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Plastic ingestion by marine biota in five Southeast Asian Nations: Complex challenges and long-term implications

Mochamad Arief Budihardjo [a,*], Muhammad Thariq Sani [b,c], Annisa Sila Puspita [d], Amin Chegenizadeh [e]

[a] Department of Environmental Engineering, Faculty of Engineering, Universitas Diponegoro, Semarang 50275, Indonesia
[b] Master of Environmental Engineering, Universitas Diponegoro, Semarang 50275, Indonesia
[c] Department of Oceanography, Faculty of Fisheries and Marine Sciences, Universitas Diponegoro, Semarang 50275, Indonesia
[d] Environmental Sustainability Research Group, Department of Environmental Engineering, Faculty of Engineering, Universitas Diponegoro, Semarang 50275, Indonesia
[e] School of Civil and Mechanical Engineering, Curtin University, Kent St, Bentley, WA 6102, Australia

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ABSTRACT

Plastic pollution has drastically increased in the world's oceans, with significant contributions from Southeast Asian countries like Indonesia, Malaysia, Thailand, the Philippines, and Vietnam, which collectively account for a substantial portion of global plastic debris due to inadequate waste management. Despite the severe ecological and health impacts of plastic ingestion on marine species, there is a lack of comprehensive studies addressing both the affected species and the methodologies used to assess plastic ingestion. The study aims to comprehensively review existing literature on plastic ingestion by marine biota in Southeast Asia, identifying gaps in knowledge about affected species and assessing the various techniques and tools used to investigate this issue. Reviewing 35 articles, this study identifies that research on plastic ingestion by marine species in Southeast Asia predominantly focuses on Teleostei (40 %) while overlooking significant gaps in studies on seabirds, sea snakes, and commercially important fish species. Necropsy is the most effective technique for evaluating plastic ingestion in larger marine species, providing detailed post-mortem insights, while laboratory inspection is ideal for studying smaller organisms like bivalves and copepods. FTIR and μ-Raman spectroscopy are the best tools for confirming plastic ingestion, with FTIR excelling in bulk analysis and polymer identification, and μ-Raman offering high spatial resolution for particle-level molecular identification.

1. Introduction

Plastic pollution has given soar to manifold global challenges, emphasizing the imperative requisite for encyclopedic and instantaneous action. Over contemporary epochs, there has been a momentous upsurge in plastic pollution in the world's oceans (Ford et al., 2022; Hayati et al., 2020). A surmised five trillion plastic items are now believed to have profusely tainted the planet's oceans (UNEP, 2021). Plastic pollution has been perceived on the surfaces of oceans throughout the entire world (Castro-Jiménez et al., 2019; Zaman et al., 2023), and even more astonishingly, plastic has permeated deeper layers of water (Alomar et al., 2020; Iskandar et al., 2021), hitting the ocean's abyssal plain (Peng et al., 2020). The preeminent source of the plastic sighted afloat in the oceans is affiliated with activities and sources on land (Cordova and Nurhati, 2019; Cordova et al., 2021), predominantly transported by rivers streaming into the ocean (Harris et al., 2021). Plastic is fabricated on an immense scale, with global plastic generation stretching approximately 360 million tons in 2018, marking a copious 1.2-fold escalation within a half-decade (UNEP, 2022). Regrettably, nearly half of this plastic culminates in sanitary landfills or the environment, eventually making its path into the oceans (Jambeck et al., 2015). Despite the adverse aftermath of plastic pollution, there has been no solemn commitment to alleviating the fabrication and utilization of plastic in communities (Pathak et al., 2023).

Indonesia, Malaysia, Thailand, the Philippines, and Vietnam are foreseen to generate an average of 1.14 kg of solid debris per person per day, designating them as the top five debris-producing countries in Southeast Asia (Puspita et al., 2024; UNEP, 2021). Even more worrisome is that these countries, where Indonesia, the Philippines, Vietnam, Thailand, and Malaysia clinched the second, third, fourth, sixth, and

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* Corresponding author.
E-mail address: m.budihardjo@ft.undip.ac.id (M.A. Budihardjo).

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eighth sequentially positions in 2015, are also the paramount culprits to the plastic debris that leaks into the oceans due to futile and scant plastic debris management (Jambeck et al., 2015). Collectively, roughly 1.7–4.6 % of the global plastic debris, as betokened in the Jambeck et al. (2015) study, terminates in coastal environments, accounting for 4.8–12.7 million metric tons of plastic debris out of the worldwide total of 99.5 million metric tons. The accretive data from 2015 lucidly illuminates that these five countries are synergistically reckons for virtually one-third of the world's plastic debris production (UNEP, 2022). The conundrum of plastic debris in their coastal areas is aggravated by the dearth of misgiving and circumscribed awareness among coastal communities regarding decorous plastic debris management (Liang et al., 2021). Additionally, data from Zenobi (2015) indicates a swift economic upswing trend in these five nations over the past three decades, with urban sprawl presumed to outdo seven-tenths by 2050. This dilemma will further amalgamate debris management challenges in the years ahead otherwise there are crucial refinements in debris handling and management.

Notwithstanding their opulent marine biodiversity and endemic marine biota (Asaad et al., 2018; Ng et al., 2020), Southeast Asia, particularly Indonesia and the Philippines, both ranking among the acme global plastic debris generators, enacts an indispensable role in the global marine ecosystem (Jambeck et al., 2015). This noteworthiness is preeminently by virtue of its location within the Coral Triangle (Jefferson and Costello, 2020), a hotspot known for its aberrantly lofty marine biodiversity (Sahri et al., 2020; Zainuddin et al., 2017). The ocean circulation in this locale disperses plastic debris across the world's oceans (Chenillat et al., 2021; van Emmerik et al., 2019), plausibly spurring pervasive turmoil in ecological, socio-economic, and human fitness facets on a global scale (Chaudhry and Sachdeva, 2021; Mofijur et al., 2021). Plastic debris in the water can undergo heterogeneous forms of fragmentation, subsuming biological, physical, and chemical processes, which may liberate precarious components (Hadiuzzaman et al., 2022; Sarminingsih et al., 2024), posing jeopardy to the prolific and eclectic marine biota (Compa et al., 2019; Gaboy et al., 2022). From an ecological slant, there is evidence of plastic ingestion by numerous marine species in these five countries (Abreo et al., 2019a; Bonifacio et al., 2022; Coram et al., 2021; Mazlan et al., 2023; Rochman et al., 2015). Prior research has identified an assortment of adverse effects, including hindrances in digestive and respiratory systems (Abreo et al., 2019a), agitations in growth and development (Naidoo and Glassom, 2019), signs of poisoning (Hamlin et al., 2015), and a serious peril of mortality (Santos et al., 2020), contingent on the type and characteristics of the ingested plastic.

Despite the extensive documentation of the detrimental effects of plastic ingestion (Gall and Thompson, 2015; Martin et al., 2019), significant knowledge gaps persist regarding the specific marine species impacted, especially within Southeast Asia. This is particularly critical given the unique characteristics of marine biota in the tropical Southeast Asian region, which differ from those found in other parts of the world, highlighting the importance of identifying key species affected by plastic ingestion. Furthermore, no comprehensive study has yet investigated the full spectrum of affected organisms or the diverse methods employed to assess plastic ingestion across these species. Considering the predominance of developing countries in Southeast Asia (Wibowo et al., 2024), it is crucial to explore which techniques are most feasible for studying plastic ingestion in this region. This research seeks to explore the marine species that have been investigated for plastic ingestion in prior studies, identify those that have not yet been studied in this regard, and evaluate the techniques that are suitable for investigating plastic ingestion in marine biota within the five Southeast Asian countries with the highest projected plastic debris emissions. In addition, the research examines the variety of analytical tools utilized in this region to understand the phenomenon of plastic ingestion.

2. Methods

This study conducted a systematic literature review with PRISMA 2020 approaches (Page et al., 2021) from the Scopus database to investigate plastic ingestion by marine species, focusing on five Southeast Asian countries with significant plastic pollution—Indonesia, Malaysia, Thailand, the Philippines, and Vietnam as pinpointed by Jambeck et al. (2015). The review targeted literature published between 2013 and 2023, using a combination of keywords and synonyms related to plastic ingestion in aquatic organisms (de Moura and Vianna, 2020). The search strategy employed the "OR" operator to broaden the scope (Zheng et al., 2020) and only included English-language articles (Fig. 1). After screening titles, abstracts, and applying inclusion criteria, 35 relevant studies were selected for analysis. These studies were fully accessible and reached the final publication stage.

Marine species mentioned in the literature were cataloged with unique codes for classification, with data processing carried out using Microsoft Excel. The scientific names of the species were verified using reliable sources like the World Register of Marine Species and FishBase. Any species without plastic content or those that were not identifiable were excluded. Additionally, the dataset incorporated endangered species from the IUCN Red List. The techniques used in the studies to detect plastic ingestion were categorized based on their methodological similarities, and instruments with comparable operational principles were grouped accordingly.

3. Result and discussion

3.1. Signs of the repercussions of ingesting plastic

This study, examining 35 literature sources, reveals that marine organisms across 11 distinct classes in the waters of five Southeast Asian countries have ingested plastic debris. These species range from tiny marine organisms like *Branchiopoda* and *Copepoda* to larger species such as *Elasmobranchii* and *Mammalia* (Fig. 2). The majority of studies focus on species within the *Teleostei* class, representing about two-fifths of the research, with a strong emphasis on the orders *Acanthuriformes*, *Scombriformes*, and *Clupeiformes*, which are favorable preferences among purchasers and routinely embedded in domestic fish markets (Azad et al., 2018; Curren et al., 2020; Karbalaei et al., 2019; Rochman et al., 2015; Widyastuti et al., 2023). Approximately 29 %, 14 %, and 11 % of the literature focus on plastic ingestion by species from the *Bivalvia*, *Malacostraca*, and *Elasmobranchii* classes, respectively. In contrast, classes such as *Gastropoda*, *Holothuroidea*, *Mammalia*, and *Reptilia* have limited representation, with less than 6 % of studies exploring these marine creatures. Notably, few studies investigate *Branchiopoda*, *Copepoda*, and *Thecostraca* classes, with each class represented by only one species.

Teleostei species dominate the research, with over 80 species examined (Table 1), including commonly studied fish like *Megalaspis cordyla* and *Siganus canaliculatus*, each discussed in four studies. Other well-researched species include *Anodontostoma chacunda* and *Rastrelliger kanagurta*, appearing in three studies each. Several other species, such as *Atule mate*, *Drepane longimana*, and *Gerres erythrourus*, have also been examined across at least two studies (Goh et al., 2021; Widyastuti et al., 2023). Teleostei species, vital to human seafood consumption, often appear in studies involving microplastic ingestion, particularly fiber-type plastics. The prevalence of these species in research is attributed to their widespread distribution, both pelagic and demersal, alongside their rapid reproduction rates and relatively low conservation concern (Chen et al., 2021; Neto et al., 2020; Savoca et al., 2021). This makes them prime candidates for studies on plastic ingestion in marine environments. While fiber-type plastics dominate the ingested plastic debris, research into *Bivalvia* and *Malacostraca* species provides insights into the ingestion of denser microplastics, such as pellet-type plastics (Bonifacio et al., 2022; Ningrum et al., 2023; Rochman et al., 2015).

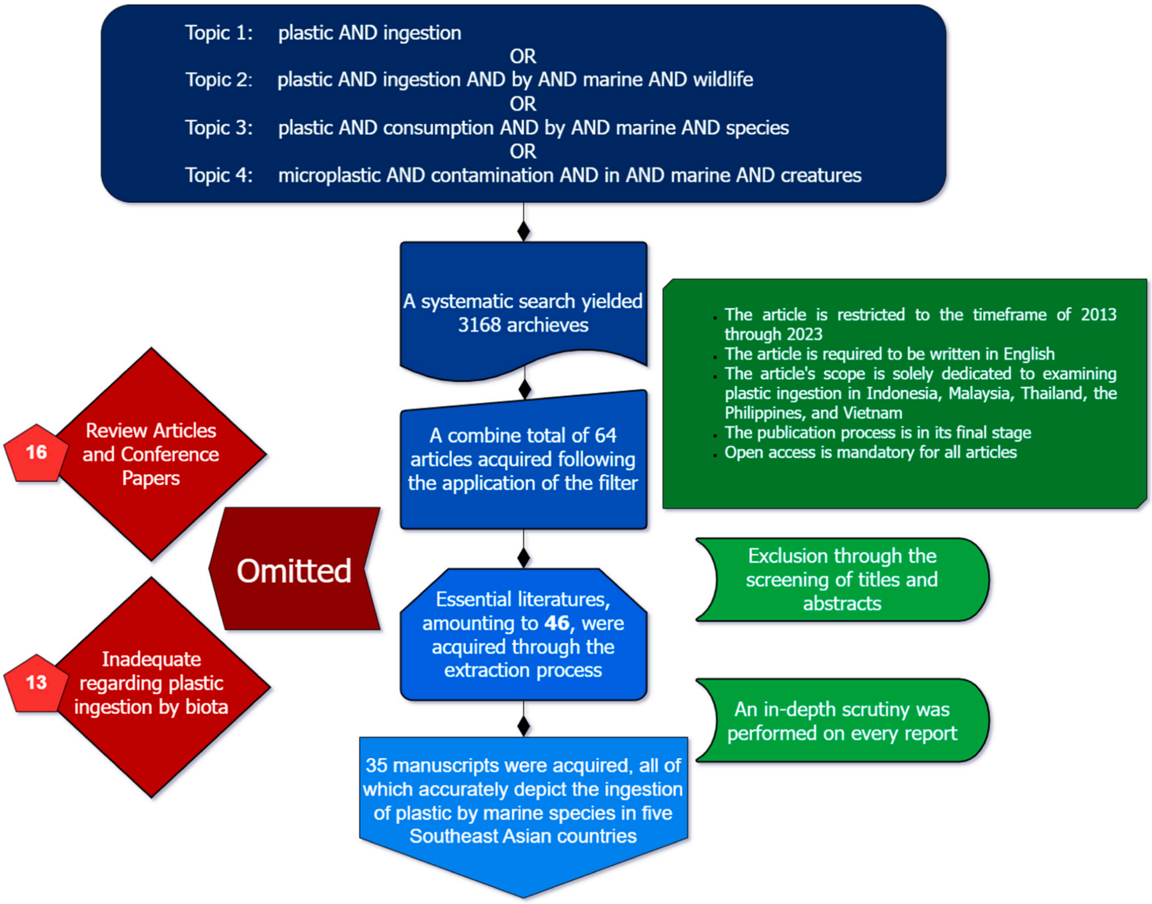

Fig. 1. The schematic tree depicting the process of exclusion and retrieval of pertinent manuscript from a Scopus search regarding the ingestion of plastic by marine creatures.

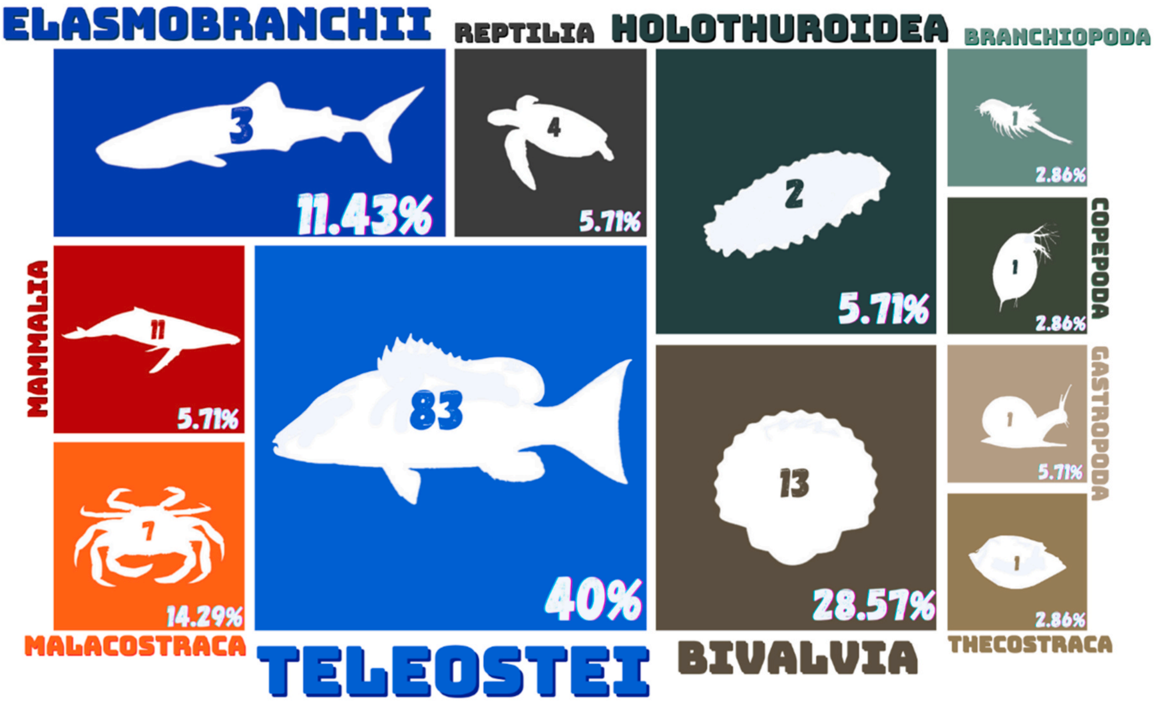

Fig. 2. The visual representation that portrays relative assessments for each marine animal category.

Table 1
Marshaling the classification of marine wildlife categories analyzed in a total of 35 literature.

Class	Order	Species	Prevailing Name	Sample Size	Author
Bivalvia	*Arcida*	*Anadara antiquata*	Antique ark	8	(Asadi et al., 2022)
		Anadara granosa	Blood clam	100	(Goh et al., 2021)
		Anadara granosa	Blood clam	125	(Namira et al., 2023)
		Tegillarca granosa	Blood cockle	150	(Ruairuen et al., 2022)
	Cardiida	*Donax trunculus*	Wedge clam	280	(Bonifacio et al., 2022)
	Mytilida	*Perna viridis*	Green mussel	4	(Ningrum et al., 2023)
		Perna viridis	Green mussel	100	(Phaksopa et al., 2023)
		Perna viridis	Green mussel	150	(Ruairuen et al., 2022)
	Ostreida	*Saccostrea forskalii*	Rock oyster	15	(Thushari et al., 2017)
	Pectinida	*Placuna placenta*	Windowpane oyster	6	(Tielman et al., 2022)
	Venerida	*Gafrarium tumidum*	Comb venus	15	(Asadi et al., 2022)
		Venerupis philippinarum	Japanese littleneck clam	15	
		Katelysia hiantina	Surf clam	280	(Bonifacio et al., 2022)
		Meretrix meretrix	Asian hard clam	280	
		Meretrix lyrata	Hard clam	30	(Tran-Nguyen et al., 2023)
		Paratapes undulatus	Undulate venus clam	30	
Branchiopoda	*Anostraca*	*Artemia franciscana*	Brine shrimp	2[a]	(Charoeythornkhajhornchai et al., 2023)
Copepoda	*Harpacticoida*	*Nitokra lacustris pacifica*	Marine copepod	90	(Amelia et al., 2020)
Elasmobranchii	*Myliobatiformes*	*Dasyatis zugei*	Pale-edged stingray	3	(Azad et al., 2018)
		Mobula alfredi	Manta ray	22[b]	(Germanov et al., 2019)
		Mobula alfredi	Manta ray	144[b]	(Argeswara et al., 2021)
	Orectolobiformes	*Rhincodon typus*	Whale shark	1	(Abreo et al., 2019a)
		Rhincodon typus	Whale shark	22[b]	(Germanov et al., 2019)
Gastropoda	*Littorinimorpha*	*Littoraria scabra*	Periwinkle snail	10	(Patria et al., 2020)
		Littoraria undulata	Periwinkle snail	50	(Thushari et al., 2017)
Holothuroidea	*Molpadida*	*Acaudina molpadioides*	Sea cucumber	20	(Mazlan et al., 2023)
	Synallactida	*Stichopus horrens*	Sea cucumber	20	(Husin et al., 2021)
Malacostraca	*Decapoda*	*Fenneropenaeus indicus*	Indian white shrimp	20	(Goh et al., 2021)
		Metapenaeus elegans	Fine shrimp	20	
		Litopenaeus vannamei	Whiteleg prawn	30	(Curren et al., 2020)
		Metapenaeus brevicornis	Yellow shrimp	16	(Pradit et al., 2021)
		Parapenaeopsis hardwickii	Spear shrimp	16	
		Metopograpsus quadridentatus	Mangrove crab	9	(Patria et al., 2020)
		Scylla serrata	Mud crab	3[b]	(Hossain et al., 2023)
Mammalia	*Cetartiodactyla*	*Globicephala macrorhynchus*	Short-finned pilot whale	3	(Coram et al., 2021)
		Grampus griseus	Risso's dolphin	2	
		Kogia breviceps	Pygmy sperm whale	5	
		Kogia sima	Dwarf sperm whale	1	
		Mesoplodon densirostris	Blainville's beaked whale	1	
		Peponocephala brevirostris	Melon-headed whale	1	
		Physeter macrocephalus	Sperm whale	4	
		Steno bredanensis	Rough-toothed dolphin	3	
		Ziphius cavirostris	Cuvier's beaked whale	1	
		Balaenoptera edeni	Rough-toothed dolphin	1	(Abreo et al., 2019b)
		Globicephala macrorhyncus	Short-finned pilot whale	1	
		Grampus griseus	Risso's dolphin	2	
		Kogia breviceps	Pygmy sperm whale	2	
		Kogia sima	Dwarf sperm whale	1	
		Mesoplodon densirostris	Blainville's beaked whale	2	
		Mesoplodon hotaula	Deraniyagala's beaked whale	1	
		Peponocephala electra	Melon-headed whale	1	
		Physeter macrocephalus	Sperm whale	2	
		Steno bredanensis	Rough-toothed dolphin	1	
Reptilia	*Testudines*	*Chelonia mydas*	Green sea turtle	9	(Abreo et al., 2019b)
		Dermochelys coriacea	Leatherback sea turtle	3	
		Chelonia mydas	Green sea turtle	251	(Prampramote et al., 2022)
		Dermochelys coriacea	Leatherback sea turtle	2	
		Eretmochelys imbricata	Hawksbill sea turtle	71	
		Lepidochelys olivacea	Olive ridley sea turtle	11	
Teleostei	*Acanthuriformes*	*Aurigequula fasciata*	Striped ponyfish	5	(Phaksopa et al., 2021)
		Deveximentum insidiator	Pugnose ponyfish	50	(Soe et al., 2022)
		Eubleekeria splendens	Splendid ponyfish	50	
		Leiognathus equula	Common ponyfish	50	
		Photopectoralis bindus	Orangefin ponyfish	50	
		Drepane longimana	Barred sicklefish	3	(Azad et al., 2018)
		Leiognathus berbis	Berber ponyfish	8	
		Leiognathus fasciatus	Striped ponyfish	3	
		Leiognathus splendens	Splendid ponyfish	10	
		Siganus canaliculatus	Whitespotted rabbitfish	65	(Paler et al., 2021)
		Siganus guttatus	Golden rabbitfish	15	
		Siganus punctatus	Goldspotted rabbitfish	1	
		Siganus spinus	Scribbled rabbitfish	17	
		Siganus virgatus	Doublebar rabbitfish	8	
		Drepane longimana	Barred sicklefish	14	(Jaafar et al., 2021)

(*continued on next page*)

Table 1 (*continued*)

Class	Order	Species	Prevailing Name	Sample Size	Author
		Drepane punctata	Spotted batfish	3	
		Drepane punctata	Spotted batfish	14	
		Eubleekeria jonesi	Jones' pony fish	10	
		Gazza minuta	Slimy pony fish	9	
		Naso thynnoides	Oneknife unicornfish	20	(Widyastuti et al., 2023)
		Scatophagus argus	Spotted scat	35	(Hastuti et al., 2019)
		Siganus canaliculatus	Whitespotted rabbitfish	30	
		Siganus argenteus	Forktail rabbitfish	2	(Rochman et al., 2015)
		Siganus canaliculatus	Whitespotted rabbitfish	2	
		Siganus canaliculatus	Whitespotted rabbitfish	60	(Cabansag et al., 2021)
	Aulopiformes	*Saurida elongata*	Slender lizardfish	35	(Phaksopa et al., 2021)
		Saurida undosquamis	Brushtooth lizardfish	17	
	Carangaria	*Eleutheronema tridactylum*	Threefinger threadfin	10	(Karbalaei et al., 2019)
		Sphyraena obtusata	Obtuse barracuda	6	(Phaksopa et al., 2021)
	Carangiformes	*Alepes apercna*	Smallmouth scad	3	(Azad et al., 2018)
		Alepes kleinii	Razorbelly scad	4	
		Alepes melanoptera	Shortfinned trevally	8	
		Alepes vari	Herring scad	3	
		Megalaspis cordyla	Torpedo scad	29	
		Scomberoides tala	Barred queenfish	3	
		Scomberoides tol	Needlescaled queenfish	3	
		Alectis indica	Indian threadfish	2	(Jaafar et al., 2021)
		Atule mate	Yellowtail scad	11	
		Carangoides hedlandensis	Bumpnosed trevally	4	
		Megalaspis cordyla	Torpedo scad	10	
		Trachurus japonicus	Jack mackeral	10	
		Atule mate	Yellowtail scad	9	(Phaksopa et al., 2021)
		Decapterus macrosoma	Shortfin scad	17	(Rochman et al., 2015)
		Megalaspis cordyla	Torpedo scad	10	(Karbalaei et al., 2019)
	Centrarchiformes	*Kuhlia rupestris*	Rock flagtail	25	(Cabansag et al., 2021)
		Terapon theraps	Largescaled terapon	5	(Azad et al., 2018)
	Cichliformes	*Oreochromis mossambicus*	Mozambique tilapia	10	(Hastuti et al., 2019)
	Clupeiformes	*Amblygaster clupeoides*	Sharpnose sardine	9	(Phaksopa et al., 2021)
		Stolephorus indicus	Indian anchovy	5	
		Anodontostoma chacunda	Chacunda gizzard shad	50	(Soe et al., 2022)
		Hilsa kelee	Kelee shad	50	
		Megalaspis cordyla	Torpedo scad	50	
		Sardinella fimbriata	Fringescale sardine	50	
		Thryssa kammalensis	Malabar Thryssa	50	
		Anodontostoma chacunda	Chacunda gizzard shad	14	(Azad et al., 2018)
		Opisthopterus tardoore	Long-finned herring	3	
		Sardinella albella	Deep-bodied sardine	14	
		Sardinella gibbosa	Sardine	3	
		Sardinella jussieu	Goldstripe sardines	8	
		Anodontostoma chacunda	Chacunda gizzard shad	10	(Hastuti et al., 2019)
		Sardinella fimbriata	Fringescale sardine	10	
		Chirocentrus dorab	Wolf herring	18	(Jaafar et al., 2021)
		Sardinella gibbosa	Sardine	8	
		Spratelloides gracilis	Silver-stripe round herring	10	(Rochman et al., 2015)
	Eupercaria	*Caesio teres*	Yellow and blueback fusilier	20	(Widyastuti et al., 2023)
		Dendrophysa russellii	Goatee croaker	3	(Azad et al., 2018)
		Johnius borneensis	Hammer croaker	3	
		Johnius carouna	Caroun croaker	20	
		Gerres erythrourus	Short silverbiddy	13	(Jaafar et al., 2021)
		Johnius borneensis	Hammer croaker	8	
		Panna microdon	Panna croaker	9	
		Gerres erythrourus	Short silverbiddy	10	(Phaksopa et al., 2021)
		Lutjanus madras	Indian snapper	5	
		Priacanthus tayenus	Purple-spotted bigeye	9	
		Scolopsis taenioptera	Redspot monocle bream	54	
		Nemipterus bipunctatus	Delagoa threadfin bream	10	(Karbalaei et al., 2019)
	Gonorynchiformes	*Chanos chanos*	Milkfish	10	(Hastuti et al., 2019)
	Lampriformes	*Lampris guttatus*	Moonfish	1	(Abreo et al., 2019b)
	Mugiliformes	*Planiliza subviridis*	Greenback mullet	50	(Soe et al., 2022)
		Crenimugil seheli	Bluespot mullet	12	(Hastuti et al., 2019)
		Mugil cephalus	Flathead grey mullet	27	
		Valamugil speigleri	Speiglar's grey mullet	35	(Cabansag et al., 2021)
	Mulliformes	*Upeneus tragula*	Freckled goatfish	5	(Phaksopa et al., 2021)
		Upeneus vittatus	Yellowstriped goatfish	21	
	Perciformes	*Epinephelus coioides*	Orange-spotted grouper	10	(Karbalaei et al., 2019)
		Epinephelus coioides	Common grouper	20	(Mardiansyah et al., 2022)
		Platycephalus indicus	Bartail flathead	5	(Phaksopa et al., 2021)
	Scombriformes	*Auxis rochei*	Bullet tuna	20	(Widyastuti et al., 2023)
		Euthynnus affinis	Skipjack tuna	4	(Ningrum et al., 2023)
		Rastrelliger brachysoma	Shortbodied mackerel	50	(Soe et al., 2022)
		Rastrelliger brachysoma	Shortbodied mackerel	3	(Azad et al., 2018)

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Table 1 (*continued*)

Class	Order	Species	Prevailing Name	Sample Size	Author
		Scomberomorus commerson	Barred spanish mackerel	4	
		Scomberomorus guttatus	Indo-Pacific king mackerel	5	
		Rastrelliger kanagurta	Indian mackerel	15	(Phaksopa et al., 2021)
		Rastrelliger kanagurta	Indian mackerel	10	(Karbalaei et al., 2019)
		Thunnus tonggol	Longtail tuna	10	
		Rastrelliger kanagurta	Indian mackerel	9	(Rochman et al., 2015)
	Siluriformes	*Arius maculatus*	Spotted sea catfish	15	(Pradit et al., 2021)
	Tetraodontiformes	*Abalistes stellaris*	Starry triggerfish	30	(Hastuti et al., 2019)
		Triacanthus nieuhofii	Silver tripod fish	5	(Jaafar et al., 2021)
		Tripodichthys blochii	Longtail tripod fish	10	
Thecostraca	*Balanomorpha*	*Balanus amphitrite*	Striped barnacles	50	(Thushari et al., 2017)

[a] signifies the total quantity of samples measured in grams, which is due to the microscopic nature of the organisms being studied. At the same time, [b] denotes the quantum of samples that engulf feces, vomit, or microplastic samples within the aquatic environment surrounding the biota's habitat. In this category, the sample size does not define the amount of biota under investigation.

Mammalia species are particularly important in understanding plastic ingestion due to their large size and filter-feeding habits, which make them prone to ingesting plastic-contaminated organisms (Lin et al., 2023; Mannocci et al., 2020). In Southeast Asia, nearly one-third of marine mammals have been associated with plastic ingestion, including stranded individuals with plastic debris like bags, fishing nets, and packaging found in their stomachs. For instance, a short-finned pilot whale was found with 80 plastic bags in its digestive system in a severe case of plastic pollution (Coram et al., 2021). However, despite the importance of marine mammals as bioindicators, many species such as the Indo-Pacific bottlenose dolphin and blue whale remain understudied, likely due to their size and endangered status (IUCN, 2011), which complicates research efforts (Lin et al., 2019; Lusseau et al., 2023; Neveceralova et al., 2022; van Weelden et al., 2021). Most studies involving mammals in this region rely on data from stranded individuals found on remote beaches, indicating the difficulty of conducting live studies on these species (Abreo et al., 2019b; Coram et al., 2021).

Elasmobranchii and *Reptilia* species, like whale sharks, manta rays, and green turtles, have also been documented to ingest plastic. These filter-feeding species are particularly susceptible to plastic pollution (Argeswara et al., 2021; Boldrocchi et al., 2023; Zantis et al., 2022), as evidenced by studies showing plastic fibers and larger debris entangled in the gills of stranded whale sharks (Abreo et al., 2019a). Several species of sea turtles have also been affected (Prampramote et al., 2022), with many mistakenly ingesting plastic debris, thinking it is food (Stokes et al., 2019). In one study, 24 green sea turtles were found with significant amounts of plastic in their digestive systems (Prampramote et al., 2022). These species, alongside others in their respective classes, are vital bioindicators of both micro- and macroplastic pollution in the ocean (Arcangeli et al., 2019; Pham et al., 2017). Despite their importance, many elasmobranchs and reptiles, including critically endangered species like the scalloped hammerhead shark, remain understudied in the context of plastic ingestion (IUCN, 2011). Vigorous captures (Gilbey et al., 2021; Mancusi et al., 2020), environmental habitat loss (including spawning, nursery, and feeding grounds) (Bennett et al., 2023), and sweeping human influence leading to substantial degradation of marine ecosystems (Carlucci et al., 2021; Doherty et al., 2021) have indisputably subdued species intimately linked to these factors, embedding them in vulnerable to critically endangered categories.

Despite the significant threat plastic pollution poses to marine biota in Southeast Asia, there is a notable lack of research on several marine species and groups. For example, no studies have explored plastic ingestion in seabirds, sea snakes, or dugongs, despite their prevalence in the region. Furthermore, key commercial fish species heavily exploited by the fisheries industry remain underrepresented in the literature. While the study identified some species, such as those in the *Decapterus* genus, the most commercially significant species have not been adequately explored (FAO, 2022). Given that over half of the region's population lives in coastal areas and relies on seafood as a primary protein source (Warren and Steenbergen, 2021; Wolff et al., 2023), the rising rate of plastic pollution poses a significant threat to both marine biodiversity and human health. With global seafood consumption projected to increase further (FAO, 2022), continued research into plastic ingestion by marine biota is critical to understanding and mitigating the long-term impacts of plastic pollution on marine ecosystems.

3.2. Sites where the species have been observed

The study of plastic ingestion among marine species across five Southeast Asian countries (Fig. 3) presents a fascinating but uneven distribution of research efforts. Each fig. embedded within the countries in Fig. 3 represents the number of publications related to studies on evident plastic ingestion by marine biota, while the silhouettes signify the categories of marine biota investigated by each country. Vietnam, despite being a major contributor to plastic emissions (0.28–0.73 million metric tons annually) (Jambeck et al., 2015), lags behind in marine species studies, with only two published works focusing on *Bivalvia* (Tran-Nguyen et al., 2023) and *Mammalia* (Coram et al., 2021). This significant gap in research is alarming, given the country's high plastic pollution levels, necessitating further investigations into its marine ecosystems. In contrast, Thailand leads in the diversity of species studied, covering nine out of the eleven marine classes identified in this region. With over one-tenth of the total studies conducted in Thailand, the country excels in research focused on *Bivalvia* and *Teleostei*, while unique studies on *Branchiopoda* (Charoeythornkhajhornchai et al., 2023) and *Thecostraca* (Thushari et al., 2017) further distinguish Thailand's contribution. The Gulf of Thailand emerges as a key geographical focus, highlighting Thailand's pivotal role in advancing the understanding of marine plastic ingestion.

Indonesia closely follows Thailand in terms of research volume, with twelve studies dedicated to plastic ingestion across six biota classes. However, unlike Thailand, Indonesia's research is heavily concentrated on *Teleostei*, accounting for more than a third of the total studies. As one of the world's largest archipelagos (Andréfouët et al., 2022) and a top global emitter of marine plastic debris (Jambeck et al., 2015), Indonesia's emphasis on marine species, particularly *Teleostei*, reflects the nation's heavy reliance on maritime resources for both economy and sustenance (Rochwulaningsih et al., 2019). Studies on *Bivalvia* and *Elasmobranchii* also feature prominently in Indonesia's research efforts, with notable work being conducted in Manta Bay, Bali. Other classes, such as *Gastropoda*, *Malacostraca*, and *Mammalia*, receive less attention, collectively accounting for just over six percent of the total studies.

Malaysia and the Philippines exhibit a similar breadth in research subjects, with each country exploring five marine classes. In Malaysia, studies are predominantly focused on *Bivalvia* and *Teleostei*, which together comprise about one-fourth of the country's plastic ingestion research. *Copepoda* also stands out as a significant subject of laboratory research exclusive to Malaysia. In the Philippines, *Teleostei* remains the most frequently studied class, making up nearly one-third of the research. However, the Philippines takes the lead in *Mammalia* studies,

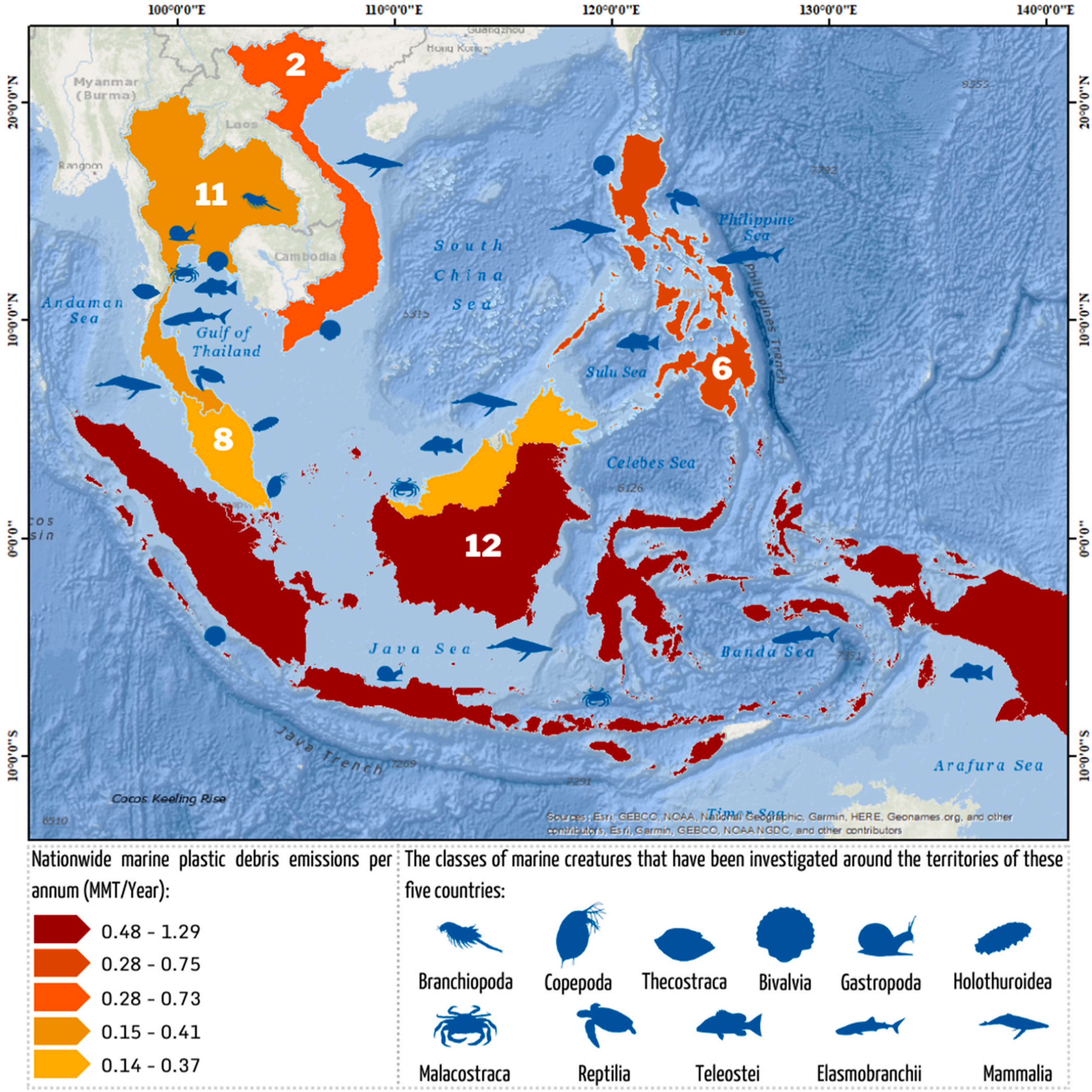

Fig. 3. An illustrative map showcasing the marine wildlife classes level peered at the five Southeast Asian countries.

with two notable investigations by the same lead author. Additionally, the Philippines and Thailand are unique in their focus on *Reptilia*, with each country devoting specific research efforts to this class. The distribution of research subjects across both countries shows a broad geographical spread, with specimen collection taking place in multiple, diverse locations.

3.3. Techniques for investigating the attestation

Necropsy emerges as the predominant technique employed in evaluating marine fauna across multifarious classes in this locale, constituting almost four-fifths of the reviewed research, as outlined in Table 2. This technique involves a meticulous post-mortem inspection of cadaver fauna to identify and scrutinize plastic content within their cells (Orós et al., 2021; Siebert et al., 2020). The ubiquitous employ of necropsy can be attributed to its pragmatism, especially since one-fifth of the studies in the region aim to assess plastic content in vogue fish species effortlessly available in local fish markets. Necropsy is applauded for the sake of its feasibility, eliminating the obligation to nourish biota specimens alive (Park et al., 2023). Oppositely, studies pertaining to *Mammalia* (Abreo et al., 2019b; Coram et al., 2021) lean on social media inquiries but execute meticulous searches for evidence of plastic ingestion through necropsy on stranded mammals. This Technique becomes essential for gigantic and vulnerable species, where capturing and appraising them alive is fanciful and wobbly. Consequently, evaluating the carcasses of stranded marine fauna from this group becomes the solitary substitute.

Just shy of ten percent of the research opts to employ laboratory

Table 2
An array of techniques and instruments employed to establish and assess the incidence of plastic ingestion within the various marine animal class levels across all the literature under analysis.

Class	Technique	Instrument	Author
Bivalvia	Necropsy, Laboratorium Inspection	Visual Scrutiny with Light Microscope, Stereoscopic Microscope, μ-Raman Spectroscopy, and Fourier-Transform Infrared (FTIR) Spectrometer	(Asadi et al., 2022; Bonifacio et al., 2022; Goh et al., 2021; Ningrum et al., 2023; Phaksopa et al., 2023; Ruairuen et al., 2022; Thushari et al., 2017; Tielman et al., 2022; Tran-Nguyen et al., 2023)
Branchiopoda	Laboratorium Inspection	Hispatology, Chemical Analysis, Visual Scrutiny with Fourier-Transform Infrared (FTIR) Spectrometer	(Charoeythornkhajhornchai et al., 2023)
Copepoda	Laboratorium Inspection	Visual Scrutiny with Inverted Fluorescence Microscope	(Amelia et al., 2020)
Elasmobranchii	Necropsy, Cause-and-Effect, Scatology	Observing directly without the assistance of visual aids, Scrutiny with Stereoscopic Microscope and Conceptual calculation, Fourier-Transform Infrared (FTIR) Spectrometer	(Abreo et al., 2019a; Argeswara et al., 2021; Azad et al., 2018; Germanov et al., 2019)
Gastropoda	Necropsy	Visual Scrutiny with Stereoscopic Microscope and μ-Raman Spectroscopy	(Patria et al., 2020; Thushari et al., 2017)
Holothuroidea	Necropsy	Visual Scrutiny with Stereoscopic Microscope and Fourier-Transform Infrared (FTIR) Spectrometer	(Husin et al., 2021; Mazlan et al., 2023)
Malacostraca	Necropsy, Cause-and-Effect	Visual Scrutiny with Inverted Microscope, Stereoscopic Microscope, Fourier-Transform Infrared (FTIR) Spectrometer, and Field Emission Scanning Electron Microscope (FESEM)	(Curren et al., 2020; Goh et al., 2021; Hossain et al., 2023; Patria et al., 2020; Pradit et al., 2021)
Mammalia	Social Media Inquiry	Performing an in-depth Facebook Investigation, Dependent on Necropsy Findings	(Abreo et al., 2019b; Coram et al., 2021)
Reptilia	Necropsy, Social Media Inquiry	Visual Scrutiny with Stereoscopic Microscope and Fourier-Transform Infrared (FTIR) Spectrometer, Performing an in-depth Facebook Investigation, Dependent on Necropsy Findings	(Abreo et al., 2019b; Prampramote et al., 2022)
Teleostei	Necropsy, Social Media Inquiry	Visual Scrutiny with Light Microscope, Stereoscopic Microscope, Digital Microscope, μ-Raman Spectroscopy, Fourier-Transform Infrared (FTIR) Spectrometer, and Field Emission Scanning Electron Microscope (FESEM), Performing an in-depth Facebook Investigation, Dependent on Necropsy Findings	(Abreo et al., 2019b; Azad et al., 2018; Cabansag et al., 2021; Hastuti et al., 2019; Jaafar et al., 2021; Karbalaei et al., 2019; Mardiansyah et al., 2022; Ningrum et al., 2023; Paler et al., 2021; Phaksopa et al., 2021; Pradit et al., 2021; Rochman et al., 2015; Soe et al., 2022; Widyastuti et al., 2023)
Thecostraca	Necropsy	Visual Scrutiny with μ-Raman Spectroscopy	(Thushari et al., 2017)

inspection to assess the ingestion and prevalence of microplastics in marine species. The utilization of laboratory inspection tremendously contributes to ameliorating our understanding of plastic ingestion, encompassing both the rate of plastic ingestion among biota and potential complications that may emerge in the bodies of marine creatures. Intriguingly, two-thirds of the studies employing this technique pay heed to microscopic marine organisms to estimate microplastic toxicity, serving as an allusion to eco-conscious plastic enhancement (Amelia et al., 2020; Charoeythornkhajhornchai et al., 2023). In a separate study, *Katelysia hiantina* exhibited a monumentally higher ingestion rate of microplastic constituents from low-density polyethylene in analogy with two other bivalves, *Donax trunculus* and *Meretrix meretrix* (Bonifacio et al., 2022).

There is a shortage of research that utilizes scatology techniques or investigates the nexus between precise math algorithm models to surmise plastic ingestion in marine fauna. Admittedly, these techniques could profoundly bolster our insight into plastic ingestion among vulnerable and critically endangered marine species. Scatology, which relies on analyzing feces (Zarzoso-Lacoste et al., 2016), can lay bare the characteristics of plastics digested by *Elasmobranchii* filter-feeders, extending across whale sharks to manta rays (Germanov et al., 2019). Synchronously, the technique in this study called the cause-and-effect technique is equally indispensable, involving the assessment of microplastic content in seawater, adopting mathematical models, and fetching steady prognostications. This technique is utterly advantageous for prophesying envisaged pitfalls in crab farms (Hossain et al., 2023) and behaves as a pivotal aiding quotation in the conservation of manta rays (Argeswara et al., 2021).

Various methods are utilized to assess plastic ingestion in marine biota, each offering distinct advantages based on the marine species involved and the research objectives. Necropsy is the most commonly applied and effective technique for larger or stranded species, such as mammals, fish, and elasmobranchs, where live capture is not feasible. This method enables a detailed post-mortem examination of plastics ingested by the animal, providing valuable insights into the types, quantities, and potential impacts of plastic debris. It is particularly useful for species like whales, dolphins, rays, and commercially significant fish. Nonetheless, its scope is limited to dead or stranded organisms, and it does not account for the real-time effects on living populations. Laboratory inspection is frequently employed, especially for smaller organisms such as bivalves (clams and mussels), copepods, and other microfauna. This technique allows for the identification of microplastics within internal tissues, often using tools like FTIR spectroscopy and microscopes. It is essential for studying plastic ingestion and toxicity in microscopic marine species. In contrast, the method is constrained by challenges in sample preparation and the risk of contamination, especially in marine environments.

Scatology is an emerging approach that is particularly useful for studying large, mobile species, such as sharks, rays, and sea turtles, where direct observation or necropsy may not be feasible. By analyzing fecal samples, researchers can gain insight into the plastic ingestion patterns of filter-feeding species, such as manta rays. Despite its promise, scatology is hindered by difficulties in consistently obtaining representative samples in the wild, especially from elusive species. Moreover, the method requires sophisticated microscopic and chemical analysis to detect small microplastics, which may be present in low concentrations. At last, cause-and-effect modeling integrates environmental monitoring with predictive mathematical models to estimate the risks of plastic ingestion in specific ecosystems, such as estuaries or coral reefs. This approach is particularly valuable for species inhabiting areas with high plastic pollution levels, like crabs or fish in contaminated habitats. It helps forecast ingestion rates and potential impacts based on environmental plastic concentrations. Notwithstanding, this technique relies on comprehensive data regarding plastic contamination and environmental variables and may not capture the real-time ingestion patterns of individual organisms.

The methodologies employed to study plastic ingestion in marine species vary according to the organism's size and characteristics. No single method is effectively and universally applicable, and researchers should select techniques based on the species, their life history, and the research objectives. Necropsy is highly effective for larger or stranded species, providing detailed post-mortem analyses of the types and quantities of ingested plastics, particularly in fish, mammals, and elasmobranchs. For smaller organisms, such as bivalves and copepods, laboratory inspection utilizing advanced techniques like FTIR and µ-Raman spectroscopy enables accurate identification of microplastics. Scatology, a non-invasive approach that analyzes fecal samples, is particularly suited for mobile species such as sea turtles and manta rays, though obtaining consistent samples presents challenges. Cause-and-effect modeling, which integrates environmental monitoring and predictive algorithms, is valuable for assessing ingestion risks in heavily polluted ecosystems. While stereoscopic microscopy facilitates initial identification of plastic debris, FTIR and µ-Raman spectroscopy are indispensable for confirming polymer types at a molecular level. Employing a combination of these methodologies enhances the comprehensiveness and accuracy of plastic ingestion studies across diverse marine taxa and habitats.

To observe and dissect the plastic ingredients ingested by marine species, it is perceivable that the stereoscopic microscope is the most prevailingly utilized instrument for this process. In defiance of not being urged, around one-fourth of studies exclusively use microscopes to identify ingested microplastics in marine creature specimens. Sporadically, affirmation procedures become a more skillful manner to identify and diligently corroborate the explicit varieties of microplastics ingested by marine species (Mecozzi et al., 2016). At that juncture, the Fourier-Transform Infrared (FTIR) spectrometer is the most prevalently employed instrument for inspecting the chromatic expression of elements reckoned to be microplastics after observation. Regarding µ-Raman spectroscopy, it is worth noting that almost one-ninth of studies utilize this state-of-the-art technique to assiduously explore the characteristics of plastics digested by marine creatures.

Microplastic analysis in the context of marine biota ingestion generally employs various methodologies, each offering specific advantages and limitations. Raman spectroscopy stands out for its high spatial resolution and ability to molecularly identify different polymer types at the particle level (Gouadec and Colomban, 2007), making it particularly effective in distinguishing microplastic compositions. However, its application can be constrained by time requirements and the need for costly equipment, which limits its use in large-scale studies. Similarly, FTIR spectroscopy, while capable of polymer identification, is better suited for bulk analyses of larger sample sizes (Primpke et al., 2018). Nevertheless, it may face interference from water absorption, especially in marine samples with high moisture content. Field Emission Scanning Electron Microscopy (FESEM), on the other hand, provides exceptional surface imaging that reveals detailed morphologies and surface features of microplastics (Li et al., 2022). Yet, it often necessitates sample preparation, such as coating, which could alter the original characteristics of the microplastics. Furthermore, FESEM is labor-intensive and has throughput limitations (Jeon et al., 2021). A more comprehensive approach involves combining these techniques, such as integrating FTIR or Raman spectroscopy with FESEM or microscopy. This combination allows for precise chemical identification, alongside visual and morphological insights, offering a more complete characterization of microplastic samples found in marine organisms. Consequently, for the most accurate and thorough analysis of microplastics ingested by marine biota, the integration of Raman or FTIR spectroscopy with FESEM is the most effective method, offering a balance between chemical analysis and morphological details.

Technological advancements and innovations in analytical methods have the capacity to significantly enhance plastic pollution monitoring by improving detection accuracy, efficiency, and scope. Techniques such as FTIR spectroscopy and µ-Raman spectroscopy enable precise identification of plastic polymers at both molecular and particle levels, facilitating the detection of microplastics in marine organisms and ecosystems. FESEM further contributes by providing high-resolution surface imaging, which allows for detailed analysis of the morphology and degradation patterns of plastic debris. The integration of multiple analytical approaches, such as combining spectroscopy with microscopy, offers a more comprehensive characterization of plastics, thereby increasing the reliability and reducing potential errors. Moreover, cause-and-effect modeling, which combines environmental monitoring data with predictive algorithms, enables the estimation of plastic ingestion risks and impacts across entire ecosystems. Non-invasive techniques, like scatology, allow for the study of plastic ingestion in elusive or endangered species without causing harm. Automation in the extraction and analysis of microplastics enhances the scalability and efficiency of research, enabling the processing of larger sample sizes at a faster rate. Collectively, these innovations not only improve the detection of plastic pollution but also enhance the ability to implement proactive monitoring and conservation strategies.

4. Long-term implications of plastic ingestion and the way out

Southeast Asia is a significant contributor to global ocean plastic pollution due to factors such as rapid urbanization, economic development, and increasing plastic consumption (Omeyer et al., 2022). The expansion of urban areas and the growth of the middle class drive the demand for single-use plastics and packaging, leading to higher plastic waste generation (Ncube et al., 2021). Nevertheless, many countries in the region face insufficient waste management infrastructure, resulting in substantial quantities of plastic waste being improperly handled (Abubakar et al., 2022). A large portion of this waste is transported by rivers, which ultimately discharge it into the ocean. Nations such as Indonesia, the Philippines, Vietnam, and Thailand are among the largest producers of plastic waste (Liang et al., 2021), significantly contributing to marine pollution. Recycling rates in Southeast Asia are also notably low, with less than a quarter of plastic waste being recycled (Liang et al., 2021), due to inefficiencies in waste sorting and a lack of adequate recycling facilities. Plus, rivers in the region act as major conduits, directly channeling plastic waste into the sea (van Emmerik et al., 2019). Some Southeast Asian countries have historically served as recipients of plastic waste from higher-income nations (Landrigan et al., 2020), further exacerbating the region's environmental burden. The combination of rising plastic consumption, inadequate waste management systems, and low recycling rates positions Southeast Asia as a key source of global ocean plastic pollution.

Plastic ingestion by marine species in Southeast Asia leads to specific ecological impacts, disrupting marine food webs and threatening biodiversity. Ingested plastics cause physical damage to marine organisms, such as digestive blockages, internal injuries, and stunted growth, often resulting in malnutrition or starvation (Alimba and Faggio, 2019), particularly in smaller species like copepods and juvenile fish. To boot, plastics serve as vectors for harmful chemicals, including heavy metals and persistent organic pollutants (Okoye et al., 2022), which accumulate in marine species and spread through the food chain, causing poisoning and reproductive harm. Filter-feeding species, such as sea turtles and manta rays, are particularly susceptible to plastic ingestion, which can severely impair their health and survival. The ingestion of plastics also contributes to population declines in vulnerable species, such as sea turtles, whale sharks, and certain fish, disrupting marine food webs. These declines in species populations disrupt the ecological balance, reducing ecosystem resilience. Furthermore, the accumulation of plastics leads to habitat degradation, especially in coral reefs and seafloor environments, which are critical to many marine species. This degradation amplifies environmental stress, further threatening the integrity of marine ecosystems.

The long-term consequences of plastic ingestion on marine ecosystems in Southeast Asia are complex and wide-ranging. The bioaccumulation of toxins through the food web, as plastics degrade and release harmful substances (Benson et al., 2022), represents a major threat to ecosystem health and biodiversity. Species such as sea turtles, marine mammals, and fish, which ingest plastics, experience population declines that disrupt essential ecological functions, thereby threatening overall biodiversity. This loss of species diminishes the resilience of marine ecosystems, making them increasingly vulnerable to additional environmental pressures, such as climate change and overfishing. Moreover, plastic pollution poses a direct threat to fisheries by compromising seafood quality and safety (De-la-Torre, 2020), negatively impacting the livelihoods of coastal communities. Plastics accumulate in vital habitats, such as coral reefs and seafloor environments, causing long-term damage to ecosystems that many marine species depend on for survival. As plastic pollution continues to persist, habitat degradation and species loss are likely to trigger a cascading effect, further destabilizing marine ecosystems.

To effectively mitigate plastic pollution in Southeast Asia's oceans, immediate action must focus on addressing the root causes of plastic waste leakage into the environment. Governments should implement and enforce stricter regulations on waste management, including policies for debris separation and recycling, to prevent plastic materials from entering marine ecosystems. Public awareness campaigns, disseminated through digital platforms and educational programs, are essential to promote responsible plastic consumption, recycling, and waste sorting. Early environmental education on the hazards of improper waste disposal and the importance of sustainability is critical for fostering long-term behavioral change. Successful mitigation will require collaborative efforts across multiple sectors, including governments, private entities, and local communities, to develop and implement sustainable waste management systems and promote eco-friendly product innovations. Regulatory policies should prioritize the reduction of disposable plastic use while incentivizing the creation of recyclable and biodegradable alternatives. Innovative solutions, such as waste banks and Plastic Tar Roads (PTR), offer practical means for waste segregation and recycling, while also contributing to economic development and infrastructure enhancement (Wu and Montalvo, 2021).

Recycling initiatives and the adoption of circular economy models present significant opportunities for reducing plastic pollution in Southeast Asia. Recycling programs help minimize waste in landfills and conserve critical resources, including energy and water, thereby advancing environmental sustainability. Programs like waste banks, successfully implemented in Indonesia, can facilitate the segregation and recycling of plastic waste while also creating income-generating opportunities for local communities (Mangindaan et al., 2022). Governments must invest in expanding and improving recycling infrastructure to make participation more accessible for the public. Moreover, reducing plastic production and consumption through regulatory measures will decrease the overall volume of plastic waste entering the marine environment. Indonesia's National Plan of Action (NPOA) for Marine Plastic Debris serves as an exemplary model, demonstrating the potential of combining public education, policy enforcement, and incentives to reduce plastic leakage (Arifin et al., 2023). Ultimately, international collaboration is essential for managing the transboundary nature of plastic pollution and ensuring the effective implementation of regional waste management systems.

Current studies on plastic ingestion in marine species across Southeast Asia reveal several critical gaps. While considerable attention has been given to *Teleostei* species, other key groups such as seabirds, sea snakes, dugongs, and commercially important fish species remain underrepresented. Geographic disparities in research efforts are evident, with countries like Vietnam receiving less focus despite being major contributors to plastic pollution. Smaller organisms, including copepods and branchiopods, are often overlooked, despite their ecological significance. Marine mammals, which serve as important bioindicators, are inadequately studied, with much of the existing research relying on stranded individuals, limiting insights into live populations. There is also a lack of standardized methodologies for assessing plastic ingestion across different species, particularly concerning both microplastics and macroplastics. Furthermore, research on commercially significant fish species, which are vital to local economies and food security, is limited, raising concerns about potential human health risks. Existing studies tend to focus primarily on larger species, neglecting smaller organisms that are also susceptible to plastic ingestion. Addressing these gaps will require more comprehensive, standardized research across a wider range of species, regions, and analytical approaches.

5. Conclusion

To recapitulate, this study conducts a thorough review of the existing literature on plastic ingestion by marine species in Southeast Asia, highlighting that *Teleostei* species have been the primary focus, represented in 14 out of the 35 studies reviewed. Studies effort are concentrated on species from classes such as *Teleostei*, *Bivalvia*, and *Elasmobranchii*, with limited studies on classes like *Branchiopoda* and *Copepoda*. Studies on plastic ingestion in Southeast Asia demonstrate notable gaps, including limited attention to underrepresented species such as seabirds, sea snakes, dugongs, and commercially significant fish, insufficient focus on smaller organisms like copepods, geographic disparities in study efforts, inadequate investigation of live marine mammal populations, and the absence of standardized methodologies for evaluating microplastic and macroplastic ingestion. Geographical imbalances are evident in the study landscape, with Thailand and Indonesia leading in the number of studies, while countries like Vietnam show marked gaps in study. Necropsy is regarded as the most reliable method for assessing plastic ingestion in larger or stranded marine species, such as mammals, fish, and elasmobranchs, due to its ability to offer comprehensive post-mortem insights. In contrast, laboratory inspection is preferred for smaller, microscopic organisms like bivalves and copepods, as it enables the identification of microplastics within internal tissues. The most effective tools for confirming plastic ingestion in marine organisms are FTIR spectroscopy and µ-Raman spectroscopy. FTIR is particularly useful for bulk analyses and the identification of polymers, while µ-Raman spectroscopy is highly effective in providing high spatial resolution and molecular identification of plastic types at the particle level.

Ethical statement for journal of open innovation: technology, market, and complexity

Hereby, I consciously assure that for the manuscript / Plastic Ingestion by Marine Biota in Five Southeast Asian Nations: Complex Challenges and Long-Term Implications/ the following is fulfilled:

1) This material is the authors' own original work, which has not been previously published elsewhere.
2) The paper is not currently being considered for publication elsewhere.
3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
5) The results are appropriately placed in the context of prior and existing research.
6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

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Mochamad Arief Budihardjo: Supervision, Methodology, Conceptualization. **Muhammad Thariq Sani:** Writing – original draft, Software, Formal analysis. **Annisa Sila Puspita:** Writing – review & editing, Resources, Investigation. **Amin Chegenizadeh:** Writing – review & editing, Visualization, Project administration.

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During the preparation of this work, the author(s) used Chat GPT-3.0 to improve readability and language understanding. After utilizing this AI technology, the author(s) meticulously reviewed and amended the content as required, ensuring its accuracy and completeness. The author (s) assume(s) complete accountability for the content of the publication.

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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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