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REVIEW

Research trends in microplastic contamination of bivalves across Southeast Asia: a comprehensive review on patterns, challenges and future directions

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Abstract Microplastics (diameter < 5 mm) have emerged as a global concern due to their ubiquitous presence and interaction with biota, especially in marine ecosystems. As one of the largest producers and consumers of plastics globally, Southeast Asia faces critical challenges related to MP contamination due to ineffective waste management and high anthropogenic activities in coastal regions. Bivalves have emerged as reliable bioindicators for assessing MP pollution in marine water and sediments due to their filter-feeding behavior and widespread distribution. This review synthesizes current research on MP contamination in Southeast Asian bivalves, focusing on Brunei, Indonesia, Malaysia, the Philippines, Thailand, and Vietnam. Findings indicate significant variability in MP concentrations across regions, influenced by proximity to pollution sources, habitat types, and species-specific traits. Fibers and fragments are the predominant MP types ingested, with polyethylene, polypropylene, and polyethylene terephthalate identified as the most common polymers. However, methodological inconsistencies, such as variations in digestion protocols, identification techniques, and data reporting units, hinder comparability across studies and underscore the need for standardized approaches. MP contamination in bivalves poses ecological and human health risks, particularly in regions where bivalves are a significant food source. The potential for trophic transfer of MPs and associated toxic chemicals remains a concern, emphasizing the importance of further research on food safety and long-term health impacts. This review highlights the urgent need for improved monitoring, mitigation strategies, and policy interventions to address MP pollution.

Keywords Bivalves . Bioindicators . Marine water . Microplastic contamination . Sediments

Introduction

Microplastics (MPs), defined as synthetic polymer particles smaller than 5 mm, are a persistent and pervasive pollutant in marine ecosystems (Fan et al. 2019; Rodríguez-Seijo and Pereira 2017). MPs originate from two primary sources: primary MPs, such as microbeads found in cosmetics and personal care prod-

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ucts (Andrady 2011; van Wezel et al. 2016) and secondary MPs, which result from the fragmentation of larger plastics due to weathering, mechanical abrasion, and ultraviolet degradation (Andrady 2011; Cau et al. 2020; Mateos-Cárdenas et al. 2020). On the other hand, physical, chemical, or biological processes like photodegradation or mechanical abrasion break down larger plastic debris to form secondary MPs (Andrady et al. 2022; X. Wu et al. 2022). Both types play a critical role in microplastic pollution in coastal areas. Microplastics undergo dynamic transport processes within marine systems, moving across different environmental compartments, including surface waters, sediments, and deep-sea ecosystems (Zhang 2017). Moreover, rivers are significant pathways for transporting MPs from land to sea, while hydrodynamic forces such as waves, currents, and tidal actions facilitate their redistribution within marine ecosystems (Chanda et al. 2024; Li et al. 2023). Globally distributed microplastics accumulate in remote locations such as polar regions, ocean gyres, and deep-sea trenches (Table 1). Their fate depends on physical properties such as size, shape, and density. For example, low-density polymers, such as polyethylene (PE) and polypropylene (PP), remain buoyant and accumulate in surface waters, while denser particles sink to the seabed (Bond et al. 2018; Schwarz et al. 2019; Zhang 2017). Biological factors, like marine organisms eating MPs, biofilm formation, and particles sticking together with other particles, also affect how MPs move and eventually end up in sediments (Fan et al. 2023). Weathering processes also play a significant role in determining the fate of MPs. Photodegradation, mechanical abrasion, and oxidative and hydrolytic reactions break larger plastic particles into smaller fragments (Duan et al. 2021). These processes enhance the bioavailability of MPs, increasing the likelihood of marine organisms ingesting them.

It can be seen that MPs are a persistent environmental issue in marine ecosystems, with their prolonged presence enabling them to permeate all ecological compartments and increasing their bioavailability to aquatic organisms (Ali et al. 2023). In addition, clams, mussels, oysters, and scallops play a critical role in marine ecosystems by maintaining water quality, cycling nutrients, and serving as a food source for other species (van der Schatte Olivier et al. 2020; Vaughn and Hoellein 2018). Bivalves hold unparalleled economic and nutritional significance in Asia due to their heavy cultivation and consumption. However, their filter-feeding nature makes bivalves efficient bioaccumulators of MPs in the water column and sediments. Their susceptibility is heightened by the similarity in size between MPs and their planktonic food, making accidental ingestion more likely (Piarulli and Airoldi 2020). Once ingested, MPs may be excreted, accumulate in the gut, or pass through the intestinal wall into the circulatory system of the mollusk (Sharifinia et al. 2020). Unlike most seafood, bivalves consume their entire body, including their digestive systems, which are the primary sites for MP accumulation (Huffman Ringwood 2021). Consequently, they provide a direct route for MPs and associated chemicals to enter the human food chain, raising significant health concerns. Furthermore, the accumulation of MPs in bivalves highlights the potential for trophic transfer. MPs ingested by bivalves can move up the food chain, affecting higher predators and, ultimately, human consumers

Table 1 Microplastic distribution in wetland surface water and sediments in Southeast Asia

Country		Sample location	Analysis method	Size (mm)	Density	Dominant polymer types	References
Indonesia	Jagir Estuary	Sediments	FTIR	0.3 – 5	92 – 590 particles/kg	PES, LDPE, PP	Firdaus et al. (2020)
Malaysia	Straits of Johor	Sediments	ATR-FTIR	0.3 – 1	100 – 300 pieces/kg-dry sediment	PE, PS, PP	Matsuguma et al. (2017)
The Philippines	Cañas, Meycauayan, Parañaque, Pasig and Tullahan, draining to Manila Bay	Surface Water	ATR-FTIR	0.075 - 5	1,580 - 57,665 particles/m^3	PP, LDPE, HDPE, PS	Osorio et al. (2021)
		Sediment Samples	ATR-FTIR	0.075 - 5	386 - 1,357 particles/kg		
Singapore	Singapore's coastline	Sediments	ATR–FTIR	0.02 – 5	12 – 62.8 particles/kg	PP, PE	Nor and Obbard (2014)
Thailand	Gulf of Thailand	Sediments	ATR-FTIR	0.3 – 1	85 – 328 pieces/kg-dry sediment	PE, PS, PAK, PCL, PEP, EVA	Matsuguma et al. (2017)
Vietnam	Tien Yen Bay	Sediments	FTIR	0.3 – 5	0 – 815 particles/kg	PE, PP, PS, PET, PA, PLE, PVC, PU	Viet Dung et al. (2021)
	Red River Delta	Sediments	FTIR	0.3 – 5	0 – 4941 particles/kg	PE, PP, PS, PET, PA, PLE, PVC, PU	Viet Dung et al. (2021)

Note: PP: polyethylene; PP: polypropylene; PS: polystyrene; PET: polyethylene terephthalate; PA: polyamide; PVC: polyvinyl chloride; RY: rayon; CE: cellophane; AL: alkyd; PEP: polyethylene propylene copolymer; EVA: ethylvinyl acetate; PAK: polyacrylates; PCL: polycaprolactone; PLE: polyester; PU: polyurethane; LDPE: low-density polyethylene; HDPE: high-density polyethylene; EPDM: ethylene propylene; SAN: styrene acrylonitrile; PC: polycarbonate; PBDE: polybrominated diphenyl ethers; DBDPE: decabromodiphenyl ethane; BTBPE: 1,2-bis(2,4,6- tribromophenoxy)ethane; TBBPA: tetrabromobisphenol A; HBCDD: hexabromocyclododecane; DP:dechlorane plus; EPR: poly(ethylene:propylene:diene)

Table 2 Microplastic distribution in bivalve species in Southeast Asia

Country	Bivalves speices	Analysis method	Density	Dominant polymer types	References
Brunei	*Saccostrea cucullata*	FTIR	0.43 – 7.20 particles/g wet tissue	Polypropylene (black fragments most dominant), transparent/gray fragments, blue/brown/red fibers	Lee et al. (2022)
Indonesia	*Anadara antiquata*	Microscope	2.41 – 6.07 particles/individual	Fiber (dominant), film, fragment	Rahmatsyah et al. (2024)
		Microscope	1.6 ± 1.51 items/individual, 0.5 ± 0.37 items/g	Fiber (92.31%), film	Asadi et al. (2022)
	Anadara granosa	Microscope, FTIR	18.3 ± 7.3 items/individual	Fiber (4.9%), film (41.5%), fragment, pellet	Hantoro et al. (2024)
	Crassostrea gigas	Dissecting microscope	0.6 ± 0.9 particles/individual (range: 0–2)	Fibers (not confirmed as plastic, possibly synthetic or natural)	Rochman et al. (2015)
	Gafrarium tumidum	Microscope	13.44 – 17.33 particles/individual	Fragment (dominant), fiber, film	Yona et al. (2023)
		Microscope	3.5 ± 2.8 items/individual, 3.2 ± 2.52 items/g	Fiber (80.77%), fragment, film, pellet	Asadi et al. (2022)
	Perna viridis	Inferred FTIR	70.7 ± 48.0 items/individual	rubber, styrene copolymer	Hantoro et al. (2024)
	Venerupis philippinarum	Microscope	5.6 ± 3.22 items/individual	Fiber (dominant), fragment	Asadi et al. (2022)
Malaysia	*Anadara granosa*	FTIR	n.e.q.	n.e.q.	Abd Rahman et al. (2024)
	Corbicula fluminea	Stereo microscope	0.34–0.42 particles/g (avg. 0.37 particles/g), 4.2 particles/sample	Microfiber (filamentous, dominant), microfragment	Nibalvos et al. (2024)
	Donax sp.	FTIR	n.e.q.	Filament/fiber (most abundant morphology, not specific polymer)	Bonifacio et al. (2022)
	Glauconome virens	FTIR	n.e.q.	n.e.q.	Abd Rahman et al. (2024)
	Meretrix lyrata	FTIR	n.e.q.	n.e.q.	Abd Rahman et al. (2024)
		FTIR	n.e.q.	Filament/fiber (most abundant morphology, not specific polymer)	Bonifacio et al. (2022)
	Katelysia hiantina	FTIR	n.e.q.	Filament/fiber (most abundant morphology, not specific polymer)	Bonifacio et al. (2022)
	Perna viridis	Stereomicroscope, FTIR	Small: 1.31 items/g (3–4 items/individual); Medium: 1.05 items/g (4–7 items/individual); Large: 0.79 items/g (4–8 items/individual)	Nylon (polyamides), predominantly fibers	Zahid et al. (2022)
		Microscope	0.0143 g/kg (Bacoor City), 1.375 × 10^{-4} g/piece	n.s.	Creencia et al. (2023)
	Venerupis philippinarum	Microscope	7.2 × 10^{-6} g/kg (Calatagan), 1.18 × 10^{-5} g/piece	n.s.	Creencia et al. (2023)
The Philippines	*Anadara granosa*	Stereo microscope	0.12 items/g, 0.38 items/individual	Fiber (68.8%), fragment (31.2%)	Tanaviyutpakdee and Karnpanit (2023)
	Crassostrea iredalei	Digital microscope	0.42 ± 0.07 items/g	Fragment	Insigne et al. (2022)
		Stereo microscope	11.80 ± 9.69 particles/oyster (1.10–30.31 μm, 68.36%)	Fragment (54%), microfiber (40%), film (5%), pellet (1%)	Jambre (2021)
	Meretrix meretrix	ATR-FTIR	4.15 ± 3.37 particles/individual	Polypropylene, rayon	Bonifacio et al. (2022)
	Katelysia hiantina	ATR-FTIR	4.15 ± 3.37 particles/individual	Polypropylene, rayon	Bonifacio et al. (2022)
	Paphia undulata	Stereo microscope	0.06 items/g, 0.14 items/individual	Fragment (50%), fiber (35.7%), pellet (14.3%)	Tanaviyutpakdee and Karnpanit (2023)
		Stereo microscope	0.07 items/g, 0.60 items/individual	Fiber (57.9%), pellet (26.3%), fragment (15.8%)	Tanaviyutpakdee and Karnpanit (2023)
	Perna viridis	FTIR	Not explicitly stated for bivalves	Rayon (40–55%)	Chinfak et al. (2021)
		Stereo microscope	0.27–0.41 particles/g wet weight	Fiber (61%, dominant), fragment, pellet	Bilugan et al. (2021)
		Digital microscope	0.93 ± 0.12 items/g	Fragment	Insigne et al. (2022)
	Venerupis philippinarum	Digital microscope	1.71 ± 0.34 items/g	Fragment	Insigne et al. (2022)
	Crassostrea gigas	FTIR	9.5 ± 0.71 particles/g, 49.60 ± 10 particles/individual	Fragment (66.67%), fiber (33.33%), polyethylene (50%), polytetrafluoroethylene (50%)	Saelee et al. (2021)
Thailand	*Mytilus edulis*	FTIR	9 ± 3.55 particles/g, 46.60 ± 15.70 particles/individual	Fragment (66.67%), polyethylene (25%), polytetrafluoroethylene (25%), styrene (25%), polystyrene (25%)	Saelee et al. (2021)
	Perna viridis	Microscope	1.26 ± 0.10 items/individual (dry season), 0.56 ± 0.15 items/individual (wet season)	Fiber (49–69%, both seasons)	Ruairuen et al. (2022)
		FTIR	Not explicitly stated for bivalves	Rayon (40–55%)	Ruairuen et al. (2022)
		μ-FTIR	1.87 ± 0.86 particles/individual	Cotton, rayon, polyethylene terephthalate	Hongsawat et al. (2024)
		μ-FTIR, Nile Red tagging	Average abundance: 15.3 ± 8.1 items/individual. Range: 1-41 items/individual	Polyester, polypropylene, polyethylene	Imasha and Babel (2021b)
		μ-FTIR, Nile Red tagging	3.2 ± 1.6 items/individual	High-density polyethylene, rubber, styrene copolymers	Imasha and Babel (2023)
	Tegillarca granosa	Microscope	0.30 ± 0.07 items/individual (dry season), 0.20 ± 0.07 items/individual (wet season)	Pellet (49%, dry season), fiber (59%, wet season)	Ruairuen et al. (2022)
Vietnam	*Anadara sp.*	Infrared microscopy	0.73 MP/g	Polypropylene and polyester '(>88%)	
		Micro-Raman Spectroscopy	1.32 ± 0.46 items/individual	Fiber (41.3%), polypropylene, polyethylene	Khuyen and Kim (2024)

Table 2 Continued

Crassostrea gigas	µFTIR	1.88 ± 1.58 particles/g or 18.54 ± 10.08 particles/individual	Nylon (50.56%), 15 polymer types total	Dang et al. (2022)
	µFTIR	1.18 ± 0.59 MPs/g or 11.55 ± 4.83 MPs/individual	Polyethylene terephthalate (42.26%), high-density polyethylene (31.95%)	X. T. T. Le et al. (2024)
Grease snail	Micro-Raman Spectroscopy	3.27 ± 1.28 items/individual	Fiber (41.3%), polypropylene, polyethylene	Khuyen and Kim (2024)
Meretrix lusoria	Microscope, ATR-FTIR	0.2 – 0.5 items/g, 1 – 3 items/individual	Fiber (69 – 92%), polyethylene terephthalate	My et al. (2023)
	ATR-FTIR, µFTIR	n.e.q.	Fiber (67%), ethylene vinyl acetate (18%), polyethylene, polypropylene, polyethylene terephthalate, nylon	Hue et al. (2021)
Meretrix lyrata	Micro-Raman Spectroscopy	3.25 ± 1.35 items/individual	Fiber (41.3%), polypropylene, polyethylene	
	Stereo microscope, Micro-Raman Spectroscopy	4.71 ± 2.15 – 5.36 ± 2.69 items/g, 12.73 ± 4.49 – 13.20 ± 7.66 items/individual	Fiber (52.9 – 60.6%), fragment (38.4 – 46.6%), polyester (22.2–30%), polyethylene (20 – 22.2%), polypropylene (20 – 22.2%)	Tran-Nguyen et al. (2023)
Paratapes undulatus	Stereo microscope, Micro-Raman Spectroscopy	2.17 ± 0.43 – 2.38 ± 1.28 items/g, 3.30 ± 0.94 – 3.43 ± 0.98 items/individual	Fiber (94.2 – 99.2%), polypropylene (25 – 33.3%), polyethylene (11.1 – 25.0%), polyethylene terephthalate (11.1 – 25.0%)	Tran-Nguyen et al. (2023)
	µ-FTIR	0.29 ± 0.14 items/g; 2.60 ± 1.14 items/individual	Polypropylene (31%), polyester (23%)	Nam et al. (2019)
	Infrared microscopy	0.87 MP/g	Polypropylene and polyester '(>88%)	Phuong et al. (2024)
Perna viridis	µFTIR	3.67 ± 1.20 MPs/g or 25.05 ± 5.36 MPs/individual	Polyethylene terephthalate (49.93 – 58.44%)	Le and Nguyen (2024)
	µFTIR	5.36 – 7.03 items/g, 27.00 – 30.67 items/individual	Fragment (69.20 – 72.43%), fiber (22.63 – 23.55%), nylon (20.75 – 40.22%), polyethylene terephthalate (22.10 – 71.19%), ethylene vinyl alcohol (4.15 – 25.72%)	Thanh, Thu, Thom, Manh, Tuan, Thao, et al. (2022)
Tapes dorsatus	ATR-FTIR, µFTIR	n.e.q.	Fiber (67%), ethylene vinyl acetate (18%), polyethylene, polypropylene, polyethylene terephthalate, nylon	Hue et al. (2021)

n.d.: no detailed; n.s.: no specified; n.e.q.: not explicitly quantified

(Carbery et al. 2018; Mercogliano et al. 2020). Once ingested, MP and their associated chemical additives (e.g., plasticizers, flame retardants) can interact with the human gastrointestinal epithelium (Zhang et al. 2022), where they have been shown in model organisms to induce oxidative stress, inflammatory cytokine production, and disruption of cellular homeostasis (Meng et al. 2022; Palaniappan et al. 2022; H. Wu et al. 2022; Zhang et al. 2022). These findings underscore an urgent need for standardized monitoring of MPs in Southeast Asian bivalves, improved quantification of human exposure pathways, and targeted epidemiological studies to elucidate dose–response relationships and long-term health outcomes.

Southeast Asia faces unique challenges related to MP contamination due to its status as the world's largest producer and consumer of plastic (Ali et al. 2024). The region generates significant plastic waste, which enters marine environments due to inadequate waste management systems and high population densities in coastal areas. Aquaculture farms' proximity to urban and industrial areas intensifies the issue, as they frequently encounter elevated levels of MPs from untreated wastewater, runoff, and abandoned fishing gear (Fred-Ahmadu et al. 2024; Wu et al. 2020; Wu et al. 2023). This has led to hotspots of MP contamination in regions with profound implications for marine ecosystems and food safety. Despite the increasing research on MPs, there are still significant gaps in understanding their long-term effects on bivalve health, reproduction, and population dynamics. Similarly, a deeper understanding of the transfer of MPs and their associated chemicals from bivalves to humans through seafood consumption is necessary. Additionally, variations in MP concentrations across different species and regions underscore the need for standardized methodologies for sampling and analysis to ensure comparability across studies. This review comprehensively assesses MP contamination in Southeast Asian bivalves, focusing on their use as bioindicators for marine pollution. It synthesizes findings on MP ingestion, accumulation, and associated chemical risks in bivalves, evaluates their ecological and human health implications, and identifies gaps in the current knowledge.

Research trends in investigating microplastics in bivalves in Southeast Asia

Bivalves, including mussels, clams, oysters, and scallops, are essential components of marine ecosystems and critical protein sources in Southeast Asian diets (Tan et al. 2022; Vaughn and Hoellein 2018). However, their filter-feeding behavior renders them vulnerable to MP ingestion. MPs are easily mistaken for food and accumulate in bivalve tissues, posing risks to marine organisms, humans, and ecosystems (Akhbarizadeh et al. 2019; Mercogliano et al. 2020). The accumulation of MPs in bivalves reflects the level of plastic pollution in surrounding waters and sediments, making these species key indicators for assessing the environmental impact of MPs (Figure 1).

Brunei

In Brunei, studies on bivalve microplastics are limited but reveal significant spatial variation in contamination levels. Research on oysters (*Saccostrea cucullata*) along the Bornean coastline showed distinct differences between estuarine and open-shore environments. Oysters in sites within the Brunei Estuarine System (BES) exhibited the highest microplastic concentrations, ranging from 0.43 to 7.20 particles/g tissue, while relatively pristine areas along the South China Sea coastline showed lower levels. Fragments dominated microplastic types, mainly black polypropylene particles smaller than 50 µm. Furthermore, microplastic accumulation was strongly influenced by proximity to pollution sources, with concentrations decreasing seaward, suggesting localized impacts and the role of environmental factors such as currents and dilution (Lee et al. 2022). Based on these results, the localized nature of microplastic contamination in Brunei was investigated, and the need for expanded monitoring was underscored to address gaps in understanding regional pollution dynamics.

Indonesia

In Indonesia, research on microplastics in bivalves highlights significant contamination across various ecosystems. For instance, studies conducted in mangrove forests in Situbondo, East Java, revealed a high prevalence of microplastics in *Geloina erosa* and *Telescopium telescopium*. A total of 459 microplastic particles were found in 40 mollusks, with fibers being the most dominant type. Interestingly, *G. erosa* exhibited higher microplastic loads than *T. telescopium*, with findings indicating a positive correlation between organism size and microplastic abundance (Yona et al. 2023). Similarly, investigations in North Sumatra identified alarming contamination levels in two commercially significant bivalves, *Anadara antiquata* and *A. granosa*. Prevalence ranged from 88% to 100%, with fiber, film, and fragment types dominating the microplastics found. Notably, the average intensity in *A. antiquata* reached 6.07 particles per individual, significantly higher than that of *A. granosa* (Rahmatsyah et al. 2024).

Furthermore, research in the coastal waters of Paciran, Lamongan, confirmed widespread contamination in wild clams, with *Venerupis philippinarum* exhibiting the highest concentrations of 5.6 particles/individual (Asadi et al. 2022). Across studies, fibers consistently dominated microplastic types, often comprising more than 70% of particles (Asadi et al. 2022; Rahmatin et al. 2024). Another study at Pari Island, Seribu Islands, Jakarta, revealed contamination in all sediment and *Gafrarium tumidum*, with

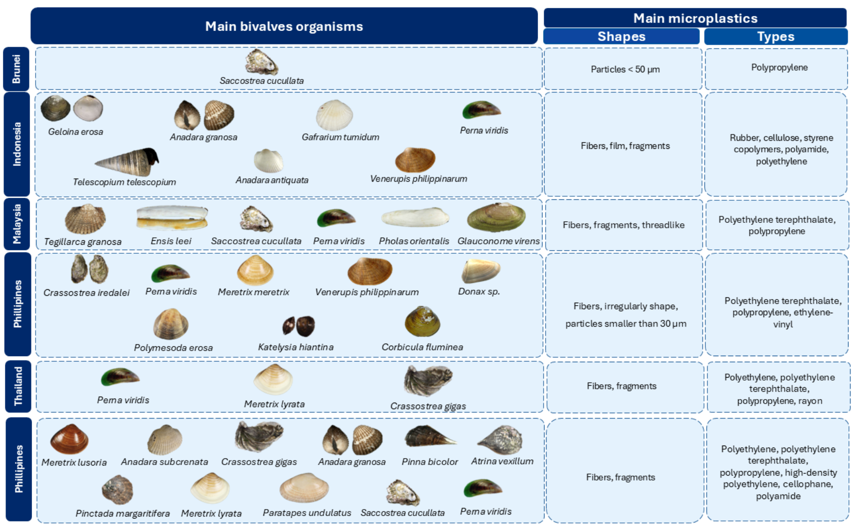

Fig. 1 Bivalve species investigated for microplastic contamination in Southeast Asia

black being the most dominant color and fibers being the most common type (Tubagus et al. 2020). Finally, in commercial seafood from the coastal region of Semarang, Central Java, microplastic contamination was observed in blood cockles (*A. granosa*) and green mussels (*Perna. viridis*), with green mussels showing the highest abundance of microplastics, particularly fragments. Regarding polymer types, rubber (12–14%), styrene copolymers (9–13%), and cellulose (4–25%) dominated MPs in green mussels. The three most critical polymers in blood cockles are cellulose (40%), polyamide (PA) (20%), and PE (11%) (Hantoro et al. 2024).

Malaysia

In Malaysia, research has similarly documented the widespread presence of microplastics in bivalves, focusing on commercially important species. Studies conducted in Pantai Remis, Kuala Selangor, found the highest density of microplastics in blood cockles (*Tegillarca granosa*), at 2.417 particles/cm³, followed by bamboo clams (*Ensis leei*) and oriental angel wing clams (*Pholas orientalis*). Fibers and fragments were the dominant types, with significant proportions of microplastics measuring 1–5 mm (Aziz et al. 2024). A study in Langkawi Island observed comparable contamination levels in rock oysters (*S. cucullata*), with threadlike microplastics being the most common form. Polymer analysis revealed polyethylene terephthalate (PET) and PP as major contributors, with potential origins linked to plastic bottles and textiles (Ghazali et al. 2022). Moreover, research on *P. viridis* in Peninsular Malaysia identified severe shell deformities potentially caused by pollution, with abnormalities ranging from 15.8% to 87.5% (Yap et al. 2023). Another study at Pantai Teluk Likas, Sabah, found that *Glauconome virens* had the highest abundance of microplastics, with fibers dominating all bivalve samples (Abd Rahman et al. 2024). The findings emphasize the urgent need for continued monitoring and mitigation efforts, particularly in regions where bivalves are both ecological indicators and vital food resources.

The Philippines

In recent years, there has been a growing interest in understanding microplastic contamination in aquatic environments, particularly in tropical regions like the Philippines. These investigations predominantly focus on bivalve species, which are widely consumed and recognized as bioindicators of marine pollution. Several recent studies highlight key findings on microplastics in bivalves across different regions of the Philippines. One notable research trend involves detecting and quantifying microplastics in edible bivalves, such as green mussels (*P. viridis*) and Philippine cupped oysters (*Crassostrea iredalei*). For instance, a study in Bacoor Bay, Cavite, revealed low concentrations of microplastics in green mussels, with fiber-shaped particles being the most abundant type (Bilugan et al. 2021). This aligns with findings from another study in the same region, which examined microplastics in *P. viridis*, *C. iredalei*, and *V. philippinarum*. The results demonstrated significant differences in the quantity and size of microplastics ingested by these bivalve species, with clams exhibiting the highest density, at1.71 ± 0.34 items/g (Insigne et al. 2022). Such studies underscore the need for further research to identify the polymers ingested and their potential risks to human health. Another emerging area of research investigates microplastic characteristics, such as color, size, and polymer composition, to better understand their sources and environmental behavior. For example, the Philippine cupped oyster (*C. iredalei*) collected from Bacoor Bay contained predominantly transparent, irregularly shaped microplastics, with particles smaller than 30 μm being the most frequent (Jambre 2021). Similarly, mud clam (*Polymesoda erosa*) from Butuan Bay showed a high prevalence of fibers, particularly blue-colored microplastics, primarily composed of ethylene-vinyl acetate and PET (Navarro et al. 2022). Such findings highlight the role of geographic and anthropogenic factors in influencing microplastic contamination levels and characteristics in different bivalve habitats.

Furthermore, studies in regions such as Sorsogon Bay and Panguil Bay have expanded the scope of research by analyzing microplastics in both farmed and wild bivalves. Microplastics were found in green mussels and pen shells in Sorsogon Bay. PET was found to be the main polymer using Fourier Transform Infrared (FTIR) spectroscopy (Syakti et al. 2018). In contrast, Panguil Bay research highlighted the ingestion of low-density PE particles by three bivalve species (*Donax* sp., *Meretrix meretrix* and *Katelysia* *hiantina*), emphasizing their vulnerability as filter feeders (Bonifacio et al. 2022). On the other hand, there is increasing recognition of the potential health risks associated with microplastic contamination in bivalves, given their role as a staple food in the Philippines. Studies have begun to explore the implications of microplastic ingestion for food safety and human health (H.-X. Li et al. 2022). For instance, a study in Eastern Samar found microplastics in economically important bivalves such as *Corbicula fluminea*, raising concerns about human exposure through consumption (Nibalvos et al. 2024). Similarly, research in Batangas and Cavite identified significant amounts of microplastics in mussels (*P. viridis*) and Manila clams (*V. philippinarum*), further emphasizing the need for targeted mitigation strategies (Creencia et al. 2023).

In summary, research on microplastics in bivalves in the Philippines has revealed critical insights into the prevalence, characteristics, and risks of microplastic contamination in these organisms. However, a pressing need remains for more comprehensive studies, including polymer identification, trophic transfer, and potential mitigation strategies. These efforts are vital for addressing the broader implications of microplastic pollution on marine ecosystems, livelihoods, and human health in this region.

Thailand

Microplastic contamination in marine organisms, particularly bivalves, has garnered increasing attention in Thailand due to its potential environmental and human health risks. Research has explored various aspects of microplastic pollution, from contamination levels in aquaculture and market-sold seafood to its implications for public health and ecosystem integrity. One major trend in microplastic research focuses on assessing contamination levels in bivalves sold in fish markets or harvested from aquaculture farms. Notably, oysters (*C. gigas*) and mussels (*P. viridis*) sold in markets have shown contamination levels of up to 9.5 particles/g and 49.6 particles/individual, highlighting significant exposure risks for seafood consumers (Saelee et al. 2021). Various studies have identified green mussels as sentinel organisms due to their filter-feeding behavior and high prevalence of microplastics, with concentrations ranging from 1.53 to 3.2 items/g (Imasha and Babel 2021a). These findings underscore the need to monitor microplastic contamination in market-sold and farmed seafood regularly.

Another emerging focus has been on the characteristics of microplastics, including their size, shape, color, and polymer types. Across various studies, fibers and fragments have emerged as the most common microplastic morphotypes in bivalves, with sizes typically ranging between 0.1 and 1 mm. The dominant polymer types include PE, PP, PET, and rayon, which are commonly used in packaging and textiles. Seasonal variations and site-specific differences in contamination levels have also been observed. For example, green mussels in Bandon Bay contained higher microplastic concentrations than clams, with microfibers being the predominant type (Chinfak et al. 2021; Ruairuen et al. 2022). Moreover, research has highlighted the sources of microplastic pollution in Thailand's coastal and aquaculture ecosystems. Riverine inputs, fishing activities, and mariculture are significant contributors. Studies in Bandon Bay and the Gulf of Thailand revealed that rivers transport vast quantities of microplastics into coastal areas, which are then accumulated by bivalves and other marine organisms (Chinfak et al. 2021; Imasha and Babel 2023; Tanaviyutpakdee and Karnpanit 2023). Similarly, microplastic contamination in farmed green mussels was higher in regions with intensive aquaculture activities, such as Sriracha Bay, emphasizing the impact of human activities on microplastic pollution in aquaculture environments (Imasha and Babel 2021a).

In addition to environmental studies, there has been a growing emphasis on assessing the health risks associated with microplastic ingestion. Research has demonstrated that microplastic contamination in bivalves can lead to human exposure through seafood consumption. For instance, estimated annual intakes (EAI) of microplastics for Thai consumers range from 20 to 1178 particles/person/year, depending on the species and source (Hongsawat et al. 2024). Despite the absence of immediate health risks, the biomagnification of microplastics along the food chain and their potential long-term effects on human health continue to raise concerns. Overall, the research trends in Thailand underscore the need for integrated strategies to address microplastic pollution. These include improved waste management, stricter regulations on plastic usage, monitoring programs for seafood safety, and public awareness campaigns. Such measures are essential for mitigating the risks posed by microplastics to marine ecosystems and human health.

Vietnam

Investigating MPs in bivalves has emerged as a significant research focus in Vietnam, reflecting concerns over food safety, Environ Pollut and human health risks (Doan et al. 2023). Various studies have been conducted across coastal regions to characterize MP abundance, shapes, polymer types, and potential risks to marine ecosystems and human consumers (Hue et al. 2021; Le and Nguyen 2024; Nguyen et al. 2024). These studies collectively highlight a growing body of evidence regarding the contamination of MPs in bivalve species widely consumed in Vietnam.

In Central Vietnam, the comprehensive study on MP contamination in bivalves such as *M. lusoria*, *A. subcrenata*, *C. gigas*, and *P. viridis* revealed MP concentrations ranging from 0.2 ± 0.2 to 0.5 ± 0.3 items/gram wet weight (g-ww) and 1.4 ± 0.8 to 3.0 ± 2.4 items/individual. Fibers, predominantly PET, were the dominant MP shape (69–92%), followed by fragments (My et al. 2023). Research on the northern coast of Vietnam has similarly documented MP accumulation in species such as the blood cockle (*Anadara* sp.) and green mussel (*P. viridis*). Seasonal and locational factors were assessed, with average concentrations of 1.84 and 4.33 items/individual and 0.73 and 0.87 items/gram wet weight, respectively. PE and PP fragments dominated the MP composition (Phuong et al. 2024). Interestingly, the study estimated that annual human exposure to MPs through bivalve consumption could reach 11,500 particles per person. However, this exposure level was lower than other pathways, such as drinking and inhalation.

Further south, in coral reef ecosystems, species such as *Pinna bicolor*, *Atrina vexillum*, *Saccostrea* sp., and *Pinctada margaritifera* were found to accumulate MPs at an average concentration of 0.45 ± 0.13 items per gram wet weight and 5.60 ± 1.49 items/individual. PE, PA, cellophane, and PET were the main polymers, with most MPs being fragments smaller than 100 µm (T. X. T. Le et al. 2024). In the southern biosphere reserve of Can Gio, MPs were detected in clams, oysters, and snails with concentrations of up to 10 particles per individual. Fibers were the most prevalent shape, measuring between 30 and 150 µm. PE, PP, and PET polymers dominated, and potential health risks from chronic exposure were discussed (Khuyen and Kim 2024). Similarly, aquaculture areas along Vietnam's coastline revealed MP contamination in *M. lyrata* and *Paratapes undulatus*, with concentrations reaching 5.36 ± 2.69 items/gram in hard clams. Removing viscera and applying depuration were recommended as mitigation measures to reduce MP ingestion risks (Tran-Nguyen et al. 2023). *C. gigas* has also been studied extensively, with research spanning Vietnam's northern, central, and southern coasts (Le et al. 2024). In Da Nang Bay, MP concentrations were 2.36 ± 2.14 items/gram and 33.25 ± 25.93 items/individual, predominantly in fragment form. Across 16 coastal provinces, *C. gigas* samples contained MPs with an average size of 112 ± 125 µm, with PET and high-density polyethylene (HDPE) being the most common polymers (Dang et al. 2022). Such large-scale studies provide critical insights into spatial patterns of MP contamination in Vietnam. Ha Long Bay has been a focal point for MP studies, particularly in green mussels (*P. viridis*). Concentrations of 30.67 and 27.00 particles/individual were recorded at Bai Chay and Gieng Day, respectively. Fragments accounted for most MPs, with sizes below 150 µm dominating. Nylon and PET were identified as the most abundant polymers, further emphasizing the widespread contamination by synthetic materials (Thanh et al. 2022).

In conclusion, research on MPs in Vietnamese bivalves demonstrates a pervasive issue that spans geographic regions, species, and environmental settings. Dominant shapes, such as fibers and fragments, and polymers like PET, PE, and PP are consistently identified across studies. While the health risks posed by MPs are evident, further investigations into mitigation strategies, monitoring programs, and public awareness are crucial to reducing contamination and safeguarding environmental and human health.

Comparative analysis of research trends on impact levels of bivalves in Southeast Asia

In Southeast Asia, research on microplastic contamination in bivalves has burgeoned over the past decade, yet it remains unevenly distributed across the region. Overall, most studies originate from Indonesia, Thailand, Malaysia, Vietnam, and the Philippines, whereas Brunei, Cambodia, Laos, Myanmar, and East Timor are far less represented. Consequently, our understanding of contamination levels and ecological risks is biased toward better-studied coastlines and policy recommendations. Moreover, despite extensive variation in local conditions, a remarkably consistent pattern emerges in the types and polymers of microplastics detected in bivalve tissues. Fibers account for the preponderance of particles across diverse habitats from mangroves to open coastlines, often exceeding 60% of total microplastics in organisms, followed by fragments and films. Likewise, PE consistently comprises Southeast Asia's most significant polymer fraction in bivalves.

Brunei Darussalam's relatively small population and limited heavy industry appear to curtail overall MP loads in coastal bivalves. Indeed, Lee et al. (2022) reported only 0.43 – 7.20 particles/gram of MP in oyster tissue (*S. cucullata*) along Brunei's coast, with concentrations sharply declining offshore from the estuary near Bandar Seri Begawan. The particles were overwhelmingly fragments (~75%, mostly black polypropylene <50 µm) likely originating from household plastics (e.g., containers, lids). These results suggest that, although Brunei's overall MP contamination is low, localized hotspots occur near urban wastewater outlets. In particular, MPs in Brunei's estuaries are traced to urban runoff and insufficient waste treatment infrastructure (e.g., aging sewage systems), indicating a need to strengthen municipal waste management to prevent local contamination (Collard et al. 2024).

By contrast, Indonesia's enormous coastal population and industrial activity have driven much higher MP leakage into marine food webs. Indonesia produces an estimated 0.48–1.29 million tonnes/year of mismanaged plastic waste (Collard et al. 2024; Lestari and Trihadiningrum 2019), reflecting a plastic fraction of about 14% in solid waste and persistently limited waste-management capacity. Consequently, densely populated bays such as Jakarta Bay and Surabaya record extremely high MP sediment loads (Lestari and Trihadiningrum 2019). These plastics readily enter filter-feeders, for example, in East Java coastal waters, cockles (*A. granosa*) contained an average of 43 –52% fiber-type MPs (by count), matching the fiber-dominated profile of nearby sediments (Rahmatin et al. 2024). Such fibers are likely shed from synthetic fishing nets, ropes, and textile materials, implicating intensive fishing activities and urban wastewater as sources.

Malaysia's rapid economic growth and coastal industrialization have likewise increased plastic emissions. The country is among the world's top contributors to marine debris, with roughly 60% of Malaysia's mismanaged waste estimated to enter the oceans (World Bank), and tens of coastal monitoring studies reporting MP pollution. Urban and industrial hotspots show even higher levels, as surveys in Peninsular Malaysia link peaks in MP concentration to areas near fishing ports, estuarine outfalls, and tourist beaches (Foo et al. 2022). In one study, surface waters near fishing jetties were heavily enriched in MPs (mostly cellophane and polyester fragments) tied to tourism and fishing activity (Zainuddin et al. 2022). Similarly, gastropods from the urban Klang River estuary contained mostly black fiber MPs, traced to urban runoff (e.g., clothing fibers, vehicle tire wear) and lost fishing gear (Zaki et al. 2021). These findings underscore how Malaysia's industrial discharges and domestic waste (packaging, textiles) become microplastics in coastal food webs.

The Philippines faces even more acute waste challenges. As an archipelago with many informal settlements along waterways, municipal waste (including single-use plastics) often enters rivers untreated. Although relatively few studies have examined shellfish, the evidence is telling. Green mussels (*P. viridis*) and clams (*Venerupis* spp.) collected in Philippine estuaries have been found to contain microplastics, predominantly PA fibers, showing that MPs are entering the bivalve food chain (Yu et al. 2024). Notably, contamination levels in milkfish (bangus) and mollusks tend to be higher near urbanized bays and municipal landfill outlets (Sembiring et al. 2020; Similatan et al. 2023; Yu et al. 2024). However, the Philippine literature on MP in seafood is limited, with only a handful of studies to date. This research gap likely reflects resource constraints, but preliminary data implicate poor local waste disposal and proximity to urban centers in driving MP loads in bivalves.

Thailand has likewise acknowledged plastic pollution as a critical issue. Recent policy measures (e.g., plastic bans, fishery clean-up campaigns) signal official concern, yet MPs remain pervasive. Abandoned or "ghost" fishing gear is recognized as a key source of secondary microplastics in Thai waters, as in many ASEAN nations (Collard et al. 2024). Empirical studies confirm substantial ingestion by cultured shellfish. For instance, farmed green mussels (*P. viridis*) from the Phee Canal (east Thailand) contained an average of 6.10 - 8.40 particles/g, predominantly polyester fibers (Cherdsukjai et al. 2022). Likewise, wild *P. viridis* from Bandon Bay (Gulf of Thailand) contained 7.74 – 10.49 particles/g, mainly fibers of PP and PET (Chinfak et al. 2021). These figures reflect Thailand's intense seafood production and illustrate how local fishing and urban effluents contribute microplastics to shellfish. Compared to some neighbors, Thailand has more studies and institutional support, which has improved understanding of contamination patterns, but continuing challenges (e.g., marine litter removal and waste infrastructure) persist.

Vietnam's booming textile, manufacturing, and aquaculture sectors similarly fuel MP pollution (Dieu et al. 2024; Nam et al. 2024; Veettil et al. 2024). Clam surveys in Central Vietnam illustrate these impacts. Notably, Tran-Nguyen et al. (2023) reported 4.7–5.4 particles/g in hard clams (*M. lyrata*) and 2.2–2.4 particles/g in venus clams (*P. undulatus*) from coastal estuaries near Da Nang, all dominated by fibers. These clams' polymer mix (e.g. nylon, PET) likely reflects inputs from local textile and plastic industries. Notably, MP concentrations were higher at sites closer to industrial zones and dense population centers. Thus, in Vietnam, as elsewhere in Southeast Asia, rapid economic growth and lagging waste treatment combine to elevate MP levels in bivalve habitats.

In summary, country-by-country comparisons in Southeast Asia reveal that socioeconomic factors such as population density, waste-management capacity, fishing intensity, and industrial activity strongly correlate with microplastic contamination in bivalves. Brunei's sparse population and limited industry produce relatively low background MP levels, whereas nations with dense coastal populations and overwhelmed waste systems (Indonesia, Philippines, Vietnam) show the higher bivalve contamination. Furthermore, marine industries such as aquaculture and shipping introduce additional sources (e.g., synthetic ropes, "ghost" gears), particularly in countries like Thailand and Indonesia with large fisheries.

Ecotoxicological consequences and human health implications of microplastic contamination in bivalves

Biomagnification of microplastics and associated toxicants in aquatic food webs

MP ingested by filter-feeding bivalves can be transferred up the food chain to higher predators. Laboratory feeding trials have demonstrated this trophic transfer. For example, mussels (*Mytilus edulis*) exposed to polystyrene (PS) MPs and then fed to shore crabs (*Carcinus maenas*) accumulated MPs in crab tissues (gills, hepatopancreas, ovary and hemolymph) (Farrell and Nelson 2013), confirming transfer of MPs through a natural predator–prey interaction. Similarly, previous studies found that MP can move from prey to predator in marine food chains (Bellasi et al. 2020; Benson et al. 2022; Habumugisha et al. 2024; Saher et al. 2025). These studies imply that bivalves contaminated with MP may pass particles (and any adhered pollutants) to fish, crustaceans, and ultimately humans. However, field evidence for biomagnification (increasing concentration at higher trophic levels) remains inconclusive. A recent meta-analysis found clear bioaccumulation of MPs within trophic levels, but no consistent evidence of in situ biomagnification of MPs across the marine food web (Miller et al. 2020). In other words, while predators can accumulate MPs by eating contaminated prey, current field data do not show a systematic increase in MP concentration at higher trophic levels. Notably, Chinfak et al. (2024) have highlighted the need to investigate this directly: a Thai study on coastal bivalves noted that although current human MP intake from seafood appears low, food-web transfer of MPs "may pose significant human health concerns" and warrants investigation.

Bivalve-associated MPs also carry sorbed chemical pollutants, facilitating their trophic transfer. MPs have large surface areas that sorb metals, hydrophobic organics, and additives (Wang et al. 2021). For instance, microplastic fragments in tropical waters were found to carry flame retardants (hexabromocyclododecane–HBCD), polycyclic aromatic hydrocarbons (PAHs), and polybrominated diphenyl ethers (PBDEs). When bivalves ingest these contaminated particles, the pollutants can enter the food web along with the plastics (Chen et al. 2018; Rani et al. 2017). Moreover, bivalves themselves bioaccumulate traditional pollutants from water and sediment. For example, Thai cockles and clams contained cadmium up to 457 µg/kg and lead up to 151 µg/kg wet weight. Such heavy metals "frequently coexist in the environment" and are well known to bioaccumulate through food chains (Tanaviyutpakdee and Karnpanit 2023). Thus, trophic transfer of MPs from bivalves is likely accompanied by transfer of any co-contaminants they carry.

Microplastic exposure effects on bivalves: physiological, reproductive and immunological disruptions

Exposure to MPs can impair bivalve health on multiple fronts. Histopathological investigations report tissue damage in MP-exposed mollusks. For example, clams and oysters exposed in the laboratory to MP fibers and fragments often show gill irritation, lamellar thickening, and digestive gland lesions (indicative of physical abrasion and inflammation). A study on clam (M. meretrix) found that leachates from PE debris significantly inhibited clam growth, demonstrating physiological stress from plastic-associated chemicals (Ke et al. 2019). In general, MPs trapped in the feeding organs or gut can reduce filtration efficiency and feeding rates (as observed in other filter feeders) (Gonçalves et al. 2019; Rosa et al. 2018; Wang et al. 2023). Nonetheless, these stressors can collectively slow growth and energy acquisition in bivalves, undermining their health. At the cellular level, MPs elicit oxidative stress and immune challenges in bivalves. Laboratory exposures of the freshwater basket clam (*C. javanicus*) to microfibers (polyester) and PE fragments altered its antioxidant defenses, as glutathione-S-transferase and catalase activities increased under polyester fiber exposure (Esterhuizen et al. 2022). In addition, studies frequently report immunological effects, MP ingestion has been shown to provoke elevated stress biomarkers (e.g. superoxide dismutase, malondialdehyde) and histological inflammation in bivalves (Li et al. 2022; Teng et al. 2021; Wang et al. 2023; Zhou et al. 2022). In addition, reproductive outcomes can also be affected by MP exposure. Reports of marine mussels and oysters exposed to MPs include reduced gamete viability and larval deformities (Bringer et al. 2021; Capolupo et al. 2021; Tallec et al. 2018). For example, Bringer et al. (2020) documented decreased gonad development in mussels fed high-MP diets.

Human health risk assessment of microplastic ingestion via bivalve consumption

In Southeast Asia, bivalves are an essential dietary component, so microplastics in these organisms can be translated into human MP intake. Recent exposure assessments in the region estimate that typical consumers ingest 0.5 – 30 MP particles/day from bivalves. For instance, a survey of edible bivalves from Thai markets found an average of 0.46 MPs per gram of tissue, leading to an estimated adult intake of about 0.52 particles/day under standard consumption patterns (Chinfak et al. 2024). A separate Thai study detected up to ~4.3 MPs per individual in cockles and clams, corresponding to a worst-case exposure of ~27.5 particles/person/day (Tanaviyutpakdee and Karnpanit 2023). Although the absolute numbers (often <1 particle/g) are modest, they represent a direct route of plastic ingestion by humans because bivalves are eaten whole. Indeed, shellfish consumption typically transfers all ingested MPs to consumers, unlike in fish, where gutting removes some particles.

Beyond the plastics, bivalves concentrate associated toxicants, raising chemical exposure concerns. The same Thai clams and cockles contained lead (Pb) and cadmium (Cd) at tens to hundreds of µg/kg wet weight (Tanaviyutpakdee and Karnpanit 2023). Calculated dietary exposures to Pb and Cd from these bivalves were generally below safety thresholds for adults. However, a high-cockle scenario posed a potential risk for children due to Cd. While specific data on phthalates and bisphenols in Southeast Asian bivalves are scarce, plastic particles often carry such additives. Previous studies have found endocrine-disruptors like Bisphenol A (BPA) associated with marine MPs, and MPs can leach plasticizers into tissues (Flaws et al. 2020; Saha et al. 2024; Ullah et al. 2023). The types of plastics identified (e.g., PET fibers) suggest possible co-exposure to typical additive chemicals. For example, plastic debris in coastal waters has been shown to harbor PAHs and flame retardants (Tang et al. 2018). Thus, human ingestion of MP-contaminated bivalves may include a considerable amount of pollutants as metals, hydrophobic organics, and plastic additives, although quantitative risk estimates remain uncertain.

Strategies for mitigation and source reduction of microplastic pollution

Mitigating microplastic contamination in Southeast Asian bivalves requires regional policy action and technical interventions targeting plastic sources. At the policy level, ASEAN countries have adopted collaborative frameworks to curb plastic pollution. The ASEAN Regional Action Plan on Combating Marine Debris (2021–2025) explicitly addresses marine plastic waste and aims to build capacity for waste management across member states (ASEAN Secretariat 2021). Complementary initiatives include the ASEAN-Norway project (launched in 2019) on local capacity building for plastic reduction, and the ASEAN+3 Marine Plastic Debris and Japan's CounterMEASURE projects on Asia-Pacific marine litter (UNEP 2017). These efforts encourage integrated waste management and intergovernmental cooperation. Nationally, several Southeast Asian countries have implemented source-reduction policies. For instance, Thailand banned microbeads in cosmetics in 2020 as a measure against primary MP (Ng et al. 2023)and multiple nations (Vietnam, Indonesia, Malaysia, etc.) have enacted single-use plastic bans or levies (Fauziah et al. 2021). These regulatory actions, along with community-led cleanups and awareness campaigns, aim to reduce the flow of plastic waste into aquatic environments.

On the technical front, practical solutions can limit microplastic release and remove particles from water. Substituting conventional plastics with biodegradable alternatives (e.g., PLA, PHA) and using natural fibers can cut future MP inputs. However, biodegradable plastics are not a panacea as many are only partially biodegradable and may still fragment or release additives under real-world conditions (Chen et al. 2021). Therefore, material substitution must be coupled with improved waste management. In aquaculture and wastewater systems, filtration provides a direct means to capture MPs. Modern wastewater treatment plants (especially those with tertiary treatment like membrane or sand filtration) can remove most MP (Liu et al. 2021; Sun et al. 2019). Techniques such as coagulation/flocculation and advanced sorbents (e.g. activated carbon, biochar) also show high MP removal in trials (Ma et al. 2019; Shen et al. 2022; Wang et al. 2020). While most such technologies remain at pilot scale, they suggest that retrofitting treatment facilities and aquaculture effluents with fine filters could substantially reduce MPs entering coastal waters. On the production side, improving garment filtration (to trap laundry fibers) and limiting pellet spillage in industry are additional source controls.

Challenges and limitations

Research on MPs in bivalves across Asia has provided significant insights into the extent of contamination and associated risks to marine ecosystems and human health. However, several challenges and limitations hinder a comprehensive understanding and practical mitigation efforts.

Limited geographical coverage and sampling bias

Despite the increasing number of studies, geographic coverage remains uneven, with certain regions receiving more attention than others. For instance, studies in Brunei and some coastal areas in Indonesia are limited to localized sites, restricting the generalizability of findings. In Brunei, the focus has been primarily on estuarine systems, leaving open-shore environments underexplored. Similarly, research efforts in the Philippines and Thailand have been concentrated in specific bays, aquaculture regions, or urbanized coastal zones. In contrast, remote and less industrialized regions still need to be studied. This uneven spatial distribution creates sampling bias, making assessing the accurate scale of MP contamination across diverse habitats difficult. Moreover, studies often rely on opportunistic sampling rather than standardized, long-term monitoring programs. Seasonal variations, tidal movements, and anthropogenic activities such as fishing and tourism significantly influence MP distribution, but these temporal aspects are rarely accounted for in short-term studies.

Variability in methodological approaches

Field investigation and monitoring are crucial in understanding the level of contamination of microplastics ingested by bivalves. However, studies use different methods to analyze microplastics. To this day, the protocol uses a digestive method with different solutions and concentrations. Lack of standardization affects analysis results, such as underestimating or overestimating the findings and failing to compare results with other research in the same region or globally. On the other hand, polymer identification is another area of concern. While studies in Malaysia, Thailand, and Vietnam have successfully identified dominant polymers, particularly in Brunei and parts of Indonesia, relying solely on morphological classifications (e.g., fibers, fragments, films). Such limitations prevent a comprehensive understanding of polymer-specific sources, environmental behavior, and degradation pathways of MPs.

Sample origin and bias in market-based specimens

Although most samples were collected in the wild, the accurate information on the origin of bivalve samples obtained from markets remains unclear (Phuong et al. 2018). According to the global trend of marine bivalve production, many bivalves come from Southeast Asia and are exported worldwide (Nair 2001;

Odeyemi et al. 2023; Wells et al. 2021). This distribution is expected to cause bias in the sampling site origin for market specimens. Therefore, tracking the origin of market samples is critical, as the concentration of microplastics in the environment varies from region to region. As mentioned, a relatively high ingestion rate occurs in bivalves sampled near areas with intensive human activity (Li et al. 2022; Reinfelder et al. 1997). This kind of information is directly related to the amount of microplastics consumed by humans. Apart from the limitations on market sample origin, two studies proposed depuration processes to reduce microplastic concentration in bivalves before human consumption (Birnstiel et al. 2019; Van Cauwenberghe and Janssen 2014). Moreover, Kazour and Amara (2020) used a cage technique after depuration to monitor contamination levels in native bivalves. This technique could minimize microplastic intake through bivalves and protect native bivalves in the wild.

Focus on specific bivalve species and ecosystems

Most studies have focused on commercially important bivalves, such as *P. viridis* (green mussels), *A. granosa* (blood cockles), and *C. gigas* (oysters). While these species serve as bioindicators and provide insights into human exposure risks, other ecologically significant bivalves, including species from coral reef ecosystems, still need to be explored. For example, Vietnamese studies have expanded research into reef-associated bivalves, but similar efforts still need to be made in other regions (Le et al. 2024). Furthermore, research efforts are often limited to ecosystems such as mangroves, estuaries, and aquaculture sites, neglecting offshore and deep-sea environments. This narrow focus restricts understanding of how MPs are distributed across diverse habitats and trophic levels.

Insufficient longitudinal and large-scale monitoring

Most existing studies are cross-sectional, providing only a snapshot of MP contamination. Long-term monitoring programs that account for temporal trends and seasonal variations are rare. For instance, MP levels are influenced by seasonal riverine inputs, yet systematic studies tracking these changes over time are limited (Wong-Wah-Chung et al. 2024). Without longitudinal data, it becomes challenging to assess the effectiveness of mitigation measures, predict future trends, or evaluate the impact of regulatory policies on plastic pollution.

Gaps in human health and ecotoxicological assessments

While many studies have quantified MP contamination in bivalves, research on the implications for human health and marine organisms remains limited. Only a study in Thailand has attempted to estimate MPs' EAI through seafood consumption (Hongsawat et al. 2024). However, the long-term health effects of MP ingestion, bioaccumulation, and potential chemical toxicity are poorly understood. In addition, there is limited investigation into the trophic transfer of MPs through the food web, particularly in aquaculture-dominated regions like Thailand, Indonesia, and the Philippines. Similarly, ecotoxicological studies exploring the physiological and behavioral impacts of MPs on bivalves are sparse. For example, shell deformities in *P. viridis* in Malaysia has been linked to pollution (Yap et al. 2023), yet the direct role of MPs remains unclear. Understanding the synergistic effects of MPs with other stressors, such as heavy metals and organic pollutants, is critical for assessing their overall ecological impact (Cao et al. 2021; Khalid et al. 2021).

Socioeconomic and policy-related limitations

Microplastic pollution in bivalves is closely tied to anthropogenic activities, including poor waste management, plastic usage, and aquaculture practices (Chen et al. 2021; Khanjani et al. 2023; Zhou et al. 2021). However, addressing these issues requires coordinated policies, infrastructure improvements, and public awareness. In many Asian countries, particularly Indonesia and the Philippines, inadequate waste disposal systems contribute to high plastic pollution levels (Akenji et al. 2020; Braaten et al. 2021; Johannes et al. 2021; Lestari and Trihadiningrum 2019), yet research linking socioeconomic factors with MP contamination remains limited. Furthermore, despite growing evidence of MP contamination, enforcing regulations on plastic production, waste disposal, and aquaculture practices still needs to be consistent across the region. For instance, while Thailand and Malaysia have made strides in monitoring seafood safety (Albasri et al. 2024; Albasri et al. 2023; Rauf et al. 2024), similar initiatives still need to be developed in Brunei and some parts of Vietnam.

Future directions

Based on the challenges and limitations identified in previous sections, several future research directions can be proposed to address critical gaps in the study of microplastics in bivalves and their implications for ecosystems and human health.

Effects of microplastics on bioaccumulation of hazardous pollutants and additives by bivalves

As discussed earlier, there remains a need for more consensus regarding the role of MPs in delivering hazardous substances, such as heavy metals and organic pollutants, into bivalves. This discrepancy arises from inconsistencies in study design, including species selection, microplastic size, type, dosage, and exposure duration. Therefore, future studies should focus on field-based observations combined with controlled simulated experiments to evaluate the role of microplastics in bioaccumulating pollutants. Efforts should include standardized methodologies to determine how microplastics enhance the uptake of hazardous pollutants, considering the implications for food safety and human health.

Assessing potential risks to human health from microplastic-contaminated bivalves

Microplastics pose significant risks to human health due to their chemical constituents, such as BPA, phthalates, and persistent organic pollutants (POPs) (Campanale et al. 2020; Godswill and Godspel 2019; Okoye et al. 2022). These hazardous substances may bioaccumulate in bivalves and transfer to humans through consumption (Ochoa-Esteso et al. 2024; Rios-Fuster et al. 2022). Future research should focus on comprehensive food safety risk assessments that evaluate the concentrations of microplastic constituents and adsorbed pollutants in edible bivalves. Longitudinal studies are needed to establish thresholds for safe human consumption and assess the cumulative risks of prolonged microplastic exposure.

Given the potential health risks of consuming microplastic-contaminated bivalves, future studies should explore effective mitigation techniques such as depuration processes. Depuration has shown promise in reducing microplastic concentrations in bivalves before human consumption (Ali et al. 2024; Pedersen et al. 2020; Toussaint et al. 2019). Additionally, the use of cage techniques for monitoring contamination levels in native bivalves offers a proactive approach to minimize human exposure. Field-based experiments should further evaluate the feasibility and effectiveness of these methods under varying environmental conditions.

Laboratory-scale vs. field-scale studies

While most studies have been conducted under laboratory conditions, they may only partially represent real-world environmental complexities. Laboratory experiments often demonstrate adverse effects on bivalves; however, extrapolating these results to natural conditions is challenging. To bridge this gap, future research should prioritize field-scale studies that monitor bivalve responses to microplastic exposure over extended periods in diverse habitats. Such studies will provide robust and ecologically relevant data that complement laboratory findings.

Exploring the impact of nano-plastics

The size-dependent toxicity of microplastics has been well documented, with nanoplastics (<100 nm) exhibiting higher toxicity than larger particles due to their ability to penetrate biological barriers (Banerjee and Shelver 2021; Sendra et al. 2021; Zhao et al. 2023). For example, nanoplastics have been shown to penetrate hepatopancreas cells of juvenile East Asian river prawns (*Macrobrachium nipponense*) more readily than microplastics, potentially delivering adsorbed pollutants directly into tissues (Li et al. 2024).

In particular, conventional spectroscopic methods lack the spatial resolution to detect nano-sized plastics: FTIR reliably identifies particles only down to ~10 µm, and even Raman microscopy typically resolves to ~1 µm (Awolesi et al. 2023). Moreover, nanoplastics aggregate during harsh sample digestion (e.g., acid treatments) or adhere to matrix components, producing larger pseudo-particles and hampering accurate sizing (Correia and Loeschner 2018). Nevertheless, recent methodological advances offer a path forward. For example, asymmetric flow field-flow fractionation coupled with multi-angle light scattering (AF4–MALS) has been shown to separate and size nanoplastics in biota samples. Correia et al. (2018) successfully recovered 100 nm polystyrene beads from digested fish tissue using AF4–MALS. Similarly, enhanced spectroscopic techniques can push detection toward the nanoscale (Cowger et al. 2024). Surface-enhanced Raman spectroscopy (SERS) can identify sub-micron plastics (e.g., ~350 nm polystyrene) by amplifying Raman signals (Mikac et al. 2023). Emerging imaging methods such as hyperspectral infrared cameras can rapidly scan filters, although current systems are tuned to >250 µm particles and must be adapted for finer resolution (Faltynkova et al. 2021). Adopting such techniques, along with strict clean-lab practices and method validation, would allow researchers in the region to begin quantifying the nano-fraction. Incorporating nanoplastics is vital because size strongly influences biological effects. Unlike larger particles, nanoplastics can cross cell membranes and potentially translocate within the organism(Liu et al. 2021). In filter-feeding bivalves (mussels, oysters, clams), which accumulate plastics from seawater and are key seafood species, this could mean enhanced bioaccumulation and novel toxic responses at the nanoscale. Thus, developing feasible nano-analytical protocols in Southeast Asia is essential for a complete size-based risk assessment in bivalves.

Standardization of methodologies

The need for standardized protocols for the digestion and identification of microplastics remains a significant limitation in the field. Various digestion solutions (e.g., KOH, H_2O_2, HNO_3) and concentrations have been used, leading to inconsistent results. Potassium hydroxide (10% KOH) has been identified as the most efficient and least deleterious reagent for digesting bivalve tissues without damaging polymers (Fraissinet et al. 2021; Zhong et al. 2022; Zhu and Wang 2020). Future studies should adopt this methodology to ensure comparability across research. Furthermore, chemical identification methods such as FTIR and Raman spectroscopy should be employed alongside microscopy to improve accuracy in microplastic characterization (Andoh et al. 2023; Chen et al. 2020; Shim et al. 2017; Xu et al. 2019).

Variability in measurement units for reporting microplastic concentrations (e.g., microplastics/gram dry weight, wet weight, or individual) has hindered study comparability. To address this issue, future research should adopt standardized reporting units, such as microplastics per gram wet weight (MPs/g ww) and microplastics per individual (MPs/ind). Consistent units will allow for more reliable comparisons and meta-analyses across studies. Reporting on a wet-weight basis aligns most closely with human and wildlife exposure (since organisms are consumed on a wet basis), and is directly comparable to contaminant limits expressed per mass. Wet-weight concentrations also avoid the ambiguity of moisture variability; where samples are reported on a wet basis, the moisture content or wet-to-dry ratio should be provided so that dry-weight conversions are possible (ITRC 2024; Zarus et al. 2021; Zhang et al. 2022). In fact, Ding et al. (2022) explicitly converted all reported bivalve MP counts to a mass-based unit (items per g wet weight) for their global assessment. Similarly, Zarus et al. (2021) highlight that wet-weight metrics are “more representative of what people eat” and that wet-weight concentrations are roughly one-tenth of dry-weight values for fish.

Applying advanced techniques in detecting and analyzing microplastics

In Southeast Asia, studies of microplastic ingestion in bivalves commonly use visual (morphological) sorting and fundamental ATR-FTIR analysis, which can limit polymer identification accuracy. For example, Abd Rahman et al. (2024)’s survey counted particles in clams by color and shape and then applied FTIR only to determine broad polymer functional groups in Malaysia, and Ta et al. (2022)’s investigation similarly used micro-FTIR to confirm that polypropylene, polyethylene, polyester and other polymers dominated mussel contamination. However, these simple approaches may misclassify chemically similar plastics or miss tiny, degraded particles; a recent regional review noted that many Southeast Asian studies still do not fully assign polymer types (often for resource reasons). Future research in the region should adopt more advanced and standardized analytical methods to address these gaps. In particular, Raman spectroscopy (including micro-Raman) can resolve micron-scale plastics and pigments with high chemical specificity (Karami et al. 2017; Matupang et al. 2023), while pyrolysis–GC/MS provides unique thermal "fingerprints" of polymers (e.g., characteristic pyrolysis products of PVC, PP, PE, PET, PAs) (Noor et al. 2024). Moreover, coupling FTIR analysis with robust spectral libraries or automated matching greatly improves polymer identification confidence (Cowger et al. 2024). Notably, experts emphasize that these techniques must be coupled with harmonized protocols (e.g., consistent sample digestion and spectral criteria) to ensure data comparability across studies.

Development of microplastic databases

Less than 1% of marine and freshwater bivalve species have been studied for microplastic contamination, focusing on economically important species such as mussels and oysters (Bom and Sá 2021). Future research should expand to include underrepresented species from diverse ecosystems, including sandy beaches, estuaries, and freshwater environments. Species from families such as Unionidae, Sphaeriidae, and Cyrenidae (freshwater) and Veneridae, Donacidae, and Tellinidae (marine) should be targeted to provide a broader ecological perspective (Bom and Sá 2021). This will facilitate a better understanding of microplastic impacts across ecosystems and trophic levels.

Establishing global databases similar to existing marine biodiversity platforms (e.g., FishBase and Matcher.org) is recommended to improve the identification and tracking of microplastics. These databases would catalog microplastic types, sizes, and associated contaminants, enabling researchers to access standardized information for cross-comparison. Such tools would enhance the accuracy of microplastic identification and foster global collaboration in addressing microplastic pollution.

Conclusion

This study shows that bivalves, particularly in areas with high human activity, collect different amounts of MPs in Southeast Asia. Fibers and fragments are the most common types, and PE, PP, and PET are the most common polymers. The widespread presence of MPs in bivalves highlights significant environmental concerns and raises potential risks to human health through seafood consumption. However, methodological inconsistencies in MP detection and analysis across studies limit comparability, requiring standardized approaches to ensure robust and reliable assessments. Moving forward, coordinated efforts to address MP pollution are crucial. This includes improved waste management systems, public awareness programs, and further research to understand the long-term effects of MP contamination on marine ecosystems and human health. Overall, this research provides valuable insights to guide policies and interventions to mitigate microplastics' impacts in Southeast Asia's marine environments.

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