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SEDAT GÜNDOĞDU

İREM NUR YEŞİLYURT

ZOHAIB ABBAS

MAKBULE BAYLAN

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Effects of microplastics on aquatic organisms: a comprehensive review

Sedat GÜNDOĞDU[1,*], **İrem Nur YEŞİLYURT**[1], **Zohaib ABBAS**[2], **Makbule BAYLAN**[1]
[1]Department of Basic Science, Faculty of Fisheries, Çukurova University, Adana, Turkiye
[2]Department of Environmental Science and Engineering, Government College University, Faisalabad, Pakistan

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Abstract: Microplastics (MPs) are pervasive pollutants that pose significant threats to marine ecosystems. This review examines the impact of MPs on marine organisms, highlighting key areas of concern and knowledge gaps. The aim of the study is to synthesize recent findings on the occurrence and biological impacts of MPs in marine environments. For this purpose, a total of 171 studies conducted in different geographical regions were examined in order to ascertain the interactions of numerous vertebrate and invertebrate taxonomic groups with MPs. Based on this analysis, the pathways through which MPs enter marine ecosystems and their interactions with marine organisms were reviewed. Additionally, this study addresses the potential genetic, physiological, and ecological effects of MP exposure. Understanding these impacts is crucial for developing effective mitigation strategies. The findings indicate that MPs are ingested by a wide range of marine organisms, causing physical damage and physiological stress. MPs have been shown to interfere with feeding, growth, and reproduction, leading to adverse effects on marine populations. This review also highlights the role of MPs in bioaccumulation and biomagnification within food webs. Moreover, MPs can carry toxic substances and pathogens, exacerbating their harmful effects on marine life. Overall, MPs represent a significant environmental threat with far-reaching consequences for marine ecosystems. Mitigating MP pollution requires global cooperation and stringent regulatory measures to protect marine biodiversity and ensure sustainable aquatic environments.

Key words: Microplastics, marine biota, genotoxicity, aquatic pollution

1. Introduction

Since it was first invented, plastic has gradually permeated every aspect of our daily lives, becoming an almost inseparable part of modern life. This is mainly due to the physical properties of plastics. Accordingly, plastics have found applications in virtually all sectors of life, including chemicals, energy, automotives, defense, aviation, logistics, transportation, real estate, tourism, packaging, and agriculture (Aydın et al., 2023; Baztan et al., 2024). The widespread consumption of plastics has led to an increase in global annual plastic production from 1.5 million tons in the 1950s to over 450 million tons in 2023 (Baztan et al., 2024). Approximately half of these produced plastics, due to their unalterable nature, end up in all layers of the ecosystem, from water and soil to the air, affecting the environment (Geyer, 2020; Aydın et al., 2023).

Thus, plastic pollution has become a widespread form of pollution today, contributing significantly to major environmental problems. The extensive production and multiple uses of these materials, combined with limited environmentally sound disposal options, result in pollution that goes beyond mere aesthetic issues and threatens all forms of life. Plastic pollution has become a transboundary issue, affecting both ecosystems and human health (Prata et al., 2019). Once plastics become pollutants, several factors contribute to their degradation. In addition, the methods used to dispose of plastics after use, such as landfills, recycling, or incineration, further contribute to their fragmentation into smaller sizes that leach into the ecosystem (Silva et al., 2021; Brown et al., 2023; Jin et al., 2024). This necessitates the categorization of plastic pollutants, as different sizes of plastics have different impacts and affect a wide range of organisms.

According to widely accepted classifications, plastic pollutants are categorized according to their sizes as megaplastics (greater than 100 cm), macroplastics (25 mm to 100 cm), mesoplastics (5 mm to 25 mm), microplastics (1 µm to 5 mm), and nanoplastics (less than 1 µm) (Kershaw et al., 2015). The most ubiquitous plastic pollutants are microplastics (MPs). To date, the Web of Science (WoS) database has catalogued approximately 20,000 studies that include the term "microplastic" in their titles (Figure). When we consider publications not indexed by WoS, the number of relevant studies is significantly higher. This demonstrates that the issue of MPs is receiving considerable attention.

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* Correspondence: sgundogdu@cu.edu.tr

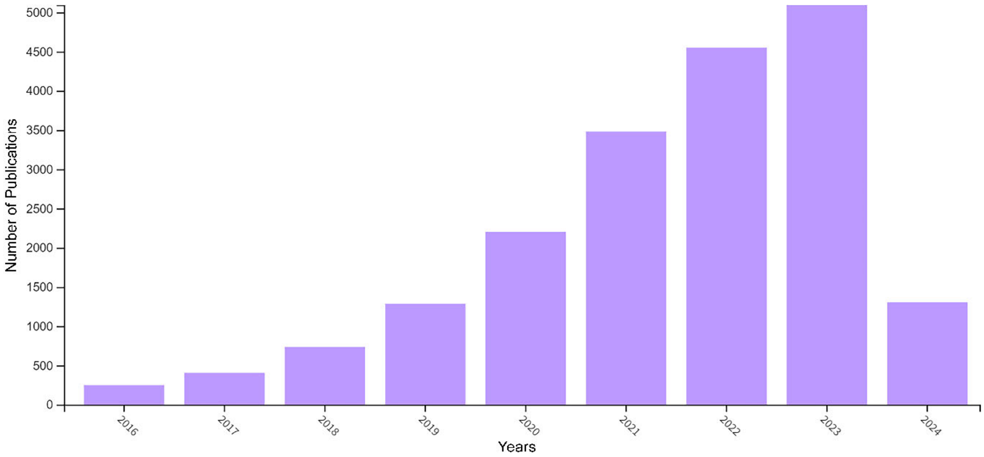

Figure. Number of publications with the term "microplastic" in their titles indexed in the Web of Science database between 2016 and 2024 (data accessed via Web of Science on 11 May 2024).

MPs, as small plastic particles formed by the breakdown of larger plastic waste, enter the marine environment through various pathways and are found throughout it, from the water's surface to the deep-sea floor. Marine organisms can ingest MPs through inhalation, ingestion, or contact, indicating extensive interactions between these plastics and marine life, which may result in genetic consequences. Considering the role of marine organisms as both vital ecosystem components and significant protein sources for humans, the presence of MPs within them and the resultant toxicological effects can adversely impact both aquatic resources and human health (Naz et al., 2024). To ensure a sustainable environment and secure food sources, it is crucial to mitigate MP pollution in marine ecosystems. Current evidence suggests that due to the persistent and cumulative nature of plastic pollution (Junaid et al., 2023a), merely improving plastic removal and recycling technologies may not adequately address the global crisis (Bergmann et al., 2022; Baztan et al., 2024). Notably, even with a 1% to 3% annual reduction in plastic production, global plastic pollution is projected to rise, with cumulative production expected to reach at least 2 billion tons by 2040 (Assefa-Aragaw et al., 2024). Consequently, there is a pressing need for binding global treaty instruments, such as the plastics treaty that the UN began negotiating in 2022. Effective mitigation of plastic and MP pollution will require these instruments to incorporate both production reductions and decreases in the use of hazardous chemicals (Bergmann et al., 2022; Dey et al., 2022; Baztan et al., 2024).

Although extensive research has been conducted on the ingestion of MPs and its consequences, detailed review publications on this topic have been scarce until recently. The predominance of bibliometric analyses over comprehensive evaluations has limited our understanding of the scientific research outcomes. This review, therefore, explores various types and interactions of MPs with different aquatic organisms in aquatic environments based on 171 studies, drawing insights from environmental science, ecology, toxicology, and genetics. It also examines MPs in the oceans and related aquatic environments, focusing on how plastic pollution levels influence ecological dynamics. Moreover, this review identifies uncertainties and knowledge gaps in our understanding of the fate, distribution, and detrimental mechanisms of MPs on aquatic organisms.

2. Microplastic occurrence in marine environments

MP pollution spans an extensive geographical area, from the Arctic to Antarctica and from deep oceans to high mountains, affecting megacities, slums, towns, rural communities, and remote settlements alike (Tekman et al., 2016; Mihai et al., 2022; Gündoğdu et al., 2023). As a result, new studies are continually providing more detailed information about the extent of this pollution, emphasizing the need for further research to address existing knowledge gaps (Mihai et al., 2022).

MPs in marine environments predominantly originate from terrestrial sources (Aydın et al., 2023). These MPs enter marine ecosystems through various pathways, including surface runoff, wind, and riverine systems. Surface currents and wind waves influence the distribution of MPs, which may remain near shorelines or be transported to the seabed over time. Additionally, MPs can directly enter marine ecosystems through maritime activities such as shipping, fishing, and aquaculture. Terrestrial sources of MPs include wastewater treatment plants (Akarsu et al., 2020), landfills, illegal dumping, the plastic production process (particularly nurdles), the use of plastics in agriculture (e.g., single-use greenhouse covers, drip irrigation system pipes, or mulching), polymer-based paints, textiles, and tire wear (Gündoğdu, 2022). One of the primary pathways for MPs entering the marine environment is via rivers (Gündoğdu et al., 2023). When MPs infiltrate river systems, they are distributed along various sections of the river. MPs can be found floating on the surface, accumulating on riverbanks, in floodplains and in coastal vegetation, suspended in the water column, and deposited on and within sediments.

MP pollution in water bodies directly impacts UN Sustainable Development Goal (SDG) 6, "Clean Water and Sanitation," and SDG 14, "Life Below Water." Therefore, there is a global call to transition from a linear economy to sustainable alternatives to mitigate plastic pollution in aquatic environments, a shift that is encapsulated in the ongoing negotiations for the UN's plastics treaty (Bergmann et al., 2022).

Plastics are notably durable, allowing them to persist in the marine environment for decades before degrading. Borrelle et al. (2020) reported that between 19 and 23 million metric tons, or 11% of the global plastic waste generated in 2016, entered marine ecosystems. They projected that 20–53 million tons of plastic would annually enter marine ecosystems by 2030. Such estimates rely on data collected using 333-µm mesh Manta or Neuston nets, which means that MPs smaller than 333 µm are not captured in such datasets. Consequently, the actual volume of MPs in marine ecosystems could be significantly higher than estimated. Studies on the concentrations of MPs in marine waters suggest that they reflect only 1% of the estimated global marine plastic budget (Mihai et al., 2022).

Depending on their origins, MPs in marine environments can be classified into primary and secondary categories. Primary MPs generally come from sources such as textiles, cosmetics, and traffic-related activities. Secondary MPs, on the other hand, are derived from the breakdown of larger plastic items due to various environmental factors. In terms of chemical composition and density, the most commonly found MPs in marine environments are low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyester (PES), and polystyrene (PS) (Gündoğdu, 2022). All other types of MPs, such as nylon and acrylic, are categorized as "others."

3. Occurrence of microplastics in aquatic organisms

High amounts of MPs in aquatic environments have become a well-recognized and growing global issue, posing a threat to aquatic life (Junaid et al., 2023b). However, it is crucial to recognize that not just MPs but all forms of plastic litter impact aquatic ecosystems (Aydın et al., 2023). It is estimated that 4076 marine species are currently threatened by marine litter, predominantly comprising plastics.[1] According to the LITTERBASE database[1], the organisms most affected by marine litter include fish (23.7%), seabirds (14.3%), crustaceans and arthropods (11.2%), and mollusks (7.9%). Reports indicate that the impacts of litter on marine organisms mainly involve ingestion (40.4%), colonization (34.3%), and entanglement (17.4%).[1] Moreover, numerous studies have shown that aquatic organisms such as fulmars, oysters, mussels, and fish are adversely affected by MPs.[1] Due to their size, even small organisms like zooplankton and fish larvae can directly ingest MPs during feeding (Lusher, 2015).

3.1. Microplastics in aquatic invertebrates

The impact of MPs found in every layer of aquatic ecosystems has been the subject of many scientific studies, especially in the last decade. In this review, we focus on MPs in aquatic organisms from studies of wild organisms and aquaculture research conducted between 2020 and 2024. Our literature review determined that the effects of MPs on 136 species belonging to the taxonomic groups Porifera, Cnidaria, Mollusca, Arthropoda, and Echinodermata were examined in 89 research articles. These studies evaluated relationships between the habitats and diets of aquatic organisms and MP uptake as well as the type, size, and trophic level transfer of MPs into different tissues.

MPs are often mistaken for food by many organisms upon their entry into the water. The acquisition of MPs by aquatic organisms can occur either directly from nature or indirectly through trophic pathways from their prey (Walkinshaw et al., 2020). The extent of MP uptake by aquatic organisms is influenced by various factors, including the species' diet and the prevailing environmental conditions (Xu et al., 2020a). Filter feeders, for instance, take up MPs from the water column, while MPs that settle in the sediment over time are ingested by grazers or deposit feeders that feed on algae in the benthic zone. Seagrass sediments have been found to contain higher levels of MPs than sandy sediments (Huang et al., 2020; Jones et al., 2020), making aquatic organisms grazing on seagrass more susceptible to MP ingestion (Jones et al., 2020; Curren et al., 2024).

The feeding mode of organisms is a key factor influencing the concentration of MPs in their bodies. Deposit feeders or grazers were found to have higher concentrations of MPs than filter feeders and predators (Xu et al., 2020a). In a study conducted on the Red Sea coast of Egypt, the MP concentration (items/g) in the tissues of

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[1] Tekman MB, Gutow L, Bergmann M, Peter C (2024). LITTERBASE. Online Portal for Marine Litter [online]. Website: https://litterbase.awi.de [accessed 30 May 2024].

filter-feeding bivalves was found to be higher than that in benthic-feeding gastropods or grazing echinoids (Abd-Elkader et al., 2023). Walkinshaw et al. (2020) studied 11 species of fish, crustaceans, and bivalves with different feeding strategies. The MP ratios of filter-feeding mussels *Mytilus* spp. and cupped oysters *Crassostrea* spp. were 0.2–5.36 MPs/g and 0.18–3.34 MPs/g, respectively, while those of planktivorous-herbivorous brown shrimp *Crangon crangon* were 0.13–1.23 MPs/g and that of piscivorous yellowfin tuna *Thunnus albacares* was 0.00059 MPs/g.

The habitat of an organism is critically important for MP ingestion, as is the type of diet. It has been found that organisms living in different habitats with the same diet type ingest different MPs (Cho et al., 2021). Xu et al. (2020a) found that the abundance of MPs varied significantly in different habitats along the coastline of Hong Kong.

There are different results on the transfer of MPs between organisms in the food chain. Evidence suggests that MPs are most concentrated in the food chain at the level of primary consumers (Sfriso et al., 2020), but there is also evidence of bioaccumulation in the food chain (Wang et al., 2021a). Walkinshaw et al. (2020) indicated that there is a decrease in the concentration of MPs in organisms as the trophic level increases. Similarly, in Antarctica, filter feeders and grazers were found to have higher MP concentrations than omnivores and predators (Sfriso et al., 2020). A study conducted on Ecuador's Pacific coastline examined the abundance of MPs in aquatic organisms such as fish, mollusks, and crustaceans. That study considered the feeding habits of these species and found that carnivorous species had an abundance of 2.04 ± 0.622 MP items in their digestive tracts, while planktivorous and detritivorous species had 1.31 ± 0.348 and 0.72 ± 0.780 MP items, respectively (Cáceres-Farias et al., 2023).

In addition, numerous experimental studies have investigated the effects of MPs on invertebrate growth, development, reproduction, mortality, and oxidative stress (D'Costa, 2022). However, these studies are not discussed here as they are beyond the scope of this review.

MPs can be found in different types and sizes in different parts of tissues (Gündoğdu, 2023; Doshi et al., 2024). MPs were studied in various parts of organisms, including soft tissues, stomachs, gills, gastrointestinal tracts (GITs), digestive glands, muscles, carapaces, guts, hepatopancreas, intestines, and eggs. PE, PP, and PET were recorded as the dominant plastic polymers in both crustaceans and mollusks. Various types and amounts of MPs were found in the tissues of living organisms, as presented in the following subsections.

3.1.1. Porifera

Sponges are filter-feeding, sessile benthic organisms. They can take up MPs and other microparticles by filtering seawater, through placoderms, or via the influence of the fauna living within them (Girard et al., 2021; Soares et al., 2022). Studies on the effects of MPs on members of the phylum Porifera are limited. In the literature review conducted within the scope of this study, three relevant publications were found (Appendix Table 1).

In the Laguna de Terminos Protected Area, the MP content in sponges was found to be much higher than that in water and sediment (Celis-Hernandez et al., 2021). Sponges may be exposed to more contamination than other organisms as a result of ingesting very small particles, such as MPs with a predominant size of 10–20 µm or less than 2 µm (Fallon and Freeman, 2021; Krikech et al., 2023). In studies conducted in different regions, blue, red, and black microfibers were found in various sponge species, such as *Haliclona implexiformis*, *Halichondria melanadocia*, and *Amorphinopsis atlantica* in Mexico (Celis-Hernandez et al., 2021); PS was found in coral sponges *Carteriospongia* sp. and *Ircinia* sp. on Bangka Island, Indonesia (Girard et al., 2021); and PP was found in *Cinachyrella alloclada* in Brazil (Soares et al., 2022). In Antarctica, thermo fibers were detected in the sponges *Dendrilla antarctica*, *Haliclona* (*Rhizoniera*) *scotti*, *Microxina sarai*, and *Mycale* (*Oxymycale*) *acerata*, which provide the raw material for clothing worn by researchers, fishermen, and tourists in the region (Corti et al., 2023). In addition, sponges can be used as bioindicators to determine MP diversity in the environment due to their abilities of filtering large amounts of seawater daily and absorbing very small amounts of MPs present in the environment (Celis-Hernandez et al., 2021; Corti et al., 2023; Krikech et al., 2023).

3.1.2. Cnidaria

Cnidarians are divided into three classes: Hydrozoa, Scyphozoa, and Anthozoa. They are widely distributed in different habitats, from seagrasses to coral reefs, from coastal areas to the deep sea, and from benthic to pelagic zones, and they are affected by MPs originating from various anthropogenic sources in many places with human impact. Hydrozoans and scyphozoans are commonly known as jellyfish, with both sessile polyp and free-living medusa forms. Although studies on the effects of MPs on the phylum Cnidaria are limited, it is possible to say that more studies have been carried out compared to Porifera. In our literature review, seven relevant studies were found (Appendix Table 1).

In the pelagic jellyfish *Aurelia aureta* in the North Sea, *Pelagia noctiluca* in the Canary Islands, *Rhizostoma pulmo* in the Adriatic Sea, benthic jellyfish *Cassiopea xamachana* in Florida, and sea anemone *Actinia equina* on the north coast of Spain, MPs were reported mostly in the form of fibers (Avio et al., 2020; Iliff et al., 2020; Devereux et al., 2021; Janssens and Garcia-Vazguez, 2021; Rapp et al., 2021). The anthropogenic contaminants PE, PP, PET, cotton, rayon/viscose fibers, acrylic, cellophane, cellulose, and linen were detected (Devereux et al., 2021; Rapp et al., 2021). In addition, jellyfish such as *Aurelia aurita* and *Pelagia noctulica* were found to be bioindicators for the determination of MPs in pelagic waters (Macali and Bergami, 2020; Rapp et al., 2021). Anthozoans, another class of Cnidaria, are a group of polyp-shaped corals and anemones, all of which are sessile. There are many experimental studies investigating the ingestion and adhesion of MPs by corals and species-specific MP uptake; the effects of MPs on corals together with chemical contaminants such as PAE, PCBs, and heavy metals; pathogen-induced diseases caused by MPs and their effects; and the symbiotic relationship between corals and Symbiodiniaceae (Huang et al., 2021). However, nonexperimental studies are limited. On Liugiu Island, Taiwan, MPs were detected on the surface of (0.35 ± 0.28 items/g) and inside (0.23 ± 0.17 items/g) *Acropora* spp., *Galaxea astreata*, and *Pocillopora verrucosa* corals. The MPs detected were over 90% fiber and included polymers such as rayon, PES/PET, nylon, PACA, PS, PP, and PE (Lim et al., 2022). Corals obtain nutrient and energy needs through symbiotic relationships with the photosynthetic family Symbiodiniaceae. This symbiotic relationship is critical for supporting healthy coral reefs. From Hainan Island, China, it was reported that MPs can induce apoptosis in the coral *Pocillopora damicornis* and that the symbiotic relationship between Symbiodiniaceae and coral may be damaged (Tang et al., 2021).

3.1.3. Mollusca

The members of the phylum Mollusca (gastropods, bivalves, and cephalopods) are economically important due to their consumption as food and the wide variety of species they encompass. In this review, we considered a total of 52 species from 36 articles. The concentration of MPs in these organisms was mostly observed in their soft tissues, with smaller amounts found in the stomach, gills, intestines, GIT, and digestive glands. In most studies, 10% potassium hydroxide was used for tissue separation, and Fourier transform infrared (FTIR) and micro-Fourier transform infrared (µFTIR) methods were used for polymer detection. The shapes of MPs were reported as fibers, fragments, films, pellets, microbeads, foam, and sheets, with fibers and fragments being predominant.

3.1.3.1. Gastropoda

Gastropods live on sediments, sandy bottoms, rocks, and the seabed and are exposed to direct and indirect MP pollution (Zaki et al., 2021). They can uptake MPs from the water column, sediment, and nutrients. MP contamination was observed especially in the outer shells, foot, pedal mucus, and feces of snails, indicating that they ingest and excrete MPs (Rodrigues et al., 2023). Gastropods are known for their diverse feeding habits, which include herbivory, detritivory, suspension feeding, scavenging, and carnivory (Srivastava and Singh, 2021). As detritivores, they feed on detritus and intake MPs from the sediment. They are also grazers on macroalgae and consume MPs in seagrasses while feeding (Curren et al., 2024).

Gastropods move by crawling with the help of their pedal mucus and feet. In the Bohai Sea, crawling species such as *Rapana venosa*, *Neverita didyma*, *Chlorostoma rustica*, *Buccinum koreana*, *Siphonalia subdilatata*, *Volutharpa perryi*, *Natica janthostomoides*, and *Natica maculosa* were found to have higher MP contents than bivalve species that burrow in the sediment or attach to rocks (e.g., *Solen gouldi* and *Mytilus galloprovincialis*) (Zhao et al., 2024). The researchers noted that the high MP ratio in crawling shells may be related to MP uptake from both sediment and water during crawling.

A study conducted in the Klang River estuary in Malaysia found that the carnivorous snails *Chicoreus cingulata* and *Thais mutabilis* contained more MPs than the herbivorous snails *Nerita articulata* and *Nerita polita*. This difference in MP concentration was attributed to the feeding habits of these snails; herbivorous snails consume algae containing MPs, while carnivorous snails consume both the MPs in the environment and in their prey (Zaki et al., 2021). This study highlighted that MPs can be transferred from one organism to another through trophic pathways, raising concerns about the potential risks posed to humans by aquatic foods that may contain MPs.

We examined the abundance of MPs in 23 gastropod species across 13 studies (Appendix Table 1). The presence of MPs in soft tissues has been studied most in the literature. The most commonly used digestion method was 10% KOH. For polymer analysis, the majority of studies utilized µFTIR and FTIR. The predominant shapes of MPs identified were fibers, followed by fragments. The most commonly detected polymers were PE and PET. The highest MP concentration was found in the mangrove snail *Littoraria scabra* in Jakarta Bay, Indonesia (mean: 75.5 MPs/individual) (Patria et al., 2020). The minimum MP concentration (mean: 0.29 ± 0.54 MPs/individual) was recorded in the limpet *Patella caerulea* in İskenderun Bay and Mersin Bay, Türkiye (Yücel and Kılıç, 2023).

3.1.3.2. Bivalvia

Bivalves include filter-feeding oysters, mussels, and clams. These organisms have been used as bioindicators to determine aquatic pollution due to their sensitivity to biotic and abiotic changes. Therefore, the sensitivity of bivalves to MPs has also been of interest and extensively studied. Some studies argue that bivalves can be used as bioindicators in determining MP pollution (Wakkaf et al., 2020; Patterson et al., 2021; Truchet et al., 2021; Wootton et al., 2022) and vice versa (Ward et al., 2019). They are also an economically important group with high consumption as seafood worldwide. Given that bivalves are consumed whole without internal organs, directly transferring their accumulated substances (Shumway et al., 2023), studying the MP concentrations in bivalves is important.

The MP concentrations and types in oysters, mussels, and clams, which are widely used as food, have been investigated in many studies. In this review, data from 19 bivalve species from 19 studies were analyzed. Researchers have primarily extracted MPs from the soft tissues of bivalves using 10% KOH. Fibers and fragments are the most common forms of these MPs. ATR-FTIR and µFTIR were predominantly used to determine polymer types. The most common polymer types were PE, PP, and PET. The Mediterranean mussel *Mytilus galloprovincialis* is the most studied species, with mean MP levels varying across different regions, from 0.5 MPs/individual on the shores of İstanbul (Galyon and Alçay, 2023) to 18.6 ± 23.0 MPs/individual on the Catalan coast (Expósito et al., 2022). These researchers estimated that daily consumption of mussels could lead to an intake of 42.8 MPs/day for adults.

The minimum MP concentration was recorded in the mussel *M. galloprovincialis* as 0.5 MPs/individual on the shores of İstanbul, Türkiye (Galyon and Alçay, 2023). The maximum MP concentration (25.3 ± 32.6 MPs/individual) was found in the mussel *Brachidontes pharaonis* on the Red Sea coast of Egypt (Abd-Elkader et al., 2023).

3.1.3.3. Cephalopoda

The number of studies conducted on MP concentrations in cephalopods is lower compared to other classes. Ten species were investigated in nine articles (Appendix Table 1). Researchers examined MPs in the soft tissues, stomachs, gills, ink sacs, intestines, digestive glands, GITs, and outer bodies of squids, cuttlefishes, and octopuses. A majority of studies focused on the stomach. Most research used 10% KOH for tissue digestion, while FTIR was the predominant technique for polymer identification. The shapes of MPs were mostly fibers and fragments. The most commonly reported polymers were PET, PE, and PP. Studies have been conducted on mean MP ratios in several commercially important species in different regions, including *Sepia officinalis* on the Adriatic coast and in Portugal, *Octopus vulgaris* in the southern Tyrrhenian Sea and off Madeira Island, *Loligo vulgaris* in the northeast Atlantic, and *Dosidicus gigas* along western South America and in the eastern Pacific Ocean (Oliveira et al., 2020; Gong et al., 2021; Pedà et al., 2022; Armellini et al., 2023; Sambolino et al., 2023; Wang and Chen, 2023). The lowest rate of MPs per individual was reported as 0.13 ± 0.35 MPs/individual in the squid *Ommastrephes caroli* off Madeira Island in the Northeast Atlantic (Sambolino et al., 2023). The highest rate was 10.30 ± 16.66 MPs/individual in *Octopus vulgaris* in the southern Tyrrhenian Sea in the western Mediterranean Sea (Pedà et al., 2022).

Cephalopods need suitable shelters to protect themselves from predators due to their soft skin and to lay their eggs during the reproductive period. The literature has reported that they use marine debris as shelters. For example, the pygmy octopus *Paroctopus cthulu* was found to use a snorkel mask for spawning (Leite et al., 2021). Additionally, Freitas et al. (2022) reported that benthic octopuses used plastic marine debris as shelters for nesting and hiding.

3.1.4. Arthropoda

The aquatic group of arthropods includes Crustacea and Merostomata. Crustaceans, which comprise economically important species such as crabs, shrimps, lobsters, and barnacles, play vital roles in ecosystems. They are widely distributed from aquatic areas to brackish waters, estuaries, freshwaters, rivers, and terrestrial areas and are used as human food. However, their true significance lies in their role as food sources for many creatures such as fish, sharks, birds, and mammals. The larval stages of crustaceans, often found within zooplankton groups like Ostracoda, Isopoda, and Copepoda, are pelagic and constitute food for many creatures. Crustaceans exhibit diverse diets, including filter feeding, detritivory, carnivory, and omnivory.

The uptake of MPs and their effects have been studied in many groups of crustaceans, such as Decapoda, Stomatopoda, Cirripedia, Cladocera, and Amphipoda. This review examined the effects of MPs on arthropods based on the findings of 65 studies (Appendix Table 1).

The highest number of studies on MP concentrations in Crustaceans have been carried out in the GIT, including many studies of the gills, stomach, intestine, gut, hepatopancreas, digestive tracts, muscles, and soft tissues, with rare studies on the carapace and only one study on eggs (Appendix Table 1). The most frequently used method for digesting tissues was 10% KOH, followed by 30% hydrogen peroxide. µFTIR, followed by FTIR, was the most commonly used method for polymer analysis. MPs were mainly obtained as fibers, followed by fragments. PE, PET, and PP were the most commonly identified polymers. Most studies have been carried out on decapods and the blue crab *Callinectes sapidus* (Appendix Table 1).

The lowest MP rate was reported in the krill *Euphasia*, a zooplankton (0.019 MPs/individual) in the Bohai Sea, China (Zheng et al., 2020). The highest MP rate was reported as 327.56 MPs/individual in the mangrove crab *Metopograpsus quadridentata* in Jakarta Bay, Indonesia (Patria et al., 2020). The size of *M. quadridentata* was large, and a positive correlation between the weight of the crabs and MP abundance was revealed. Additionally, there were no data indicating that contamination conditions were minimized in the study, so contamination may be another important reason for the high concentration of MPs.

Barnacles are sessile benthic filter-feeding organisms. In the Capo Milazzo Marine Protected Area, the pelagic barnacle *Lepas* (*Lepas*) *anatifera* was found to contain an average of 1.74 ± 0.80 MPs and natural fibers in its GIT, as reported by Scotti et al. (2023). This concentration is higher than that reported in two other studies on barnacles (Xu et al., 2020b; Zhang et al., 2022). MPs have been detected even in Antarctica, where human density is limited (Sfriso et al., 2020; Primpke et al., 2024). In the South Shetland Islands and the South Orkney Islands, MP concentrations in the Antarctic krill *Euphausia superba* have been studied. The average MP rate in Antarctic krill was found to be 0.29–0.33 MPs/individual, with sizes ranging from 20 to 195 μm (Zhu et al., 2023a). The primary polymers within the compositions of MPs found in Antarctic krill are PE, PP, and PS, which are also the main constituents of MPs in subsurface seawater surrounding the Antarctic Peninsula (Zhang et al., 2022). PE and PP are commonly used in household materials and have emerged as the predominant types of plastic polymers manufactured globally (Liao et al., 2021).

A total of four species of the class Merostomata have been found along the coasts of North and Central America and in the Indo-Pacific. Horseshoe crabs are prey for many birds, fish, and sea turtles. They also provide a habitat for many species of mollusks and crustaceans, leading to symbiotic relationships. In Asia, they are economically important due to their biomedical use. In a study conducted in the Beibu Gulf of China, which has the world's highest horseshoe crab population, researchers investigated the contamination of juvenile three-spined horseshoe crab *Tachypleus tridentatus* by MPs. The average MP content in the GIT was found to be 21.1 ± 13.4 MPs per individual, which was significantly higher than the MP content in other mollusks and crustaceans in the same region of China. That study also revealed that 99% of the MPs were fibers, with cellophane being the most abundant polymer (Wang et al., 2022).

3.1.5. Echinodermata

The presence and effects of MPs have been studied in several species of benthic starfish, sea urchins, and sea cucumbers. MPs were investigated in Haizhou Bay, China, in the starfish *Asterias rollestoni*, the sea urchin *Hemicentrotus pulcherrimus*, and the sea cucumber *Acaudina molpadioides*; in the Canary Islands in the sea urchin *Diadema africanum*; in the Adriatic Sea in the sea urchin *Paracentrotus lividus*; and off the island of Ibiza, Spain, in the sea cucumber *Holothuria tubulosa*. These MPs were mostly in the form of fibers, and the most commonly detected polymers were PE, PP, and PET (Avio et al., 2020; Lombardo et al., 2022; Xie et al., 2024a). MPs in the sea urchins *Echinometra mathaei* and *Diadema setosum* of the islands of Pari and Harapan, Indonesia, were predominantly reported as fragments (75%). PES and PP were reported to have the highest rates (Rahmawati et al., 2023). In Jiaozhou Bay, China, echinoderms were reported as the taxon with the highest MP occurrence after fish (93%) and the highest MP uptake after crustaceans (20.9 ± 17.4 MPs/g) (Zhang et al., 2023). In a study conducted by Barros et al. (2020), it was observed that the sea urchin *Lytechinus variegatus* in Todos os Santos Bay, Brazil, exhibited a preference for marine debris, with plastic accounting for 68% of the debris, over natural materials such as shells and rocks for shelter.

3.2. Microplastics in aquatic vertebrates

The ubiquitous existence of MPs in aquatic environments has raised apprehension about their effects on aquatic vertebrates. From deep depths to the surface layers of fresh and marine water environments, MPs are found everywhere and affect various aquatic organisms. MP existence causes disturbances in hematological parameters of the Korean bullhead fish *Pseudobagrus fulvidraco* (Lee et al., 2023), induces retardation in the antipredator behavioral responses of frog tadpole (Scribano et al., 2023), and causes excessive accumulation in the bodies of aquatic mammals (Nabi et al., 2022). Understanding the existence and impact of MPs on aquatic vertebrates is thus of extreme importance, as these variations can have far-reaching costs across the whole ecosystem.

3.2.1. Fishes

Recently, the ingestion of MPs by fish in aquatic environments has garnered significant attention due to concerns about MP contamination in seafood (Srisiri et al., 2024). Monitoring MP ingestion by fish is crucial for assessing the risks of consuming MP-contaminated fish for human health (Motivarash et al., 2024). Piskuła and Astel (2024) recently investigated MP uptake in globally consumed fish species such as rainbow trout and perch. Their results indicated that, on average, each fish contained 1 to 12 MP items, with 56% being fibers and 46% particle-shaped MPs. In another study, 68% of MPs, predominantly LDPE, were found in the edible tissues of 400 individual fish from the coastal area of Gujarat, India (Motivarash et al., 2024). De Azevedo et al. (2024) also examined the presence of MPs in two fish species, *Hoplosternum littorale* and *Pterygoplichthys pardalis*, which are often consumed by humans, becoming a direct source of MP contamination. These fish were found to contain 683 MP particles, ranging from 1 to 43 MPs per individual. Blue-colored and fiber-shaped MPs were the most abundant in both species. Similarly, Srisiri et al. (2024) found that fibrous-type and blue-colored MPs (PE and PES) were also prevalent in edible marine fishes, with an average concentration of 1.6 ± 0.5 pieces per individual. Fish can consume MPs either directly by mistaking them for natural prey items or indirectly by consuming other organisms that have ingested MPs (da Costa et al., 2023).

The occurrence of MPs in various fish species, including their concentration, shape, size, polymer type, color, and location, has been extensively documented in both marine and freshwater species as presented in Table 1.

Most information on the occurrence of MPs in fishes comes from analyses of items found in the GIT (Arafat et al., 2023; Rasta et al., 2023; Khan et al., 2024). MPs are primarily accumulated in the digestive tract, especially the stomach (Rivas-Mena et al., 2024), and the gut–gills axis (Zheng and Wang, 2023). The presence of MPs may lead to structural and functional alterations in the GIT, potentially impairing fish growth and nutrition (Lai et al., 2021; Hao et al., 2023). Fishes from a wide range of species and habitats are reported to be contaminated with MPs, which often vary in terms of polymer type, color, and shape. Fish digestive tracts frequently contain HDPE, PE, PP, PES, and PS, the most commonly produced polymers worldwide (Hollerova et al., 2023; Yedier et al., 2023; Gorule et al., 2024). The most commonly found forms of MPs in fish are fibers and fragments, with fish showing a preference for consuming black- and blue-colored plastic polymers over white fragments. Very small plastic particles can traverse living cells and enter the lymphatic or circulatory systems, potentially dispersing throughout the body. Unfortunately, there is still a lack of information about MPs in fish tissues outside of their digestive systems.

3.2.2. Sea turtles

Sea turtles lead complex lives, facing numerous anthropogenic threats including climate change, coastal development, fishing, direct exploitation, and pollution. These pressures not only affect their survival rates but can also lead to significant reductions in their populations. Given their crucial ecological roles, from contributing to the health and maintenance of coral reefs and seagrass beds to acting as biological carriers that transport marine nutrients and energy to coastal ecosystems, the impact of pollution on sea turtles demands careful consideration.

The aquatic environment, a critical accumulation point for MPs, affects numerous species, particularly sea turtles. Sea turtles, as large marine vertebrates, are especially susceptible to MP pollution due to their feeding behaviors and habitat preferences. Sea turtles, akin to humans, experience exposure to MPs through inhalation, ingestion, and dermal contact. This similarity provides valuable insights into the trophic transfer of MPs within aquatic ecosystems. Consequently, assessing the exposure of sea turtles to MPs is crucial for understanding broader ecological impacts.

Since MPs are one of the most problematic pollutants for sea turtles, among other pollutants, they are experiencing higher individual impacts and concentrations of MPs compared to fish, marine mammals, and seabirds (Curl et al., 2024). Although our understanding of plastic ingestion by sea turtles has greatly improved over the last decade, quantified data on the amount of ingested debris are still missing from risk assessments and review articles; these studies tend to focus solely on the frequency of occurrence. The pervasive and persistent nature of MPs in the environment poses a considerable risk to sea turtles, many species of which are already threatened, vulnerable, or critically endangered (IUCN, 2023). The primary threat to sea turtles is entanglement in marine litter, such as ghost nets and ropes. Their lifecycle, which includes using sandy beaches for nesting and nearshore habitats for hatchling foraging before migrating to the open sea, significantly exposes them to plastic pollution. Compared to other aquatic species, sea turtles are more prone to ingesting plastic debris due to their visual feeding strategy, which often leads them to mistake soft floating plastics for jellyfish, especially during their young pelagic phase; additionally, their backward-facing esophageal papillae prevent regurgitation, facilitating particle buildup in the gut.

Various injuries via both mechanical and chemical actions have been documented in the digestive tracts of all sea turtle species reported to have ingested plastic items (Himpson et al., 2023). Global studies on the occurrence and entanglement of plastics in sea turtles include research from the Eastern Mediterranean by Duncan et al. (2024), from the Mexican Caribbean by Aranda et al. (2024), and from the Gulf of Oman by Yaghmour et al. (2022), as well as a hazard assessment from the Northwest Atlantic Ocean by Blais and Wells (2022). Table 2 highlights the fact that turtles are severely affected by MPs, with a high percentage of individuals contaminated and a significant average number of MPs found per turtle. The green sea turtle (*Chelonia mydas*) and the leatherback sea turtle (*Caretta caretta*) are particularly vulnerable to MPs due to their herbivorous and gelatinous diets, respectively.

Turtles' extensive geographic range and migratory habits mean that they often spend stages of their lives in areas heavily contaminated with MPs, leading to significant environmental accumulation of these particles. The types and amounts of plastic waste ingested by sea turtles vary by species, life stage, and diet (Choi et al., 2021; Palmer et al., 2021). The frequency at which wild turtles encounter or ingest plastic is still poorly understood. Due to ethical concerns about the lethal sampling of these critically endangered species, most studies on turtle plastic ingestion are anecdotal, based on one-time observations, or predominantly involving dead or dying turtles. Moreover, the first of only five international review articles on turtles ingesting plastic was published 39 years ago (Balazs, 1985). Further research is needed to determine if ingesting plastic poses a greater risk to sea turtles compared to nonmarine species. With increasing plastic pollution, the urgency for such studies escalates.

Table 1. Summary of latest studies conducted on the occurrence of microplastic in aquatic fish species.

Group	Location and environment	Species studied	Individuals examined	Organ analyzed	Prominent polymer type	Prominent shape	Prominent size	Advanced technology	Prominent color	Concentration (items/ individual/g ± SD)	References
	Bay of Bengal, Bangladesh, Marine	*Pampus chinensis, Cynoglossus lingua, Cynoglossus cynoglossus, Drepane longimana, Karalla daura, Harpadon nehereus*	49	GIT	PP (43.18%) and PE (36.15%)	Fibers (67.96%), fragments (21.36%), and foam (10.68%)	100–1500 µm	FTIR	Transparent (26.86%), black (24.92%), and red (23.95%)	4.38–10 items/individual	Siddique et al. (2024)
	Sundarban, India Marine	*Boleophthalmus boddartii, Odontamblyopus rubicundus*	45	Skin, gills, bucco-opercular cavity and GIT	PE (33%), PP (32%), and PVC (21%)	Fibers (82%) and fragments (13%)	100–300 µm	ATR-FTIR + Raman spectra	Transparent, white, blue, green, red, yellow, black, and purple	0.84–2.62 items/ individual	Chatterjee et al. (2024)
	Türkiye, Freshwater	*Squalius sp.*	69	GIT	PE (38.5%) and PET (29.7%)	Fibers (79.1%), fragments (17.6%), and films (3.3%)	1000 µm	FTIR	Black (35.2%), white (27.4%), red (16.5%), green (7.7%), blue (6.6%), transparent (4.4%), and yellow (2.2%)	0.27 ± 0.19 items/ individual	Gedik et al. (2024)
	Coastal areas, Zakynthos Island, Marine	*Mullus surmuletus*	122	GIT	PVA (50%), PP (35%) and PET(31.25 %)	fragments (50%), fibres (48%), and film (2%)	0.1–0.5 µm	FTIR	Blue (48%) and red (18%)	0.15–0.55 items/ individual	Patsiou et al. (2024)
	River Stour, UK, Freshwater	*Platichthys flesus, Merlangius merlangus,Clupea harengus*	53	Stomach and intestine	PP (61 %), PE (25%), EVA (8.3%), cellulose (3.5%), and rubber (1.8 %)	Fibers	25 µm	FTIR	Blue	1.98, 2.46, 1.47 items/ individual	Horton et al. (2024)

Table 1. (Continued.)

	River Nile in Khartoum, Sudan, Freshwater	*Oreochromis niloticus*	30	GIT	HDPE and PP	Fibers (85%), fragments (9.5%), and films (4.6%)	<0.5 mm (30.51%), 0.5–1 mm (25.93%), 1–2 mm (27.69%), and 2–5 mm (15.88%)	Raman spectra	Green (26.63%), black (18.69%), blue (14.29%), red (8.82%), grey (7.23%), and white (3.53%)	18.90 ± 9.17 items/ individual	Saad and Alamin (2024)
	Bay of Bengal, Bangladesh, Marine	*Escualosa thoracata, Tenualosa ilisha, Johnius belangerii, Trichiurus lepturus, Planiliza parsia, Mystus gulio*	120	GIT	PE (35% to 43%), PET (28% to 35%), PA (20% to 31%), and PS (0% to 7%)	Fibers (19% to 76%), fragments (6% to 61%), films (8% to 35%), microbeads (0% to 5%), and foams (0% to 2%)	0.3–5 mm	FTIR	Transparent, black, green, and blue	7.7 items/ individual	Fatema et al. (2024)
	Turag River, Bangladesh, Freshwater	*Channa striata, Puntius sophore, Anabas testudineus*	60	GIT	PP (40%), LDPE (30%), and PS (30%)	Fibers (89–93%), fragments (21–35%), films (0–26%) and foams (0–5%)	<0.5 mm	FTIR	Blue (69–83%), red (20–33%), black (11–14%), green (8–20%), and purple (6–8%)	3.0 ± 1.9 items/ individual	Khan et al. (2024)
	Gulf of Cadiz, SW Europe, Marine	*Scomber colias*	104	Stomach	PA (64%), PP (15%), PS (12%), PVC (5%), and PE (4 %).	Fibers (91.1%) and fragments (8.9 %)	170 ± 143 µm	FTIR	Black (32.0%), blue (24.3%), green (19.4%), and red (14.6%)	5.4 items/ individual	Rivas-Mena et al. (2024)
	River Ile-Oluji, Ondo State, Nigeria, Freshwater	*Clarias gariepinusl, Oreochromis niloticus*	18	GIT	PP (46%), PE (36%), PET (10%), and PS (8%)	Fragments, fibers, pellet, and film	0.5–5.0 mm	ATR-FTIR	Blue (37 %), red (27%), white (12%), black (12%), purple (7%), and green (5%)	4.33 ± 1.71 and 1.44 ± 0.70 items/ individual	Samuel et al. (2024)

Table 1. (Continued.)

	Arabian sea Karachi, Pakistan, Marine	*Otolithus ruber, Terapon jarbua*	15	GIT	PA, PET, PVA, PP, and PE	Fibers (42%), pellets (27%), and fragments (20%)	0.34 mm (*Otolithus ruber*) to 2.1 mm (*Terapon jarbua*)	FTIR	Blue (21.60–66.23%), transparent (12.17–54.35%), white (11.96–42.32%), red (1.09–19.20%), green (1.18–10.49%), and black (0–3.2%)	20.833 ± 2.522–76.400 ± 7.869 items/ individual	Arshad et al. (2023)
	Chattogram and Patuakhali, Bangladesh, Brakishwater, Freshwater, Estuaries	*Harpadon nehereus, Trichiurus sp., Setipinna phasa*	240	GIT, gills and muscles	LDPE (38%), PS (22%), PVC (16%), PA (13%) and EVA (9%)	Fibers (66%), fragments (27.38%), microbeads (3.59%), film (1.48%), foam (1.31%), and pellet (0.25 %)	0.5 mm	FTIR	Red (41.55%) brown (22.11%), blue (16.32%), pink (11.69%), purple (5.10%), and green (2.25%)	*H. nehereus* (0.21 items/g), *S. phasa* (0.06 items/g), and T. *S. phasa* (46.00 items/g)	Hasan et al. (2023)
	Uttar Pradesh, India, Freshwater	*Cyprinidae, Channidae*	35	GIT, gills, and dorsal muscles	LDPE and HDPE	Fibers (73.3%), fragments (21.9%), and pellets (4.74%)	250–500 µm	Raman spectra	Black (35.9%) and blue (26%)	7.86 ± 2.0 items/ individual	Pandey et al. (2023)
	Punta Verde, San Antonio, Marine	*Eleginops maclovinus*	90	Stomach	HDPE and PP	Fibers (90%) and fragment (10%)	0.09 to 1.5 mm	FTIR	Blue (32%), red (26%) yellow (15%), black (10%), orange (10%), and transparent 7%)	3–5 items/ individual	Mendoza et al. (2023)

Table 1. (Continued.)

Osteichthyes	Eastern Sea of Marmara, Türkiye, Marine	*Rachurus mediterraneus, Chelon auratus, Merlangius merlangus, Mullus barbatus, Symphodus cinereus, Gobius niger, Chelidonichthys lastoviza, Chelidonichthys lucerna, Trachinus draco, Scorpaena porcus, Scorpaena porcus, Pegusa lascaris and Platichthys flesus*	374	GIT	PET (75%)	Fibers (74%), films (18%), and fragments (7%)	1.82–1.59 mm	FTIR	Blue (62%)	1.77 ± 0.95 items/individual	Aytan et al. (2023)
	Mexico, Marine	*Caulophryne jordani, C. pátzcuaro*	25	GIT	PS, ABS, PVA, ethylene-propylene copolymer, nylon-6, cellophane, and viscose	Fibers (67.55%), fragments (29.18%), film (3.00%), and sphere (0.27%)	<500µm (84%)	ATR-FTIR	Transparent (67.35%)	*C. jordani* (15.17 ± 5.90 items/g), *C. pátzcuaro* (7.82 ± 2.90 items/g)	Kutralam-Muniasamy et al. (2023)
	Antarctic, Marine	*Trematomus eulepidtus, Chionodraco rastrospinosus, Notolepis coatsi, Electrona carlsbergi*	114	GIT and gills	PP, PA, and PE	Fiber and fragments	<3 mm	FTIR	N/A	*Trematomus eulepidotus* (1.7 ± 0.61 items/individual), *Chionodraco rastrospinosus* (1.4 ± 0.26 items/individual), *Notolepis coatsi* (1.1 ± 0.57 items/individual), and *Electrona carlsbergi* (0.72 ± 0.19 items/individual).	Zhu et al. (2023b)

Table 1. (Continued.)

	Magdalena River, Colombia, Freshwater	*Andinoacara latifrons, Astyanax magdalenae, Caquetaia krausii, Oreochromis niloticus* and *Poecilia gilli*	228	GIT	PA (53.8%), PS (34.7%), PMMA (7.7%), and PTFE (3.8%)	Fiber (93%)	2 mm	FTIR	Blue and white	2.8 ± 2.7 items/ individual (wet season) and 2.0 ± 3.6 MPs/ individual (dry season)	Miranda-Peña et al. (2023)
	Vaal river, South Africa, Freshwater	Carp Fish	26	GIT	HDPE, LDPE, PP, PET, and PTFE	Fibers (69%), fragments (23%), films (6.2), pellet (0.7), and foams (0.9)	0.5 mm (48%), 0.5 to 2 mm (44%) and 2–5 mm (8%)	Raman spectra	Green (36%), blue (25%), black (21%), red (6%), white (4%) and others (2%)	2623 ± 12.7 items/ individual	Saad et al. (2022)
	Orontes River, Türkiye, Freshwater	Prussian carp, Abu mullet, Common carp, European ell, North African catfish, and Goldfish	153	Stomach	PE (34%), PE derivatives (34%) and PA (5%)	Fibers (95%) and fragments (4%)	1000 µm	FTIR	Black (53%), blue (17%), white/ transparent (12%), red (11%), green (4%), brown (2%), and orange (1%)	5.1 ± 2 items/ individual	Kılıç and Yücel (2022)
	Han River, South Korea, Freshwater	Demersal and pelagic fishes	106	GIT (Stomach and Intestine)	PP (≥40%), PE (≥23%), and PTFE (≥16%)	Fragments (>95%) and fibers (5%)	0.54 ± 0.93 mm	FTIR	N/A	17.4 ± 11.9 items/ individual	Park et al. (2022)
	South Tamil Nadu, India, Marine	*Sardinella gibbose, Leiognathus lineolatus*	677	Stomach	PP polymers predominated (96.77% and 95.23%) and PS (3.22% and 4.76%)	Fragments, fibers	2 mm	FTIR	Blue, black	1.34 ± 0.56 items/ individual	Kalaiselvan et al. (2022)
	Mendoza River, Argentina, Freshwater	*Oncorhynchus mykiss, Salmo trutta, Hatcheria macraei*	46	GIT	Fibers	Fiber (80%) and fragments (20%)	0.4–5 mm	N/A	Blue (57.75%), black (26.76%), red (7.04%), white (5.63%), and yellow (2.21%)	3.02 ± 1.01 items/ individual	Ríos et al. (2022)

Table 1. (Continued.)

	Eastern Coast of Thailand, Marine	Demersal and pelagic fishes	274	GIT and gills	PET (83.33%), PE (8.33%), and PP (8.33%)	Demersal fish (Fibers 83.33%, film 16.67%) and pelagic fish (Fibers 88.89%, fragment 7.14%, film 3.57%%)	0.33–5.00 mm	FTIR	Demersal fish (black 66.67%, blue 22.22%, others 11.11%) and pelagic fish (black 50%, red 33.33%, green 16.67%)	0.14 items/ individual	Phaksopa et al. (2021)
	Bangladesh Marine	Demersal and pelagic fishes	48	GIT	HDPE, PP-PE copolymer, and EVA	Fibers (75%), fragments (19%), foam (5%) and filaments (1%)	61 µm to 5 mm,	FTIR	Transparent, blue, and red	9–0.5 items/ individual	Parvin et al. (2021)
	South Sulawesi, Indonesia, Freshwater	Milkfish	50	Intestine	HDPE	Line (92.6%) and fragments (7.4%)	<1 mm	N/A	Blue (70%), purple (25.7%) black (13.7%), grey (8.6%), red (6.29%), yellow (4%), and transparent (1.71%)	3.5 items/ individual	Amelinda et al. (2021)
	Kermanshah city, Iran, Freshwater	*Leuciscus cephalus, Capoeta trutta, Alburnus chalcoides, Capoeta damascina, Barbus capito, Cyprinion macrostomum, Luciobarbus caspius*	48	GIT (Stomach)	PS, PE, and nylon	Fibers (85.12%) fragments (12.32%), films (1.22%), foam (0.77%), microbeads (0.56%)	0.025–1 mm	FTIR	Black (63%), white (18%), blue (7%), red (7%), yellow (3%), and green (2%)	6.04 ± 2.07 items/ individual	Heshmati et al. (2021)

Table 1. (Continued.)

	Bohai Sea, China, Marine	Commercial fishes	584	GIT	Cellophane (77.5%), PET (16.9%) and PP (2.5%), PAN (0.9%), PE (0.5%), PVA (0.5%), PA (0.4%), PS (0.4%), polybutene (0.2%), and PC (0.2%)	Fibers (93.3%), Fragments (3.6%), pellet (2.0%), and film (1.1%)	18.73-500 µm	µ-FTIR	Transparent	2.14 ± 1.81 items/ individual	Wang et al. (2021b)
	Lagoon of Bizerte, Tunisia, Marine, Brakish	*Liza aurata*, *Sarpa salpa*	5	GIT	PP (77.27%) and PE (22.73%)	Fibers (53.57–66.46%), fragments (33.23–46.42%), and Films (0.30–0.31%).	>1–3 mm (43.14%), 3–5 mm, (34.64%), 0.5–1 mm, (19.20%) and 0.2–0.5 mm, (3.03%)	ATR -FTIR	Black, blue, red, and yellow	22.40–66.40 items/ individual	Abidli et al. (2021)
	Beibu Gulf, South China Sea., Marine	Demersal and pelagic fishes	481	GIT (Stomach, Intestine) and gill	PES (44%), nylon (38%), PP (6%), PE (6%), and acrylics (6%)	Fibers (96%) were the dominant MPs shape followed by fragments (2%), and films (2%)	0.02–3.00 mm	FTIR	Transparent (83%), blue (11%), red (4%) and green (2%)	0.027 to 1.000 items/ individual	Koongolla et al. (2020)
	Aegean, and Mediterranean coasts, Türkiye, Marine	Leaping mullet, red mullet, surmullet, Mediterranean horse mackerel, and sand steenbras	243	GIT	PP (26%), PE (21.9%), PET/ PES (8.2%), and cellulose (7.5%)	Fibers (50.6%) and fragments (49.4%)	1.63 ± 0.07 mm	µ-Raman spectra	N/A	2.5 items/ leaping mullet, 1.1 items/red mullet, 0.6 items/ sand steenbras, and 0.4/ Mediterranean horse mackerel and surmullet	Gündoğdu et al. (2020)

Table 1. (Continued.)

Chondrichthyes	North Atlantic Ocean, Marine	*Galeocerdo cuvier*	8	Stomach	PP (29%) and acrylic (23%)	Fragments (57%), fibers (41%), films, foams, and spheres (0–2%)	>355 µm	ATR-FTIR + Raman	Blue (49%), clear (30%) and black (11%)	N/A	Munno et al. (2024)
	South-East coast, Ibiza, Marine	*Scyliorhinus canicula*, *Galeus melastomus*	32	Intestine	PS, PE, silicone, nylon, cellophane, and nitrile	Fibers (64%)	N/A	µ-ATR-FTIR	Blue (60.1%), black (29.1%), white (3.9%), transparent (3.0%), red (1.5%), purple (1%), pink (1%), and orange (0.5%)	6.34 ± 1.5 items/ individual	Torres et al. (2024)
	Rainbow Beach, Queensland, Australia, Marine	*Carcharhinus leucas*, *Carcharodon carcharias*, (*Galeocerdo cuvier*, *Sphyrna lewini*	14	Intestine	Cellulosic fibers (70%), PET, PE and PP (30%)	N/A	90–4860 µm	FTIR	N/A	3.1 ± 2.6 items/ individual	Lu et al. (2024)
	Peninsular Malaysia, Marine	*Carcharhinus dussumieri*, *Carcharhinus sorrah*, *Chiloscyllium hasseltii*, *Chiloscyllium punctatum*, *Scoliodon laticaudus*	74	Stomach + gills	PES (43.95%), PE (23.77%), PP (18.39%), PET (10.76%), and PU (3.14 %)	Fibers (84.44%) fragments (14.16%) and foams (1.36%)	0.001–1 mm	Raman spectra	Black (40.07 %), blue (31.48 %), red (7.19 %), white (7.15 %), yellow and transparent (6.06 %), other colors, such as green, purple, and silver, were less frequent	29.88 ± 2.34 items/ individual	Matupang et al. (2023)
	South of Sicily, Marine	*Scyliorhinus canicular*	61	Intestine	N/A	Fibers (84%) and fragments (16%)	0.05–42.3 mm	N/A	Black (19 %), blue (18 %), transparent (15 %), and red (11 %)	2.4 items/ individual	Monique et al. (2022)
	Bay of Bengal, India, Marine	*Rhizoprionodon acutus*	40	Intestine	PE, PA, and PP	Fibers (42%), fragments (26%), granules (20%), film (5%), and foam (7%)	3.2 ± 2.2 mm	FTIR	Blue, pale white (54.0%), transparent, black, red, yellow, and others (13%)	4.67 items/ individual	Janardhanam et al. (2022)

Table 2. Summary of characteristics and abundance of microplastics in sea turtles around the world.

Location	**Species studied**	**Individuals examined**	**Organ analyzed**	**Prominent polymer type**	**Prominent shape**	**Prominent size**	**Prominent color**	**Advanced technology**	**Concentration (items/ individual/g ± SD)**	**References**
Mexican Caribbean	Green sea turtle Chelonia mydas	22	Feces	Nylon (75%), PVC (10%), PP (5%), PE (5%), and cellulose (5 %)	Fibers (98%) and fragments (2%)	2100 µm ± 925	Blue, black, and transparent	FTIR + Raman spectra	21–40 items/g	Aranda et al. (2024)
Gulf of Oman	Green and loggerhead sea turtles	63	Esophagus, stomach and intestines	Green turtle (PP 44.7%, PE 22.6%) and loggerhead turtle (PP 36.2%, PE 36.2%)	Green turtle (bottle caps (72.4%), plastic wrapping sheets (20.5%) and unknown materials (6.2%) and loggerhead turtle (plastic wrapping sheets (43.4%), bottle caps (40.8%), plastic bags (8.63%) and ropes and rope monofilaments (7.3%)	N/A	N/A	ATR-FTIR	47.50 ± 12.49 items/g	Yaghmour et al. (2022)
Balearic Islands coast	*Caretta caretta* and *Linnaeus*	45	GIT and fecal	HDPE (42.3%), PP (33.8%), LDPE (17.8%), PS (2.8%), nylon (2.3%), and PU (2%)	Threads, sheets, fragments and foam	77.1 ± 26.7 mm	White (42.7%), transparent (29.7%), black (8.1%), green (5.7%), blue (4.9%), gray (2.7%), colored (2.4%), red (1.8%), brown (0.9%), yellow (0.8%), orange (0.6%), and pink (0.3%)	FTIR	12.7 ± 4.7 items/ individual	Solomando et al. (2022)

Table 2. (Continued.)

Southern Tyrrhenian, Italy	*Caretta caretta*	12	GIT	PE (48.2%), PP (34.2%), PS (7.05), PES (4.0%), polyisoprene (1.7%), HDPE (0.9%), PVC, PA and PU (0.9%)	Fragments (52.6%), sheets (38.6%), nylon, net fragments, elastic-plastic, foamed plastic, and industrial granules (8.8%).	5–25 mm	White-transparent (64.9%), followed by light (19.3%) and dark (15.8%)	ATR-FTIR	2.7 ± 1.8 items/individual	Bruno et al. (2022)
Korea	*Caretta caretta, Chelonia mydas, Dermochelys coriacea* and *Lepidochelys olivacea*	34	GIT	PE, PP, and expanded PS	Film (42%), fibers (39%), fragment (10%) and foam (9%)	70.9 ± 63 mm	White/transparent (65%), green (11%), mixed (11%), yellow (6%), black (3%), and others (each <3%)	FTIR	38 ± 61 items/individual	Moon et al. (2022)
Western Mediterranean subregion	*Caretta caretta*	226	GIT	PE (65.98%) and PP (26.23%)	Sheets and fragments	N/A	N/A	FTIR	0.17 ± 2.17 items/individual	Camedda et al. (2022)
North Atlantic Subtropical Gyre (NASG)	Green turtles (*Chelonia mydas*)	21	Esophagus, stomach and intestines	PE	Fragments (96%), soft plastic (1.5%), pellets (1%), threads (1%) and foam (0.5%)	1–5 mm	White/transparent (98.5%), black, blue, and red (0.5% each)	N/A	0–168 items/individual	Rodríguez et al. (2022)
Southern Brazil	*Chelonia mydas*	17	Stomach	Plastic bags, plastic sheets, hard plastic, and threadlike plastic	N/A	1 to >100 mm	White (76.5%), transparent (52.9%), green (41.1%), yellow, blue (35.2%), red and black (17.6%), brown (11.7%) and pink, purple, grey, and orange (5.8%)	N/A	38.4 ± 88.5 items/individual	Petry et al. (2021)

Table 2. (Continued.)

Coast of Texas, USA	*Chelonia mydas*	464	Esophagus/ stomach, and small and large intestines	N/A	Sheets (37.8%), fragments (27.1%) and threads (22.9%)	N/A	Clear (33.09), white (24.95), brown (14,70%), black (9.10%) yellow (6.40%), green (4.10%), blue (2,51%), red (1.91%), pink (1.122%), grey (1.42%), and orange (0.595)	N/A	6.2 ± 14.1 items/ individual	Choi et al. (2021)
Florida's central Atlantic coast (USA)	*Caretta caretta, Chelonia mydas* and *Eretmochelys imbricata*	380	GIT	PE	Fragments	3.57 ± 2.4 mm	White and clear	FTIR	33 ± 23 items/ individual	Rice et al. (2021)
Queensland, Pacific Ocean (PO) and indian ocean (IO), Australia	Green turtle, loggerhead turtle, flatback turtle, hawksbill turtle, and olive ridley turtle	121	GIT	PE (PO-58%; IO-39%) and PP (PO-20.2%; IO-23.5%)	PO (Fragment 52% and sheets 38%) and IO (filaments 52% and sheets 35%)	>1 mm	Clear (PO 36%; IO: 39%), white (PO 36%), green, and blue (IO: 16%; 16%)	FTIR	N/A	Duncan et al. (2021)
East Mediterranean Sea, Greek	*Caretta caretta*	36	Oesophagus, stomach, and intestine	PP (56%), PE (29%), nylon (7%), PVC (2%), PS (2%) and PET (1%).	Threads (45%), sheets (36%), fragments (16%), foam (2%), and unclassified item (1%)	47 ± 3.6 mm	White and transparent	FTIR	7.94 ± 3.85 items/individual	Digka et al. (2020)
North Atlantic subtropical gyre	Caretta caretta	24	Oesophagus, stomach, and intestines	PE (60%), PP (20%), and other polymers (12%)	Fragments (67.6%), sheets (31.1%) and foam (1.3%)	1–5 mm	White (45%) and transparent (21%)	µ-FTIR	15.83 ± 6.09 items/ individual	Pham et al. (2017)

3.2.3. Mammals

Small plastics disperse more rapidly in the aquatic environment than larger ones, increasing the likelihood of ingestion by a wide range of mammals. Research has shown that MPs are prevalent in marine mammals at high trophic levels (Dool and Bosker, 2022; Kangas et al., 2023). Often, the majority of MPs found in whales and dolphins are believed to result from trophic transfer rather than direct ingestion (Dool and Bosker, 2022; Moore et al., 2022). Aquatic mammals ingest significant amounts of MP particles, likely through direct consumption from sediment or seawater, as well as through trophic transfer, i.e. via prey species that have consumed plastic. MPs have been discovered in the feces and stomachs of pinnipeds and cetaceans, as well as throughout their digestive tracts (Merrill et al., 2023). Direct accidental ingestion of MPs by aquatic mammals can lead to blockages in the GIT (Trani et al., 2023). The survival of aquatic fauna, particularly top predators like aquatic mammals, is seriously threatened by MPs, which pose significant health risks (Nabi et al., 2022). Many aquatic mammals are of conservation concern due to various anthropogenic stressors, and they serve as indicators of the aquatic ecosystem's health, especially concerning pollution. Similar to sea turtles and humans, aquatic mammals have long lifespans and feed at high trophic levels, exposing them to chemical pollutants in food. They may therefore serve as useful sentinels to detect effects that could eventually impact humans. The European Marine Strategy Framework Directive has proposed large aquatic mammals as indicators for the occurrence, consumption, and monitoring of MPs. As can be seen in Table 3, the occurrence and ingestion of MPs in mammals confirm that these aquatic mammals commonly ingest MPs due to their feeding activities.

According to Wan et al. (2023) and Werth et al. (2024), cetaceans may consume tens of thousands of pieces of MPs daily during feeding. The most frequently consumed MPs, including PE of both high and low density, PP, PET, and PS, come in various sizes, from tiny fragments to large sheets, and have been found in mammalian stomachs and intestines. The abundance of MPs is randomly dispersed, irrespective of the animal's body length or sexual maturity. In cetaceans, maturity did not significantly correlate with MP counts, as observed in harbor porpoises (Philipp et al., 2021). Similarly, there was no significant correlation between MP abundance and body length. Zhang et al. (2021) noted a similar trend as the body length of humpback dolphins showed an insignificant relationship with the abundance of MPs. The sex of the individual did not significantly impact the number of MPs in different cetaceans (Xie et al., 2024b). Moreover, MPs have been discovered in the GITs of almost all aquatic mammals (Battaglia et al., 2020; Yang et al., 2023; Wulf, 2023). The presence of MPs in GITs sometimes leads to wear and tear of the digestive tract and impairment in the intestinal tract of mammals such as baleen and beluga whales (Yang et al., 2023; Werth et al., 2024). MPs were found throughout the GITs, and a sizable amount of what was consumed was frequently expelled in feces (Harlacher, 2020; Yong et al., 2021). MPs can disperse into the body during their transition from the stomach, which stores food, to the intestine, which absorbs nutrients (Ma et al., 2021). Absorption and excretion of MPs by large aquatic animals require further investigation. Researching large aquatic animals poses challenges due to factors such as difficulty in obtaining samples and their protected status, potentially leading to an underestimation of the MP issue. During necropsies, obtaining viable samples from large cetaceans can be challenging. It is advised that global assessments of the dangers associated with cetaceans consuming MPs and the presence of MPs in their environments be carried out. More research in various regions will be required to gather more details regarding MP ingestion/occurrence in large aquatic mammals.

4. Effects of MPs on aquatic organisms

Oceans today are increasingly impacted by human-induced factors, such as MP pollution. MPs pose a significant threat to aquatic ecosystems, and the extent of their impact on the genetics of aquatic life is an active area of research. Understanding the genetic effects of MP pollution is crucial for the conservation and sustainability of aquatic ecosystems. Aquatic organisms become contaminated with MPs primarily through ingestion, either from contaminated prey or through direct uptake of particles from the water, exposing them to numerous potential health risks (Baalkhuyur et al., 2020). Studies have shown that MPs can negatively affect the reproductive capabilities of aquatic organisms (Junaid et al., 2024). For example, exposure to MPs can impair egg development and larval growth in fish and disrupt the reproductive cycles of aquatic shellfish. The genetic impacts of MPs on aquatic organisms are mediated through several mechanisms, including DNA damage, changes in gene expression, genetic mutations, and epigenetic effects.

4.1. DNA damage

MPs can cause DNA damage in aquatic organisms due to various chemicals they absorb and toxic substances secreted by other biological organisms onto their surfaces. This damage can directly cause fractures or mutations in DNA chains. Chemicals such as phthalates and bisphenol A, commonly found in some plastics, can adversely affect the reproduction and development of aquatic organisms. For example, Gonçalves et al. (2022) investigated the effects of PS nanoplastics on the marine mussel *Mytilus galloprovincialis.* They used a multiple-biomarker

Table 3. Summary of recent studies on the occurrence of microplastics in aquatic mammals along with type, shape, color, and concentrations.

Group	Location	Species studied	Individuals examined	Organ analyzed	Polymer type	Shape	Size	Advanced technology	Color	Concentration (items/ individual/g ± SD)	References
Seals	Donna Nook, Lincolnshire.	*Halichoerus grypus*	66	Fecal	N/A	Fibers (61%) and fragments (39%)	248 ± 264 µm	FTIR	Light blue (36%), clear (29%), blue (14%), white (11%), yellow, black, and red (3%)	0.81 ± 0.77 items/ individual	Desclos-Dukes et al. (2022)
	Zakynthos Island	Monk seal	12	Fecal	PA and PC	Filaments (84.9%), fragments (14.6%), and spheres (0.6%)	Filaments (2.78 mm), fragments (509.6 mm), and spheres (132.74 µm)	FTIR	Blue (39.16%), transparent/ translucid (34.34%), red (7.83%), green (6.02%), yellow (6.02%), and other (5%)	6-24 items/ individual	Hernandez-Milian et al. (2021)
	Liaodong Bay, Northeast of China	*Phoca largha*	2	Stomach	PE (40%), PP (20%), PAN (13.33%), and others (26.66%)	Fibers (60%), fragments (33.33%), and pellets (6.67%)	1196 ± 671 µm	N/A	N/A	1.33 ± 1.52 items/g	Wang et al. (2021c)
	Southeastern Massachusetts, USA	Harbor seal and grey seal	161	Fecal	Alkyd resin, Cellophane, d poly (ethylene:propylene:diene) and rubber	Fibers and fragments	>5 mm	FTIR	Tan, white, purple and red	N/A	Hudak and Sette, (2019)
	Irish south coast	*Halichoerus grypus*	13	Intestine	N/A	Fibers (85%), fragments (4%) and films (1%)	N/A	N/A	N/A	27.9 ± 14.7 items/ individual	Hernandez-Milian et al. (2019)

Table 3. (Continued.)

Dolphin	Southeastern coast, Brazil	*Sotalia guianensis*	12	Forestomach + intestine	PP (28.57 %) and PE	Fragments (87.79 %), films (10.56 %), and spheres (1.64 %)	6.39–1701.72 µm	N/A	Blue (61.73 %), black (22.06 %), green (6.8 %), and red (6.1 %)	N/A	Da Silva et al. (2024)
	Western Coast, Taiwan	*Delphinus delphis*, *Kogia breviceps*, *Mesoplodon ginkgodens*, *Sousa chinensis*	9	Intestine	PET (39.5%), PP (17%), PS (14.5%), PA (8%), rayon (6.7%), and PE (3%)	Fibers (23.7–96.9%)	0.5–5 mm	FTIR	Transparent (48.6%), white (15.6%), black (14.4%), yellow (8.5%), blue (7.1%), red (3.5%), and green (2.6%)	86.44 ± 12.22 items/individual	Aierken et al. (2024)
	Romanian coast, Black Sea	*Phocoena phocoena relicta*, *Tursiops truncatus ponticus*	9	Stomach + intestine	N/A	Fibers (91.78%), fragments (8.12%), and spherical beads (0.09%)	22.86–5776 µm	N/A	Black (34%), blue (32%), clear (28%), red, white, grey, brown and green (6%)	N/A	Filimon et al. (2024)
	Eastern Baja California Sur, México	*Coryphaena hippurus Linnaeus*	51	Stomach + intestine	Nylon (29%), PP (29%), PE (11%), PET (6%), and HDPE (8%)	Fragments (68%), Fibers (29%), and films (1.3%)	N/A	ATR-FTIR	White, yellow, blue, black, green, red, rose, and transparent	N/A	Rosas et al. (2023)
	Northeastern Brazil	*Sotalia guianensis*	40	Stomach	PU, PET, EVA (18% each), styrene-butadiene rubber, PP, PA, ABS and HDPE (9% each)	Fragments (57.2%), filaments (15.8%), foam (10.3 %), films (9.6%), and beads (7.1 %)	0.36 ± 0.03 mm	N/A	White and black (39.5%), blue (13.2%), green (4.2%), and red (3.5%)	7.77 ± 1.25 items/individual	Pereira et al. (2023)

Table 3. (Continued.)

	Pearl River Estuary China	*Sousa chinensis*	12	Stomach	PP (20.3%), PE (19.9%), cellulose (12.5%), cellophane (12.5%), PET (12.0%), nylon 6 (7.4%), chloroprene rubber (6.2%), PVA (4.0%), polyphenylene sulfide (2.1%), polyp-phenylene oxide (2.0%), EVA (0.5%), PS (0.3%), and PVC (0.3%)	Fibers (69.6%), irregular particles (22.5%), films (4.8%), and pellets (3.1%)	1.69 ± 1.04 mm	FTIR	White (31.9%), gray (16.5%), black (16.5%), blue (10.1%), yellow (8.2%), orange (6.9%), brown (3.4%), red (3.3%), green (1.9%), and pink (1.4%)	53 ± 35.2 items/ individual	Zhang et al. (2021)
	Coast of New Zealand	*Delphinus delphis*	15	Stomach	PET (65%), PP (31%), and ABS (20%)	Fragments (77%) and fibers (23%)	100–1000 μm	FTIR	Translucent/ clear (46%), black (10%), orange (10%), and multicolored (10%)	7.8 ± 1.4 items/ individual	Stockin et al. (2021)
	South Carolina, USA	*Tursiops truncatus*	7	Forestomach Fundic + pyloric Intestine	PP, PE, PET	Fibers, Fragments, Films and Foams	1–5 mm	FTIR-ATR	White/clear (66.6%), black/ grey (12.6%), blue (9.1%), red/ pink (3.4%), yellow (3.4%), orange (1.8%), brown/tan (1.7%), green (1.0%), and purple (0.4%)	280.6 ± 113.0 items/ individual	Battaglia et al. (2020)
	Western Mediterranean Sea	*Stenella coeruleoalba*	47	Intestine	PA (40.9%), PET (27.3%), alginic acid (13.6%), and HDPE (9.1%)	Fibers (73.6%) and fragments (23.87%)	N/A	FTIR	Black (50.1%), red (21.2%), translucent (10.9%), white (3.8%), and other less frequent colors, such as yellow	14.9 ± 22.3 items/ individual	Novillo et al. (2020)

Table 3. (Continued.)

Whales	Alboran Sea	Cuvier's beaked whales	2	Stomach	Cellulose fiber (26.9%), polyacrylic fiber (23.1%), PP (15.4%), and PET (11.5%)	Fibers	11.29 ± 9.73 mm	µ-FTIR	Black (64.0%), red (20.0%), and blue (16.0%)	10.9 ± 11.8 items/ individual	López-Martínez et al. (2023)
	Coastal Auckland waters, New Zealand	Baleen whales	2	Scats	Cellulose, PES, and PE	Fibers (99%) fragments and films (1%)	1085 ± 1395 µm	FTIR	Blue or black fibers (83%), red (9%), clear (3%), green (2%), brown (2%), and purple (1%)	N/A	Zantis et al. (2022)
	Oslob, Cebu, Philippines	*Rhincodon typus*	40	Fecal	PP (59.2%), PE (33.5%), PES (4.5%), PS (2.2%), and nitrile rubber (0.6%)	Fragments and fibers	1.12 ± 0.7 mm	ATR-FTIR	Transparent (54.8%), blue (17.9%), and white (14.5%)	N/A	Yong et al. (2021)
	Western Iceland	Fin whales	25	Stomach	Cellulose (37.5), PE (18.8%), PS (18.8%), PP (18.8%) and acrylonitrile (6.1%)	Fibers (69%) and fragments (31%)	0.5 mm	µ-FTIR	Blue (62.5%), red and black (37.5)	N/A	Garcia-Garin et al. (2021)
	Eastern Beaufort Sea	*Delphinapterus leucas*	7	Stomach, intestine, and fecal	PET/PES and others	Fragments (51%) and fibers (49%)	<5 mm	FTIR	N/A	97 ± 42 items/ individual	Moore et al. (2020)
	North Atlantic Ocean	*Galeocerdo cuvier*	8	Stomach	PP (29%) and acrylic (23%)	Fragments (57%), fibers (41%), films, foams, and spheres (0–2%)	>355 µm	ATR-FTIR + Raman	Blue (49%), clear (30%), and black (11%)	N/A	Munno et al. (2024)
	South-East coast, Ibiza	*Scyliorhinus canicula, Galeus melastomus*	32	Intestine	PS, PE, silicone, nylon, cellophane, and nitrile	Fibers (64%)	N/A	µ-ATR-FTIR	Blue (60.1%), black (29.1%), white (3.9%), transparent (3.0%), red (1.5%), purple (1%), pink (1%), and orange (0.5%)	6.34 ± 1.5 items/ individual	Torres et al. (2024)
	Rainbow Beach, Queensland, Australia	*Carcharhinus leucas, Carcharodon carcharias,* (*Galeocerdo cuvier, Sphyrna lewini*	14	Intestine	Cellulosic fibers (70%), PET, PE, and PP (30%)	N/A	90–4860 µm	FTIR	N/A	3.1 ± 2.6 items/ individual	Lu et al. (2024)

Table 3. (Continued.)

Condroichties	Peninsular Malaysia	*Carcharhinus dussumieri, Carcharhinus sorrah, Chiloscyllium hasseltii, Chiloscyllium punctatum, Scoliodon laticaudus*	74	Stomach + gills	PES (43.95%) PE (23.77%), PP (18.39%), PET (10.76%), and PU (3.14 %)	Fibers (84.44%) fragments (14.16%), and foams (1.36%)	0.001–1 mm	Raman spectra	Black (40.07 %), blue (31.48 %), red (7.19 %), white (7.15 %), yellow and transparent (6.06 %), other colors, such as green, purple, and silver, were less frequent	29.88 ± 2.34 items/ individual	Matupang et al. (2023)
	South of Sicily	*Scyliorhinus canicular*	61	Intestine	N/A	Fibers (84%) and fragments (16%)	0.05–42.3 mm	N/A	Black (19 %), blue (18%), transparent (15%), and red (11%)	2.4 items/ individual	Monique et al. (2022)
	Bay of Bengal, India	*Rhizoprionodon acutus*	40	Intestine	PE, PA, and PP	Fibers (42%), fragments (26%) granules (20%), film (5%), and foam (7%)	3.2 ± 2.2 mm	FTIR	Blue, pale white (54.0%), transparent, black, red, yellow, and others (13%)	4.67 items/ individual	Janardhanam et al. (2022)

approach, including genotoxicity assessments with a comet assay on mussel hemocytes, and evaluated antioxidant enzymes (superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx)), a biotransformation enzyme (glutathione-S-transferase (GST)), and oxidative damage (lipid peroxidation (LPO)) in the gills and digestive glands. Their findings indicated that exposure to nanoplastics suppressed antioxidant enzymes, leading to oxidative damage in tissues, and that mussel tissues struggled to cope with this emerging stressor.

Similarly, Jaouani et al. (2023) explored the effects of aging PE MPs in *Mytilus edulis*, widely used as a bioindicator of aquatic ecosystems, at varying concentrations in marine waters both in vitro and in vivo. They assessed changes in gene expression levels related to detoxification, the immune system, the cytoskeleton, and cell-cycle control through quantitative RT-qPCR. The results showed variable expression levels dependent on the state of plastic degradation (aged vs. unaged) and exposure mode (in vitro vs. in vivo).

Recent studies on the biological effects of MPs have increased exponentially, but knowledge of their impact on freshwater fish and the mechanisms of these biological effects remains limited. PP MPs, for example, persist in freshwater ecosystems and biota, presenting ongoing threats. Continuous ingestion of these MPs disrupts fish homeostasis; elevates levels of reactive oxygen species (ROS); alters antioxidant parameters such as SOD, CAT, GST, and GPx; and increases lipid oxidation and the denaturation of the neurotransmitter enzyme acetylcholinesterase (AChE). Moreover, higher rates of apoptosis, DNA damage, and histological changes have been observed in liver tissues of *Oreochromis mossambicus*, *Danio rerio*, and *Perca fluviatilis* exposed to MPs (Kaloyianni et al., 2021; Umamaheswari et al., 2021; Jeyavani et al., 2023). Another study revealed that including PP MPs in the diets *of D. rerio* and *P. fluviatilis* inhibited cellular functions in the gills and hepatic cells due to lipid peroxidation, DNA damage, protein proliferation, apoptosis, autophagy, and metabolic changes (Bobori et al., 2022).

In Nile tilapia (*Oreochromis niloticus*), SOD, CAT, total peroxides, and oxidative stress index activities, as well as lipid peroxidation and DNA fragmentation, increased in a dose-dependent manner in groups exposed to MPs at the early juvenile stage. MPs caused an overproduction of ROS, leading to oxidative stress and DNA damage by altering antioxidant parameters (Hamed et al., 2020). In rainbow trout (*Oncorhynchus mykiss*), inhibition of GSH levels and antioxidant enzyme activities was detected in all tissues targeted for the monitoring of oxidative stress. Exposure to different PE MP-supplemented feeds significantly upregulated DNA damage, apoptosis profiles, and ROS-mediated apoptotic responses in a dose-dependent manner (Atamanalp et al., 2023).

4.2. Changes in gene expression

MP pollution can alter gene expression in aquatic organisms, potentially leading to changes in biological processes. Barboza et al. (2018) demonstrated that exposure to binary mixtures of MPs and mercury in juvenile European sea bass (*Dicentrarchus labrax*) for 96 h resulted in neurotoxicity, as evidenced by inhibition of AChE, increased LPO in the brain and muscles, and altered activities of energy-related enzymes lactate dehydrogenase (LDH) and isocitrate dehydrogenase (IDH). Specifically, this study indicated that MPs and mercury, both alone and in combination, caused neurotoxicity, oxidative stress, and changes in energy-related enzyme activities in offspring.

Biofilm layers formed on the surfaces of MPs can also impact the genetic structure of aquatic organisms by modifying gene expression. This could negatively affect reproduction, growth, immune function, and other biological processes. Arias-Andres et al. (2018) compared biofilm-forming bacterial communities on MPs and discovered that aquatic bacteria can transfer a model antibiotic resistance plasmid. They used exogenous and red fluorescently labeled *Escherichia coli* as a donor strain and green fluorescently labeled pKJK5, which has trimethoprim resistance, as a plasmid. Their findings indicated a higher frequency of plasmid transfer in bacteria associated with MPs compared to free-living or naturally aggregated bacteria, suggesting that horizontal gene transfer may significantly influence the ecology of aquatic microbial communities globally. Furthermore, they noted that the spread of antibiotic resistance through MPs could have profound implications for the evolution of aquatic bacteria.

Plastic degradation results in nanoplastics that enter terrestrial and aquatic ecosystems, including oceans, rivers, and lakes. Martin-Folgar et al. (2023) explored changes in gene expression in zebrafish embryos at 120 h after fertilization following exposure to different concentrations of PS nanoplastics (30 nm). They observed that the gene encoding heat shock protein (*hsp70*) was downregulated in a dose-dependent manner, while genes encoding superoxide dismutase (*SOD1* and *SOD2*), apoptotic genes (*cas1* and *cas8*), and interleukin 1-β (*il1β*) were activated at a PS nanoplastic concentration of 3 ppm. Conversely, the antiapoptotic gene *Bcl2α* was inhibited at both 0.5 and 3 ppm. Most changes in gene expression related to oxidative stress, apoptosis, and inflammation occurred at the highest nanoplastic concentration. In another study, Qiang et al. (2020) examined potential transgenerational effects in zebrafish offspring after parental exposure to PS MPs. qRT-PCR analysis revealed an increase in mRNA expression of the *hmgcra*, *hmgcrb*, and *hsd3b2* genes associated with fish gonads in response to MPs of 1 µm at 1000 µg/L. They also reported significant MP accumulation in zebrafish intestines and notable changes in steroidogenic mRNA expression in gonads at concentrations above 100 µg/L.

MPs, and particularly PP, cause various changes in gene expression. Corinaldesi et al. (2021) studied the nutritional activity of red coral (*Corallium rubrum*) exposed to MPs, assessing defense mechanisms, tissue damage due to physical contact, and molecular responses such as gene expression and DNA damage. They found significant changes in malnutrition responses, mucus production, and gene expression levels of *cytb*, *mtMutS*, *hsp70*, and *EF1* in corals exposed to medium and high concentrations of MP particles.

In a study of fish immune systems, Liu et al. (2019) evaluated the effect of MPs on enzyme activity and gene expression in Chinese mitten crab *Eriocheir sinensis* juveniles over 7, 14, and 21 days. Their findings indicated that MPs impacted immune enzyme activities (hemocyanin (Hc), alkaline phosphatase (AKP), phenoloxidase (PO), lysozyme (LSZ), and acid phosphatase (ACP)) and immune-related gene expression, altering the diversity and composition of the gut microflora in *E. sinensis*.

4.3. Genetic mutations

MPs can cause genetic mutations by interfering with DNA replication and repair processes. These mutations may reduce the genetic diversity of aquatic organisms and contribute to genetic differences between individuals. Gao et al. (2021) noted that with the rise of nanomaterials, the detrimental effects of MPs in aquatic environments have increased, presenting health risks. In their research, they evaluated the toxic effects of PS MPs of different sizes on zebrafish, both with and without the presence of copper nanoparticles. They found that MPs affected chromosome structure and significantly disrupted the cell cycle by altering palmitoyl hydrolase activity. Additionally, MPs were shown to inhibit DNA replication, delay the progression of the S phase and G2/M phase of the cell cycle, and predominantly impact the cell-cycle pathway.

MPs also enter the organs of vertebrates, altering their behavior and triggering mutagenic and cytotoxic processes, which can lead to significant ecological consequences in freshwater ecosystems. For example, da Costa Araújo et al. (2022) studied the effects of PE MPs through an experimental food chain involving two fish species from different taxonomic groups, *Poecilia reticulata* and *D. rerio*. They observed that animals exposed to MPs exhibited higher rates of nuclear abnormalities and changes in the size and shape of erythrocytes and nuclei, suggesting mutagenic and cytotoxic effects. In the same study, da Costa Araújo et al. (2022) examined the effects of MPs mixed with other pollutants (organic and inorganic) on freshwater fish. Their findings indicated that MPs, whether alone or in combination with other pollutants, displayed genotoxic and mutagenic effects in freshwater fish but did not exhibit antagonistic, synergistic, or additive effects when mixed with the other pollutants.

4.4. Epigenetic effects

MP pollution can induce epigenetic changes in aquatic organisms. Epigenetics reflect the ways in which environmental conditions can modify the genome. These modifications typically include changes to histone proteins, structural alterations of chromatin, DNA methylation, and interference by small RNAs (Schrey et al., 2013). DNA methylation is particularly well studied among epigenetic mechanisms. Such genomic modifications can alter gene regulation without changing the DNA sequence itself, affecting gene expression and leading to variations in morphology and phenotype (Russo et al., 1996).

MPs are ingested by microscopic aquatic organisms, such as zooplankton, and can bioaccumulate up the trophic levels. The accumulation of MPs in the gut of organisms can lead to several consequences, including starvation due to blockages in the digestive tract, leakage of plastic-associated chemicals into cells, and genomic modifications. Methylation, which often correlates with decreased gene activity, is one such modification. Wilkinson (2020) explored how methylation accumulates in the genomes of cells in MP-exposed bluegill (*Lepomis macrochirus*) using methylation-sensitive amplified fragment length polymorphisms (MS-AFLPs). His findings indicated that most loci in the bluegill EBF-2 cell line were sensitive to methylation and thus susceptible to epigenetic changes. This study suggested that the duration of exposure might not be a critical factor for the increase in methylation observed in experimental cultures, implying that the mere presence of MPs is sufficient to cause cellular damage.

5. Conclusions, knowledge gaps, and future recommendations

This review has comprehensively examined the pervasive presence and ecological impacts of MPs in aquatic environments, drawing from a wide range of studies and highlighting significant findings. MPs originate from various sources, including terrestrial and aquatic activities. Terrestrial sources include wastewater treatment plants, landfills, illegal dumping, and agricultural practices, while aquatic sources encompass maritime activities such as shipping, fishing, and aquaculture. These MPs are distributed through surface runoff, wind, and riverine systems, ultimately reaching aquatic environments. MPs pose serious risks to aquatic organisms. They affect the feeding, growth, and reproductive health of aquatic species and act as vectors for harmful contaminants like persistent organic pollutants and heavy metals, exacerbating their toxicity.

MPs have become widespread pollutants, now detected in almost all studied organisms. Their impact varies across different trophic levels and feeding types. Considering the seasonal increases in pollutants due to currents, input amounts, and the rising production of plastics, future studies should extend beyond one-time assessments to long-term investigations that take into account complex food-web relationships and regional accumulation characteristics.

Invertebrates possess rich species diversity with different developmental stages, reproductive types, feeding strategies, and trophic levels, making their interactions with MPs diverse and complex. Detailed research is needed to study the uptake, excretion, and accumulation of MPs in invertebrates of the same species at different developmental stages, age groups, and sexes. Long-term and periodic (seasonal or monthly) studies in the same regions are recommended to examine the impact of MPs on species life-history traits such as growth, mortality, and reproduction. It is particularly crucial to study the effects of MPs on the molting process, which is critical for crustaceans at various life stages (e.g., zoea, megalopa, juvenile, and adult) in natural environments.

Various methods have been used for MP analysis in invertebrates, with MPs measured in tissues in different units (e.g., grams, liters, or individuals). There is a need for standardization of methodology and units within the same taxonomic groups. Due to their adhesive properties, MPs carry different pollutants and microorganisms. Examining these pollutants and pathogens in natural samples alongside the effects of MPs on aquatic organisms will provide more comprehensive results. Additionally, studying the community-level effects of MPs and nanoplastics on the food chain will contribute to the understanding of their impact on aquatic ecosystems.

Although ingestion is considered the primary exposure route for all vertebrates, inhalation and dermal exposure are also crucial for organism health. These exposure routes are largely unknown in fish, sea turtles, and other aquatic mammals, indicating significant knowledge gaps. Therefore, long-term studies should also consider nonoral exposure pathways.

Various organisms, from the smallest microalgae to the largest whales in aquatic systems, have been limitedly studied for the trophic transfer and biomagnification of MPs. This aspect requires further investigation. More research using nondestructive sampling methods is needed to understand the extent of MP impact on endangered species, such as whale sharks and humpback dolphins, and other threatened species.

Most studies rely on necropsies to understand the presence of MPs in organisms. There is a need for methodological advances to identify secondary markers for MP presence, enabling more sustainable research with less harm to natural ecosystems and organisms. While researching the effects of MPs on aquatic organisms, it is evident that most studies use pollutant concentrations that represent best-case and worst-case scenarios. Conducting studies that consider environmentally realistic concentrations is crucial for obtaining accurate results. Toxicity studies conducted with standard test materials are insufficient to understand the effects of real-environment plastics, which consist of various combinations. Considering that plastic production uses approximately 16,000 chemicals, studies conducted with raw plastics make it impossible to understand the actual toxicological impact.

Furthermore, given the potential of plastics to absorb and interact with other pollutants, different pollutant combinations should be investigated with realistic environmental concentrations and different scenarios. There is still insufficient information about which organisms are most affected by plastic pollution. Comprehensive and long-term studies are needed to identify the most sensitive, most resilient, most affected, and least affected organism groups.

Evaluating the impact of MPs in conjunction with climate change will contribute to a more accurate understanding of these effects. Negotiations for the plastics treaty initiated by the UN/UNEP in 2022 are expected to be concluded by 2025. This treaty must be legally binding, enforce production restrictions, and limit chemical use in plastic production. Local governments and central authorities should regulate the use of plastic objects, especially in areas adjacent to the feeding grounds of endangered mega-, macro-, meso-, and microfauna, imposing restrictions on plastic use.

Future research should include the genetic effects of MPs on organisms across a broader range of aquatic environments, including deep-sea and polar regions.

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Effects of microplastics on aquatic organisms: a comprehensive review

Sedat GÜNDOĞDU[1,*], **İrem Nur YEŞİLYURT**[1], **Zohaib ABBAS**[2], **Makbule BAYLAN**[1]
[1]Department of Basic Science, Faculty of Fisheries, Çukurova University, Adana, Turkiye
[2]Department of Environmental Science and Engineering, Government College University, Faisalabad, Pakistan

Appendix Table 1. Summary of recent studies on the occurrence of microplastic in aquatic invertebrates.

	Species	**Total individuals**	**Tissue**	**Digestion method**	**Anaysis**	**Microplastic shape**	**Polymer type**	**MP Size range**	**Average concentration**	**Location**	**Reference**
Porifera	*Aplysina cauliformis*	3		6% NaOCl	Fluorescence microscopy			10–3000 µm	113 ± 23 MPs/g dry w	Saigon Bay, Panama	Fallon and Freeman (2021)
	Amphimedon compressa	3						10–3000 µm	14 ± 2 MPs/g dry w		
	Callyspongia vaginalis	3						10–5000 µm	169 ± 71 MPs/g dry w		
	Ircinia campana	3						10–5000 µm	71 ± 20 MPs/g dry w		
	Mycale laevis	3						10–5000 µm	6 ± 4 MPs/g dry w		
	Niphates erecta	3						10–5000 µm	75 ± 38 MPs/g dry w		
	Ircinia variabilis				SEM/EDX			<10 µm	7.99 × 10^5 ± 1.6 per/g	Mediterranean coast of Morocco,	Krikech et al. (2023)
	Petrosia ficiformis							<10 µm	7.83 × 10^5 ± 1.5 per/g		
	Chondrosia reniformis							<10 µm	6.40 × 10^5 ± 0.6 per/g		
	Sarcotragus spinosulus							<10 µm	4.62 × 10^5 ± 1.6 per/g		
	Cinachyrella alloclada	10			Raman spectra		PP	(mean) 1.31 ± 2.32 mm	1.37 ± 0.94 g of sponge	Pituba Beach, Brazil	Soares et al. (2022)
Cnidaria	*Cosmetira pilosella*	4			FTIR	Fibers (93%)	PET, Cascamite 14 powdered resin		0.014 MPs mL^{-1}	North Sea	Devereux et al. (2021)
	Cyanea capillata					Fibers (88%)	PE, PP, PAA, PAN, PVC, PC		0.150 MPs mL^{-1} – 0.219 MPs mL^{-1}		
	Cyanea lamarckii	36				Fibers (84%)					

Appendix Table 1. (Continued.)

	Aurelia aurita					Fibers (97%)	PE, PAA, PET				
	Pelagia noctiluca	30	Tentacle, umbrella	10% KOH	µ-FTIR	Fibers (91%), fragments (6%), lines (3%)	Cotton, VI/viscose fibers. Acrylic, CP, cellulose, linen, PP, PE	N/A	2.47 ± 2.01 MPs/individual (tentacle) 1.17 ± 1.70 MPs/individual (umbrella)	Canary Island, North Atlantic	Rapp et al. (2021)
	Cassiopea xamachana	115		HNO3	µ-FTIR	Fibers (94%), fragments	VI, nitrocellulose, PU			Florida, USA	Iliff et al. (2020)
	Rhizostoma pulmo	14	Soft tissue	15% H2O2	µ-FTIR	Fibers, fragments, lines, films, pellets			2 ± 1.15 MPs/individual	Adriatic Sea	Avio et al. (2020)
	Actinia equina	50		30% H202	FTIR	Fibers (88%), fragments (12%)	VI, PE , PES, PET, PP, PA, PS, PVB, and acrylic fibers		N/A	North coast of Spain	Janssens and Garcia-Vazguez (2021)
	Galaxea astreata	2	surface and inside	H2O2 37%HCl	µ-FTIR	fibers (100%)	VI, PES/PET, PA,PP, PACA	0.5-5 mm	0.95 ± 0.66 MPs/g	Liuqiu Island, southwestern Taiwan	Lim et al. (2022)
	Acropora spp	5				fibers (100%)	VI, PES/PET, PA, PE	0.5-5 mm	0.77 ± 0.47 MPs/g		
	Pocillopora verrucosa	8				fibers (100%)	VI, PES/PET, PA, PACA, PS, PP	0.1-5 mm	0.36 ± 0.16 MPs/g		
	Pocillopora damicornis			10% KOH	µ-FTIR	fiber (93%), fragment, film	CP > PET > PS> PE	500-3500 µ	3.68 ± 3.94 MPs/cm^{-2}	Eastern coast of Hainan Island, China Sea	Tang et al. (2021)
	Galaxea fascicularis								5.89 ± 5.15 MPs/cm^{-2}		
Mollusca Gastropoda	*Littoraria scabra*	10	Soft tissue	65% HNO3		Fiber (67%), film (32%), fragment (1)			75.5 MPs/ind	Jacarta Bay, Indonesia	Patria et al. (2020)
	Batillaria multiformis	10	Whole body	10% KOH	µ-FTIR	Fiber (93%), pellet (7%)	CP (44%), PET (20%), PA (17%), PP (8.45%), PE (7%), PAN (4%)		5.37 ± 1.24 MPs g^{-1} ww	South China Sea	Xu et al. (2020a)
	Nerita chamaeleon								1.50 ± 0.20 MPs g^{-1} ww		
	Phorcus lineatus	50		30% H202	FTIR	Fiber (88%), fragment (12%)	VI, PE, PES, PET, PP, PA, PS, PVB, and acrylic fibers		0.56–148.28 MPs/g	North coast of Spain	Janssens and Garcia-Vazguez (2021)
	Steromphala umbilicaris										
	Neverita didyma	33	Soft body	10% KOH	µ-FTIR	Fiber > film > fragment > pellet	PE, PET, ABS, PAA, PVAL, PAN/PAA, PAN, PS, PF, PAN/PVC, PS/PAE, PS/PAN, PVA/PVEC	786 ± 634 µm	1.18 ± 1.40 MPs/individual	Liaohe Estuary, China	Wang et al. (2021)
	Rapana venosa	33				Fiber > film > fragment > pellet	PE, PET, PP, PVAL, PAN/PAA, PP/PE, PP/PE/PDI, PE/PVA/PVC, ABS, PSI, PAN, PD, PMA, PVC	938 ± 758 µm	1.97 ± 1.53 MPs/individual		
	Nerita articulata	67		69% HNO3 + 30% H2O2	FTIR	Fiber (91 %), fragment (9 %)	PE-PDM, PES, PU	30–1850 µm	0.25 to 0.88 MPs/individual	Klang River estuary, Malaysia	Zaki et al. (2021)
	Nerita polita	14							0.50 to 1.75 MPs/g		
	Chicoreus capucinus	14									
	Bolinus brandaris	123	Soft tissue	KOH	ATR-FTIR, µ-FTIR	Fibers, fragments, film	PE, PES, synthetic cellulose, PVDF, PP, PAN, PA, PC, PS	20-5 000 µm	0.94 ± 0.62 MPs/g ww	Catalan Coast	Expósito et al. (2022)
	Tectus dentatus	10		10% KOH		Fragments > fibers	PTFE, PA, PEVA	<1500 µm	14.8 ± 13.5 MPs/individual	Red Sea coast of Egypt	Abd-Elkader et al. (2023)
	Strombus tricornis	10				Fragments > fibers	PEVA	<5000 µm	9.6 ± 8.4 MPs/individual		
	Conus vexillum	10				Fibers > fragments	PA, PEVA	<2000 µm	10.2 ± 8.2 MPs/individual		
	Telescopium telescopium	60		10% KOH	FTIR	Filament, fragment	PE, PP, PU	21–435 µm	4-23 MPs/individual	Mangroves in Mumbai, India	Jaffer et al. (2023)

Appendix Table 1. (Continued.)

	Patella caerulea	40		H202	FTIR	Fibers (80%), fragments (20%)	PE (38%), PP (32%), PET (15%), HDPE (15%)	0.13–4.3 mm	0.29 ± 0.54 MPs/individual	İskenderun and Mersin Bay, southeastern coast of Türkiye	Yücel and Kılıç (2023)
	Babylonia areolata	435	Soft tissue	69% HNO3	µ-FTIR	Fiber (95%), film (4%), fragment (1%)	PET (25%), PES (16.7 %), PE (8%), PP (8%), PTFE (8%)	<1 mm, 1–5 mm	2.77 ± 0.94 MPs/g ww	Eastern coast of Thailand	Hongsawat et al. (2024)
	Neverita didyma	120	Soft tissue	10% KOH +30% H202	µ-FTIR	Fiber (98%), fragment (1%), film (1%)		87–5000 µm	3.99 ± 2.45 MPs/individual	Bohai Sea	Zhao et al. (2024)
	Chlorostoma rustica	40				Fiber (98%), fragment (1%), film (1%)			3.08 ± 1.92 MPs/individual		
	Buccinum koreana	20				Fiber (98%), fragment (1%), film (1%)			5.15 ± 2.46 MPs/individual		
	Siphonalia subdilatata	20				Fiber (98%), fragment (1%), film (1%)			6.10 ± 2.53 MPs/individual		
	Volutharpa perryi	20				Fiber (98%), fragment (1 %), film (1%)			2.25 ± 1.37 MPs/individual		
	Rapana venosa	169				Fiber (98%), fragment (1%), film (1%)			4.28 ± 2.94 MPs/individual		
	Natica janthostomoides	40				Fiber (98%), fragment (1%), film (1%)			2.13 ± 1.39 MPs/individual		
	Natica maculosa	10				Fiber (98%), fragment (1%), film (1%)			4.30 ± 2.87 MPs/individual		
	Rapana venosa	8	Whole body	10% KOH	µ-FTIR	Fiber (88%), fragment, film, microbead	CP, PET, PE, PP, PA, PP-PE, VI, PVC, PAN	<1000 µm	17.63 ± 15.40 MPs/individual	Haizhou Bay, China	Xie et al. (2024)
	Neverita didyma	11				Fiber (88%), fragment, film, microbead	CP, PET, PE, PP, PA, PP-PE, VI, PVC, PAN	<1000 µm	9.82 ± 3.52 MPs/individual		
	Eatoniella sp.			1% NaOH	µ-FTIR		PA, PE, PTFE, POM, PF, PP, PS, XT Polymer	33 to 1000 µm	0.01–3.29 MPs mg^{-1}	Terra Nova Bay, Antartica	Sfriso et al. (2020)
	Ruditapes philippinarum										
Bivalvia	*Mytilus galloprovincialis*	48	Soft tissue	15% H2O2	µ-FTIR	Fiber, fragment, line, film, pellet	PE, PP, PS, PVC, PET, PA, EVA, PI, PEST, PU, epoxy resin, PBT, polyterpene rubber, PVOH, silicone, polyacrylate, copoly(EVA/PA), copoly(PVC/PVOH/PE)	N/A	1.2 ± 0.45–1.5 ± 0.58 MPs/individual	Adriatic Sea	Avio et al. (2020)
	Mytilus galloprovincialis	342	Soft tissue	30% H2O2	FTIR	Fragments (67%), fibers (28%), films (4%)	PET, EVA, PA, PAC, PC, PE, PAN, PS, PP, PVC, PVF, CA	1.66 ±1.45 mm	0.69 MPs/individual	Turkish Coast (Black Sea, Marmara, Aegean Sea)	Gedik and Eryaşar (2020),
	Mytilus galloprovincialis	317	Whole body	30% KOH: NaClO	µ-Raman	Fiber (63%), fragment (37%)	PE, PP, CE, PA 6, PET, E, UI	1.7 ± 0.1 mm	0.6 ± 0.1 MPs/individual	Türkiye	Gündoğdu et al., (2020)
	Mytilus galloprovincialis	232	Soft tissue	10% KOH	ATR-FTIR	Fibers, fragments, films	PE, PP, CE		7.7 ± 3.8 MPs/individual	Bizerte lagoon, Northern Tunisia, southern Mediterranean	Wakkaf et al. (2020)
	Mytilus galloprovincialis		Digestive systems	10% KOH	ATR µ-FTIR	Fiber (45%), fragment (23%), film (28%)	PVC, VI, CP, PES, CPE, PET, PVDF	7–5000 µm	0.8–2.1 MPs/individual	Jiaozhou Bay, Yellow Sea, China	Ding et al. (2021)
	Chlamys farreri								0.5–2.9 MPs/individual		
	Crassostrea gigas								1.2–3.3 MPs/individual		

Appendix Table 1. (Continued.)

Ruditapes philippinarum								4.3–57.2 MPs/individual		
Mytilus galloprovincialis	60	Soft tissue	30% H_2O_2+ HNO_3	No polymer analysis	Fiber (87%), film (7%), fragment (5%)		0.015–1 mm, >1 mm	8.72 ± 5.30 MPs/individual, 3.90 MPs/g	İzmir Bay, Aegean Sea	Yozukmaz (2021)
Ruditapes decussatus	60							4.14 MPs/g		
Mytilus galloprovincialis	30		10% KOH	ATR-FTIR	Films (43%), fiber (35%), fragments (22%)	PA (38%), LDPE (17%), PET (17), PP (7%), PVA (7%), UPVC (5%), ABS (3%), HDPE (3%), PS (2%), PVC (2%)	200–5000 µm	0.5 MPs/individual	İstanbul shores, Türkiye	Galyon and Alçay (2023)
Mytilus galloprovincialis	412	Soft tissue	30% H202	FTIR	Fiber (81%), fragment, film	PET (66%), PE (15%), PP (8%)	0.1–4.99 mm	0.30–7.53 MPs/individual (2.06 MPs/individual)	Marmara coastline of Türkiye	Gedik et al. (2022)
Mytilus galloprovincialis	283	Gastric gland	10% KOH	ATR-FTIR	Fibers, fragments, films, pellets, styrofoam	PET (42%), PE (30%), PS (28%)	<1 mm	1.28 MPs/individual	Salento coastal seas, southern Adriatic Sea, northern Ionian Sea,	Trani et al. (2023)
Mytilus galloprovincialis	180	Soft tissue	10% KOH	ATR-FTIR	Fiber, fragment, line, film	EPDM, EPR, PA 6, PET, PMP, PS	0.1–5 mm	2.08 ± 1.43 – 9.45 ± 3.20 MPs/individual	Sea of Marmara	Tunçelli and Erkan (2024)
Mytilus galloprovincialis	373	Soft tissue	KOH	ATR-FTIR and µ-FTIR	Fibers, fragments, film	PE, PES, synthetic cellulose, PVDF, PP, PAN, PA, PC, PU,PS	20–5000 µm	6.47 ± 7.95 MPs/ g ww	Catalan Coast	Expósito et al. (2022)
Donax trunculus	1632							1.92 ± 0.85 MPs/g ww		
Ensis siliqua	59							2.45 ± 2.59 MPs/g ww		
Tapes decussatus	74							4.97 ± 4.78 MPs/g ww		
Crassostrea gigas	47							2.09 ± 1.12 MPs/g ww		
Mytilus edulis	300	Soft tissue	10% KOH	µ-FTIR	Fragment (69%), fiber (31%)	30% PP, 25% PES/PET, 7% PE, 6% PS, 5% polyacrylate, 4% PA, 2% PEVA, 2% polystyrene-butadiene	<300 µm	0.37 ± 0.29 MPs/g, 1.67 ± 1.50 MPs/individual	Coast of Korea	Cho et al. (2021)
Ruditapes philippinarum	300				Fragment (72%), fiber (28%)	40% PP, 20% PE, 20% PES/PET, 6% polyacrylate, 4% PA, 2% PS, 2% PEVA, 2% PVC	<300 µm	0.43 ± 0.32 MPs/g and 2.19 ± 1.20 MPs/individual		
Crassostrea gigas	300				Fragment (69%), fiber (31%)		<300 µm	0.15 ± 0.08 MPs/g, 1.00 ± 0.72 MPs/individual		
Crassostrea and Saccostrea genera	660		30% H_2O_2	µ-Raman	Fragments (66%), fibers (28%), flakes (2%), spheres (3%)	PET (70%), PP (9%), PVC (6%), HDPE (5%), PS (4%), PA (3%), PE (2%)	91.73 ± 5.95 µm to 482.68 ± 37.49 µm	3.24 ± 1.02 MPs/g ww	Coastal areas of Taiwan	Liao et al. (2021)
Crassostrea gigas and Saccostrea glomerata	245	Soft tissue	10% KOH	µ-FTIR	Fibers (62%), fragments (38%)	PES, PE, PS, PP, PVA	>1 mm	0.83 ± 0.08 MPs/individual	Southern Australia	Wootton et al. (2022)
Crassostrea madrasensis	30	Soft tissue	10% KOH	Raman spectra	Fiber (70%), fragment (25%), film (4%), pellets (0.15)	PE (28%), PP (18%), PA (16%), PES (14%)		20.57 ± 9.24 MPs/individual	Southwest coast of India	Abisha et al. (2024)
Perna perna	30				Fiber (70%), fragment (25%), film (5%)	PE (28%), PP (18%), PA (16%), PES (14%)		3.02 ± 1.29 MPs/g		
Perna perna	180		10% KOH + 30% H202	ATR-FTIR	Fiber (77%), fragment (16%), films (4%), foams (3%)	PE, PP, PA, PS, PET, PEST	500 µm–3 mm	0.87 ± 0.55 to 10.02 ± 4.15 MPs/individual	Coast of Tamil Nadu and Kerala	Patterson et al. (2021)
Perna viridis	360							0.1 ± 0.03 to 2.05 ± 0.33 MPs/g		

Appendix Table 1. (Continued.)

	Perna viridis		Soft tissue	69% HNO3	μ-FTIR	Fiber (93%), fragment (3%), film (3%), pellet (1%)	PE (28%), PP (12%), PET (4%)	<1 mm, 1–5 mm	2.41 ± 0.66 MPs/g ww	Eastern coast of Thailand	Hongsawat et al. (2024)
	Amarilladesma mactroides	160	Soft tissue	10% KOH	μ-ATR	Fiber (76%), fragment (22%), pellet (2%)	PA (27%), PE (18%), PET (9%), PVC (7%), PI (7%), cellulose (7%), PP (6%), PLA, POM, PU,	<10,000 μm	2.3 ± 5.4 MPs/g ww	Coastal region of southern Brazil	Jankauskas et al. (2024)
	Amarilladesma mactroides	30		10% KOH	μ-ATR	100% fiber	Cellulose, PA, others	0.5–5 mm	0.3–0.5 MPs/g ww	Coast of Argentina	Truchet et al. (2021)
	Brachidontes rodriguezii	90				100% fiber		<0.5 mm	0.15–0.25 MPs/g ww		
	Tridacna maxima	10		10% KOH		Fibers > fragments	PA, PP, LDPE, PEVA	<1500 μm	14.2 ± 13.8 MPs/individual	Red Sea coast of Egypt	Abd-Elkader et al. (2023)
	Pinctada radiata	10				Fragments > fibers	PA, PP, HDPE, PEVA	<5000 μm	16.2 ± 20.7 MPs/individual		
	Brachidontes pharaonis	10				Fragments > fibers	LDPE	<2000 μm	25.3 ± 32.6 MPs/individual		
	Tegillarca granosa		Soft tissue	69% HNO3	μ-FTIR	Fiber (96%), fragment (2%), film (2%)	PS (48%), PE (30%), PES (9%)	<1 mm, 1–5 mm	2.84 ± 0.66 MPs/g ww	Eastern coast of Thailand	Hongsawat et al. (2024)
	Mactra veneriformis	33	Soft body	10% KOH	μ-FTIR	Fiber > fragment > film	PET, PVAL, PAN/PAA, PE, PAS, PF, PVP, PS/PMMA, PE/PVA/PVC, PVA/PVEC	952 ± 743	1.58 ± 1.70 (0–6)	Liaohe Estuary, China	Wang et al., (2021)
	Sinonovacula constricta	30	Soft body	10% KOH	μ-FTIR	Fiber > film > fragment	PET, PVAL, PAN/PAA, PP/PE, PP, EP, PE/PVC, PVC/PVA	931 ± 705	0.83 ± 0.99 (0–3)		
	Scapharca subcrenata	15	Whole body	10% KOH	μ-FTIR	Fiber (79%), microbead, fragment, film	PET, PE, PP	<1000 μm	3.20 ± 2.85 MPs/individual	Haizhou Bay, China	Xie et al. (2024)
	Mactra veneriformis	10				Fiber (79%), microbead, fragment, film	PET, PE, PP	<1000 μm	6.60 ± 3.89 MPs/individual		
	Ruditapes philippinarum	10				Fiber (79%), microbead, fragment, film	PET, PE, PP	<1000 μm	5.00 ± 2.35 MPs/individual		
Cephalopoda	*Dosidicus gigas*		Stomach, gill, intestine	10% KOH	FTIR	Fiber (93%), fragments (7%)	CP, PAA, PET, PP	80 to 4632 μm	0.20 to 0.74 MPs/g ww	Northern Humboldt Current, western South America, Peru	Gong et al. (2021)
	Dosidicus gigas	50	Stomach	10% KOH	FTIR	Fragment (54%), fiber (43%), film (13%)	PET (32%), CP (18%), PS (11%), EP, PA, PP, PVC, PAN, AC, SBR, PDMS	58–2944 μm	0.88 ± 1.12 MPs/individual	Eastern Pacific Ocean	Wang and Chen (2023)
	Uroteuthis duvaucelli		Soft tissue (without gut and viscera)	10% KOH	FTIR	Fibers, fragments and sheet	PP (40%), PE (27%), PS (20%)	100–200 μm and 200–300 μm	0.18 ± 0.48 MPs/individual	Coast of Kerala, India	Daniel et al. (2021)
	Loligo vulgaris		Stomach, gills, ink sac	10% KOH	No polymer analysis	Fibers		<0.5 mm, 0.5–1 mm	0.25 ± 0.71 MPs/individual	Madeira Island, northeast Atlantic	Sambolino et al. (2023)
	Ommastrephes caroli					Fibers		<0.5 mm	0.13 ± 0.35 MPs/individual		
	Sthenoteuthis pteropu					Fibers and films		<0.5 mm, 0.5–1 mm, 1–2.5 mm, 2.5–5 mm	8.75 ± 12.34 MPs/individual		
	Vampyroteuthis infernalis			NaOH	LDIR	Fibers, fragments, films and foam	PE, PET, PVC, PA, SBR, CPI, PU	<5 mm	9.58 ± 8.25 MPS/individual	Southwestern Atlantic	Ferreira et al. (2022)
	Abralia veranyi					Fibers (37%) and fragments (63%)		<5 mm	2.37 ± 2.13 MPs/individual		
	Octopus vulgaris	6	Gastrointestinal track	10% KOH	FTIR	Fibers (50%), fragments (38%), filaments	PET/PES (68%), PE (13%), PVC (11%), SR (5%), PA (3%)	1.56 ± 2.26 mm	10.30 ± 16.66 MPs/individual	Southern Tyrrhenian Sea, western	Pedà et al. (2022)

Appendix Table 1. (Continued.)

						(8%), films (4%).				Mediterranean Sea	
	Sepia pharaonis	16	Outer body, gills, intestines	70% HNO3	no polymer analysis	Fibers, fragments, films		< 0.25 to 2.0 mm		North Jakarta, Indonesia	Prasetyo and Putri (2021)
	Sepia officinalis	122	Gastrointestinal track	10% KOH	no polymer analysis	Fragments, fibers, and spheres			6.82 ± 5.52 MPs/individual	Adriatic coast	Armellini et al. (2023)
	Sepia officinalis		Digestive gland, stomach, caecum/intestine	Enzymatic digestion	FTIR	Fibers (87%), fragments (8.4%), microfilm pieces (4.6%)	N/A		1.85 fibers/g (digestive gland)	Portugal	Oliveira et al. (2020)
Arthropoda											
Crustacea	Brachyura larvae		Whole body	10% KOH	µ-FTIR	Fiber (100%) and fiber (86%), fragment (14%)		49–10,331 µm	0.061 MPs/individual, 0.033 MPs/individual	Bohai sea, China	Zheng et al. (2020)
	Mantis shrimp larvae					Fiber (60%), Fragment (40%)	CP (53%), PET (18 %), Polymerized, oxidized organic material (14%)	49–10,331 µm	0.040 MPs/individual		
	Amphipoda					Fiber (100%)	CP (68%), PET (20%), PMA (4%), PVC (4%), DEA (4%)	77–4346 µm	0.036 MPs/individual		
	Copepoda					Fiber, fragment		49–10,331 µm	0.03 MPs/individual, 0.025 MPs/individual		
	Euphasia					Fiber (100%)		49–10,331 µm	0.019 MPs/individual, 0.022 MPs/individual		
Euphausiacea	*Euphausia superba*	355		15% KOH	FTIR	Fiber (77%), fragment (17%), sheet	PE (33%), PP (24%), PES (21%)	80 µm	0.29 ± 0.14 MPs/individual	South Shetland Islands, Antartica	Zhu et al. (2023)
		82				Fiber (87%), fragment, sheet	PE, PES, PA, PP	43 µm	0.20 ± 0.083 MPs/individual	South Orkney Islands, Antartica	
	Euphausia superba	40	Stomach	10% KOH + 30% H2O2	µ-FTIR				0.4 ± 0.5 MPs/individual	Antarctica Peninsula	Primpke et al. (2024)
Cirripedia	*Amphibalanus amphitrite*	50		10% KOH	FTIR	Fiber (96%), fragment (3), pellet (1%)	CP (58%), PET (11%), PP (10%), PE (8%), PA(6%)		0–8.63 MPs/g	Coast of Hong Kong, China	Xu et al. (2020b)
	Capitulum mitella	50							0–1.90 MPs/individual		
	Tetraclita japonica japonica	50									
	Fistulobalanus albicostatus	50									
	Balanus albicostatus			10% KOH		Fiber > fragment	CP (28.17%), PP (25.35%), PE (23.94%)	69–3743 µm (without tube) 194–2885 µm (with tube)	0.52 ± 0.38 MPs/individual (without tube) 0.08 ± 0.08 MPs/individual (with tube)	The Yellow Sea, China	Zhang et al. (2022)
	Lepas anatifera	120	Gastrointestinal tract	10% KOH	FTIR	Fibers (86%) and fragments (14%)	PA, PVC, PE	1–2 mm	1.74 ± 0.80 MPs/individual	Capo Milazzo Marine Protected Area, Sicily, Tyrrhenian Sea	Scotti et al. (2023)
Stomatopoda	*Oratosquilla oratoria*	30	Gastrointestinal tract	10% KOH	µ-FTIR	Fragment > fiber	PE, PDMS, PP, PF, PVAL, PP/PE, PE/PVA/PVC, PET, EP, PAN, PC, POA, PEI, PAN/PAA, PP/PE/PDI, PMVA, PS/PMMA/PAN, PAA	910 ± 700 µm	1.33 ± 1.39 (0–7)	Liaohe Estuary, China	Wang et al. (2021)
	Squilla mantis		Soft tissue	15% H2O2	µ-FTIR	Fragment, line, film, pellet	PE, PP, PS, PVC, PET, PA, EVA, PI, PEST, PU, epoxy resin, PBT, polyterpene rubber, PVOH, silicone,	N/A	1.25 ± 0.5 – 2 ± 1.4	Adriatic Sea	Avio et al. (2020)

Appendix Table 1. (Continued.)

							polyacrylate, copoly(EVA/PA), copoly(PVC/PVOH/PE)		MPs/individual		
	Oratosquilla oratoria	11	Soft tissue	10% KOH	μ-FTIR	Fiber (88%), fragment, film, microbead	CP (30%), PET (25%), PE (17%), PP, PA, PP-PE, VI, PVC, PAN	<1000 μm	7.36 ± 4.57 MPs/individual	Haizhou Bay, China	Xie et al. (2024)
Amphipoda	*Talorchestia nipponensis, Ampithoe valida, Trinorchestia trinitatis*			30% H_2O_2	FTIR	Fiber	PE, PP, PS, PET	59 ± 8.6 μm	5.5–76.3 MPs/individual	Japanese coastal enviroment	Katte et al. (2023)
	Themisto spp.			20% KOH	FTIR	Fiber	PES, acrylic, PA, PP, PBT			Sub-Antarctic Scotia Sea, Western Antarctic Peninsula	Jones-Williams et al. (2020)
Decapoda	*Paratya australiensis*		Whole body	2N NaOH	μ-FTIR	Fibers	VI and PES	<1 to 2 mm	24 ± 31 MPs/g	Streams and wetlands in Northern central Victoria, Australia	Nan et al. (2020)
	Macrobrachium rosenbergii		Gastrointestinal track	10% KOH	Raman spectra	Fibers	Cellulose, PP, PE	<0.5–5 mm	5–12 MPs/individual	Pearl River Estuary, South China (farmed)	Li et al. (2021)
	Fenneropenaeus indicus		Whole body	10% KOH	FTIR	Fibers, fragments, and films	PE, PP, PA	157–2785 μm	0.04 ± 0.07 MPs/g	Kochi, India	Daniel et al. (2020)
	Aristeus antennatus		Gastrointestinal track	Stomach contents		Fibers	Cellulosic, PET, acrylic	0.16–37.9 mm	Fiber load from <1 mm to >1000 mm/individual	Catalan coast, Spain	Carreras-Colom et al. (2020)
	Pleoticus muelleri		Abdominal muscle with GI	10% KOH+ 30% H_2O_2	μ-Raman spectra	Fibers	PE, PP, cellulose	0.5–5 mm	1.31 fibers/g	Bahia Blanca Estuary, Atlantic Ocean, Argentina	Fernández Severini et al. (2020)
	Parapenaeopsis hardwickii		Flesh	10% KOH+ 30% H_2O_2	μ-FTIR	Fibers	Cellulose and PP	74–2000 μm	0.95 ± 0.28 MPs/individual	Xiangshan Bay, China (farmed)	Wu et al. (2020)
	Metapenaeus monoceros,		Gastrointestinal track	69% HNO_3	Raman spectra	Fibers, fragments, beads, pellets and films	PE, PP, PET, PES, and PA	100–250 μ	7.23 ± 2.63 MPs/individual	North-eastern Arabian Sea	Gurjar et al., (2021)
	Parapeneopsis stylifera								5.36 ± 2.81 MPs/individual		
	Penaeus indicus								7.40 ± 2.60 MPs/ind		
	Penaeus kerathurus		Soft tissue	15% H_2O_2	μ-FTIR	Fragment, line, film, pellet			1 ± 0 MPs/individual	Adriatic Sea	Avio et al. (2020)
	Palaemon sp.	21				Fiber, fragment, line, film, pellet			1.21 ± 0.44MPs/individual		
	Metapenaeus monoceros, Penaeus monodon		Gastrointestinal track	30% H_2O_2	μ-FTIR	Fibers, particles and fragments	PA 6, VI	<250 μm–5mm	3.40 ± 1.23 MPs/g	Northern Bay of Bengal, Bangladesh	Hossain et al. (2020)
	Metapenaeus affinis		Gastrointestinal track	10% KOH	Confocal Raman spectra	Fibers, films	PET, PP, PS	Between <100 and >1000 μm	1.02 MPs/g	Musa Bay, Iran	Keshavarzifard et al. (2021)
	Litopenaeus vannamei		Intestine	10% KOH	μ-FTIR	Fibers		<0.5 mm	14.08 ± 5.70 MPs/g	Zhuhai City, Guangdong Province, China (farmed)	Yan et al. (2021)
	Litopenaeus vannamei		GIT, gills, exoskeleton	65 % HNO_3 + 68 % $HClO_4$	N/A	Fiber, fragment, films, granule			114.7 ± 33.2 MPs/g, 13.7 ± 5.3 MPs/g, 3.0 ± 0.5 MPs/g	Gulf of California	Valencia-Castañeda et al. (2022)
	Acanthephyra curtirostris	16	Stomach	Nitric 70%+ perchlori	FTIR	Fragment	Polyethyl acrylate acrylamide copolymer, PE–PP copolymer	>270 μm	0.88 MPs/individual	Gulf of Mexico	Bos et al. (2023)

Appendix Table 1. (Continued.)

			c acid 70%							
A. purpurea	43				Fiber	Alkyd resin		0.30 MPs/individual		
Bentheogenemma intermedia	15				Fragment	Alkyd resin		0.73 MPs/individual		
Gennadas capensis	15				Fiber	CP		0.87 MPs/individual		
G. valens	21				Fiber, fragment	CP, PE, alkyd resin, PU		0.62 MPs/individual		
Notostomus gibbosus	15				Fiber	CP		0.53 MPs/individual		
Plesionika richardi	46				Fragment	PP		0.32 MPs/individual		
Systellaspis debilis	46				Fragment	PE, PP copolymer, CP		0.26 MPs/individual		
Penaeus monodon		Gastrointestinal tract (GIT) and muscle	30% H2O2	FTIR	Fibers (30%) and fragments (29%)	LDPE, HDPE, PP, PMMA, PVC, EVA	<100 µm	9.22 MPs/g GIT, 1.81 MPs/g muscle	Bay of Bengal	Mercy and Alam (2024)
Caridina cantonensis								25.32 MPs/g GIT, 6.32 MPs/g muscle		
Penaeus indicus								15.54 MPs/g GIT, 1.43 MPs/g muscle		
Metapenaeus dobsoni								10.01 MPs/g GIT, 4.50 MPs/g muscle		
Penaeus merguiensis								23.63 MPs/g GIT, 3.31 MPs/g muscle		
Metapenaeus monoceros								21.51 MPs/g GIT, 2.73 MPs/g muscle		
Palaemon styliferus								21.96 MPs/g GIT, 9.76 MPs/g muscle		
Nephrops norvegicus		Soft tissue	15% H2O2	µ-FTIR	Fragment, line, film, pellet	PE, PP, PS, PVC, PET, PA, EVA, PI, PEST, PU, EP, PBT		1 ± 0 MPs/individual	Adriatic Sea	Avio et al. (2020)
Nephrops norvegicus		Stomach and intestine	stomach contents	µ-FTIR	Fragments and films	PE, PP, PS	0.2–1 mm	2.1 ± 0.6 MPs to 3.9 ± 0.5 MPs/individual	Coast of Sardinia Island, Mediterranean Sea	Cau et al. (2020)
Nephrops norvegicus		Gastrointestinal tract	10% KOH + Tween 20, 69% HNO3		Fibers	PS, PP, PES, PC and PE	2.81 mm	1.75 ± 2.01 MPs/individual	West and northeast coast of Ireland	Hara et al. (2020)
Nephrops norvegicus		Gut, hepatopancreas and tail	Tween 20, protease digestion +30% H2O2	µ-FTIR	Fragments and fibers	PES, PA 6, PVC and PE	50–100 µm	17 MPs/individual	Adriatic Sea	Martinelli et al. (2021)
Palinurus elephas	60	Stomach and gill	20% H202	µ-FTIR	Fragments (99%), fiber (2%)	PC, PVC, PPS, HDPE,	0.02–0.22 mm (majority size)	76.6 ± 51.5 MPs/individual (in stomach)	Northwest Aegean Sea, Greece	Kampouris et al. (2020)
						PET, PP, polyisoprene chlorinate, aramid	0.02–0.12 mm (majority size)	82.9 ± 58.6 MPs/individual (in gill)		
Neohelice granulata		Gill, gastrointestinal tract	30% H2O2	Microscopy	Fibers and fragments		<500–1500 µm fibers, <200 µm fragments	Between <5 and >18 MPs/g	Bahia Blanca Estuary, Argentina	Villagran et al. (2020)
Chiromantes dehaani					Fibers	PET, PP	2700 ± 410 µm	1–2 MPs/individual	Osaka Bay, Japan	Nakao et al. (2020)
Metopograpsus	9		65% HNO3		Fiber (68%), film (29%),	N/A	N/A	327.56 MPs/individual	Pramuka Island, Indonesia	Patria et al. (2020)

Appendix Table 1. (Continued.)

quadridentatus					fragment (1), granula (1%)					
Carcinus maenas *Eriocheir sinensis*		Gill, gastrointestinal tract	10% KOH	µ-FTIR	Fibers, films and fragments	PP, PES	52 µm to 34 mm	1–10.3 MPs/individual	Thames Estuary, UK	McGoran et al. (2020)
Tubuca dussumieri *Cranuca inversa* *Gelasimus vocans*		Whole tissue	10% KOH	Microscopy	Fibers		0.45–4.2 mm	0.13–1.24 MPs/g 0.33–0.52 MPs/g 0.79 MPs/g	Kenyan Coast	Awuor et al. (2020)
Pachygrapsus transversus		Stomach			Fibers	PA	>2 mm	1 MPs/individual	Brazil	de Barros et al. (2020)
Parasesarma bidens *Parapleptuca splendida* *Metopograpsus frontalis* *Thalamita crenata*		Stomach, gill	35% H_2O_2	FTIR	Fibers, fragments, particles	PE, PET, VI		91.53 MPs/individual 25.61 MPs/individual 69.21 MPs/individual 41.57 MPs/individual	Mangroves of Hong Kong	Not et al. (2020)
Parasesarma biden, Ocypode ceratophtalmus *Uca arcuata, Pyrhila pisum, Gelasimus borealis* *Metopograpsus frontalis,Parasesarma plicatum* *Hemigrapsus penicillatus, Austruca lactea* *Macromedaeus distinguendus, Gaetice depressus* *Macrophtalmus convexus*	total 71	Whole body	10% KOH	µ-FTIR	Fibers, fragments	CP, PET, PA, PP, PE		<1 to 2.84 ± 0.44 MPs/g	South China Sea	Xu et al. (2020a)
Chiromantes dehaani		Gill and gastrointestinal tract	30% H_2O_2	µ-Raman spectra	Fibers	PE, PET	1–20 µm, 20–5000 µm	0.39–2.83 MPs/individual, 0.74–4.96 MPs/individual	Beibu Gulf mangrove wetland, China	Zhang et al. (2021b)
Portunus trituberculatus, *Matuta planipes* *Charybdis japonicus,* *Dorippe japonica*		Gastrointestinal track, muscle and gills	10% KOH	µ-FTIR	Fibers, fragments, films and spheres	CP, PES, PE, PP, PA	19.97–4976.22 µm	5.17 ± 4.43 MPs/individual	Yellow sea and east China sea, China	Zhang et al. (2021a)
Chionoecetes opilio		Whole soft tissue	10% KOH	µ-FTIR	Fragments, fibers	PVAL, PES, PA, PE	0.87 ± 0.14 mm	0.0–0.6 MPs/individual	Chukchi Sea, Arctic Ocean	Fang et al. (2021)
Portunus trituberculatus	30	Gastrointestinal tract	10% KOH	µ-FTIR	Fiber > film > pellet > fragment	PET, PE, PVAL, PS, PP, PP/PE, PF, PC	1005 ± 789 µm	1.33 ± 1.24 MPs/individual	Liaohe Estuary, China	Wang et al. (2021)
Portunus pelagicus		Soft tissue without	10% KOH	FTIR	Fragments	PP, PE, PS	100–300 mm	0.14 ± 0.44 MPs/individual	Coast of Kerala, India	Daniel et al. (2021)

Appendix Table 1. (Continued.)

		gut and viscera								
Portunus pelagicus		Gastrointestinal tract	10% KOH	ATR-FTIR	Fiber > film > fragment	PE, PP	0.5–2 mm	0.10 ± 0.05	Thoothukudi coast, India	Keerthika et al. (2023)
Callinectes sapidus					Fibers, fragments	PE, PET, PA,VI, PES,CP	>100	2.5 ± 1.6 MPs/individual out of which 20% are microplastics	Lesina lagoon, İtaly	Renzi et al. (2020)
Callinectes sapidus		Stomach			Fibers, fragments, pellets and beads	Cellulose/Viscose, PES, PAN, PS, PET, PC, phenoxy resin	10–400 µm	0.87 MPs/individual	Gulf Coast, Corpus Christi Bay	Waddell et al. (2020)
Callinectes sapidus	90	Gut	10% KOH	ATR-FTIR	Fibers, pellets, microbeads, and fragments	HDPE, PP, PE, LDPE	0.1–5 mm	43 to 50 MPs/individual	Albania	Aliko et al. (2022)
Callinectes sapidus		Gills	30% H_2O_2	ATR-FTIR	Fragment > fiber	SI (53.1%), PE (12.5%), PL	Mean 2.4 ± 1.4 mm	37.9 g/individual	Gulf of Mexico	Capparelli et al. (2022)
		Digestive tract					Mean 3.8 ± 1.2 mm	8.62 MPs/individual		
		Muscle					Mean 2 ± 0.5 mm	6.89 MPs/g		
Callinectes sapidus	120	Stomach	10% KOH	µ-ATR-FTIR	Fiber (72%), fragment (26%), film and granule	LDPE (39%), PP (18%), HDPE, 26%		2.1 ± 1.5	Balearic Island, Spain	Compa et al. (2023)
Callinectes sapidus(juveniles)	77	Gastrointestinal tracts, stomach and gill	35% H_2O_2	Raman spectra		PA, PE		0.28 MPs/individual	Antinioti lagoon, Greece	Simantiris et al. (2024)
Leptuca festae		Gills, hepatopancreas and gastrointestinal tract	30% H_2O_2	Observation using microscopy	Fibers, fragments			7.58 ± 3.96 to 29.81 ± 18.13 MPs/g tissue	Isla Santay, Ecuador	Villegas et al., (2021)
Minuca ecuadoriensis								0.50 ± 0.87 to 22.93 ± 10.77 MPs/g tissue		
Leptuca uruguayensis		Carapace	10% KOH	ATR µ-FTIR	Fiber, fragment, paint sheet	Cotton PA, CE		1.5 ± 1.7 MPs/g ww	Bahía Blanca estuary, Buenos Aires, Argentina	Truchet et al. (2022)
		Gills						1 ± 1 MPs/g		
		Gut						0.36 ± 0.25 MPs/g		
		Carapace, gills, gut						0.70 ± 0.6 MPs/g		
Cyrtograpsus angulatus		Carapace	10% KOH	ATR µ-FTIR	Fiber, fragment, paint sheet	Cotton PA, CE		0.67 ± 0.52 MPs/g	Buenos Aires, Argentina	Truchet et al. (2022)
		Gills						0.11 ± 0.07 MPs/g		
		Gut						0.19 ± 0.11 MPs/g		
		Carapace, gills, gut						0.25 ± 0.3 MPs/g		
Neohelice granulata		Carapace	10% KOH	ATR µ-FTIR	Fiber, fragment, paint sheet	Cotton PA, CE		0.11 ± 0.07 MPs/g	Buenos Aires, Argentina	Truchet et al. (2022)
		Gills						0.17 ± 0.14 MPs/g		
		Gut						0.06 ± 0.07 MPs/g		
		Eggs						4 ± 2 MPs/g		
		Carapace, gills, gut, eggs						1.08 ± 1 MPs/g		
Emerita analoga	480	Digestive tract	10% KOH		Fiber (88%), film (7%), fragment (3%)		<1000 µm	0.02 ± 0.13 – 1.82 ± 6.31 MPs/individual	Beaches of Lima	García et al. (2023)
Charybdis japonica	10	Soft tissue	10% KOH	µ-FTIR	Fiber (88%), fragment, film, microbead	CP, PET, PE, PP, PA, PP-PE, VI, PVC, PAN	<1000 µm	5.50 ± 4.01 MPs/individual	Haizhou Bay, China	Xie et al. (2024)

Appendix Table 1. (Continued.)

	Portunus trituberculatus	11	Soft tissue			Fiber (88%), fragment, film, microbead	CP, PET, PE, PP, PA, PP-PE, VI, PVC, PAN	<1000 μm	4.55 ± 3.08 MPs/individual		
	Charybdis variegata	8	Soft tissue			Fiber (88%), fragment, film, microbead	CP, PET, PE, PP, PA, PP-PE, VI, PVC, PAN	<1000 μm	5.50 ± 7.45 MPs/individual		
	Dorippe japonica	7	Soft tissue			Fiber (88%), fragment, film, microbead	CP, PET, PE, PP, PA, PP-PE, VI, PVC, PAN	<1000 μm	9.71 ± 5.94 MPs/individual		
	Eucrate crenata	10	Soft tissue			Fiber (88%), fragment, film, microbead	CP, PET, PE, PP, PA, PP-PE, VI, PVC, PAN	<1000 μm	13.80 ± 8.73 MPs/individual		
	Eriocheir leptognathus	9	Soft tissue			Fiber (88%), fragment, film, microbead	CP, PET, PE, PP, PA, PP-PE, VI, PVC, PAN	<1000 μm	15.00 ± 4.72 MPs/individual		
Anomura (hermit crab)	*Pagurus pubescens*		Stomach	stomach contents		Fibers and fragments				Pechora Sea, North-West Russia	Gebruk et al. (2021)
Merostomata	Juvenile *Tachypleus tridentatus*		Gastrointestinal tract	10% KOH	µ-FTIR	Fiber (99%), flake (1%)	CP), SR, PP, PE, PAN, PA, PVC, PVA	<5 mm	21.1 ± 13.4 MPs/individual	Northern Beibu Gulf, China	Wang et al. (2022)
Echinodermata											
Asteroidea	*Asterias rollestoni Bell*	7	Whole body	10% KOH	µ-FTIR	Fiber (88%), fragment, film, microbead	CP, PET, PE, PP, PA, PP-PE, VI, PVC, PAN	<1000 μm	35.71 ± 18.54 MPs/individual	Haizhou Bay, China	Xie et al. (2024)
Echinoidea	*Paracentrotus lividus*	21	Soft tissue	15% H2O2	µ-FTIR	Fiber, fragment, line, film, pellet	PE, PP, PS, PVC, PET, PA, EVA, PI, PEST, PU		1 – 1.66 ± 0.58 MPs/individual	Adriatic Sea	Avio et al. (2020)
	Diadema africanum	33	Digestive tract and gonads	33% H2O2	µ-Raman	Fibers (97%), fragments (2%), films (1%)	Cellulosic (46.0%), PP (24.3%), PET (24.3%),	83–11,638 μm	9.7 ± 3.9 MPs/individual	Canary Island, Spain	Sevillano-González et al. (2022)
	Echinometra mathaei	5	Digestive tract	30% H2O2	FTIR	Fragment (75%), fiber (25%)	PES (31%), PE (21%), PP (21%), PVC (10%), EP (10 %),	200–2070 μm	0.27 ± 0.28 MPs/g dry w	Pari and Harapan Islands, Indonesia	Rahmawati et al. (2023)
	Diadema setosum	16				Fragment (75%), fiber (25%)	PP (67%), PES (33%)	140–2690 μm	3.93 ± 2.25 MPs/g dry w		
	Hemicentrotus pulcherrimus	10	Whole body	10% KOH	µ-FTIR	Fiber (88%), fragment, film, microbead	CP, PET, PE, PP, PA, PP-PE, VI, PVC, PAN	<1000 μm	5.50 ± 2.46 MPs/individual	Haizhou Bay, China	Xie et al. (2024)
	Echinoidea and Ophiuroidea	7	Whole body	10% KOH	ATR µ-FTIR	Fiber (94%), fragment (6%)	PE (81%), PET (6.3%), PA (12.5%)	<500 µ, 500–5000 µ	20.9 ± 17.4 MPs/g	Jiaozhou Bay, China	Zhang et al. (2023)
Holothuroidea	*Holothuria tubulosa*		Digestive tract	N/A	FTIR	Fibers (84%), fragments (16%)	PP (27%), PE (17%), and PS (16%)		3.5 ± 0.7 MPs/individual	Eivissa Island (Spain), Western Mediterranean	Lombardo et al. (2022)
	Acaudina molpadioides	21	Whole body	10% KOH	µ-FTIR	Fiber (97%), film (3%)	CP, PE, PVC, PET	<1000 μm	7.05 ± 5.13 MPs/individual	Haizhou Bay, China	Xie et al. (2024)

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