%), fiber (8%), granules (72%)	PS (40%), PE (38%), PP (19%), PVC (3%)	

Table 2
Microplastics recorded from the seawater of southeast Asia.

Country	Location	Sampling period	Microplastic concentration	Size range	Depth (m)	Microplastic category	Polymer type	Reference
Indonesia								
Riau Island Province	Bintan	NA	450 pieces/L	>100 μm	0	Fragment (50%), fiber (26%), film (13%), granules (9%)	PP (54%), PE (17%), LDPE (18%), PS (10%), others (1%)	Syakti et al. (2018)
Northern Surabaya	Lamong Bay	Mar 2017	0.38–0.61 pieces/L	>300 μm	0	Fragment (34%), fiber (3%), foam (58%), granules (4%)	PS (58%), PE (18%), PP (18%), PET (1%), Others (6%)	Cordova et al. (2019)
	Kenjeran Beach		0.46–0.55 pieces/L					
	Wonorejo Beach		0.44–0.53 pieces/L					
Semarang	Tambak Lorok	Jul-Sep 2018	900-11100 pieces/L	>1 μm	NA	Fiber, Filament	PP	Khoironi et al. (2020)
South Sulawesi	Makassar City	NA	NA	>500 μm	0	NA	NA	Afdal et al. (2019)
East Nusa Tenggara	Sumba	Aug 2016	0-120000 pieces/L	>300 μm	5, 50, 100, 300	Fiber (45%), Granule (36%), Others (19%)	PE (64%), PP (23%), PS (9%), PA (4%)	Cordova and Hernawan (2018)
Java Island	Cilacap coast	May 2016	270-540 pieces/L	>250 μm	0	NA	PP	Syakti et al. (2017)
Malaysia								
Terengganu	Kuala Nerus	Sep-Oct 2015	0.13–0.69 pieces/L	>200 μm	0	Fragment (76%), Fiber (24%)	PA, PP	Khalik et al. (2018)
Pahang	Kuantan		0.14–0.15 pieces/L			Fragment (66%), Fiber (34%)	PS,PA, PVC, PE	

reported the combined weight of microplastics observed. From Sanbutong beach, there was an average of 0.0358–0.411 g of microplastics, where Trombol beach had an average of 1.54–1.73 g of microplastics collected (Noik and Tuah, 2015, Table 1).

The beach sediments of southwestern Luzon, Philippines were examined for the presence of microplastics. From Talim Bay, an average of 260 microplastic pieces/kg were observed (Paler et al., 2019, Table 1). Fragments were the dominant microplastic form at 52% (Paler et al., 2019). In another study, three beaches of Macajalar Bay, Philippines were investigated for microplastics. Fragments were the dominant form of microplastics, at 83% (Kalnasa et al., 2019, Table 1). The highest abundance of microplastics were recorded in Opol (400 pieces/kg), followed by El Salvador City (340 pieces/kg) then Alubijid (380 pieces/kg; Kalnasa et al., 2019, Table 1). Opol, which was the innermost station of Macajalar Bay, had the greatest microplastic concentration recorded due to its growing coastal ecotourism (Felisilda et al., 2018). Opol's proximity to two cities allows the easy accumulation of land-litter in the coastal region, resulting in the high abundance of

Table 3
Microplastics recorded from sediments of southeast Asia.

Country	Location	Sampling period	Depth (m)	Microplastic concentration	Size range	Microplastic category	Dominant type	Reference
Indonesia								
Java Island, Madura Strait	Jagir estuary Wonorejo coast	NA	NA	92-414 pieces/kg 484-590 pieces/kg	>1 μm	Fiber (57%), Film (36%), Fragment (7%)	PES (57%), LDPE (25%), PP (18%)	Firdaus et al. (2020)
Semarang	Tambak Lorok	Jul-Sep 2018	NA	8000-49000 pieces/kg	>1 μm	Fiber, fragments	PP	Khoironi et al. (2020)
Java Island	Banten Bay	Apr 2016	1–28	267 pieces/kg	>100 μm	Foam (30%), Fragment (27%), Granules (24%), Fibers (19%)	CP (71%), PET (17%), PP (6%), PE (6%)	(Falahudin et al. (2020)
Jakarta Bay	Pluit	Dec 2015–Jan 2016	NA	37440-38592 pieces/kg	>20 μm	Fiber (1%), Fragment (98%), Granule (1%)	PP, PET, PE	Manalu et al. (2017)
	Ancol			18405-27284 pieces/kg		Fiber (1%), Fragment (97%), Granule (2%)		
Lombok Island	Sekotong	Mar 2017	NA	35-77 pieces/kg	>200 μm	Foam (41%), Fragment (33%), Granule (22%), Fiber (4%)	PS, PP, PE	Cordova and Hernawan (2018)
East Java	Lamongan	Oct 2018	0–0.3	145-354 pieces/kg	>300 μm	Fiber (85%), Fragment (12%), Film (3%)	NA	Asadi et al. (2019)
Western Sumatra	East Indian Ocean	May 2015	66.8–2182	10-140 pieces/L	>20 μm	Granule (86%), Fiber (14%)	NA	Cordova & Wahyudi (2016)
East Java	Java Sea	Mar 2018	NA	206-897 pieces/kg	>300 μm	Fragment (54%), Fiber (42%), Film (4%)	NA	Yona et al. (2019)
	Baluran National Park	Oct 2018	0–0.3	35.8–153.1 pieces/kg	>300 μm	Fiber (37%), Film (33%), Fragment (29%), Foam (1%)	NA	Asadi et al. (2019)
Sulawesi	Spermonde Archipelago	Jul-Sep 2017	4–6	2.96–28.29 pieces/kg	>63 μm	Filament	NA	Tahir et al. (2019)
Philippines								
Negros Oriental	Sillman Beach, Dumaguete	Oct–Dec 2018	1–2.5	82 pieces/kg	>8 μm	Fiber (86%), fragment (16%)	RY (84%), PET (11%), PVC (3%), PR (2%), AF (2%)	Bucol et al. (2020)
Thailand								
Gulf of Thailand	Gulf of Thailand	2010–2011	0–0.05	25-363 pieces/kg	>20 μm	Fiber	RY (37%), PES (16%), AF (9%), PE (3%), PVC (2%), others (33%)	Wang et al. (2020)

microplastics obtained (Kalnasa et al., 2019).

Microplastics were also examined from the coastal sediments of Singapore (Curren and Leong, 2019). Three sites were surveyed across the northern and southern coasts of Singapore. Sembawang beach was a recreational beach near a residential area that was commonly used for activities such as fishing and jogging. Changi beach was located near a busy harbour and Lazarus beach was located on an island with little tourist activity. From the northern coast, the microplastic abundance from Sembawang and Changi beach was 31.1 pieces/kg and 59.9 pieces/kg, respectively (Curren and Leong, 2019, Table 1). From Lazarus beach of the southern coast, the microplastic abundance was 9.16 pieces/kg. From sites of the northern strait, foam microplastic pieces were the dominant microplastic type. Fibers were the dominant microplastic type from Lazarus beach (Curren and Leong, 2019, Table 1). Both Sembawang and Changi had a greater abundance of microplastics due to the Johor Strait, which is eutrophic and more polluted than the Singapore Strait (Curren and Leong, 2019; Leong et al., 2015). The Johor Strait has a lower flow of water compared to the Singapore Strait due to the causeway that links both Singapore and Malaysia, resulting in an increased accumulation of pollutants and debris (Leong et al., 2015).

Three locations along the beaches were sampled: the high-strand, middle strand and low-strand line. Among the tide lines, the high-strand line had the greatest abundance of microplastics across the four sites. From the Tien Giang province, the high-strand line of the estuary and Tan Thanh had 112.7 and 12.0 pieces/kg of sand, respectively (Table 1). Fragments were dominant at 60.2%. Both locations had an average of 42.5 and 44.6 pieces of microplastics/kg, respectively (Table 1). From Vung Tau City, Pineapple and Back beaches had 2.5 and 112 pieces/kg of sand, respectively from the high-strand line. Both Pineapple and Back beaches were tourist beaches that was used for recreation. Back beach was more popular with tourists. There was an average of 2.5 and 4 pieces of microplastics/kg, from both locations, respectively. Microplastic granules were the most prevalent at 71.7% (To et al., 2020, Table 1). The higher abundances of microplastics observed from the estuary and Back beach was due to the high level of human activities such as oyster and clam aquaculture surrounding those areas (To et al., 2020).

Across various beach sediments, the abundance of microplastics were greater in areas of where the levels of anthropogenic activities were higher. Tourism, fishing and marine aquaculture contributed to a greater microplastic concentration observed.

3.2. Microplastics from surface waters

There is evidence that microplastic abundance from surface waters is influenced by anthropogenic activities from places such as housing settlements and ship harbors. Surface water samples of 11 locations around small islands in Bintan Regency, Riau Island Province, Indonesia were examined for floating microplastics from 100 μm to 5 mm (Syakti et al., 2018, Table 2). The average density at these stations were 0.45 pieces/m^3 of surface seawater. Sampling stations with the highest concentration of microplastics (0.94 pieces/m^3) were located closest to the ferry harbor of the province capital, Tanjungpinang City (Syakti et al., 2018). The lowest number of microplastics corresponded to a resort which banned the use of single-use plastic. Majority of microplastics from these 11 locations were PP, PE, LDPE and PS (Syakti et al., 2018, Table 2). Microplastics from >300 μm to 5 mm were also examined in the northern coastal waters of Surabaya, Indonesia. The highest microplastic abundance was recorded in Lamong Bay (0.61 pieces/L), which was located closest to harbor activities and housing settlements (Cordova et al., 2019, Table 2). Beaches such as Kenjeran and Wonorejo had

Table 4
Microplastics recorded from marine organisms from Southeast Asian waters.

Country	Location	Sampling period	Organism	Microplastic concentration	Size range	Microplastic category	Dominant type	Reference
Indonesia								
Riau Island province	Tanjung-pinang	May 2018–Jan 2019	Grey-eel catfish *Plotosus canius*	20-87 pieces/ individual	>50 μm	Fragment, fiber	NA	Lubis et al. (2019)
	Bintan, Kepulauan	Mar 2019	Gonggong snail *Laevistrombus turturella*	460-628 pieces/ individual	>1 mm	Fiber (68%), Fragment (23%), Film (9%)	NA	Hamra and Patria (2019)
Jakarta	Pantai Indah Kapuk	Mar–Jul 2015	Mozambique tilapia *Oreochromis mossambicus*	0-13 pieces/ individual	>200 μm		NA	Hastuti et al. (2019)
			Spotted scat *Scatophagus argus*	0-16 pieces/ individual				
			White-spotted rabbitfish *Siganus canaliculatus*	4-52 pieces/ individual				
			Bluespot mullet *Crenimugil seheli*	1-39 pieces/ individual				
			Flathead grey mullet *Mugil cephalus*	2-27 pieces/ individual		Fiber (90%), Fragment (6%), Film (4%)		
			Milkfish *Chanos chanos*	0-23 pieces/ individual				
			Chacunda gizzard shard *Anodontostoma chacunda*	7-33 pieces/ individual				
			Fringescale sardinella *Sardinella fimbriata*	7-33 pieces/ individual				
			Starry triggerfish *Abalistes stellaris*	2-50 pieces/ individual				
East Kalimantan	Talisayan harbor	NA	Anchovy *Stolephorus* spp.	366 pieces/ individual	>20 μm	Film (50%), Fiber (29%), Fragment (18%), Foam (3%)	PP, HDPE, PA	Ningrum et al. (2019)
Jakarta Bay	Pramuka Island, Seribu Islands	Apr 2018	Sea hare *Dolabella auricularia*	2325-4575 pieces/ individual	NA	Film, Fiber, Fragments	NA	Priscilla et al. (2019)
Makassar Strait	Spermonde Archipelago	Jul–Sep 2017	Collector urchin *Tripneustes gratilla*	0.50 pieces/ individual	>0.45 μm			Tahir et al. (2019)
			Mussel *Pinna* sp.	0.50 pieces/ individual		Fiber	NA	
			Oyster *Pinctada* sp.	0.30 pieces/ individual				
			Tiger cowry *Cypraea tigris*	0.30 pieces/ individual				
West Java	Pangandaran Bay	Apr 2018	Cutlassfish *Trichiurus* sp.	0.75–4.67 pieces/ individual	>300 μm	Fragment (50%), Fiber (23%), Film (27%)	NA	Ismail et al. (2019)
			Croaker fish *Johnius* sp.	0.21–1.17 pieces/ individual				
Philippines								
Negros Oriental	Ayungon	Oct 2018–Jan 2019	Rabbitfish *Siganus fuscescens*	0.033 pieces/ individual	>8 μm	NA	PA (100%)	Bucol et al. (2020)
	Bais			0.067 pieces/ individual		NA	PE (50%), PA (50%)	
	Dumaguete			0.67 pieces/ individual		NA	PS (5%), PE (53%), PET (25%), PA (12%), PP (5%)	
	Manjuyod			1.47 pieces/ individual		NA	PE (3%), PA (3%), PP (94%)	
Cavite	Bacoor Bay	Jan 2016	Asian green mussel *Perna viridis*	NA	>11 μm		NA	Argamino & Janairo (2016)
Thailand								
Chonburi	Angsila	Mar-May 2015	Striped barnacle *Balanus amphitrite*	0.43 pieces/g	>11 μm	Fragment	PA (60%), PET (40%)	Thushari et al. (2017)

(*continued on next page*)

Table 4 (*continued*)

Country	Location	Sampling period	Organism	Microplastic concentration	Size range	Microplastic category	Dominant type	Reference
			Rock oyster *Saccostrea forskalii*	0.57 pieces/g			PA (70%), PET (18%), PS (12%)	
			Periwinkle *Littoraria* sp.	0.23 pieces/g			PA (70%), PET (30%)	
	Bangsaen		Striped barnacle *Balanus amphitrite*	0.33 pieces/g			PS (50%), PA (30%), PET (20%)	
			Rock oyster *Saccostrea forskalii*	0.37 pieces/g			PET (62%), PA (28%), PS (10%)	
	Samaesarn		Striped barnacle *Balanus amphitrite*	0.23 pieces/g			PA (85%), PET (15%)	
			Rock oyster *Saccostrea forskalii*	0.43 pieces/g			PA (60%), PET (40%)	
			Periwinkle *Littoraria* sp.	0.17 pieces/g			PET (60%), PA (40%)	
Songkhla Province	Sathing Phra	Aug-Dec 2017	Demersal fish	0.97 pieces/ individual	<5 mm	Fragment, fiber	NA	Azad et al. (2018)
			Pelagic fish	1.75 pieces/ individual				
			Reef-associated fish	1.24 pieces/ individual				
Vietnam								
Thanh Hoa Province	Thinh Gia	Mar 2019	Asian green mussel *Perna viridis*	2.60 pieces/ individual	>12 µm	Fragment (70%), fiber (30%)	PP (31%), PE (23%), PES (15%), PA (8%), PS (7%), Others (16%)	Phuong et al. (2019)

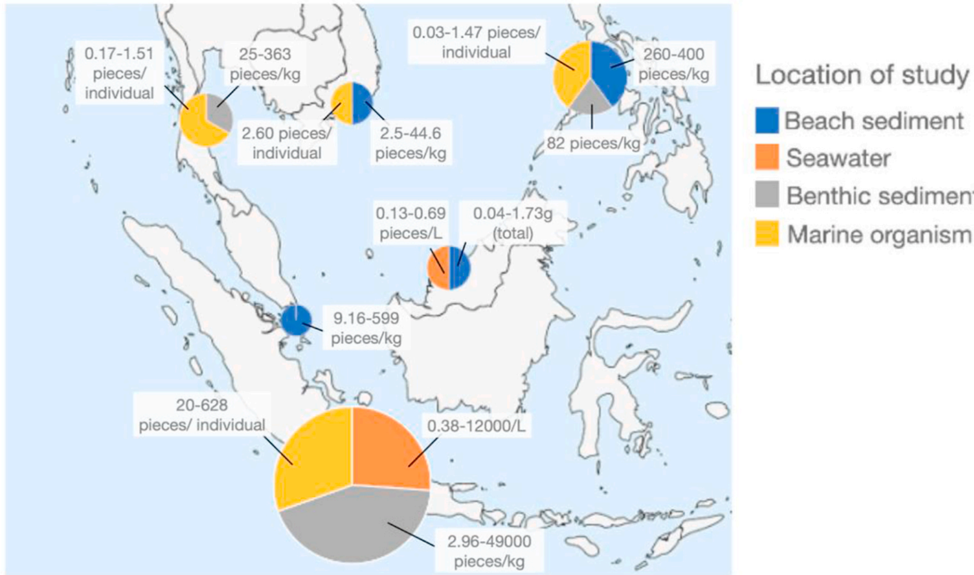

Fig. 2. Distribution of studies in Southeast Asia identifying the abundance of microplastics in beach sediments, seawater, benthic sediments and marine organisms. A total of 36 studies were conducted across six countries. The location and number of studies for each country are depicted by the colour and size of the circles, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

a relatively lower concentration of microplastics, at 0.46–0.55 pieces/L and 0.44–0.53 pieces/L, respectively, due to a low level of urbanization (Cordova et al., 2019). Foam (58%) particles were the dominant form of microplastic, with PS being the dominant type (Cordova et al., 2019, Table 2).

Microplastics were studied from the coastal surface waters of Tambak Lorok, Semarang, Indonesia. Microplastic abundance from surface seawater ranged from 900 pieces/L to 11100 pieces/L (Khoironi et al., 2020, Table 2). The coastal waters of Makassar City, South Sulawesi, Indonesia were investigated for the presence of microplastics. The dominant size of microplastics was 1.1–2.5 mm (31–40%). A total of 14 colours of microplastics were observed, with transparent (30%) and blue (28%) being the most abundant (Afdal et al., 2019, Table 2). Light-coloured microplastics pose a greater threat to marine organisms as they are more easily mistaken as food (Andrady, 2011). For this study, no concentration of microplastics were determined (Afdal et al., 2019).

Microplastics were studied at 4 depths of seawater in Sumba, East Nusa Tenggara, Indonesia (Cordova & Hernawan, 2018). At 5 m, 50 m, 100 m and 300 m depth, there were an average of 120, 60, 0 and 20 microplastic pieces/m^3, respectively (Cordova & Hernawan, 2018, Table 2). Microplastics were dominated by PE fibers (45.45%; Table 2). Cordova & Hernawan (2018) also attributed the presence of a thermocline zone from a depth of 53–144 m, to the absence of microplastics at the 100 m depth. This is due to the transitional nature of the thermocline, where microplastics are pushed to the bottom of this layer (Kooi et al., 2017). PE fibers were the dominant form of microplastics at 45.5% (Cordova & Hernawan, 2018, Table 2).

The abundance of floating microplastic was examined from Cilacap coast, Java Island, Indonesia (Syakti et al., 2017). Microplastic abundance ranged from 0.27 to 0.54 pieces/m^3, with PP being the dominant plastic polymer at 68% (Syakti et al., 2017, Table 2). The dominant form of microplastic was not recorded in this study.

Surface water samples from the east coast of Peninsular Malaysia were examined for microplastics. Kuantan Nerus, Terengganu is a place of tourist activities and commercial fishing, while Kuantan port, Pahang is a popular multi-cargo port. Microplastic abundance ranged from 0.13 to 0.69 pieces/L for Kuala Nerus and 0.14–0.15 pieces/L for Kuantan Port (Khalik et al., 2018, Table 2). Fragments accounted for 51–66% of total microplastics obtained in this study (Khalik et al., 2018, Table 2).

Across the surface water samples from Southeast Asia, the microplastic concentration ranged from 0.13 to 11000 pieces/L. The greatest number of surface microplastics were observed from Tambak Lorong, Semarang, Indonesia.

3.3. Microplastics from benthic sediments

Microplastics from sediments samples were also examined and characterized. Sediment samples from five sites from Jagir estuary and Wonorejo coast of Surabaya, Indonesia were analyzed for microplastics (Firdaus et al., 2020). Fiber (57%) and film (36%) microplastics were the dominant microplastics observed (Table 3). Firdaus et al. (2020) observed that the abundance of microplastics increased from 92 pieces/kg of sediment within the upper Jagir estuary, to 590 pieces/kg of sediment along the Wonorejo coast in the Madura Strait (Table 3). The increase in microplastic abundance from the estuary to the mouth of the sea was due to heavy pollution caused solid domestic waste entering the Jagir river from Surabaya City (Riani et al., 2011). From the lower Jagir estuary, fish farming, ecotourism and fishing activities contributed to the heavy pollution observed (Kusmana et al., 2018). From these samples, PES microfibers were the most abundant (57%). The dominance of microfibers was attributed to wastewater from textile materials of the 600 laundry businesses operating in Surabaya city (Firdaus et al., 2020).

Microplastics were studied from the coastal sediments of Tambak Lorok, Semarang, Indonesia. Microplastic abundance from sediments ranged from 8000 pieces/kg to 49000 pieces/kg (Table 3). PP microfibers were dominant in sediment samples, with biofilms often observed on these fibers (Khoironi et al., 2020, Table 3). The large number of microplastics in sediments were attributed to the untreated wastewater which entered from the Bangar river of Semarang city. This is due to the Bangar River being a dumping area for the local community (Khoironi et al., 2020).

Sediments of Banten Bay, Indonesia were analyzed for microplastics. Expanded polystyrene (EPS) was the most dominant microplastic polymer (30.4%) (Falahudin et al., 2020, Table 3). This was attributed to the use of a styrofoam buoyancy system for marine aquaculture that was used in the area (Eo et al., 2018). Generally, EPS has a lower density than seawater and is expected to float on the water surface. However, EPS in this study were fouled with microorganisms and as a result, sunk to the sediments layer (Falahudin et al., 2020). The sediments of Pluit and Ancol, Jakarta Bay, Indonesia, were investigated for the presence of microplastics. Pluit had a higher abundance of microplastics (38223 particles/kg) compared to Ancol (21780 particles/kg). In addition, at both locations, microplastic abundance was greater as the sites were closer to the sea (Manalu et al., 2017). This was attributed to the accumulation of microplastics flowing from upstream with dense village settlements and a high level of tourist activity (Manalu et al., 2017). Majority of the microplastics collected from Pluit and Ancol were PP fragments (70–80%).

Microplastics were also examined from coral reef sediments in Sekotong, Lombok Island, Indonesia (Cordova et al., 2018, Table 3). The abundance of microplastics ranged from 33 to 77 particles/kg of sediment. Foam (PS) microplastics were the most dominant, at 41.2% (Cordova et al., 2018, Table 3). The authors attributed the primary source of microplastics from the sediments of Sekotong to be due the usage of styrofoam, from food consumption and fishing activities (Cordova et al., 2018).

The intertidal sediments of Lamongan, Indonesia were examined for microplastics (Asadi et al., 2019, Table 3). There was an average of 206 pieces/kg, with fibers being the dominant type at 85% (Asadi et al., 2019). In addition, Asadi et al. (2019) found that the type of sediment at the sampling stations impacted the abundance of microplastics found. Clay-like silts contained a significantly higher abundance of microplastics (354 pieces/kg) compared to other sediments such as sand (150 pieces/kg) and gravel (170 items/kg; Asadi et al., 2019). This is because an increased abundance of microplastics is generally correlated with finer sediment (Ling et al., 2017).

Microplastics from the deep-sea sediments of western Sumatra were examined. Sediments from a depth of 66.8 m–2812 m were obtained (Table 3). Cordova & Wahyudi (2016) observed a range of 10–140 pieces/L from sediments of 66.8 m–2812 m. Granules formed the majority of microplastics collected (85.3%). The highest number of microplastics were observed in the Sunda Strait, of 88.5 m depth, with 140 pieces/L. The high number is likely to be due to the Sunda Strait being a busy international shipping route, supporting the passage of over 2200 vessels and 100 000 passengers each year (Rusli, 2012). This is as container ships are known to contribute to microplastic pollution, leaving behind a 'trail' of these small particles during their voyage (Gaylarde et al., 2021).

Microplastics from sediments of the eastern waters of the Java sea were examined (Yona et al., 2019, Table 3). The abundance of microplastics ranged from 206 to 896 particles/kg. The mangrove contained the highest number of microplastics, at 896 particles/kg (Yona et al., 2019). Fragments formed the dominant microplastics, at 54% (Yona et al., 2019, Table 3). This was due to the fragmentation of larger plastic particles that originated from the improper disposal of domestic waste from settlements nearby (Yona et al., 2019).

The coastal sediments of Bama Resort, Baluran National Park, Indonesia were examined for microplastic pollution (Asadi et al., 2019, Table 3). Intertidal sediments from 10 to 30 cm depths were obtained, resulting in a range of 35.8–153.1 pieces/kg (Asadi et al., 2019). Fibers were the dominant form of microplastics (37.8%). The authors found a correlation between sediment depth and microplastic abundance, where 55.5% of microplastics were found from depths 0–10 cm (Asadi et al., 2019). In comparison to other coastal areas such as Pluit and Ancol from Jakarta Bay, the abundance of microplastics in the sediments of Bama Resort was approximately 176 times lesser. This could be due to the Bama Resort being in the marine protected zone of Baluran National Park, which is strictly managed for conservation (Wianti, 2014).

The sediments of seagrass beds of Kodingareng Lompo, Bone Tambung, and Langkai from the Spermonde Archipelago of Makasssar Strait, Indonesia were investigated for microplastic pollution (Tahir et al., 2019, Table 3). Microplastic abundance ranged from 2.96 to 28.29 pieces/kg. Kodingareng Lompo had the greatest concentration of microplastics, at 28.29 pieces/kg. Filaments were the most abundant microplastic type, at 84% (Tahir et al., 2019, Table 3).

The sediments near Silliman Beach, Dumaguete, Philippines had a microplastic abundance of 82 pieces/kg (Bucol et al., 2020, Table 3). The sediments were dominated by rayon (RY) microfibers at 90% (Bucol et al., 2020, Table 3).

Microplastics from the sediments (0–5 cm) of the Gulf of Thailand were examined for the presence of microplastics (Wang et al., 2020, Table 3). The abundance of microplastics ranged from 25 pieces/kg to 363 pieces/kg. The site with the greatest concentration of microplastics (363 pieces/kg) was found at the bottom of the upper Gulf of Thailand, where the circulation of opposing currents results in a sink of microplastics (Buranapratheprat and Bunpapong, 1998; Wang et al., 2020). RY Fibers formed the dominant microplastic type across the sampling stations at 37% (Wang et al., 2020, Table 3). The authors also observed a correlation between microplastic abundance and size of sediment grain, where stations with a coarser grain size (silt) recorded a greater abundance of microplastics (Wang et al., 2020).

From the above studies, the greatest number of microplastics from the sediments was in Jarkarta bay, Indonesia, with an abundance of 18405-27284 pieces/kg (Manalu et al., 2017). The least number of microplastics were observed from the sediments of the Spermonde Archipelago of Sulawesi, Indonesia, with a record of 2.96 pieces/kg (Tahir et al., 2019).

3.4. Microplastics from marine organisms

Marine organisms from southeast Asian waters were investigated for the presence of microplastics (Table 4). The Grey-eel catfish (*Plotosus canius*) is a commonly consumed fish species endemic to Indonesian waters. Lubis et al. (2019) investigated the digestive tracts of these catfish from Tanjungpinang and found a range of 20–87 pieces of microplastics/individual from the areas of Laut Teluk Keriting, Laut Sei Jang and Laut Pelantar Kud (Lubis et al., 2019, Table 4). These areas are densely populated by villagers that build homes above the sea. These villages also have active fishing communities. The marine snail gonggong (*Laevistrombus turturella*) is a commonly consumed seafood found in the coastal regions of Bintan, Riau island province. Hamra and Patria (2019) examined the body of snails from the villages of Madong, Pengudang, Busung and Kawal. They recorded an average of 492, 476, 460 and 628 pieces of microplastics/individual for these locations, respectively (Table 4). Majority of the microplastics were observed to be microfibers (68%) (Hamra & Patria, 2019).

The digestive tracts of 9 species of commercial fishes from the Pantai Indah Kapuk coast, Jakarta, Indonesia, were studied for the presence of microplastics (Hastuti et al., 2019, Table 4). For Mozambique tilapia (*Oreochromis mossambicus*), spotted scat (*Scatophagus argu s*) and white-spotted spinefoot (*Siganus canaliculatus*) microplastic abundance ranged from 0 to 13, 0–16 and 4–52 pieces/individual. For Bluespot mullet (*Crenimugil seheli*) and Flathead grey mullet (*Mugil cephalus*), microplastics ranged from 1 to 39 and 2–27 pieces/individual. For milkfish (*Chanos chanos*), microplastics ranged from 0 to 23 pieces/individual. For the Chacunda gizzard shard (*Anodontostoma chacunda*), and Fringescale sardinella (*Sardinella fimbriata*), microplastics ranged from 7 to 33 pieces/individual for both species. For Starry triggerfish (*Abalistes stellaris*), 2–50 pieces of microplastics/individual were observed (Hastuti et al., 2019). Fibers were the most dominant microplastic type in all the 9 species, forming 89.6% of microplastics obtained (Hastuti et al., 2019, Table 4). The organism's feeding behaviour often influences the type of microplastics ingested (Markic et al., 2018). In this study, these omnivorous fish consumed mainly microplastic fibers. In addition, Hastuti et al. (2019) observed a negative correlation between abundance of microplastics and body weight of fish. They suggested that carnivorous fish with a smaller body size contained a greater number of microplastics compared to herbivorous fish (Hastuti et al., 2019).

Anchovies (*Stolephorus* spp.) from Talisayan harbor, East Kalimantan, Indonesia, were examined for the presence of microplastics in their digestive tracts (Ningrum et al., 2019). An average of 366 microplastic pieces/individual were found, with 50% as film (Ningrum et al., 2019, Table 4). The digestive tracts of the sea hare (*Dolabella Auricularia*) were studied for the presence of microplastics (Priscilla et al., 2019). The abundance of microplastics ranged from 2325 to 4575 pieces/individual (Table 4). The high abundance of microplastics was attributed to Pramuka Island being a fishing hub, which has high levels of pollution such as plastic bags and fishing gear (Priscilla et al., 2019). From Pangandaran Bay, two species of fish were investigated for the microplastic pollution. The abundance of microplastics in cutlassfish (*Trichiurus* sp.) ranged from 0.75 to 4.67 pieces/individual and croaker fish (*Johnius* sp.) had 0.21–1.17 pieces/individual (Ismail et al., 2019, Table 4).

The rabbitfish (*Siganus fuscescens*) is a commercially important fish in central Philippines. Microplastics were extracted from the digestive tracts of *S. fuscescens* obtained from 4 locations along the coastal areas of Negros Oriental, central Philippines (Bucol et al., 2020). These fish have high fidelity with very limited home ranges, enabling them to be natural indicators of the surrounding microplastic pollution. The abundance of microplastics ranged from 0.033, 0.067, 0.67 and 1.47 pieces/individual for the locations Ayungon, Bais, Dumaguete and Manjuyod, respectively (Bucol et al., 2020, Table 4). PP fragments were the dominant microplastic polymer, at 61.5% (Bucol et al., 2020).

The Asian green mussel (*Perna viridis*) cultured in Bacoor Bay, Cavite, Philippines, was studied for the presence of microplastics (Argamino & Janairo, 2016). Fragments and fibers were observed from digested mussel tissue. The authors did not quantify the abundance of microplastics obtained in this study.

Microplastics were observed from sessile invertebrates from the eastern coast of Thailand (Thushari et al., 2017). The three most abundant intertidal organisms, rock oyster (*Saccostrea forskalii*), striped barnacle (*Balanus amphitrite)* and periwinkle (*Littoraria* sp.) were examined from the Angsila, Bangsaen and Samaesarn beaches of the Gulf of Thailand (Thushari et al., 2017). These species were found with microplastics at an abundance of 0.2–0.6 particles/g (Table 4). Across the three locations, organisms obtained from Angsila had the greatest abundance of microplastics, due to the lax pollution control measures from commercial aquaculture and fishing activities. In addition, filter feeders *S. forskalii* and *B. amphitrite* had a slightly higher concentration compared to *Littoraria* sp. across the three sites (Thushari et al., 2017). The rock oyster *S. forskalii* had the greatest microplastic abundance across the three sites (Thushari et al., 2017). The difference in microplastics observed is due to the variation in feeding strategy among the organisms. Oysters are filter feeding organisms that extend their cirri outwards to trap food particles in the water (Chaparro et al., 2001), whereas periwinkles are substrate grazers, which result in less microplastics taken into the organism.

Other commercially important fish from the lower Gulf of Thailand were investigated for the presence of microplastics (Azad et al., 2018, Table 4). Fish from 24 species across three trophic levels-demersal, pelagic and reef-associated were examined. Demersal fish included species such as the Beris ponyfish (*Leiognathus berbis* Valenciennes) and Splendid ponyfish (*Leiognathus splendens* Cuvier). The Caroun croaker (*Johnius carouna* Cuvier) and Blackfin scad (*Alepes melanoptera*) were among the pelagic fish examined. The Torpedo scad (*Megalaspis cordyla* Linnaeus) and White Sardinella (*Sardinella albella* Valenciennes) were some reef-associated fish studied. On average, pelagic fish species had the highest abundance of microplastics (1.75 pieces/individual), followed by reef-associated fish (1.24 pieces/individual) and demersal fish had the least number of microplastics (0.97 pieces/individual). The difference in microplastic abundance observed among the groups of fish was attributed to the presence of more herbivorous and plankton-feeding fish in the pelagic group compared to the reef-associated and demersal group (Azad et al., 2018). These pelagic fish then mistake microplastics as food more easily and hence are identified to have more microplastics (Azad et al., 2018).

The Asian green mussel, *P. viridis* was examined from the coastal waters of Tinh Gia, Thanh Hoa province, Vietnam (Phuong et al., 2019, Table 4). Microplastic abundance was an average of 2.6 pieces/individual. Microfibers were the major microplastic type, with PP forming the dominant microplastic polymer at 31% (Phuong et al., 2019, Table 4).

The observed microplastic abundance in marine organisms can be attributed to two factors-the organism's feeding pattern and the abundance of microplastic in the surrounding environment.

Across these studies, the greatest concentration of microplastics were observed in the Sea hare *Dolabella auricularia* (2325–4575 pieces/individual), and the Gonggong snail *Laevistrombus turturella* (460–628 pieces/individual; Table 4). Both *D. auricularia* and *L. turturella* are gastropods, which graze on substrates. Grazers are known to indiscriminately ingest microplastics, which could have resulted in the large numbers of microplastics observed (Vroom et al., 2017). In the case of *D. auricularia,* it is a gastropod mollusc which feeds on seagrass. The large number of microplastics observed was attributed to the high level of microplastic adsorption onto seagrass blades found on the southern coast of Pramuka Island, Indonesia (Priscilla et al., 2019).

In other studies, microplastics have been found also in frozen seafood, such as shrimp and mussels. Frozen shrimp including species such as *Fenneropenaeus indicus* and *Pleoticus muelleri* which were sold in the supermarkets of Singapore had microplastics that ranged from 13.4 to 7050 pieces/g of shrimp (Curren et al., 2020). Mussels from the supermarkets of the United Kingdom contained microplastics, ranging from concentrations of 0.9–1.4 pieces/g of mussel (Li et al., 2018). The presence of microplastics has not only been identified in seafood of commercial importance but has been recorded across taxa of varying trophic levels (Au et al., 2017). This ranged from microorganisms such as copepods (Cole et al., 2015), to gastropods (Gutow et al., 2019), and larger organisms such as sea turtles (Caron et al., 2016) and whales (Fossi et al., 2016). Furthermore, there is evidence of microplastic bioaccumulation within each trophic level (Akhbarizadeh et al., 2019).

Across Southeast Asia, marine organisms of commercial importance were investigated for the presence of microplastics. More commonly studied fish were catfish, tilapia, rabbitfish, mullet (Table 3). Other organisms such as rock oysters and the Asian green mussel were also studied as they are popular seafood in southeast Asia (Table 3). In other parts of Asia, microplastics have been found in commercial aquatic species at aquaculture sites (Wu et al., 2020). Species such as shrimp *Parapenaeopsis hardwickii* and clam *Sinonovacula constricta* from Xiangshan Bay, China were examined, with an average of 1–2 pieces/individual recorded (Wu et al., 2020). In most of these organisms, the presence of microplastics were found to be concentrated within their digestive tracts. Microplastics have also been identified from other parts of the organism. In addition, these contaminants had translocated out of their digestive organs, entering the circulatory system and even penetrating surrounding tissue. In the fiddler crab *Uca rapax*, ingested microplastics are found to translocate to the gills, stomach and hepatopancreas (Brennecke et al., 2015). In the brown shrimp *Crangon crangon*, microplastics were identified in the tail tissue (Devriese et al., 2015). In the case of shrimp, this means that microplastics will still be present in the organism even if the digestive tracts are removed, forming a route of exposure through human consumption.

To date, there has been evidence of microplastics in human stool samples, with an average of 2 pieces/g of stool, ranging from 50 to 500 μm in size (Schwabl et al., 2019). A recent study by Abbasi and Turner (2021) identified microplastics in human hair and saliva, with an average of 3.5 pieces of microplastic per individual. Besides seafood, microplastics have also been identified in drinking water of up to 10 particles/L (Koelmans et al., 2019) and in air samples with an exposure of up to 15 microplastic particles over 24 h (Abbasi et al., 2019). The presence of microplastics in seafood will only increase human ingestion and exposure to microplastic contamination.

Furthermore, microplastics are known to adsorb pollutants such as toxic organic compounds and metal ions and hence can act as vector of these pollutants. These substances can leach from the surfaces of microplastics and enter the organism which has consumed these plastic particles, or into the surrounding water (Guo et al., 2019a; Guo & Wang, 2019b). The adsorption and transport of pollutants on microplastics intensify the risks microplastics pose to the marine environment. These pollutants are found to be toxic to the early life stages of sea urchin larvae and jellyfish ephyrae (Cormier et al., 2021).

In this study, a total of six main types of microplastics were identified-fragments, film, foam, granules and fiber. The composition of microplastic particles across the different matrices was summarised, with the three major types being fragments (41%), fiber (29%) and granules (11%; Table 5; Fig. 3). Microplastic fragments were dominant across beach sediments, seawater and benthic sediments at 46%, 45% and 37%, respectively. Fibers were dominant in marine organisms, at 48%. One-way ANOVA calculations demonstrated that there was a significant difference in the abundance of foam microplastics across sites. Tukey's HSD pairwise comparisons showed a significant difference in foam microplastics across beach and benthic sediments, with beaches having more than twice the abundance of microplastics compared to benthic sediments (Table 5). The values of HSD = 43.80 and Q = 4.23 ($p < 0.05$; Table 6). This could because foam microplastics are less dense than seawater and are accumulated on beaches due to them washing up on beaches. In marine organisms, fibers were the most dominant and this could be due to fibers being more difficult to egest, resulting in greater accumulation. In mussels, more microplastic fibers were retained compared to granules, which were more easily removed by the organism (Qu et al., 2018) (see Fig. 4).

Twelve major microplastic polymer types were identified across the studies in this paper. PE was the dominant polymer type from beach sediments and seawater at 36% and 33%, respectively. RY and PA were the dominant microfibers from benthic sediments and organisms, at 30% and 47%, respectively. From this study, fragments and fibers were the two dominant microplastic types observed. This is not surprising as many studies cite the improper disposal of trash in villages as a major contributing factor towards the high microplastic abundance, and this trash often includes many big items such as plastic chairs, fans, car tyres and toys, which will degrade over time, resulting in secondary microplastic fragments (Laskar & Kumar, 2019). Furthermore, the International Union for Conservation of Nature (IUCN) attributes 35% of primary plastic ocean pollution to originate from textiles, followed by car tyres at 28%, giving rise to microplastic fibers and fragments (Boucher & Friot, 2017).

A summary of the microplastics from the surface seawater of Southeast Asia revealed a concentration of 0.13–11100 pieces/L. This figure is comparable with the abundance of microplastics across various locations in the world including the Arctic Ocean and the Santa Monica Bay (Table 7). Regions such as the Southern Ocean (Isobe et al., 2017) and the South Yellow Sea, China (Jiang et al., 2020) were less contaminated than the seas of Southeast Asia (Table 7). The coastal region of Hangzhou Bay, China also had a much lower concentration of microplastics compared to the seawater of Southeast Asia, with an abundance of 1.4×10^{-3} pieces/L (Wang et al., 2020). The microplastic seawater surface concentration of 11100 pieces/L recorded by Khoironi et al. (2020) was greater than most abundances observed (Table 7). This could be due to the sampling conducted during the end of the inter-monsoon period, which could result in a greater accumulation of microplastics (Ibrahim et al., 2021).

Although there has been much research conducted, there are gaps in the current status of microplastic pollution in Southeast Asia that needs to be addressed. The sampling locations in the various studies are often conducted in locations where the water quality is very contrasting such as a polluted village or pristine waters of a conservation site. This often leads to the common conclusion that anthropogenic activities contribute to microplastic pollution. Furthermore, the lack of standardization and consistent protocols that were used make comparisons across these studies a challenge. This is evident as the units for quantification of microplastics were not standardized. It ranged from measuring an aggregate weight, to pieces/kg of sand (of beach sediments), pieces/L to pieces/m^3 (of seawater), pieces/L to pieces/kg (of benthic sediment) and pieces/individual to pieces/g (of marine organism; Tables 1–3). To better assess the impact of microplastics on the marine environment, a standardized protocol regarding microplastic sampling, processing and analysis should be engaged. In recent years, there have been various sets of recommended protocols detailing the steps for microplastic sampling, processing and quantification to facilitate comparison among different studies. Standardized protocols have been published for microplastics monitoring in seawater (Gago et al., 2018), sediments (Frias et al., 2018) and in biota (Bessa et al., 2019). Furthermore, many of these studies regarding microplastic abundance identification are spatial with little or no characterisation of its temporal distribution. The temporal characterisation of microplastic pollution is crucial for monitoring purposes as factors such as floods, storms and other weather variations can affect the accumulation of microplastics (Gündoğdu et al., 2018) and hence should be studied in the long term. In some studies, benthic sediments in marine environments have been prioritized as the matrix for microplastic monitoring, as these sediments are found to be a sink for microplastics (Woodall et al., 2014) and are likely to reflect the true abundance of these pollutants in the long term.

With the increased public awareness towards microplastics pollution, many Southeast Asian countries have established strategies and solutions to mitigate this issue. Since 2020, Thailand has officially banned the use of microbeads in the production, sale and import of cosmetic products. The call to reduce single-use plastics have also been taken up by Cambodia, which is working on a sub-decree that bans the import, production and consumption of single-use plastics such as spoons, cups and straws. In 2020, Singapore also passed a law to restrict the export of plastics that are difficult to recycle. However, the

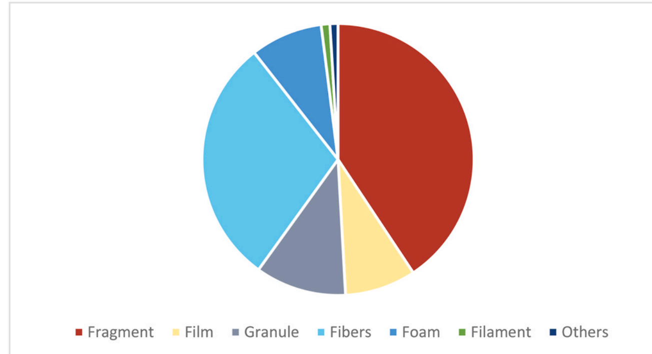

Fig. 3. Overall composition of microplastic types found across beach sediments, seawater, benthic sediments and marine organisms. A total of six main microplastic types were identified.

Table 5
Composition of microplastic particles across beach sediments, seawater, benthic sediments and organisms. Values are in percentages.

	Fragment	Film	Granule	Fiber	Foam	Filament	Others
Beach sediment	45.9 ± 18.7	5.4 ± 10.2	19.8 ± 23.6	8.3 ± 6.6	14.8 ± 22.0	4.1 ± 11.7	0
Seawater	45.2 ± 29.9	2.6 ± 5.8	9.8 ± 15.1	26.4 ± 15.5	11.6 ± 25.9	0	3.8 ± 8.5
Benthic sediment	37.3 ± 35.1	7.6 ± 14.3	13.5 ± 27.2	34.6 ± 32.7	7.2 ± 15.1	0	0
Organisms	33.4 ± 26.0	18.0 ± 20.7	0	48.0 ± 29.5	0.6 ± 1.3	0	0

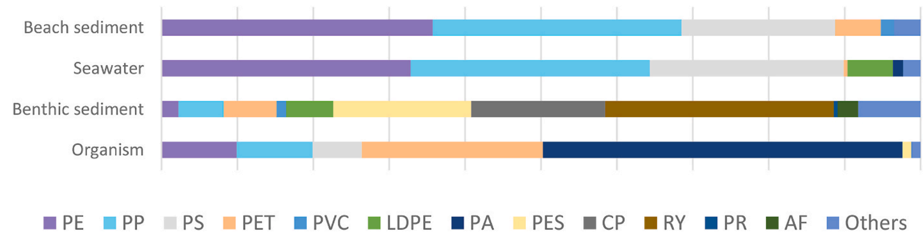

Fig. 4. Composition of microplastic polymer type across beach sediments, seawater, benthic sediments and marine organisms. 12 major polymer types were identified. The abbreviations in the legend are as follows: Polyethylene (PE), Polypropylene (PP), Polyethylene terephthalate (PET), Polyvinyl chloride (PVC), Low-density polyethylene (LDPE), Polyamide (PA), Polyester (PES), Cellophane (CP), Rayon (RY), Phenoxyresin (PR), Acrylic fiber (AF).

Table 6
F-ratio and p-values for one-way ANOVA comparing microplastic types across sites. The asterisk (*) denotes p-values smaller than 0.05.

	F-ratio	P-value
Fragment	0.26	0.86
Film	1.02	0.41
Granule	2.24	0.12
Fiber	3.83	10.0
Foam	1.08	0.38*
Filament	1.00	0.42

Table 7
Comparison of the concentration of microplastics from seawater with various regions around the world.

Region	Microplastic abundance (pieces/L)	Reference
Arctic Ocean	0–18000	La Daana et al. (2020)
Hangzhou Bay, China	1.4×10^{-3}	Wang et al. (2020)
South Yellow Sea, China	4.5–67.5	Jiang et al. (2020)
Northeastern Pacific Ocean	279000	Desforges et al. (2014)
Southern Ocean	30	Isobe et al. (2017)
Santa Monica Bay	3920	Lattin et al. (2004)
Mediterranean Sea	150	de Lucia et al. (2014)
Northeastern Atlantic Ocean	2460	Lusher et al. (2014)
Southeast Asia	0.1–11100	This study

regulation of single-use items such as plastic bags is still challenging in many nations such as Singapore and Malaysia, where total ban of plastic bags is not yet implemented, but instead have imposed charges on these items in places such as supermarkets and some retailers for a start. While the legislation of plastic use such as banning single-use plastics and microplastics in products are important, the change in mindset of the general public regarding plastic cannot be ignored. Future public education campaigns and citizen science programs educating the responsible use and impact of plastics on the environment can be implemented.

4. Conclusion

Plastic pollution is a global issue that has widespread effects. In the coming years, the increase in anthropogenic influences will only worsen the spread of microplastic contamination in the marine environment. In Southeast Asia, microplastic fragments were dominant across the various locations, with 12 major polymers identified. Across the different sampling matrices, there was evidence that microplastic abundance was greater at sites with higher levels of anthropogenic activity. In multiple studies, the sampling locations for microplastics were located near places with high human activities such as aquaculture farms, textile factories and harbours. Illegal dumping and release of untreated sewage waste by local villages or factories were a common contributor of increased microplastic contamination. Tourism was also a contributing factor, where there were significantly more microplastics identified at tourist beaches. Furthermore, the type of microplastic corresponded to the anthropogenic activity near the sampling location. The presence of microplastics in seafood is alarming as seafood ingestion is a potential route of exposure to humans and the effects of microplastic ingestion on the human body has not been widely researched. There has been much research quantifying the abundance of microplastics in marine beaches, seawater and sediments. However, the impact of these microplastics can only be fairly compared and assessed if standardized protocols are used for sampling, processing and analysis. Furthermore, a long-term monitoring program involving the spatial and temporal characterisation of microplastics would be crucial to establish the levels of marine microplastic contamination. More extensive research is required to better characterize the sources, fate and implications of microplastic contamination in the marine environment of ASEAN nations.

Author statement

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Declaration of competing interest

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

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