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RESEARCH

Ingested microplastics: a comparative analysis of contaminated shellfish from two sites in the Makassar Strait

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Abstract Marine plastic debris, particularly microplastics (MPs), is an urgent and significant threat to the global marine environment. The emergence of MPs in the marine environment and their potential presence in human-consumed seafood necessitates immediate investigation. In light of this, a study was conducted on the occurrence of MPs in shellfish collected from two locations in Makassar Strait with distinct oceanographic conditions. Three commonly consumed shellfish species (*Perna viridis*, *Meretrix meretrix*, and *Mactra chinensis*) were collected by fishermen and examined for microplastic contamination, with a total sample size of 170 individuals. Microplastics were extracted from the soft tissue of the bivalves using the alkaline digestion method. The results revealed a significantly higher number of microplastics ingested by P. *viridis* and M. *chinensis* in samples collected from the Sanrobengi Islands (14.64 MPs/individual and 2.29 MPs/individual, respectively), compared to the P. *viridis* and M. *meretrix* from Mandalle coastal area (0.70 MPs/individual and 1.00 MPs/individual, respectively).

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The predominant microplastic form detected was blue microfibres. A prevalence of MP contamination between 58 and 100% and the results of Fourier Transform Infrared Spectroscopy (FTIR) analysis indicated that polystyrene was the dominant polymer present, threatening the welfare of the bivalve mollusks and posing potential health risks to seafood consumers. The results emphasize the urgent need for pollution control measures such as reducing plastic waste discharges and improving waste management systems. In addition, a comprehensive study focusing on the long-term ecological and health effects of microplastic pollution is necessary to guide future policy interventions.

Keywords Shellfish · Microplastics · Sanrobengi · Mandalle · South Sulawesi

Introduction

The ocean encompasses most of the world's economic zones and is the primary source of edible protein and financial income for human populations. Massive increases in the production of various plastic applications worldwide over the last 60 years have resulted in excessive marine plastic debris. This is now recognized as a serious threat to the marine environment. Marine litter is human-generated waste deliberately or accidentally discharged into the sea and ocean. A significant proportion of marine debris, estimated at 60–80%, is plastic (O'Brien & Thompson, 2010), which dominates beach litter in terms of the number of items (Derraik, 2002). Furthermore, approximately 80% of plastics in the ocean originate from land-based sources, including beach litter. However, beach litter can also originate from the sea due to fishing, recreational activities, and shipping (Andrady, 2011). Microsized particles and fibers of 5 mm or less (microplastics: MPs) are one of the most common types of litter in the marine environment, with an estimated 5.35 trillion particles floating on the sea and ocean surfaces, equivalent to 265,000 tonnes (Eriksen et al., 2014).

As the main inflow of the Indonesian Throughflow (ITF), the Makassar Strait carries marine plastic debris from the Pacific Ocean to the Indian Ocean. The debris can end up in the local waters and beaches of South Sulawesi (Purba et al., 2021) and can remain in the Makassar waters for longer periods of time throughout the year (Kisnarti et al., 2024). A recent study by Yuan et al. (2023) found that the Makassar Strait has a higher abundance of MPs than the Northwest Pacific, making it more vulnerable to plastic pollution. They also point out that in addition to ocean circulation, land-based sources of microplastics from river runoff are considered important sources of microplastics in the Makassar Strait.

More than 52 polymers are produced globally (Takada & Karapanagioti, 2019). However, generally, only six of them dominated plastic applications products: polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), polyurethane (PU), and polyethylene terephthalates (PET) (GESMP, 2019). Today's most commonly used plastic polymers are highly resistant to the degradation process. Coupled with adsorbed complex persistent pollutants, marine plastic debris is a risk to the environment and human health (Galloway, 2015).

All marine organisms face risks of interacting with microplastics through several mechanisms, such as adhesion, absorption, ventilation, and ingestion, including bivalves in intertidal zones (Kühn et al., 2017). Plastic ingestion occurs across taxa within different trophic levels, including marine mammals, fish, invertebrates, and fish-eating birds (Gall & Thompson, 2015). MPs are ingested by a large variety of farmed and wild species, including fish (Lusher et al., 2013; de Miranda & de Carvalho-Souza, 2016; Rochman et al., 2015) and various invertebrate groups, such as crabs (Watts et al., 2016), bivalves (Farrell & Nelson, 2013; Fernández Severini et al., 2019; Li et al., 2016; Mathalon & Hill, 2014; Naji et al., 2018; Santana et al., 2016; Van Cauwenberghe & Janssen, 2014) and shrimps (Devriese et al., 2015) and scleractinian corals (Hall et al., 2015). Since plastic marine debris is ubiquitous, there is a growing global concern about MPs, as they have been shown to enter marine food webs (EFSA, 2016).

Studies have shown that microplastics are present in large quantities in shellfish, and estimates suggest that seafood consumers can ingest thousands of microplastic particles every year, contributing significantly to human exposure (Danopoulos et al., 2020). The presence of microplastics in shellfish is a matter of physical contamination and a vector of harmful substances (Yang et al., 2015). Microplastics can absorb and concentrate toxic pollutants from surrounding seawater, including heavy metals and persistent organic pollutants (Batel et al., 2016; Oliva-Hernández et al., 2021). When shellfish consume these microplastics, they can accidentally consume these harmful pollutants and then transfer them to humans when consumed. This raises critical concerns about seafood safety, especially in regions where shellfish consumption is prevalent. In addition, proof of the abundance of MPs in shellfish will help raise awareness of MPs' bioavailability to marine life and the potential risks and relevance of this emerging contaminant to seafood consumers.

This study aims to evaluate the occurrence of MPs in bivalve mollusks from a small island, Sanrobengi, in Takalar District and compare it with those collected from the coastal area of Mandalle in Pangkajene Kepulauan (Pangkep) District, South Sulawesi Province, Indonesia. Both sampling sites are located in the Makassar Strait and are separated by a distance of 100 km. The oceanographic characteristics of both sites are mainly influenced by water circulation. The coastal area of Mandalle is solely influenced by the massive water mass flow from the South Pacific Ocean into the Makassar Strait, while Sanrobengi Island also receives water mass flow from the Flores Sea, which has been influenced to some extent by the Indian Ocean (Gordon, 2005). The water circulation patterns at both sites undoubtedly influence the occurrence of MPs in bivalve mollusks from these areas.

Materials and methods

Samples of the marine bivalves *Perna viridis* (Mytillidae) and *Mactra chinensis* (Mactridae) were collected from fishers at Sanrobengi Island in Takalar District (5° 19′ 21.238″ S 119° 20′ 35.178″ E) in July 2019, whereas the other *P. viridis* and *Meretrix meretrix* (Veneridae) samples were collected from fishers in the coastal area at Mandalle (4° 35′ 0.13″ S 119° 35′ 16.80″ E) in Pangkep District in August 2019 (Fig. 1). In Sanrobengi, P. *viridis* were collected from hard substrates like wooden bridge and rocks, meanwhile, at Mandalle they were mostly collected from seaweed cultivation ropes and buoys. Both M. *meretrix* and M. *chinensis* were taken from the surrounding sediment at both locations. The P. *viridis* mussel is a fisheries commodity commonly consumed by Indonesians as a cheap protein source. Genus *Mactra* is a mussel with characteristics of a shell in equivalent form, oval or trigonal transverse elongated with a maximum length of 5 cm. It commonly occurs in sand-muddy habitats (Carpenter & De Angelis, 2016). *Meretrix* spp.'s morphological characteristics are shell form resembling a triangle with an external pattern of sleek texture dominated with brown, white, and dark brown colors, with a maximum length of 8 cm, and a preferred habitat with fine sand (Anderson, 2014).

Following collection, all samples were cleaned in seawater and then rinsed in distilled water. After collection, all samples were placed immediately in sealed icebox coolers with ice packs to maintain low temperatures, preventing any degradation or contamination. The refrigerators were transported to the laboratory within 24 h, and the samples were promptly processed to ensure the integrity of the collected materials. Each refrigerator was labeled with sample details, including collection location, date, and time. Morphometric data were taken for whole bivalves to assess body size and total living tissue within each animal. The shell's total weight and tissue ($\pm$0.1 g) were recorded, and the shell's maximum length ($\pm$0.1 mm) was measured along the anterior–posterior axis using calipers. Collected living tissue was placed in clean 150 ml HDPE bottles and submerged in 20% potassium hydroxide (KOH), equaling three times the tissue volume (Lusher et al., 2017a). Samples of tissues in KOH were left for 2 weeks at room temperature to allow complete digestion of organic materials. The liquefied remains of the digested tissue samples were then examined for MPs in a clean petri dish using a stereo microscope (Euromex-SB1903-Si). To ensure quality control during the extraction and measurement of microplastics, all equipment and workspaces were thoroughly cleaned with filtered distilled water before and after use to prevent contamination. Each batch contained procedural blanks to monitor possible air pollution, and only those with fewer than 5 fibers or particles were considered reliable. In addition, two independent analysts conducted a double-blind analysis to verify the identification and classification of microplastics based on morphological characteristics. The morphological characteristics of MPs were classified according to the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESMP, 2019). Polymer identification

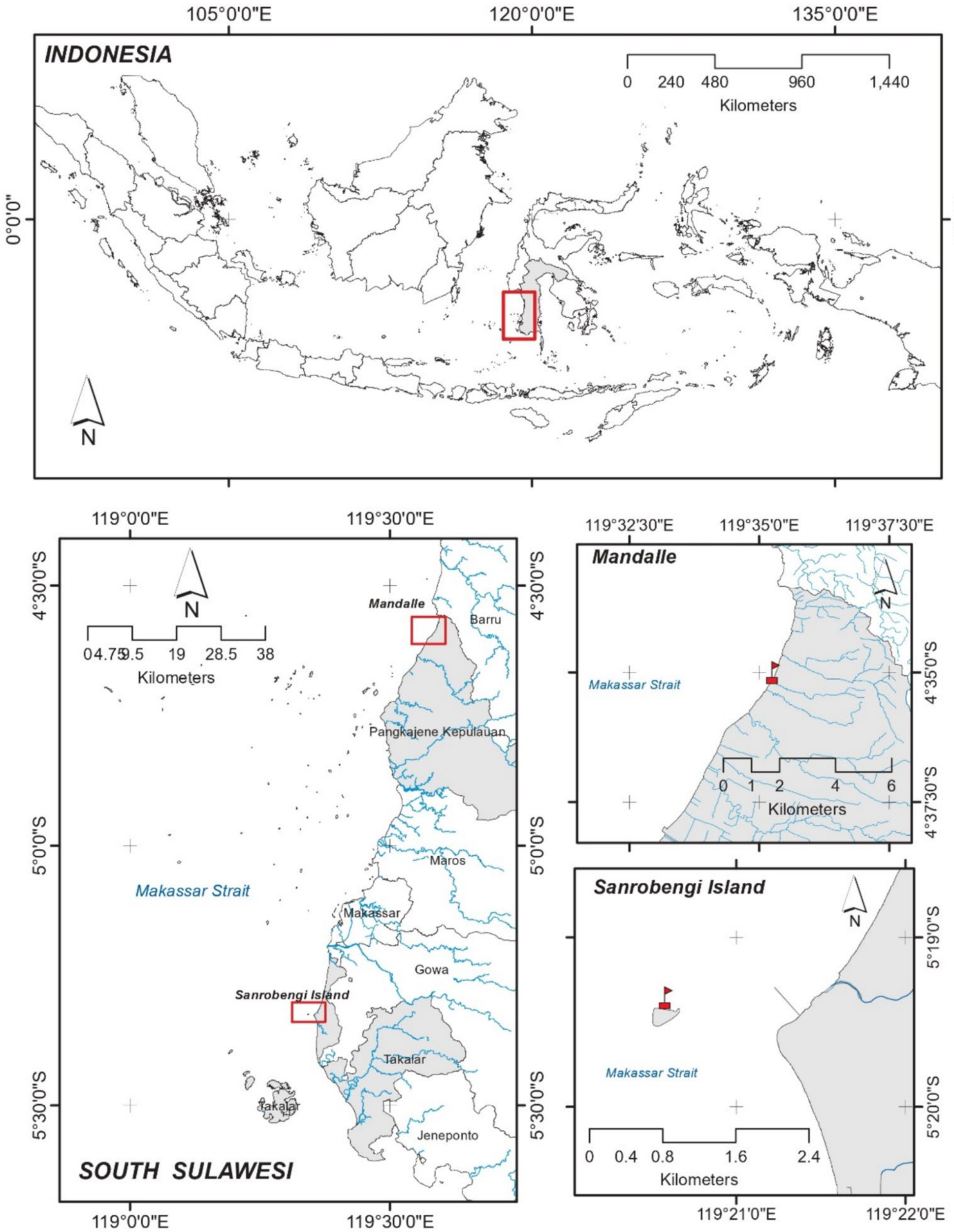

Fig. 1 Sampling locations at Sanrobengi Island and Mandalle coastal area in the Makassar Strait, South Sulawesi

of MPs was conducted using FTIR Shimadzu Prestice-21. Polymers were identified through spectrum analysis based on absorbance bands in wave numbers displayed per cm^{-1} indicators of their functional groups, for example, N–H; CH_2^-; CH_3; C = O (Dachriyanus, 2004; Jung et al., 2018). Bivalve species identification followed the National Introduced Marine Pest Information System (Anderson, 2014), and the World Register of Marine Species (WoRMS, 2020). All mussel species investigated in the current study are widely distributed in areas of the Indo-Pacific, Japan, India, Malaysia, the South China Sea, Thailand, the Philippines, Indonesia, and Papua New Guinea.

Results

From 170 individual mussels collected, samples were divided into four size categories based on their total length (Fig. 2). *Perna viridis* bivalves from Sanrobengi Island were longer (3.2–8.7 cm) than their counterparts collected in the Mandalle coastal area (4.3–6.5 cm). At Sanrobengi, M. *chinensis* measurements ranged from 2.1 to 2.6 cm, while M. *meretrix* from Mandalle had a total length range of 3.9 to 5.8 cm. From the total body weight (with shells) measured, P. *viridis* specimens from Sanrobengi (5.73–13.26 g) were also heavier than those collected from Mandalle (5.55–5.8 g).

Microscopic analysis of specimens from Sanrobengi revealed an MP size range of 0.181 to 5 mm in P. *viridis* and 0.084 to 5 mm in M. *chinensis*. In specimens from Mandalle, P. *viridis* size range was 0.565 to 4.98 mm, and M. *meretrix* size range was 0.142 to 3.02 mm. A greater quantity of samples contaminated with MPs was detected in both mussel species from Sanrobengi Island than in the corresponding species from the Mandalle coastal area (Table 1). Mann–Whitney non-parametric analysis revealed a highly significant difference between sites ($p < 0.0001$) in MP abundance in P. *viridis*, with individuals from Sanrobengi exhibiting 20 times more MP items/individual compared to the same species from Mandalle. Although relatively smaller in size, M. *chinensis* from Sanrobengi also showed a significant difference ($p < 0.005$) in MP abundance compared to M. *meretrix* from Mandalle (Fig. 3). Statistical analysis using a non-parametric Spearman correlation also showed no correlation in any of the species examined between bivalves' total lengths and MP abundance.

There were diverse colors and three forms identified in microplastic particles in this study, with the predominant color being blue > transparent > black > red, and more than 90% being in line form (Fig. 4).

The analysis of the total 35 suspected particles, using FTIR Shimadzu Prestice-21, revealed that polystyrene (PS) was the predominant polymer (40%), followed by nylon (NYL), polyurethane (PUR), and polypropylene (PP) (Fig. 5).

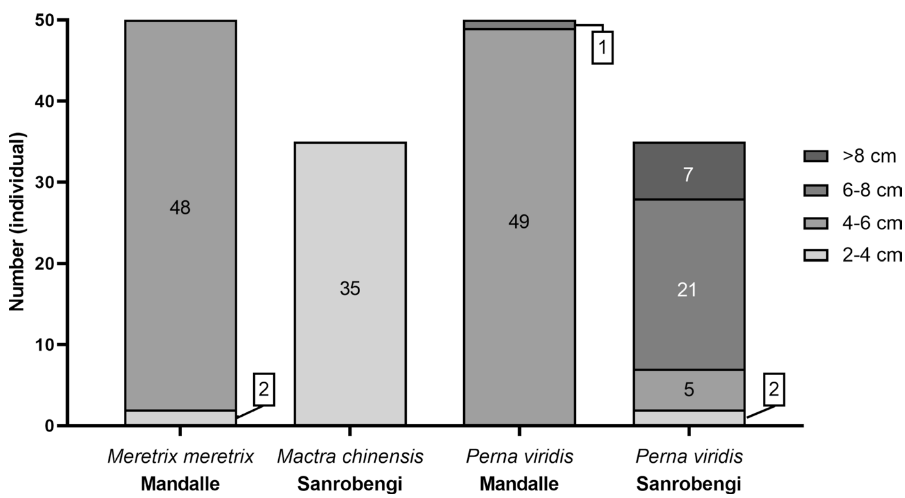

Fig. 2 Distribution of mussel individual numbers by total length class

Table 1 Occurrence, distribution, and percentage of mussel samples contaminated with marine plastics (MPs)

Location	Species	Individual with MPs	# MPs observed	% samples contaminated with MPs
Mandalle	*Perna viridis* ($n = 50$)	29	35	58
	Meretrix meretrix ($n = 50$)	35	50	70
Sanrobengi	*Perna viridis* ($n = 35$)	35	512	100
	Mactra chinensis ($n = 35$)	27	74	77.14

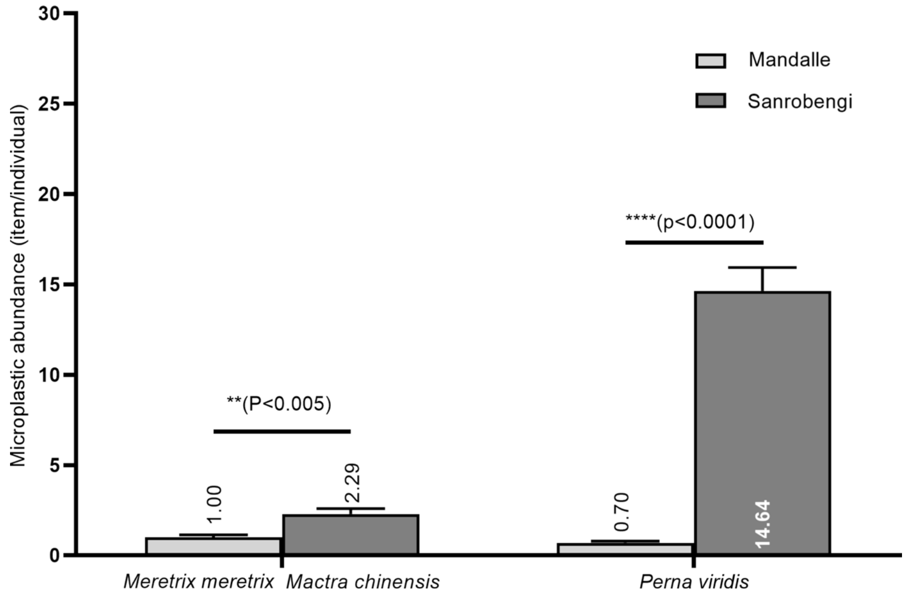

Fig. 3 Differences in MP abundance in both mussel samples (values are means ± SE)

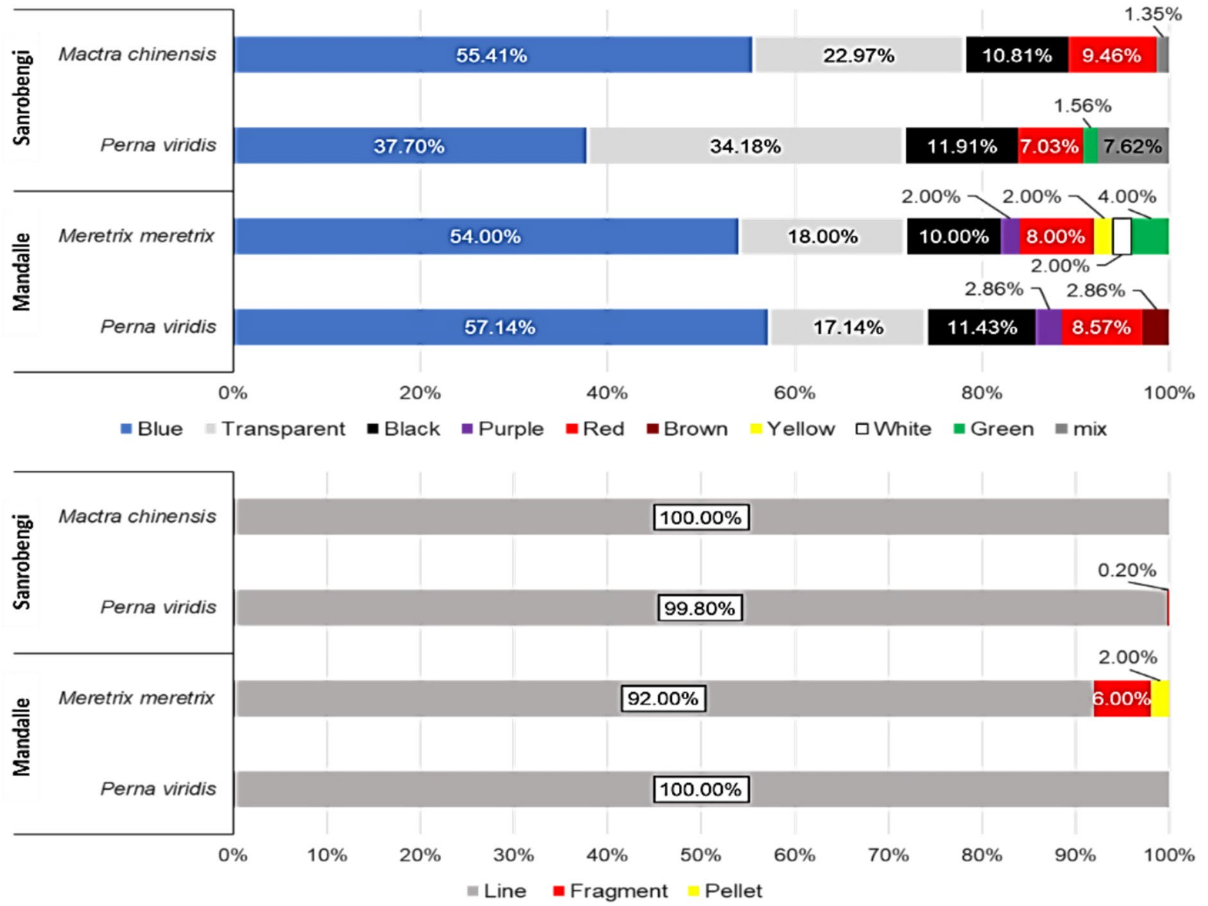

Fig. 4 Distribution of MPs colors (upper) and forms (lower) in all mussel samples

Representatives of MP forms associated with different polymer types are depicted in Fig. 6.

Discussion

Aquatic animal food consumption has been shown to represent a significant pathway for human microplastic exposure, as indicated by global aquatic animal food intake, which represents around 20% of all protein consumed (FAO, 2024). Risks associated with small MP fragments come from the material itself, as well as from chemical pollutants absorbed from the surrounding water. However, the hazards associated with the complex mixing of plastic and accumulated pollutants are mainly unknown.

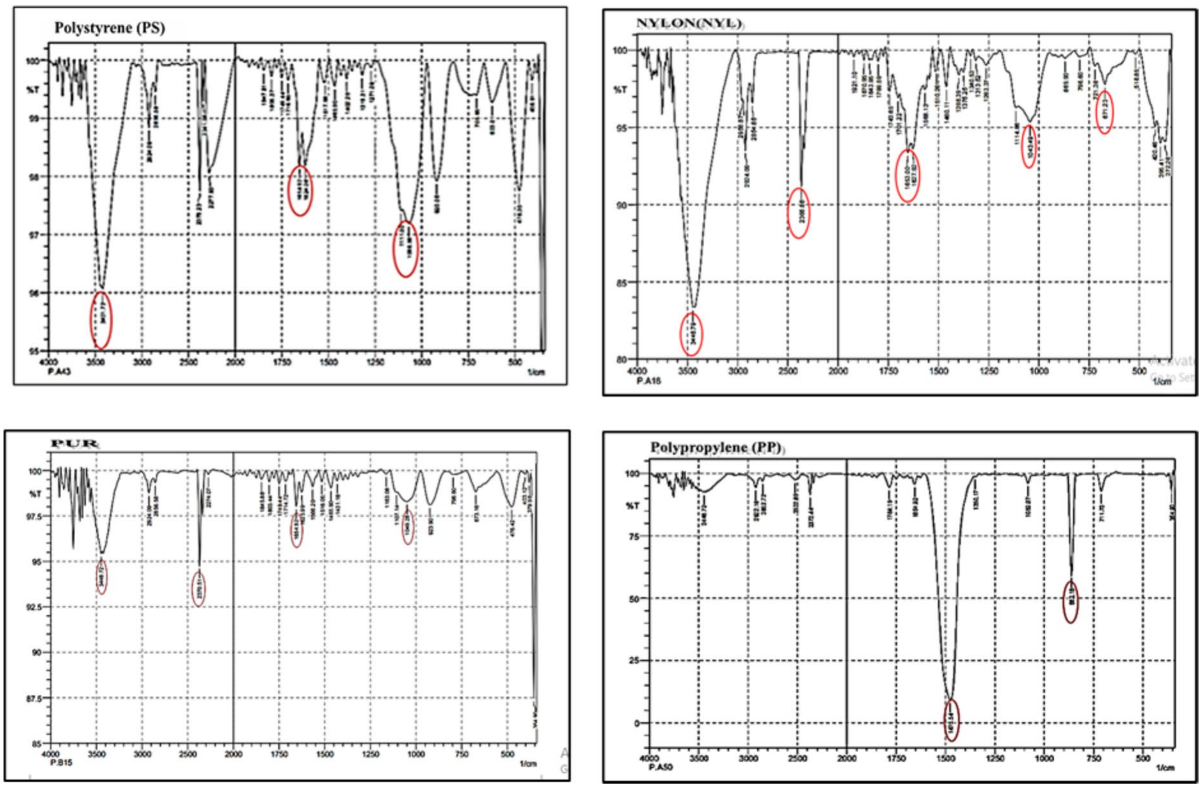

Fig. 5 FTIR wave spectrum read with polystyrene (PS) as the most predominant polymer identified (40%), followed by nylon (NYL, 25.71%), polyurethane (PUR, 22.86%), and polypropylene (PP, 11.43%) ($n = 35$). The red circle indicates the spectral peak that indicates the polymer type

Fig. 6 Representatives of MP forms with PS (**A**), NYL (**B**), and PP (**C**) observed from mussel samples

Nevertheless, one of the most disturbing facts is that, as filter feeders, bivalves will ingest all materials from the surrounding water and sediments. The entire body of the bivalve, including microplastics (MPs) found in the guts and other body parts, is consumed when humans consume bivalves. This poses higher risk levels associated with microplastic intake for humans than other seafood, as highlighted in the GESAMP report (GESMP, 2019). A study demonstrated that the potential risk to human health would likely increase in correlation with elevated microplastic abundance in bivalves and the prevalence of bivalve consumption (Ding et al., 2022).

Bivalves from Sanrobengi were found to have ingested more MPs than those from Mandalle, possibly owing to the geographical location of this small island ± 27 km south of Makassar city, with a population of ca. 2.2 million people. The total waste generation in Indonesia is relatively lower (0.5 kg/capita/day; (Tun et al., 2020)) compared to neighboring countries such as Singapore and Malaysia. However, diverse anthropogenic activities and inadequate solid waste management have compounded waste generation, making Makassar one of Indonesia's hotspots of plastic waste leakage (Shuker & Cadman, 2018; Kisnarti et al., 2024). Furthermore, year-round sea currents in the Makassar Strait have always drifted southward from the South Pacific Ocean (Gordon, 2005), accumulating much higher quantities of drifted materials, including plastic debris, in the Sanrobengi area. On the other hand, the Mandalle coastal area has relatively calm waters with less dynamic oceanographic actions, owing to the shielding effect of 49 small islands at varying distances from the coast.

Table 2 shows a comparison of the results of this study with similar species of shellfish in other locations. The results of the study show that the abundance of microplastics in *Meretrix* spp. from South Sulawesi is lower compared to other locations like the Philippines and Bangka (Indonesia) (Bonifacio et al., 2022; Listianingrum et al., 2023). The differences may be due to differences in pollution levels, urbanization, industrial activities near sampling sites, and changes in sampling methods and analytical

Table 2 Microplastic characteristics found in *Meretrix* spp., *Mactra* spp., and *Perna* spp. from various location

Species	Location	Polymer type of MPs found*	Abundance of MPs	Reference
Meretrix spp.	South Sulawesi (Indonesia)	PS, NYL, PUR, PP	1.00 MPs/individual	This study
	Philippine	ABS, AZ, CA, EVA, PA6, PR, PE, PET, PP, PS, PVC, RY	4.16 ± 2.86 MPs/Individual	Bonifacio et al. (2022)
	Bangka (Indonesia)	n.a	1.35–3.05 MPs/individual	Listianingrum et al. (2023)
	Luwu (Indonesia)	n.a	1.18–3.74 MPs/g	Tamrin et al. (2021)
	Pondicherry (India)	PU, PVCA, PVC, PES, PET, ABS, SBR, PVK, PEVA	0.5 ± 0.11 MPs/Individual	Dowarah et al. (2020)
	Vietnam	PES, PE, PP	4.71–5.36 MPs/g	Tran-Nguyen et al. (2023)
Mactra spp.	South Sulawesi (Indonesia)	PS, NYL, PUR, PP	2.29 MPs/individual	This study
	China	CP, PU, PET, Polyester, PE, PP, PVAc, PAN	5.10 ± 3.57 MPs/individual	Liu et al. (2021)
	China	CP, PET	3.50 ± 1.35 MPs/g	Zhang et al. (2020)
Perna spp.	South Sulawesi (Indonesia)	PS, NYL, PUR, PP	0.70–14.64 MPs/individual	This study
	Jakarta (Indonesia)	n.a	5.35–39 MPs/g	Fathoniah and Patria (2021)
	Tamil Nadu and Kerala India	PE, PP, PA, PS, PET, PEST, PEU, EVA, CP, PMMA, PBA	1.5–7.6 MPs/individual	Patterson et al. (2021)

**PE* polyethylene, *PET* polyethylene terephthalate, *PS* polystyrene, *NYL* nylon, *PUR* polyurethane, *pp* polypropylene, *ABS* acrylonitrile butadiene styrene, *AZ* azlon, *CA* cellulose acetate, *EVA* ethylene vinyl acetate, *PA6* polyamide 6 (nylon 6), *PR* phenol formaldehyde resin, *PVC* polyvinyl chloride, *RY* rayon, *PU* polyurethane, *PVCA* polyvinyl chloride acetate, *PES* polyester, *SBR* styrene butadiene rubber, *PVK* polyvinyl ketone, *PEVA* polyethylene vinyl acetate, *CP* cellophane, *PVAc* polyvinyl acetate, *PAN* polyacrylonitrile, *n.a.* not available techniques. Furthermore, the abundance of microplastics in *Meretrix* spp. from Pondicherry (India) is lower than that found in South Sulawesi and the Philippines, indicating a potential regional difference between microplastic contamination sources and the ecological characteristics of sampling sites (Bonifacio et al., 2022; Dowarah & Devipriya, 2019).

The presence of polystyrene (PS) polymer in MPs isolated from all mussel species at both sampling locations may have originated from the fragmentation of Styrofoam, such as food packaging, buoys, and fisher cool boxes. Nylon polymer, meanwhile, is widely used in fabrics and fishing materials, so its presence amongst the MPs recorded was not unexpected. Polyurethane (PUR) polymer was only found in MPs ingested by M. *chinensis* at Sanrobengi. PUR has extensive applications in the automotive industry, sports, construction, and furniture. It is also commonly used as a mixture in premium ship paints, owing to its durability in protecting the ship's body from heat, chemicals, and scratching (Gondikas et al., 2023; Turner, 2021). The application of such paint in fishing boat production at Takalar is likely to be the primary source of this polymer.

In addition, the comparison of polymer types indicates some overlaps and some significant differences from MPs found in several species from other locations. The South Sulawesi specimen (this study) contained polymers such as PS, NYL, PUR, and PP, while the other regions showed a wider range of polymers such as PVC, PET, and PU found in Pondicherry and China (Dowarah & Devipriya, 2019; Liu et al., 2021). This variation in the type of polymer suggests regional differences in the use of plastics, waste management practices, and environmental degradation processes. For example, the high concentrations of polyester in Vietnamese samples may reflect the spread of the textile industry in the region (Tran-Nguyen et al., 2023). The study provides important baseline data on Indonesian bivalve MPs, and comparisons with international data highlight the need for standardized methods to understand better and mitigate factors influencing microplastic contamination in different environments.

In the current study, MPs were predominantly of blue color with line form, and the highest contamination levels were found in *P. viridis* from Sanrobengi. Research on blue mussel *Mytilus* spp. from Norwegian coastal areas showed that 76.6% of all individuals observed were contaminated with MPs (Lusher et al., 2017b). In comparison, Widianarko and Hantoro (Widinarko & Hantoro, 2018) found 100% of *Anadara granosa* samples observed from Semarang, Indonesia, to be contaminated with MPs, while Su et al., 2018) found 0.4 to 5 MP items/individual with microfibers as the dominant form (60–100%) in the Asian clam (*Corbicula fluminea*) in the middle-lower Yangtze River basin of China. MP ingestion also causes acute exposure of all bivalve body parts to MPs, leading to diverse physiological effects (Avio et al., 2015).

The results of this study emphasize the need for a comprehensive strategy to combat microplastic pollution in the Makassar Strait. Because the predominant forms of microplastics studied are blue microfibers and polystyrene, nylon, polyurethane, and polypropylene fragments, targeted measures should address terrestrial and marine sources of pollution. Strategies such as improving waste management infrastructure, especially in coastal communities, can significantly reduce plastic waste entering the marine environment(Giang, 2022; Lebreton et al., 2017). Increasing recycling rates and encouraging alternative packaging and fishing equipment materials can also help reduce dependence on non-degradable polymers. Furthermore, stricter regulations on the operation and fishing practices of ships, including guidelines to prevent the disposal of plastic waste in the sea, are essential to curb pollution of the oceans.

In response to the increase in plastic pollution, the Indonesian government announced the National Plan of Action on Marine Plastic Debris (NAP-MPD) as part of its greater commitment to reducing plastic waste by 70% by 2025 (World Bank, 2022). The action plan highlights improved waste management, recycling efforts, and community-based coastal cleaning to combat plastic pollution. The government is also seeking to improve the regulation of industrial discharges and promote the use of biodegradable materials. Strengthening the monitoring and implementing these policies is crucial to achieving a long-term reduction in plastic pollution. In addition, efforts should be made to implement standard monitoring of microplastics in seafood to ensure that contamination levels are regularly evaluated and addressed. Encouraging the public to know the potential risks of consuming high-protein seafood can promote better-informed consumer choices and safeguard human health. Integrating these measures can improve the marine ecosystem's health and fisheries' safety, benefiting the environment and coastal communities dependent on these resources.

Conclusions

The ingestion of microplastics by bivalves observed in this study showed a high microplastic contamination dominated by microfibers, with significant differences between the two sampling sites. Bivalvia from Sanrobengi had significantly higher levels of microplastic contamination than Mandalle's. The most dominant types of microplastics found were blue microfibers, followed by transparent, black, and red fibers. Fourier transform infrared spectroscopy (FTIR) analysis revealed that polystyrene was the main polymer, followed by nylon, polyurethane, and polypropylene. The high prevalence of these polymers indicates potential sources such as fishing equipment, paints, and packaging materials. These conclusions emphasize the need for a targeted mitigation effort in areas where microplastic pollution is common, as there are potential health risks to seafood consumers and marine ecosystems.

To address these challenges, possible mitigation strategies should focus on improving waste management practices, reducing single-use plastic consumption, and enforcing more stringent regulations on fishing equipment. The Indonesian government has made significant progress in preventing plastic waste by establishing a national plastic waste management plan (NAP-MPD). These policies aim to improve waste collection systems, promote recycling, and implement coastal clean-up initiatives. Furthermore, stricter regulations should be imposed on waste disposal from ships and fishing activities to reduce the influx of microplastics into the aquatic environment. In addition, public awareness campaigns to highlight the health risks associated with microplastics in seafood could encourage more responsible consumption practices. Implementing standard microplastic monitoring protocols in aquaculture and wild fish is vital to improving the quality and safety of seafood. By integrating these measures, the Makassar Strait can gradually reduce microplastic pollution and ensure safer seafood consumption and healthier aquatic ecosystems.

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Author contribution S.W.: conceptualization, methodology, data curation, writing-original draft, writing-review and editing, supervision, and funding acquisition; E.A.W.: methodology, formal analysis, writing-original draft, writing-review and editing; M.A: formal analysis and investigation; K.S.: investigation and project administration; R.N.: investigation and visualization; W.S.: writing—review and editing; R.M.: writing—original draft preparation and project administration; S.G.: investigation; L.F.: investigation; A.M.: investigation; A.F.: visualization. All authors have read and approved the final manuscript.

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Data availability Data are available upon request to the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

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