Environmental and Morphological Detrimental Effects of Microplastics on Marine Organisms to Human Health

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Abstract

The ubiquitous presence of microplastics (MPs) in all oceans has become a significant threat to nature as global plastic production continues to increase. Now, and over the next 20 to 30 years, it is the time to address the consequences of the rise of the plastic industry global production of millions of items, ranging from a single pen to automobiles. Inappropriate management, lack of awareness of the harmful effects, reckless universal use, and indiscriminate disposal of plastics have turned the earth into a "plastic planet". The aim of the present study review is to identify the scenarios for the structure, and functions of MPs and the resulting impacts on marine organisms. The different origins of MPs in the oceans and their negative impacts on marine organisms are critically discussed in this review. Due to their small size, these plastic particles are easily ingested by a wide range of marine organisms (e.g., fish, Mollusca, Arthropoda, Annelida, Echinodermata, Nematoda, phytoplankton, zooplankton, algae, birds, Mammalia, marine reptiles, and corals), posing a threat to their health. The ability of MPs to absorb a variety of hazardous hydrophobic chemicals from the environment allows transfers these toxins to enter directly into the food chain, ultimately becoming a threat to human health. As a result, numerous policies and laws have been created to address the major problems of marine pollution. However, these regulations need to be improved and implemented worldwide. To avert future threats, it is crucial to stop the production of toxic chemicals associated to the production of plastics and replaces them with environmentally suitable alternatives.

Introduction

Reported all over the world, microplastics (MPs) fragment into smaller particles and remain in the environment accumulating in all marine habitats where marine organisms inhabit (Alfaro-Núñez et al. 2021; Bhuyan et al. 2020; Waller et al. 2017). In marine ecosystems, the number of MPs continues to increase due to the ever-increasing production of plastics manufacture, which reached 335 million tons in 2016 (Plastics Europe, 2017). In 2019, over 350 million tons of plastics were produced, according to Plastics Europe (2020). In 2010, approximately 4.8 to 12.7 million tons of plastics were dumped into the oceans, and this number is expected to increase by 2025. By 2100, the mass of floating MPs would increase from 2.5×10^7 to 1.3×10^8 tons, a 50-fold increase in the total mass of MPs (Everaert et al. 2018). High levels of MPs ($>10 \cdot 10^4$ pieces/m³) have been found in garbage areas in the middle of large ocean basins as well as in the North Sea, Mediterranean Sea, Black Sea, and South China Sea (Waldschläger et al. 2020).

MPs have been reported in the world's oceans, estuaries, and other coastal regions in highly anthropogenically-populated locations (Frère et al. 2017). Two main countries are the major contributors of plastic production that end up discarded into the oceans (Fig. 1). Both primary and secondary MPs have been detected in many species after entering the ocean. MPs have been reported in the stomachs of a wide range of marine organisms, including fish, phytoplankton, polychaetes, worms, tubifex worms, amphipods, cetaceans, seabirds, molluscs, crustaceans, echinoderms, zooplankton, mammals, and corals (Alfaro-Núñez et al. 2021; Bhuyan et al. 2020; Lusher et al. 2015; Besseling et al. 2015; Hall et al. 2015; Mathalon and Hill, 2014; Cole et al. 2013). MPs have been found to reduce feeding activity, cause oxidative stress, genotoxicity, neurotoxicity, and growth retardation in marine organisms (Ribeiro et al. 2017; Li et al. 2016; de Sá et al. 2015; Della Torre et al. 2014).

Fig. 1. Plastic volume production by country around the world (Data source: World Population Review, 2021).

The water and sediments of many oceans, estuaries, and coastal lagoons are contaminated with MPs, putting marine organisms (e.g., shellfish) that grow up in these locations at risk for consumption (Lusher et al. 2017). For example, the amount of MPs particles per 10 g of mussels in commercial mussels from Belgium ranged from three to five (de Witte et al. 2014). MPs were found in *Mullus barbatus*, *Merluccius merluccius*, *Gadus morhua*, *Sardina pilchardus* and *Sparus aurata* from different localities (Alomar et al. 2021; Solomando et al. 2020; Compa et al. 2018). Nearly up to 9% and 28% of MPs were found in the gastrointestinal tract (GI) of fish traded in marketplaces in the United States and Indonesia, respectively (Rochman et al. 2015). As a regional example, Brazil's eastern coast, Miranda and Carvalho-Souza (2016) discovered MPs in the digestive tracts of two important edible fish species. Neves et al. (2015) detected MPs in 19.8% of edible fish collected off the Portuguese coast. MPs were also found in the stomachs of economically important Mediterranean fish (in the GI and liver of anchovies and sardines) (Compa et al. 2018; Collard et al. 2017).

MPs can be ingested by marine animals through their gills and digestive tract (Alomar et al. 2021; Solomando et al. 2020; de Sá et al. 2015). Ingestion could occur due to the inability to identify MPs from prey or ingestion of organisms from lower trophic levels containing these particles (de Sá et al. 2015). MPs can also attach directly to organisms (Cole et al. 2013). MPs are potentially accessible to a wide range of organisms by ingestion due to their small size, which overlaps with the size range of their prey (Galloway et al. 2017). Several marine organisms are impacted by ingestion of MPs. MPs are reportedly ingested by cod, pilchard, horse mackerel, mussels, red mullet, oysters, shrimp, and sea bass (Lusher et al. 2013; Bellas et al. 2016; Güven et al. 2017). As previously stated, MPs are consumed when they

are mistaken for prey, however, they can also be ingested through depositional feeding and active filtration systems (de Sá et al. 2015; Naji et al. 2018).

Once ingested, MPs are absorbed, distributed through the cardiovascular system and into numerous tissues and cells, where they can have a range of harmful potential consequences (Foley et al. 2018; Avio et al. 2017; Wright et al. 2013). MPs particles and other toxic compounds present in prey are passed to marine predators. (Mattsson et al. 2017). MPs in aquatic organisms showed a median concentration of 400 µg/L (Chae and An, 2020; Choi et al. 2020; Li et al. 2020; Wang et al. 2019), while a median ambient concentration of 0.003 µg/L (from environmental samples) was found in three research studies involving 13 sites (Lacerda et al. 2019). This is equivalent to organisms being exposed to MPs levels almost 100000 times higher than what they would be exposed to in their natural habitat.

Recently, several studies on the uptake of MPs by commercially important marine species have been conducted worldwide, with MPs being frequently detected: 36.5-63.5% on the Portuguese coast (Neves et al. 2015), 14.6% in the Red Sea coast (Baalkhuyur et al. 2018), 34% in the Yellow Sea (Sun et al. 2019), 19.7-23.3% in the Mediterranean Sea (Giani et al. 2019), 37%-43% in the northern Bay of Bengal (Hossain et al. 2019), 83.4-86.3% in the Lebanese coast (Kazour et al. 2019), 56.6-83.3% in Irish waters (Hara et al. 2020), 1.8%-21% in the North Sea (Kühn et al. 2020), 94.1% in the southern Tyrrhenian Sea (Capillo et al. 2020), 34.6-57.7% in the Gulf of Beibu, South China Sea (Koongolla et al. 2020), and 20-93% in the tropical eastern Pacific and Galapagos islands (Alfaro-Núñez et al. 2021).

Consumption of edible marine animals containing MPs poses a risk to human health (Bhuyan et al. 2020). MPs have been detected in 11 of the 25 species representing the largest contributors to global fisheries (FAO, 2016). Consumers in European countries with high shellfish consumption ingest up to 11000 MP particles per year. Consumers in countries with low-shellfish-consumption ingest an average of 1800 MPs/year, which is yet a significant amount (Van Cauwenberghe and Janssen, 2014). Estimates suggest that each person from coastal areas around Europe ingests about 175 MP particles per year from shrimp consumption alone (Devriese et al. 2015). MPs have been detected in *Mytilus edulis* and *Mytilus galloprovincialis* mussels from five European countries (Vandermeersch et al. 2015).

The occurrence of MPs in the GI of fish does not mean that humans are exposed, as this organ is rarely consumed (Alfaro-Núñez et al. 2021; Wright and Kelly, 2017). Whole seafood (such as molluscs, crustaceans, and juvenile fish) has a higher risk of infection than gutted fish or sliced shrimp. MPs were found in the gutted meat of *Chelon sub viridis* and *Johnius belangerii* at much higher concentrations than in the removed organs, suggesting that gutting does not always minimize the risk of MPs ingestion by humans (Karami et al. 2017). MPs have also been found in the muscle of commercially valuable fish species and a crustacean (Alfaro-Núñez et al. 2021; Akhbarzadeh et al. 2018). These findings highlight the implications for human consumers and their health.

Microplastics (Mps)

MPs are the most common type of plastic debris (tiny particles, fibres, and granules) found in seawater (Bhuyan et al. 2020). The high level of MPs contamination in the oceans is directly related to this family of products being cheap, versatile, and durable, which explains the large quantities of plastics produced, used, and easily discarded (Alfaro-Núñez and Bermudez, 2018). Plastics are ultimately found on the seabed (Fig. 2). Primary and secondary MPs are the two types of MPs found in the ocean (Auta et al. 2017). Tiny plastic fragments that enter the environment directly through domestic and industrial effluents, spills, and sewage discharges are referred to as primary MPs. Fragments, fibres, pellets, films, and spheres are among the basic MP particle forms (Li et al. 2016; Lusher et al. 2015). Personal care and cosmetics products, detergents and facial cleansers, children's products, insecticides, skin care products, and pharmaceuticals (Duis and Coors, 2016), as well as residues from shipbreaking and blasting, are primary MPs (Andrady, 2011). Secondary MPs are formed when large plastic particles already present in the environment are gradually fragmented by inorganic deposition, microbial treatment, structural decay, and photodegradation (Andrady, 2011; Duis and Coors, 2016). Polyethylene (PE), polystyrene (PS), polypropylene (PP), polyester (PES), polyvinyl chloride (PVC), polyamide (PA), acrylic polymers (AC), polyether (PT), cellophane (CP), polyurethane (PU), and polyethylene terephthalate (PET) are synthetic polymers commonly found as MPs in the ocean (Rocha-Santos and Duarte, 2015). MPs, both primary and secondary, occur in high concentrations in marine ecosystems and pose a significant risk to marine life and biological processes (Bhuyan et al. 2020).

Fig. 2. Litter on the seafloor of the Bay of Bengal, Bangladesh [Photo: Sharif Sarwar]. (2a) Plastic tea cup attaches to Gorgonia coral (2b) Discarded net covering live coral (2c) Plastic bottle (spark) on coral (2d) Discarded net covering coral (2e) Discarded net attached to Gorgonia soft coral (2f) Plastic packet (Mr. Twist) of the chip (2g) Discarded tore net over seaweed & coral (2h) Plastic bottle of cold drink (7up).

Organisms Studied Worldwide

Fish, amphibians, birds, mammals, reptiles, crustaceans, molluscs, echinoderms, annelid worms, cnidaria, porifera, and rotifers were the focused creatures under this review research. Zooplankton was included in the "small crustaceans" category, while all other crustacean species were included in the "large crustaceans". Most of the research to date has focused on fish; more information is needed on the effects of MPs on other taxa, particularly invertebrates (Alfaro-Núñez et al. 2021; De Sá et al. 2018).

Characteristics Of Microplastics

Plastics have a variety of properties that make them usable in a wide range of applications, from construction to medicine (Bhuyan et al. 2020). Corrosion resistance, weak electrical and thermal conductivity, durability, and the ability to carry additional resources and manufacture at low cost are some of the notable features. The presence of plastics in the environment is problematic due to these characteristics. Existing information of the wide-ranging effects of large plastic fragments and their fragmentation in MPs on marine diversity is still limited (Alfaro-Núñez and Bermudez, 2018).

It should also be noted that during the manufacturing process of plastics, they are molecularly mixed with other chemical compounds that give them the special properties mentioned above and prove harmful when consumed (Fries et al. 2013). Plastics in the environment can potentially absorb other toxic chemicals (Velzeboer et al. 2014). MPs particles have a great potential to absorb environmental pollutants such as polycyclic aromatic hydrocarbons and metals due to their enormous surface area to volume ratio (Ashton et al. 2010).

Although plastic can degrade over time into smaller pieces to nanoplastics, it remains unbroken as a plastic polymer and attracts persistent organic pollutants (POPs) such as dioxins and 1,1-dichloro-2,2-bisethylene, also known as DDE, in addition to the toxic substances already present in MPs (Alfaro-Núñez and Bermudez, 2018). Polyethylene (PE) accounts for 28% of total production in Europe, followed by polypropylene (PP) with 19%, polyvinylchloride (PVC) with 10%, and polystyrene with 7% (Plastics Europe, 2020). The density of the different plastic polymers determines MP behaviour in the aquatic environment (Nizzetto et al. 2016). Furthermore, MPs occur in a variety of forms that distribute differently in different compartments of the aquatic environment due to differences in shape and density, which affects their availability to species (Cole et al. 2011).

Behaviour And Fate Of Microplastics

MPs are resistant to biodegradation at the molecular level and can persist in ecosystems for hundreds of years, posing an eminent threat to the environment and organisms. MPs enter the marine environment mainly through human activities (Duis and Coors, 2016; Bhuyan et al. 2020). The abundance of MPs and the increase in human population density have been shown to have a very logical growth correlation, leading to an increase in the accumulation of plastic debris in the marine environment (Rochman et al. 2013a). Physical and chemical characteristics, as well as with hydrodynamic and environmental conditions, may affect their transit dynamics, thereby influencing their distribution and accumulation in different marine environments (Rocha-Santos and Duarte, 2015). MPs have been recorded in intertidal ecosystems, deep-sea sediments, and polar regions (Alomar et al. 2017; Van Cauwenberghe et al. 2015).

MPs can be ingested by virtually all-living organisms in the ocean and are well documented in a variety of marine organisms with different feeding strategies within the food web (Table 1). MPs can affect phytoplankton, zooplankton, echinoderms, sediments, and suspended feeders (Fossi et al. 2016; Avio et al. 2015a; Cole et al. 2013). MPs can be ingested directly from the water by giant marine species, or indirectly through consumption by many other animals that may ingest or metabolize them. Numerous fish, seabirds, marine mammals and turtles have been shown to become tangled or ingest plastic items such as ropes, fishing nets, plastic bags, etc., which can lead to ulcers or starvation and ultimately death of the animal (Alfaro-Núñez and Bermudez, 2018). MPs can be stored in the organism or transported through body tissues, or they can be excreted or ingested via pseudo-faeces (Avio et al. 2015a; Van Cauwenberghe and Janssen, 2014). MPs that accumulate in the ecosystem can have a variety of negative effects on the organisms that ingest them. Internal or external trauma, digestive system blockages leading to pseudo saturation, and physiological stress, alteration of nutrition and growth retardation, loss of infertility, fecundity, and progeny survival are just a few examples (Sussarellu et al. 2016; Welden and Cowie, 2016; Cole et al. 2015). MPs can also serve as a vehicle for contaminated intrusion into marine species (Wang et al. 2016; Brennecke et al. 2016).

Table 1
Evidence of microplastics occurrence in fish and shellfish.

Fish						
Species	MP levels (particles/ind.)	Size range	Parts	Debris types	Location	References
<i>Coryphaena hippurus</i>	87%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Centropomus robalito</i>	60%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Cynoscion stolzmanni</i>	73%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Cynoscion analis</i>	73%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Alopias pelagicus</i>	87%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Mugil cephalus</i>	60%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Peprilus medius</i>	53%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Larimus argenteus</i>	80%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Hemanthias peruanus</i>	60%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Urotrygon chilensis</i>	80%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Diapterus brevirostris</i>	80%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Selene peruviana</i>	73%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Chloroscombrus orqueta</i>	60%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Diplectrum maximun</i>	67%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Lethrinus microdon</i>	10; 20%	1480 µm (mean)	Gastrointestinal tract	Fibres, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. 2018
<i>Lipocheilus camolabrum</i>	7; 28.57%	1870 µm (mean)	Gastrointestinal tract	Fibres, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. 2018
<i>Lutjanus kasmira</i>	10; 16.67%	2160 µm (mean)	Gastrointestinal tract	Fibres, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. 2018
<i>Parascolopsis eriomma</i>	5; 60%	1380 µm (mean)	Gastrointestinal tract	Fibres, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. 2018
<i>Plectorhinchus gaterinus</i>	6; 33.33%	3310 µm (mean)	Gastrointestinal tract	Fibres, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. 2018
<i>Pristipomoides multidens</i>	10; 20%	3800 µm (mean)	Gastrointestinal tract	Fibres, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. 2018

Fish						
<i>Sprattus sprattus</i> ****	515; 18.8%	100 - > 5000 µm	Gastrointestinal tract	Fibres, fragments	Baltic Sea	Beer et al. 2018
<i>Clupea harengus</i> ****	299, 21%	100 - > 5000 µm	Gastrointestinal tract	Fibres, fragments	Baltic Sea	Beer et al. 2018
<i>Mugil cephalus</i>	30; 16.7% (captive)	< 2000–5000 µm	Gastrointestinal tract	Fibres	Hong Kong From fish farms	Cheung et al. 2018
<i>Cynoscionacoupa</i>	552; 51%	< 5000 µm	Gut	Filaments, hard MPs	Goiana estuary, Brazil	Ferreira et al. 2018
<i>Odontesthes regia</i>	9; 11.1%	Not specified	Gut	Fragments	Southeast Pacific Ocean	Ory et al. 2018
<i>Scomber japonicus</i> ****	30; 3.3%	<2100 µm	Gut	Fragment	Southeast Pacific Ocean	Ory et al. 2018
<i>Solea solea</i>	533; 95%	< 100-500 µm	Gastrointestinal tract	Fibres, fragments	Adriatic Sea	Pellini et al. 2018
<i>Scyliorhinus canicula</i>	20; 5%	1500 µm	Stomach	Micro-bead	North Sea	Smith, 2018
<i>Engraulis encrasicolus</i>	10; 80%	124-438 µm	Liver	Not specified	Mediterranean Sea	Collard et al. 2017
<i>Sardina pilchardus</i> ****	2; 100%	124–438 µm	Liver	Not specified	Mediterranean Sea	Collard et al. 2017
<i>Argyrosomus regius</i>	51; 75%	> 9.07 µm	Gastrointestinal tract	Fibres, hard plastic, nylon	Mediterranean Sea	Güven et al. 2017
<i>Mullus barbatus</i>	207; 66%	> 9.07 µm	Stomach and intestine	Fibres, hard plastic, nylon	Mediterranean Sea	Güven et al. 2017
<i>Mullus surmuletus</i>	51; 35 and 49%	> 9.07 µm	Gastrointestinal tract	Fibres, hard plastic, nylon	Mediterranean Sea	Güven et al. 2017
<i>Sardina pilchardus</i> ****	7; 57%	> 9.07 µm	Gastrointestinal tract	Fibres, hard plastic, nylon	Mediterranean Sea	Güven et al. 2017
<i>Scomber japonicus</i> ****	7; 71%	> 9.07 µm	Gastrointestinal tract	Fibres, hard plastic, nylon	Mediterranean Sea	Güven et al. 2017
<i>Sparus aurata</i>	110; 44%	> 9.07 µm	Gastrointestinal tract	Fibres, hard plastic, nylon	Mediterranean Sea	Güven et al. 2017
<i>Gadus morhua</i> ****	302; 18.8%	< 5000 µm- > 20,000 µm	Stomach	Fibres, fragments, granule, film	Norwegian coast	Brate et al. 2016
<i>Merluccius merluccius</i>	12; 16.7%	380–3100 µm	Stomach	Fragments, Fibres, film, spheres	Spanish Atlantic	Bellas et al. 2016
<i>Mullus barbatus</i>	128; 18.8%	380–3100 µm	Stomach	Fragments, Fibres, film	Mediterranean coast	Bellas et al. 2016

Fish						
<i>Scyliorhinus canicula</i>	72; 15.3%	380-3100 µm	Stomach	Fragments, Fibres, film	Mediterranean coasts	Bellas et al. 2016
<i>Merluccius merluccius</i>	3; 100%	10–5000 µm	Gastrointestinal tract	Fragments, line, film, pellet	Adriatic Sea	Avio et al. 2015a
<i>Mullus barbatus</i>	11; 64%	10–5000 µm	Gastrointestinal tract	Fragments, line, film, pellet	Adriatic Sea	Avio et al. 2015a
<i>Sardina pilchardus</i> ****	99; 19%	10–5000 µm	Gastrointestinal tract	Fragments, line, film, pellet	Adriatic Sea	Avio et al. 2015a,b
<i>Brama brama</i>	3; 33%	217-4810 µm	Gastrointestinal tract	Fibres	Portuguese Coast *From local market	Neves et al. 2015
<i>Merluccius merluccius</i>	12; 29%	217–4810 µm	Gastrointestinal tract	Fibres	Portuguese Coast	Neves et al. 2015
<i>Dentex macrophthalmus</i>	1; 100%	217-4810 µm	Gastrointestinal tract	Fibres	Portuguese Coast *From local market	Neves et al. 2015
<i>Mullus surmuletus</i>	4; 100%	217–4810 µm	Gastrointestinal tract	Fibres	Portuguese Coast	Neves et al. 2015
<i>Scomber japonicus</i> ****	35; 31%	217-4810 µm	Gastrointestinal tract	Fragments, Fibres	Portuguese Coast	Neves et al. 2015
<i>Scomber scombrus</i> ****	13; 31%	217-4810 µm	Gastrointestinal tract	Fragments, Fibres	Portuguese Coast	Neves et al. 2015
<i>Trigta lyra</i>	31; 19%	217-4810 µm	Gastrointestinal tract	Fragments, Fibres	Portuguese Coast	Neves et al. 2015
<i>Zeus faber</i>	1; 100%	217-4810 µm	Gastrointestinal tract	Fibres	Portuguese Coast	Neves et al. 2015
<i>Argyrosomus regius</i>	5; 60%	217-4810 µm	Gastrointestinal tract	Fibres, fragments	Portuguese Coast *From local market	Neves et al. 2015
<i>Thunnus thymus</i>	34; 34.4%	< 5000 µm	Stomach	Fragments	Mediterranean Sea	Romeo et al. 2015
<i>Xiphias gladius</i>	56; 12.5%	< 5000 µm	Stomach	Fragments	Mediterranean Sea	Romeo et al. 2015
<i>Sardinella longiceps</i> ****	10; 60%	500–3000 µm	Gut	Fragments	Indian Coast	Sulochanan et al. 2014
<i>Clupea harengus</i> ****	566; 2%	> 1000 µm	Gastrointestinal tract	Fibres, fragments	North Sea	Foekema et al. 2013
<i>Gadus morhua</i> ****	80; 13%	> 1000 µm	Gastrointestinal tract	Fibres, fragments	North Sea	Foekema et al. 2013
<i>Merlangius merlangus</i>	50; 32%	1000-2000 µm	Gastrointestinal tract	Fibres, fragments, beads	English Channel	Lusher et al. 2013
<i>Micromesistius poutassou</i> ****	27; 51.9%	1000–2000 µm	Gastrointestinal tract	Fibres, fragments, beads	English Channel	Lusher et al. 2013

Fish						
<i>Trachurus trachurus</i>	56; 28.6%	1000-2000 µm	Gastrointestinal tract	Fibres, fragments, beads	English Channel	Lusher et al. 2013
<i>Zeus faber</i>	42; 47.6%	1000-2000 µm	Gastrointestinal tract	Fibres, fragments, beads	English Channel	Lusher et al. 2013
Shellfish						
Species	MP levels (particles/ind.)	Size range	Parts	Debris types	Location	References
<i>Saccostrea palmula</i>	0.71 ± 0.29	734–1585 µm	Digestive tract	Fibres, fragments	Galapagos Islands	Jones et al. 2021
<i>Holothuria kefersteini</i>	0.99 ± 0.34	165.5 – 952 µm	Digestive tract	Fibres, fragments	Galapagos Islands	Jones et al. 2021
<i>Dosidicus gigas</i>	93%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Penaeus occidentalis</i>	20%	150-5000 µm	Digestive tract	Fibres	Ecuadorian coast	Alfaro-Núñez et al. 2021
<i>Modiolus modiolus</i>	3.5 ± 1.29	200 - > 2000 µm	Soft tissue	Fibres	Scottish coast	Catarino et al. 2018
<i>Amiantis purpuratus</i>	6	10-5000	Soft tissue	Fibres, fragments, pellets, film	Coastal water of The Persian Gulf, Iran, Asia	Naji et al. 2018
<i>Cerithidea cingulata</i>	12	10-5000 µm	Soft tissue	Fibres, fragments, pellets, film	Coastal water of The Persian Gulf, Iran, Asia	Naji et al. 2018
<i>Thais nitabilis</i>	3	10-5000 µm	Soft tissue	Fibres, fragments, pellets, film	Coastal water of The Persian Gulf, Iran, Asia	Naji et al. 2018
<i>Pinctnda radiata</i>	11	10-5000 µm	Soft tissue	Fibres, fragments, pellets, film	Coastal water of The Persian Gulf, Iran, Asia	Naji et al. 2018
<i>Mytilus galloprovincialis</i>	6.2-7.2 particle/g	760-6000 µm	Valves, hepatopancreas and gills	Filaments	Italy From maricultured and natural stocks	Renzi et al. 2018
<i>Pernapema</i>	26.7% ind. with MP	Not specified	Digestive tract and entire tissue	Fibres	Santos Estuary, Brazil	Santana et al. 2016
<i>Eriocheir sinensis</i>	13% ind. with MP	Not specified	Stomachs	Fragments, filaments	Baltic coastal	Wojcik-Fudalewska et al. 2016
<i>Crangon crangon</i>	0.68 particles/g individual	200-1000 µm	Whole shrimp and peeled shrimp (abdominal muscle tissue)	Fibres	Belgium	Devriese et al. 2015
<i>Crassostrea gigas</i>	0.6 particles/g individual	> 500 µm	Entire tissue	Fibres	California, USA From local market	Rochman et al. 2015
<i>Cyclina sinensis</i>	4.82 ± 2.17	5-5000 µm	Soft tissue	Fibres, fragments, pellets	China From the local fish market	Li et al. 2015
<i>Alectryonella plicatola</i>	10.78 ± 4.07	5-5000 µm	Soft tissue	Fibres, fragments, pellets	China From the local fish market	Li et al. 2015

Fish						
<i>Meretrix ktsoria</i>	9.22	5-5000 µm	Soft tissue	Fibres, fragments, pellets	China From the local fish market	Li et al. 2015
<i>Mytilus galloprovincialis</i>	4.33 ± 2.62	5-5000 µm	Soft tissue	Fibres, fragments, pellets	China From the local fish market	Li et al. 2015
<i>Patinopecten yessoensis</i>	57.17 ± 17.34	5-5000 µm	Soft tissue	Fibres, fragments, pellets	China From the local fish market	Li et al. 2015
<i>Ruditapes philippinarum</i>	5.72 ± 2.86	5-5000 µm	Soft tissue	Fibres, fragments, pellets	China From the local fish market	Li et al. 2015
<i>Scapharca subcrenata</i>	45 ± 14.98	5-5000 µm	Soft tissue	Fibres, fragments, pellets	China From the local fish market	Li et al. 2015
<i>Sinonovacula constricta</i>	14.33 ± 2.21	5-5000 µm	Soft tissue	Fibres, fragments	China From the local fish market	Li et al. 2015
<i>Tegillarea granosa</i>	5.33 ± 2.21	5-5000 µm	Soft tissue	Fibres, fragments	China From the local fish market	Li et al. 2015
<i>Crassostrea gigas</i>	0.47 particles/g individual	5-25 µm	Soft tissue	Not specified	Atlantic Ocean Market from Brittany, France	van Cauwenberghe and Janssen, 2014
<i>Mytilus edulis</i>	0.36 ± 0.07 particles/g	5-25 µm	Soft tissue	Not specified	North Sea	Van Cauwenberghe and Janssen, 2014
<i>Nephrops norvegicus</i>	83% ind. with MP	Not specified	Stomach	Filaments	Clyde, UK	Murray and Cowie, 2011
****According to the FAO (2016), this species is on the list of the most often collected marine species in the world.						

Sources Of Microplastics In The Ocean

Synthetic and natural fibres are used in a variety of products in our daily lives (Gago et al. 2018). MPs contamination is largely caused by abrasion and fibre release from synthetic garments. Washing a single polyester garment resulted in the release of >1900 MP fibres and microbeads, resulting in >hundred fibres/l of wastewater (Browne et al. 2011). Compared to fabrics made solely of acrylic or polyester, polyester-cotton blends lose far fewer fibres (Bhuyan et al. 2020; Napper and Thompson, 2016).

Polyester is a polyethylene terephthalate fabric that is widely used for its strength, physical properties, and distinct wear properties (Carr, 2017). Polyester, which accounts for about half of the world's fibre industry, is mainly used for apparel fabrics and other processed textile goods (Carr, 2017). 35% of fibres from MPs are generated from washing synthetic textiles and 28% from tyre erosion particles (Boucher and Friot, 2017). MP fibres are released into the environment throughout the manufacturing process, while washed end products are released into the oceans as textiles and unwashed materials disintegrate (Bhuyan et al. 2020).

Construction site debris from insulation materials is also among the listed sources of MPs (Waldschläger et al. 2020; Mishra et al. 2019). MPs include granules from pre-production and elements in a variety of items, including fragments of fishing gear, packaging and beverage cans, synthetic textiles, vehicle tyres, coatings, skin care, and beauty products, and electronic devices (Andrady, 2011; GESAMP, 2016). Sources and transport of MPs in the ocean are shown in Fig. 3.

Another more recent vast source of MPs, which ultimately ends up wasted into the oceans, comes from the massive global production of disposal masks, face screens, plastic laboratory, medical materials, and antigen rapid test kits (home self-testing) that has substantially increased during the current COVID-19 pandemic (Alfaro-Núñez et al. 2021).

Fig. 3. Source and transportation of MPs in the ocean.

Transformation Of Microplastics

Microplastics deterioration

Weathering effects such as UV-light, wind, salinity, etc., and biofouling are aging processes that can alter the physicochemical properties of MPs in the ocean (Vroom et al. 2017). MPs break down as a result of these processes, shrink in size and form an uneven shape and surface, eventually increasing their total surface area (Lambert et al. 2017). Once MPs enter the oceans, a layer of organic and inorganic compounds forms. This can lead to the formation of a biofilm due to attractive and repulsive interactions between the MP and microorganisms in the environment (Rummel et al. 2017; Oberbeckmann et al. 2015). A large majority of previous research have used unstained, "virgin" MPs in their experiments, which does not correspond to MPs found in the marine environment. The MPs were forced to age by being soaked in natural seawater for three weeks while a biofilm was allowed to grow on their surface. This shows that weathering and biofouling processes increase the bioavailability of MPs (Mazurais et al. 2015).

Density Transformation By Biotechnology

The buoyancy of plastic debris can be affected by biofouling. As the plastic sinks, it becomes accessible to marine organisms at greater depths in the water, resulting in greater density and impartial/harmful upwelling (Bhuyan et al. 2020). According to Kooi et al. (2017), biofouling causes a size-dependent vertical migration of MPs, with maximum concentration at intermediate depths. This results in a lower amount of MP at the water surface and prevents its accumulation at the seabed. As a result, zooplankton, migrating through the vertical zones, comes into contact with these MPs on their way. MPs can also be transported to deeper water by faecal pellet digestion and upward migration during the day. Other marine species that eat faeces pellets contributes to particulate matter vertically flow, which is considered part of the biological pump (Cole et al. 2016). The low-density of MPs detected in faecal pellets affects their sinking rate, which could impact CO₂ sequestration in the deep sea (Cole et al. 2016). Moreover, coprophagy makes these lower density faecal pellets accessible to a variety of species. MPs may also be incorporate into the secretion of mucus used by species such as *Bathochordaeus stygius* to concentrate food particles through active filtration, often referred to as "houses" (Katija et al. 2017). When these dwellings become clogged, they are shed and sink rapidly, exposing another biological transport mechanism that carries MPs from surface water to the seafloor (Katija et al. 2017).

Aggregations

The hydrophobic properties of MPs allow them to collect and incorporated into marine aggregates such as marine snow. Depending on the type of plastic, there is an increase in total particle size, which can affect density. As a result, they become bioavailable to species of different sizes and in different layers of the water column. Externally, MPs has been observed to accumulate on the copepod antennae, limbs, swimming appendages, feeding apparatus, and furca (Cole et al. 2013). This led to blockages that would further limit motility, feeding, reproduction and mechanoreception. The formation of these accumulations has also been observed in the digestive system (Vroom et al. 2017; Cole et al. 2013).

Economic Loss Due To Microplastics Management

The economical loss caused by MP's can directly impact marine organisms and human health (Oliveira et al. 2019). The annual economic impact of lost marine capital is estimated to be between \$33,000 and \$2500 billion/ton of MPs trash in 2011 (Beaumont et al. 2019). A decline in tourism due to plastic waste could threaten the survival of many communities and, in turn their health. For example, the Azores archipelago in the Northeast Atlantic lost 710,698€ (0.02% of GDP) in 2016 due to problems caused by marine litter, such as repairs, lost production, and clean up (Rodríguez-Torres et al. 2020). The lost funds could be used for social and environmental goals such as long-term sustainability by addressing the environmental and economic impacts of marine litter, as well as the lesser-known impacts of MPs.

Substrate For Pathogens

Pathogenic microorganisms that cause infections can be detected on the surface of MPs and benefit from the aggression that these particles generate. For example, MPs have been found to contain *Vibrio* sp. in the environment, a bacterial species associated with foodborne illness (Letchumanan et al. 2019; Kirstein et al. 2016). Ingestion of MPs can cause respiratory problems in marine organisms, which have a better chance of survival if they are shielded by airborne particles (Prata, 2018). *Arcobacter* sp., *Clostridium perfringens*, *Escherichia coli*, *Enterobacter* sp. and *Helicobacter* sp. were identified in sterilized polyethylene microparticles kept in situ in river water for fourteen days, suggesting the presence of potential human disease (Murphy et al. 2020). MPs have been linked to the spread of antimicrobial or pathogenic microorganisms (Hu et al. 2019), as these particles have been shown to increase the frequency of *in vitro* resilience plasmid transfer from *E. coli* to wild bacterial colonies (Arias et al. 2019). In addition, MPs can increase the density and severity of toxic algal blooms, which can have detrimental consequences for other organisms in the ocean (Yokota et al. 2017) and potentially affect the food supply. For example, the number of antibiotic-resistant bacteria in MPs particles in a marine aquaculture system was 100-5000 times higher than in ambient water, posing a threat to human and fish welfare (Zhang et al. 2021).

Materials And Methods For The Data Collection And Analyses

Online study sites

Data have been collected from many countries around the world. Results from the publications of various scientists and researchers are presented.

Data collection

The first phase involved the identification of related studies. In order to conduct a systematic literature search, the following specifications were created for the database:

- **Searching database**
- Scopus, Web of Science, Google Scholar, PubMed, Dimension
- **Searching conditions**
- Journal articles written in English
- Impact of MPs on marine organisms-related journals, book chapters, conference proceedings
- Accessible over the internet (No time limitation)
- **Searching strings**

The data were tagged with the keywords "*Impacts of microplastics on marine organisms*" "*Effects of microplastics on marine organisms*" "*Toxicity of microplastics on marine organisms*" or "*Adverse impacts of microplastics on marine organisms*" or "*Biomagnification of microplastics on marine organisms*" or "*Impacts of microplastics on marine fish*" or "*Impacts of microplastics on marine invertebrates*" or "*Impacts of microplastics on marine birds*" or "*Impacts of microplastics on marine turtles*" or "*Impacts of microplastics on marine molluscs*" or "*Impacts of microplastics on marine Arthropoda*" or "*Impacts of microplastics on marine Annelida*" or "*Impacts of microplastics on marine Echinodermata*", etc. A search for "*Impacts of microplastics on marine organisms*" in the Dimension database revealed numerous research papers (Fig. 4).

Results Of The Bibliometric Analysis

The dataset of article information was recorded in the Dimension database as a CSV file. Then, the CSV file was used in the VOS viewer software (version 1.6.17) for the bibliometric analysis. The type of analysis and the unit of analysis were set up as co-authorship and authors, respectively. The full count method was implemented for this analysis. The threshold for the minimum number of publications for authors was and the number of citations was set to 1. Association was used as the normalization method. Then, the program was run providing the following results. A total of 64 clusters were recorded, where cluster 1 contained 18 items, cluster 2 contained 15 items, cluster 3 included 13 items, cluster 4 included 11 items, cluster 5 comprised 10 items, cluster 6 covered 9 items, cluster 7 included 8 items, cluster 8 contained 8 items, cluster 9 covered 7 items and cluster 10 included 7 items (Fig. 5). "*lyons, daniel m*" showed the highest total link strength (19) followed by "*oral, rahime*", "*pagano, giovanni*", "*thomas, philippe j*", "*toscanesi, maria*" and "*trifuoggi, marco*". "*rochman, chelsea m*" have a total connection strength of 18 and are closely connected.

Impacts

Impacts of microplastics on marine organisms

Most natural nano-plastics and MPs are less than 100 nm in size and are found in seawater. In general, these microscopic particles have a detectable impact on marine species (Table 2). MPs, on the other hand, cannot molecularly be degraded or assimilated after consumption because marine organisms do not have the necessary enzyme pathways to degrade the synthetic polymers, and can therefore be classified as bioinert substances (Andrady, 2011). It has long been known that ingestion of MP can cause a number of health problems. MPs are known to harm aquatic organisms in a variety of ways, including effects on growth and development, reduced food intake, gut blockage, changes in swimming behaviour, and impaired reproductive success (Lo and Chan, 2018; Lee et al. 2017; Wright et al. 2013). The ability of MPs' to bind and absorb metals and POPs (e.g., polychlorinated biphenyls, polycyclic aromatic hydrocarbons, dichloro-diphenyl-trichloroethane and polybrominated diphenyl ethers) from the ecosystem is of concern (Gewert et al. 2015; Rochman et al. 2014). The nature of polymeric materials (e.g., glassy, or rubbery), the weathering and residence time of plastic debris in seawater, and the biological colonisation of their surfaces may increase the ability to absorb MPs (Wang et al. 2016). MPs can absorb POPs in greater quantities than larger plastics due to their greater surface area to volume ratio (Cole et al. 2011), which is detrimental to the ecosystem (Gewert et al. 2015). Hirai et al. (2011) estimated the average global amount of POPs in marine plastic pellets to be 1-10,000 ng/g.

MPs can collect and store metals, most of which come from a variety of sources, including industrial wastewater, waste incineration, and antistatic coatings (Brennecke et al. 2016; Rochman et al. 2013b). Due to the widespread distribution of plastic debris and the small size of MPs, both primary and contaminated MPs can be ingested by a variety of marine animals and have potentially hazardous effects. One or more sources, such as residual monomers and additives in plastics, products formed during partial fragmentation, or substances adsorbed to them, can cause these effects. Furthermore, the number of MPs ingested, and the time they remain in the tissues or organs of an organism are critical factors in determining their potential effects (Wright et al. 2013a; Wang et al. 2016). Several studies have demonstrated that MPs, alone or in combination with other marine contaminants, pose a significant health risk to many marine biotas.

Impacts on bivalve-molluscs

There is a historical financial connection between humans and molluscs. Two of the three main groups within the phylum Mollusca are bivalves and gastropods. Molluscs provide various commercial benefits, such as fishing and mariculture, but they can also cause significant economic losses causing misery in communities that depend on this income (Levin, 2013). They are a diverse group found in a variety of aquatic habitats. They play a critical role in ecosystem engineering, by reshaping aquatic bottom conditions while also providing habitat, security, and food for a variety of other taxa (Fernández Pérez et al. 2018).

Detrimental human health consequences from MP fibres associated with the consumption of marine molluscs have attracted much attention recently. Molluscs are a group of filter feeders that are vital to both the environment and the economy. These sessile animals filter a considerable amount of water, which is absorbed and deposits a wide range of marine toxins that humans can tolerate to some level in their tissues. Bivalves such as *Mytilus galloprovincialis* and *Mytilus edulis* are heavily used in the food industry and that also serve as bioindicators of pollution (Bat et al. 2018; Capillo et al. 2018; Savorelli et al. 2017). *Ostrea edulis* has been contaminated by MPs, both conventional and biodegradable (Green, 2016). As bivalves filtrated their food, they may represent an important source of MPs accumulated toxins to humans (Mincarelli et al. 2021; Van Cauwenberghe and Janssen, 2014).

De Witte et al. (2014) found that *M. edulis* samples collected from the Belgian coast and purchased in shops contained 0.26 to 0.51 fibres per gram of tissue, with variation due to environmental availability. Mathalon and Hill (2014) found approximately 30 and 70 fibres per individual of *M. edulis* collected from a Nova Scotia port and purchased from an aquaculture site, respectively. Li et al. (2015) found large amounts of fibres in a variety of molluscs from a Chinese fisheries market.

MP exposure affected the homeostasis of bivalves *Mytilus* sp. resulting in increased energy consumption, decreased binding strength, interference with key metabolic enzymes, and increased regulation of antioxidant indicators (Green et al. 2018; Détrée and Gallardo-Escárate, 2017, 2018; Van Cauwenberghe et al. 2015). This is most likely the result of the need to assimilate inactive material while maintaining metabolic balance (von Moos et al. 2012). Changes in immunological indicators, oxidative stress, neurotoxicity and genotoxicity as well as transcriptional effects have been observed in mussels with high pyrene concentrations (Mincarelli et al. 2021). Early

granulocytoma development (inflammation), an increase in haemocytes, and a significant decrease in lysosomal membrane stability (LMS) have also been noted (Browne et al. 2008). In addition, the amount of energy provided for immunological functions may be decreased, resulting in damage to all normal physiological processes. The result is the deterioration of individual fitness and ecosystem. Furthermore, the constant consumption and accumulation of MPs in bivalves shall have long-term negative consequences (Avio et al. 2015b).

Table 2. Effects of microplastics on aquatic biota.						
Classes	Species	Exposure time (hrs)	MPs		Effects ^b	Ref.
			Type (size µm) ^a	Tested Concentration		
Annelida	<i>Arenicola marina</i>	672	PS (400-1300)	100 gL ⁻¹	↓ Feeding activity	Besseling et al. 2013
		240	PVC (250)	n.s	↑ Oxidative stress	Browne et al. 2013
		336	PE, PS (<100)	110 MPs g ⁻¹ of sediment	↑ EC ↑ Protein content	Van Cauwenberghe et al. 2015
		48, 672	PVC (130)	5-50g of MPs Kg ⁻¹ of sediment	↓ Energy reserves ↓ Feeding activity ↑ Phagocytic activity ↑ Inflammatory response ↓ Lipid reserves ↑ MPs retention	Wright et al. 2013
		744	PE, PVC (1.4-707)	0.2-20 g of MPs Kg ⁻¹ of wet sediment	↑ Metabolic rates	Green et al. 2016
Echinodermata	<i>Lytechinus variegatus</i>	24	PE	200 ml of MPs L ⁻¹	↑ Anomalous larvae development	Nobre et al. 2015
	<i>Paracentrotus lividus</i>	6-48	PS (0.04-0.05)	1-50 µg ml ⁻¹	↑ MPs accumulation ↑ Malformations ↑ Disruption of cell membrane ↑ <i>Cas8</i> (related with apoptotic processes) ↑ Oxidative stress ↑ <i>Abcb1</i> gene (involved in multidrug resistance)	Della Torre et al. 2014
		48	PS (6)	10 ³ -10 ⁵ MPs ml ⁻¹	↓ Fertilization rate ↓ Growth ↑ Larval development abnormalities	Martinez-Gomez et al. 2017
			PE (>0-80)	0,005-5 g of MPs L ⁻¹	↑ Larval development abnormalities	
	<i>Tripneustes gratilla</i>	120	PE (10-45)	300 MPs ml ⁻¹		Kaposi et al. 2014

					↓ Growth	
Rotifera	<i>Brachionuskoreanus</i>	288	PS (0.05-6)	0.1 – 20 µg ml ⁻¹	↓ Growth rate ↓ Fecundity ↓ Lifespan ↑ Reproduction time	Jeong et al. 2016
Mollusca	<i>Crassostrea gigas</i>	1440	PS (2-6)	0.023 mg L ⁻¹	↑ Microalgae consumption ↑ Absorption efficiency ↑ Maintenance costs ↓ Oocyte number ↓ Sperm velocity	Sussarellu et al. 2016
	<i>Mytilus edulis</i>	336	PE, PS (<100)	110 MPs ml ⁻¹	↑ EC	Van Cauwenberghe et al. 2015
		3-96	PE (0-80)	2.5 g L ⁻¹	↑ MPs accumulation ↑ Granulocytoma formation ↓ LMS ↓ Lysosomal integrity	von Moos et al. 2012
		8	PS (0.03)	0.1-0.3 g L ⁻¹	↓ Filtering activity	Wegner et al. 2012
	<i>Mytilus galloprovincialis</i>	0.5-4	PS (0.05)	1-50 µg L ⁻¹	↓ LMS ↓ Phagocytic activity ↑ Lysozyme release ↑ ROS ↑ NO production ↑ Apoptotic processes ↓ MMP Cytotoxicity	Canesi et al. 2015
		168	PE, PS (<100)	20 g L ⁻¹	↓ Granulocytes ↓ LMS ↑ DNA breaks in haemocytes ↑ Nuclear anomalies ↓ AChE, Se-D-GPx, and CAT activities ↓ Lysosomal integrity	Avio et al. 2015a
		24	PE (1-50)	1.5x10 ⁷ MPs L ⁻¹	↓ PK and SD in the haemolymph and gills (genes involved in the carbon metabolism) ↑ PK and SD in the digestive gland and mantle (genes involved	Détrée and Gallardo-Escárate, 2017

in the carbon metabolism)

↓ *ID* in the haemolymph (gene involved in the carbon metabolism)

↑ *ID* in the mantle (gene involved in the carbon metabolism)

↓ *PGRP* in the digestive gland and haemolymph (gene involved in immunity)

↑ *TLR* in the digestive gland and mantle (gene involved in immunity)

↑ *Myticin A* in the digestive gland and mantle (gene involved in immunity)

↓ *Myticin A* in the gills (gene involved in immunity)

↑ *Myticin B* in the gills, haemocytes and mantle (gene involved in immunity)

↓ *Myticin B* in the mantle (gene involved in immunity)

↑ *Myticin B* in the gills, haemocytes and mantle (gene involved in immunity)

↑ *p53* in the digestive gland, mantle, gills and haemolymph (gene involved in apoptosis)

↑ FADD in the digestive gland and mantle (gene involved in apoptosis)

↑ *Caspase 3/7* in the mantle (gene involved in apoptosis)

↑ SOD and CAT activities (digestive gland and mantle)

Scrobicularia plana

336

PS (20)

1 mg L⁻¹

↑ SOD, CAT, GPx and GST activities (gills)

↑ SOD activity (digestive gland)

↓ CAT activity (digestive gland)

↑ GPx activity after 3 days exposure (digestive gland)

↓ GPx activity after the remaining time (digestive gland)

Ribeiro et al. 2017

					↓ GST (digestive gland) ↓ AChE activity (gills) ↑ LPO levels (digestive gland) Genotoxicity	
Crustacea	<i>Hyalella azteca</i>	240, 1008	PE (10-27)	0-100000 MPs ml ⁻¹	↑ Mortality ↓ Reproduction ↓ Growth	Au et al. 2015
			PP (20-75)	0-90 MPs ml ⁻¹	↑ Mortality ↓ Growth ↓ Weight	
	<i>Carcinus maenas</i>	1-24	PS (8)	10 ⁶ -10 ⁷ MPs L ⁻¹	↓ Hemolymph sodium ions ↑ Hemolymph calcium ions ↑ Oxygen consumption	Watts et al. 2016
	<i>Tigriopus japonicus</i>	2 generation test	PS (0.05-0.5)	0.125-25 µg ml ⁻¹	↑ Mortality ↓ Survival ↓ Fecundity	Lee et al. 2013
	<i>Centropagestypicus</i>	24	PS (0.4-3.8)	40x10 ³ -1x10 ⁶ MPs ml ⁻¹	↓ Ingestion rates	Cole et al. 2013
	<i>Nephrops norvegicus</i>	5760 (feeding test)	PP (3000-5000)	5 MPs feeding ⁻¹	↓ Feeding rate ↓ Body mass ↓ Metabolic rate	Welden and Cowie, 2016
	<i>Palaemonetes pugio</i>	3h	PE,PS,PP (30-165)	50 000 MPs L ⁻¹	↑ Mortality	Gray and Weinstein 2017
	<i>Gammarus fossarum</i>	672	PA (500)	100-13.380 PA MPs cm ⁻² base area	↓ Assimilation efficiency	Blarer and Burkhardt-Holm, 2016
		24	AC (Acrylic glass) (32-250)	10-100000 MPs individual ⁻¹	↓ Assimilation efficiency ↓ Wet weight gain	Straub et al. 2017
			PES (32-250)		↓ Wet weight gain	
	<i>Artemia franciscana</i>	24	PS (0,1)	0,001-10 mg L ⁻¹	↓ Swimming speed	Gambardella et al. 2017
		48			↑ Swimming speed ↓ AChE activity ↑ PChE and CAT activities	Cui et al. 2017
	<i>Daphnia galeata</i>	120	PS (0.05)	5 mg L ⁻¹	↑ Mortality ↓ Reproduction Abnormal development	

<i>Daphnia magna</i>	504	PS (0.07)	0.22-103 mg L ⁻¹	↓ Reproduction ↓ Body size ↑ Mortality	Besseling et al. 2014
	24,48	AC (Acrylic resin) (0.086-0.125)	0.01-1000 mg L ⁻¹	↑ Immobilization	Booth et al. 2016
	48	PES (62-1400)	12.5-100 mg L ⁻¹	↑ Mortality	Jemec et al. 2016
	48	PS (0,2)	1-30 mg L ⁻¹	↑ Immobilization	Kim et al. 2017
	6,24	PS (0.09-0.1)	10 µg ml ⁻¹	↑ MPs retention ↑ Stress ↓ Feeding rate ↓ Survival rate	Nasser and Lynch, 2016
	0.008 - 504	PE (1-5)	10 ² -3x10 ⁴ MPs L ⁻¹	↑ Mortality ↓ Feeding ↓ Growth	Ogonowski et al. 2016
	96	PE (1-100)	12.5-400 mg L ⁻¹	↑ Immobilisation	Rehse et al. 2016
	24,504	PS (0.1-2)	0.1-1 mg L ⁻¹	↓ Feeding rate	Rist et al. 2017
	24	PS (0.052)	0.075-0.15 g L ⁻¹	↑ Mortality	Mattsson et al. 2017
<i>Amphibalanus amphitrite</i>	48	PS (0.1)	0.001-10 mg L ⁻¹	↓ Swimming speed ↑ AChE, PChE and CAT activities	Gambardella et al. 2017
	96	PE, PS, PP, PVC, PES	0.10 and 0.50 m ² L ⁻¹	↑ Mortality ↓ Settlement	Li et al. 2016
<i>Calanus helgolandicus</i>	24, 216	PS (20)	65-75 MPs ml ⁻¹	↓ Predatory performance ↓ Reproductive output ↓ Survival Energetic depletion	Cole et al. 2015
<i>Paracyclopsina nana</i>	24	PS (0.05-6)	0.1-20 µg mL ⁻¹	↑ Intracellular ROS level ↑ Phosphorylation of extracellular signal-regulated kinase (p-ERK) and p38 (p-p38) ↑ GR, GPx, GST and SOD activities	Jeong et al. 2017
<i>Parvocalanus crassirostris</i>	144, 576	PES (5-10)	10000-80000 MPs mL ⁻¹	↓ Egg production ↓ Population size ↑ <i>H3</i> (gene involved in chromatin structure of	Heinder et al. 2017

eukaryotic cells)						
Fish	<i>Dicentrarchus labrax</i>	864	PE (10-45)	10 ⁴ -10 ⁵ MPs g ⁻¹ of diet	↑ Mortality ↑ CYP P450	Mazurais et al. 2015
		2160	PVC (300)	1 g kg ⁻¹ of diet	↑ Structural alterations of the DI ↓ Regular structure of serosa, muscularis mucosa and submucosa/mucosa Occurrence of rodlet cells in the intestinal mucosa	Peda et al. 2016
	<i>Pomatoschistus microps</i>	96	PE (1-5)	0.184 mg L ⁻¹	↓ AChE activity	Oliveira et al. 2012
		96	PE (1-5)	0.184 mg L ⁻¹	↓ AChE activity	Oliveira et al. 2013
		0.002 (predatory test)	PE (450-500)	100 MPs L ⁻¹	↓ Predatory performance ↓ Predatory efficiency	de Sá et al. 2015
		96	PE (1-5)	0.184 mg L ⁻¹	↓ AChE activity	Luis et al. 2015
	<i>Sparus aurata</i>	720 (40-150)	PVC (40-150)	100-500 mg of MPs Kg ⁻¹ of individual	↑ ASP and CK activities (serum parameters) ↑ albumin and globulin (serum parameters) ↓ Glucose (serum parameters) ↑ Peroxidase activity and skin mucus IgM (Humoral immune parameters) ↑ Phagocytic capacity ↓ <i>prdx5</i> and <i>hsp90</i> (genes related to stress) ↑ <i>prdx1</i> , <i>prdx3</i> , and <i>ucp1</i> (genes related to stress)	Espinosa et al. 2017
PE-Polyethylene; PS-Polystyrene; PP-Polypropylene; PVC-Polyvinylchloride; PLA-Biodegradable plastic; AC-Acrylic; PES-Polyester.						

The feeding ability of Pacific oyster (*Crassostrea gigas*) larvae was not affected by different sizes of polystyrene microbeads (Cole and Galloway, 2015). This could be due to the simplicity of the oyster's digestive tract, which allows less MP to be retained as they are more easily ingested. The Pacific oyster *C. gigas* (Alfaro-Núñez et al. 2021; Revel et al. 2020) and the blue mussel *Mytilus* sp. exhibited no adverse effects, but the black-lipped pearl oyster *Pinctada margaritifera* had problems with energy balance and reproduction (Revel et al. 2019; Gardon et al. 2018).

The main effect of MPs ingestion in *M. galloprovincialis* is cell destruction in response to oxidative damage (Sureda et al. 2018; Pagano et al. 2017). Experiments in the marine mussel *M. galloprovincialis* exposed to PE MPs showed a range of adverse effects in molluscs, including immunological responses, oxidative damage, and cytotoxicity (Avio et al. 2015a). Enzymatic changes were observed in the marine mollusc *M. galloprovincialis* following exposure to PS and PE MP (Avio et al. 2015a). Two mollusc species showed additional ecotoxicological consequences after exposure to PS MPs. Increased neurotoxicity and genotoxicity were found in a *Scrobicularia plana* research (Ribeiro et al. 2017).

Impacts on gastropods-molluscs

Non-filter-feeding, larger organism like gastropods feed on certain amounts of MPs fibre to ensure retention through ingestion and impact analysis (Ehlers et al. 2020; Jabeen et al. 2018). *Radix balthica* has been recorded to eat a biofilm of MPs fibres during feeding. Subsequently, MPs fibres were gradually absorbed into a fibre-free medium via faeces, which took three days (Ehlers et al. 2020). *Planorbella campanulata* was exposed to exceptionally high levels of polyester textiles in the marine environment, and the fibres accumulated in the snail's mouth, resulting in a higher mortality rate than in control snails (Philips et al. 2020). As a result, degradation at local hot spots with high fibre concentrations can lead to blockage of feeding and death of snails. In addition, snails produced more offspring when treated with polyester fibres. This is thought to be because death triggers an increase in offspring or because the chemicals evaporated from the fibres have estrogenic effects (Philips et al. 2020). Ingestion of polystyrene microbeads by veliger of the marine gastropod *Crepidula onyx* resulted in a slowed development rate as well as premature settling on the seafloor (Lo and Chan, 2018), which may negatively impact post-settlement efficacy. Moreover, those individuals subjected to the microbeads only during the larval stage grew more slowly 65 days after MPs removal. This highlights the potential for adverse long-term effects of early-life exposure on development. In contrast, the adult stage was unaffected at environmentally relevant MP concentrations.

Impacts on Arthropoda

Filter and deposit-feeding decapods passively ingest MP fibres, while selectively feeding decapods aggressively feed on them. Consumption of MP fibres by isopods and predatory crustaceans has been studied by adding fibres to their food (Watts et al. 2015; Hamer et al. 2014). When the number of fibres eaten was measured in different parts of the gastrointestinal tract and in faeces, there was no evidence of aggregation within the digestive system (Watts et al. 2015; Hamer et al. 2014). MPs of various shapes and sizes were exposed to dagger shrimp (*Palaemonetes pugio*) in the water column (Gray and Weinstein, 2017). Due to water flow, all MPs became attached to the gill region, while shrimp that were picky foragers, ingested the MPs. Considering the short exposure time, shrimp died within the first three hours after treatment and during the subsequent 96-hour depuration period. The different sizes of polypropylene fibres tested triggered mortality, and mortality rates for fibres were higher than for fragments of different sizes (Gray and Weinstein, 2017).

The high lethality of MP fibres has been linked to intestinal tissue damage from engulfment (Gray and Weinstein, 2017). The higher toxicity of fibres, on the other hand, could be related to their weathered state. After a 96-hour exposure, untreated polyester fibres did not cause increased mortality in grass shrimp (Leads et al. 2019; Gray and Weinstein, 2017). The differences in lethality could be attributed to the different plastic fibres used or the degree of degradation of the fibres, indicating the effects of fibre properties on decapods (Leads et al. 2019; Gray and Weinstein, 2017). In a later two-day test with bacteria (*Vibrio campbellii*), shrimp exposed to polyester did not die, which was related to the fact that the polyester fibres degraded relatively quickly within 48 hours, reducing their immunotoxicity (Leads et al. 2019).

Individual fitness of several crab species was affected by exposure to MP fibres over a prolonged period of time (Watts et al. 2015). Horn et al. (2019) reported higher mortality in *Emerita analoga* that were treated with 1 mm thick polypropylene fibres. This indicated that Pacific mole crabs and other non-selective feeders cannot tell the difference between plastic and food, which puts them at risk when fibre content increase in the environment (Horn et al. 2019). Similarly, exposed *E. analoga* exhibited lower clutch retention and higher heterogeneity in embryonic development. Ingested MP fibres may affect reproduction, or the colour associated with these fibres may be leached (Horn et al. 2019).

Ziajahromi et al. (2017) found that water fleas (*Ceriodaphnia dubia*) did not consume polyester fibres from water, but tactile contact with the fibres was associated with reduced development, reproduction, and aberrant swimming behaviour. *Hyalella azteca* exposed to high fibre concentrations exhibited dramatically slower growth and weighed 50% less than controls (Au et al. 2015). The effects of PP MPs on *H. azteca*, revealed more harmful than PE MPs (Au et al. 2015). *Daphnia magna* was found to be dead after consuming polyester fibres present in the water column for 48 hours (Jemec et al. 2016). MPs caused immobility (Rehse et al. 2016), mortality (Aljaibachi and Callaghan, 2018) and reproductive failure (Pacheco et al. 2018) in the planktonic crab *D. magna*, with transgenerational effects such as of lower growth and reproduction (Martins and Guilhermino, 2018).

Impacts on fish

Humans and all living organisms require a lot of protein, and fish is a good source of it. Therefore, the presence of MPs in fish and their potential consequences deserve special attention (Wang et al. 2020a). MPs have been found in a variety of fish species caught in the oceans, and seas (Alfaro-Núñez et al. 2021; Bessa et al. 2018; Pazos et al. 2017). Fish ingests MPs by mistaking them for natural prey, by deliberate ingestion during foraging, and by direct ingestion of animals containing MPs (Ghosh et al. 2021; Ory et al. 2017; Lusher et al. 2013). In practise, fish ingested MP fibres at various life stages from larval to sexual maturity (Gove et al. 2019; Kühn et al. 2018; Mizraji et al. 2017). Fibres were the most common MP form in larvae and juveniles, raising concerns about younger life stages that are

particularly susceptible to ingesting MPs fibres (Barboza et al. 2020). According to the dispersal patterns of fibres, the ingestion of MPs fibres by fish from the Mediterranean Sea was positively related to coastal human population, river inputs, and shipping routes (Sbrana et al. 2020).

In a study of *Pomatoschistus microps*, MPs with chromium (VI) resulted in neurotoxicity and death, among other effects (Luis et al. 2015). PE MPs has been shown to cause neurotoxicity in fish (Luis et al. 2015) and a loss of predatory performance and efficacy in *P. microps* (de Sá et al. 2015). Mortality has been reported in the European bass, *D. labrax* (Mazurais et al. 2015). MPs are neurotoxic; impair energy-related enzymes, negatively affect swimming performance, and cause oxidative stress and lipid peroxidation in juvenile *D. labrax* (Barboza et al. 2018a).

Oryzias latipes, a Japanese medaka fish was found to contain chemical contaminants (PAHs, PCBs and PBDEs) that accumulate in the body, as evidenced by bioaccumulation. Liver stress and early tumour formation were reported after animals were exposed to both pieces of primary and marine plastic pieces for a short time (Rochman et al. 2013b). After exposure scanning electron microscopy revealed structural damage in the gills, including epithelial denudation at the gill arches, fusion of the main lamellae, and increased mucus production (Hu et al. 2020). Polyethylene with absorbed chemical pollutants from marine waters can disrupt hormonal system function in adult *O. latipes* fish (Rochman et al. 2014). In males, gene expression of choriogenin (ChgH) was down regulated, while in females, gene expression of vitellogenin (VTgl), ChgH, and oestrogen receptor (ER) were down regulated. The main concern should be the long-term effects of exposure during the early developmental stages of an organism, which could jeopardize reproductive success and threaten biota (Rochman et al. 2014).

Omnivorous fish (*Girella laevis*) accumulated large amounts of red MPs fibre instead of the red algae they regularly eat. Specimens with higher amounts of MPs fibre in their digestive system were found to present poorer body condition (Mizraji et al. 2017), suggesting that ingested fibre may directly affect fitness. In the wild, a decline in predatory activity may reduce the ability of juvenile gobies to capture prey and escape from predators. As a result, there is a possibility that individual health and thus population fitness may be threatened, affecting in juvenile development rates and species survival (Mizraji et al. 2017).

MPs significantly reduced swimming speed and resistance time of young European seabass, *D. labrax* (Barboza et al. 2018b). Additionally, behavioural abnormalities such as sluggish and irregular swimming activity were observed. These results highlight the importance of assessing the combined effects of MPs and other environmental contaminants, focusing on the behaviour of fish and other marine animals, and using fish responses as a susceptible endpoint to determine the effects of contamination by MPs (Barboza et al. 2018b).

Impacts on Annelida

Annelids are marine worms that irrigate and provide oxygen and promote the growth of crops and algae. The ecological role of marine worms in oceanic reefs is to provide food for aquatic species higher up the food chain (von Palubitzki and Purschke, 2020). Species inhabiting sediments can be affected by MPs, which, depending on the degree and concentration of exposure, can lead to serious changes such as alteration of gut microbiota, suppression of growth, and reproduction of collembolan in the soil (Zhu et al. 2018).

In response to high doses of HDPE, PLA, and PVC in sandy sediments, respiration rates of *Arenicola marina* increase (Green et al. 2016). Decreases in energy reserves have also been noted, which may be due to inflammatory responses in tissues, as well as decreased food intake to decolonize or deposit of MPs in digestive cavities (Wright et al. 2013). As a result, stress may affect the health and behaviour of the polychaete *A. marina*, such as feeding performance and sediment transformation, negatively impacting ecological processes (Green et al. 2016). In addition, *A. marina* accumulated nonylphenol and triclosan from PVC when exposed to high levels of plastics, resulting in immune system impairment physical stress, and death (Browne et al. 2013). Exposure to PS MPs has ecotoxicological effects on the polychaete *A. marina*, including reduced feeding activity and lysosomal membrane stability (Besseling et al. 2013). When *A. marina* was exposed to PS MPs, it was noted an increase in energy consumption (Wright et al. 2013). Lipid stores of *A. marina* exposed to sediment PVC were emptied, and an inflammatory response was observed.

Impacts on Echinodermata

Echinoderms are a vital component of the ocean food web, as well as a source of food and medicine for humans (PiRuby, 2018). PE MPs have been shown to alter larval growth of *Tripneustes gratilla* without affecting its persistence in echinoderms (Kaposi et al. 2014). For *Lytechinus variegatus* larvae, Nobre et al. (2015) confirmed these results. In the echinoderm *Paracentrotus lividus*, Della Torre et al. (2014) described the effects of PS MPs on gene expression and counted an upregulation of the gene Abcb1 involved in shielding and confrontation with multiple agents (Shipp and Hamdoun, 2012).

MPs affected oceanic planktotrophic pluteus larvae of the sea urchin *P. lividus* (Messinetti et al. 2018). When sea urchins, *Lytechinus variegatus*, were exposed to seepage generated from unused polyethylene beads, abnormal embryonic development increased by 66.5 percent (Nobre et al. 2015). Compounds leached from the primary plastic components were responsible for these physical and biological effects. This demonstrates the susceptibility of early life stages to exposure to internal and external MP and the unknown long-term effects on organismal ontogeny (Nobre et al. 2015).

Impacts on Nematoda

Nematoda is one of the most diverse taxonomic groups on the planet. Marine nematodes play an important role in the marine ecosystem by recycling carbon and nutrients needed for other marine organisms (Yeates et al. 2009). In the nematode *Caenorhabditis elegans*, systemic inflammatory permeability and the development of Reactive Oxygen Species (ROS) have been observed with increasing MP levels, but this has not yet converted into morbidity (Zhao et al. 2017; Dong et al. 2018). The function of translocation in ion transport was underlined by enhanced deleterious effects in *acs-22* mutants with higher gut flora (Qu et al. 2018). Toxicity tests performed at environmentally relevant concentrations of MPs showed crucial negative effects on particularly sensitive endpoints and species in a variety of situations (Qu et al. 2018). Finally, for pelagic marine species, the Predicted No Effect Concentration (PNEC) was estimated to be 6650 particles m⁻³, which is likely to be exceeded at hotspot sites (Everaert et al. 2018).

Impacts on phytoplankton

Phytoplankton is the mainstay of the entire marine food chain and provides the primary food source for much of the ocean's biodiversity. The impact of MPs on microalgae is also becoming an increasingly important issue of global concern (Cunha et al. 2020; Ansari et al. 2021). Microalgae are an important source of energy for most marine ecosystems, feeding a wide range of organisms from tiny zooplankton to molluscs and crustaceans (Glibert, 2019). These species are the next in the food web to be preyed upon. Phytoplankton are credited with generating half of the Earth's photosynthetic activity and thus much of the new biomass that is converted to chemical energy by the sun's energy and underpins trophic webs. Because of their important, there is concern about the adverse effects of micro and nanoplastics on them (Koenigstein, 2020).

It is known that algae cells of the genera *Chlorella* and *Scenedesmus* can aggregate and absorb nanoplastic beads (0.02 µm) due to their shape and motility, leading to a reduction in photosynthesis and the development of oxidative damage (Bhattacharya et al. 2010). The physicochemical properties of MP's and the physical and metabolic properties of algae appear to be responsible for this adsorption; in particular, a strong attraction between algae and positively charged plastic particles has been described (Bhattacharya et al. 2010). Sjollem et al. (2015) found no suppression of photosynthesis in the marine flagellate *Dunaliella tertiolecta* when exposed to different types of plastic particles of different sizes. Uncharged polystyrene beads inhibited microalgae development by 45%, but only at very high levels (250 mg/L). The negative effect increased with decreasing particle size (Sjollem et al. 2015).

Impacts on zooplankton

Zooplankton is considered a vital diet source for various secondary marine organisms. It serves as a pathway for MPs to enter the food web and reach the higher trophic levels (Botterell et al. 2019). Zooplankton can exhibit different feeding behaviours depending on species, life stage, and prey accessibility (Cole et al. 2013). Prey selection is influenced by the size of the hunter relative to the prey, their swimming behaviour, and the susceptibility of each prey type to the predator once encountered. A combination of mechano- and chemoreceptors also aid in the selection of suitable prey (Cole et al. 2013). MPs are likely ingested through unselective feeding techniques, such as suspension feeding, where prey are often not selectively eaten (Cole et al. 2013). Some zooplankton species may alter their feeding habits to prefer one algal species to another, and plastic pellets can be mistaken as a prey. In addition, when exposed to MPs and algal prey, the copepod *Calanus helgolandicus* preferred algal prey of smaller size (Cole et al. 2015). This change in feeding behaviour suggests that copepods alter their feeding habits to avoid ingesting MPs. MPs have not been found in all zooplankton species. Cole et al. (2013) reported ingestion of MPs in *Parasagitta* sp. and *Siphonophorae* sp. across a size range. However, both species are raptors, and active foragers require an animal prey response, which may explain why immobile MP prey did not tempt them (Table 3).

Table 3. Impacts of microplastics in marine copepods.

Species	MPs Type	Size(nm)	Concentration	Effects	References
<i>Acartia clausi</i> <i>Calanus helgolandicus</i> <i>Centropages typicus</i> <i>Temora longicornis</i>	Fluorescent polystyrene beads	0.4-30.6	635-1 x 10 ⁶ beads/ mL	- There is proof of size-based selectivity in copepods. - Fecal pellets packed with MPs are consumed by copepods. - Algal feeding is considerably reduced when exposed to 7.3 µm MPs (> 4000 beads/mL).	Cole et al. 2013
<i>Acartia tonsa</i> <i>Calanus helgolandicus</i>	Polystyrene beads, Fibres, and fragments	20, 20 x 10, and < 20	80 MPs/mL	- Variable species of copepods have different bioavailability of MPs depending on their sound structure. -In the presence of the infochemical dimethyl sulfide, copepods' ingestion rate of MPs can significantly rise.	Botterell et al. 2020
<i>Acartia</i> sp. <i>Eurytemora affinis</i> <i>Limnocalanus macrurus</i>	Fluorescent polystyrene microspheres	10	1 x 10 ³ , 2 x 10 ³ or 1 x 10 ⁴ particles/mL	- The amount of microsphere consumed is related to the concentration. - After 12 hours, <i>E. affinis</i> ingests microspheres.	Setälä et al. 2014
<i>Calanus finmarchicus</i>	Nylon MP granules or Fibres	10-30 or 10 x 30	50 MPs/mL	-Exposure to polyester fibres reduces algal intake rates by <i>C. finmarchicus</i> by 40% on average, although no effect is seen with nylon granules. - <i>C. finmarchicus</i> revealed to nylon MPs molt considerably faster than control <i>C. finmarchicus</i> .	Cole et al. 2019
<i>Calanus finmarchicus</i> <i>Calanus glacialis</i> <i>Calanus hyperboreus</i>	Polyethylene spheres	20	200 and 2000 MPs/L	- MPs had no effect on copepods' fecal pellets growth rate. - Copepods that were exposed to MPs experienced stress-induced reproduction.	Rodriguez-Torres et al. 2020
<i>Calanus finmarchicus</i> <i>Pseudocalanus</i> sp. <i>Acartia longiremis</i>	Polystyrene beads Polystyrene fragments	15 and 30 < 30	50-200 beads/ fragments/mL	- Both <i>A. longiremis</i> and <i>C. finmarchicus</i> can eat MPs, albeit <i>A. longiremis</i> only eats the smaller (15-µm) particles and <i>C. finmarchicus</i> eats both sizes, whilst <i>Pseudocalanus</i> sp. cannot eat any MPs. - Copepods consume older MPs than new ones.	Vroom et al. 2017
<i>Calanus helgolandicus</i>	Fluorescent PE microspheres Nylon Fibres Polyethylene terephthalate Fibres Nylon fragments	10-32	100 MPs/mL	- Copepods exposed to MP fibres have a larger effect on their eating than copepods exposed to pieces. - Feces having small polyethylene sink at a slower pace than controls, but when high-density MPs are mixed into the fecal pellets, the sinking rates dramatically increase.	Coppock et al. 2019
<i>Calanus helgolandicus</i>	Polystyrene beads	20	75 MPs/ mL	-Microbead exposure reduces algal cell intake by 89 percent and carbon biomass ingestion by 60 percent in <i>C. helgolandicus</i> , respectively.	Cole et al. 2015

				-Long-term exposure to polystyrene beads reduces reproductive output considerably, but has no effect on egg formation rates, breathing, or longevity.	
<i>Paracyclops nana</i>	Polystyrene microbeads	0.05, 0.5, 6	10 ng/mL	- The 0.05 µm pellets can be found everywhere over <i>P. nana</i> 's body, whilst the other two sizes are predominantly found in the digestive systems. - When compared to the other two sizes (0.5 and 6 µm), the 0.05 µm nanobeads have a longer retention duration in the body. - In copepods, MPs lead to oxidative stress.	Jeong et al. 2017
<i>Parvocalanus crassirostris</i>	Polyethylene terephthalate	5-10	1 x 10 ⁴ -8 x 10 ⁴ particles/mL	- Egg production is lowered in a dose-dependent approach after 5-days of exposure to MPs. - In contrast to the control, exposure to MPs (2 x10 ⁴ plastics/mL) for 6-d reduces population size by 75%, whereas populations exposed for a longer period of time (24-d) exhibit more severe depletion (i.e., 60 percent of control).	Heindler et al. 2017
<i>Pseudodiaptomus annandalei</i>	Monodisperse Polystyrene microspheres	0.5, 2, and 10	20, 200, and 2 x 10 ³ µ/L	- MPs of three sizes were consumed by <i>P. annandalei</i> . MPs with diameters of 0.5 and 2 micrometers were consumed at higher rates than MPs with diameters of 10 micrometers. - <i>P. annandalei</i> ingested MPs through fecal pellets.	Cheng et al. 2020
<i>Temora turbinata</i> <i>Tigropus fulvus</i> <i>Tigropus japonicus</i>	Polystyrene microbeads Polyethylene MPs Polystyrene Microbeads	20 1-5 0.05, 0.5, 6	100 and 1 X 10 ³ beads/mL 0-1-10 mg/L 9.1x 10 ¹¹ particles/ml. 9.1x 10 ⁵ particles/ml. 5.25 x 10 ⁵ particles/mL	- Microbeads have a considerable impact on copepod swimming behavior. - In the marine ecosystem, MPs can be transported from copepods to jellyfish ephyrae. - When compared to the control, exposure to 0.5- and 6-µm polystyrene microbeads dramatically reduces fecundity at concentrations (1.25-25 mg/L), however 0.05-µm PS nanobeads have no effect on this feature.	Suwaki et al. 2020 Costa et al. 2020; Lee et al. 2013
<i>Tigropus japonicus</i>	Polystyrene beads	6	0.023 and 0.23 mg/L	- MPs (0.23 mg/L) caused a significant decrease in life expectancy, nauplii/clutch number, and fertility. -MPs had a considerable intergenerational transmission proteome plasticity in copepods due to their two-generational influence.	Zhang et al. 2019
<i>Tigriopus japonicus</i>	Polystyrene Microbeads	0.05 and 10	20 mg/L	- Intake of both small and large MPs causes an excessive production of reactive O ₂ species, as well as a considerable impact on the antioxidant defense system.	Choi et al. 2020
<i>Tigriopus japonicus</i>	Polyethylene and polyamide-nylon 6 MPs	10–30 and 5–20	0,12.5, 25, 50,100, 200, and 400 mg/L	- In <i>T. japonicus</i> , MPs had a deleterious effect on eating, reproduction, and longevity. - MPs had no effect on the body size of <i>T. japonicus</i> after one generation.	Yu et al. 2020

MP fibres made up 43.9-93% of MP items in zooplankton, which is similar to amounts identified in different organisms like clams, shrimps, and fish (Zheng et al. 2020). The majority of laboratory studies have exposed copepods to MPs, concluding they can be consumed by a

variety of copepods (Botterell et al. 2020; Zhang et al. 2019). Choi et al. (2018) reported that *Cyprinodon variegatus* larvae readily ate irregular polyethylene forms. Desforges et al. (2015) discovered that the copepod *Neocalanus cristatus* preferred to eat particles with a diameter of 556 micrometres. Vroom et al. (2017) studied the ingestion of MPs as well as microbeads.

Copepods in contact to nylon pieces or fibres reduced their food ingestion in treatments with suspended fibres, but not in the fragment's treatments (Coppock et al. 2019). Reduced food ingestion and the resulting decrease in existing energy will have a long-term impact on fitness (Watts et al. 2015). When the maritime copepods *C. helgolandicus* and *T. japonicas* were exposed to PS MPs, it was found a reduction in survival and productiveness (Cole et al. 2015; Lee et al. 2013). In the small crustaceans *A. franciscana* and *Paracyclopina nana*, some changes in enzymes were identified (Gambardella et al. 2017; Jeong et al. 2017). Irregular shaped MPs harmed the larvae's swimming behaviour, reducing the total distance travelled and maximum velocity (Yu et al. 2020; Wang et al. 2020b).

Impacts on algae

Algae capture and utilise energy from sunlight, and biochemically transform carbon dioxide (CO₂) and water (H₂O) to make organic matter. They are regarded as an essential component to the health of the world's oceans (Singh and Singh, 2014). This cycle contributes to the ocean's life balance. Algae can also be used as a source of food and medicine for people. MPs caused morphological alterations, lower growth, and photosynthetic activity is lowered (Table 4) in the microalgae *Chlorella pyrenoidosa* (Mao et al. 2018). MPs, for example, increased the toxicity of the medicine doxycycline in the marine microalgae *Tetraselmis chuii* and the restricted chemical methamphetamine in the green algae *C. pyrenoidosa* (Qu et al. 2020; Prata et al. 2018).

Table 4. Impacts of microplastics on marine algae.

Species	MPs type	Duration of exposure	Endpoints	Effects	References
<i>Skeletonema costatum</i>	polyvinyl chloride (PVC)	96h	Growth inhibition	There was a 39.7% growth reduction in 1 µm particle exposure, but no influence on algal growth. There is a lot of absorption and aggregation.	Zhang et al. 2017
<i>Tetraselmis chuii</i>	fluorescent red polyethylene	96h	Growth inhibition	No significant growth rate inhibition	Davarpanah and Guilhermino, 2015
<i>Oxyrrhis marina</i>	virgin and fluorescent polystyrene	60 min	Uptake and motility	Increased uptake; bio-fouling formation	Lyakurwa, 2017
<i>Rhodomonas baltica</i>	virgin and fluorescent polystyrene	60 min	Uptake and motility	Increased uptake; bio-fouling formation	Lyakurwa, 2017

Impacts on birds

Ingestion of plastic impacts seabirds around the world. Wilcox et al. (2015) estimated that by 2050 plastic will be found in the gastrointestinal tract of 99% of all seabird species and that 95% of individual members of avian species will have ingested plastics (>5 mm). Moreover, studies have shown that young seabirds consumed more MPs than adult seabirds (Kuhn and van Franeker, 2012; Provencher et al. 2014). Juvenile fulmars (*Fulmarus glacialis*) were found to have a greater amount of plastic in their stomachs than adult birds (Kuhn and van Franeker, 2012). Studies of seabirds off the Norway coast confirmed this, with ingested MPs having minor effect on tissue (Herzke et al. 2016). MPs have also been detected in the vomit and faeces of wild *Cinclus cinclus* (D'Souza et al. 2020), *Scomber scombrus*, and in caged *Halichoerus grypus* (Nelms et al. 2018).

Impacts on Mammalia

Cetacean species such as baleen whales have been reported to consume MPs (Simmonds, 2012). Macro filters large organisms from the seawater column, such as whales, due to their non-selective feeding behaviour ingest MPs. Stomachs of *Pontoporia blainvillei*, *Mesoplodon mirus*, *Balaenoptera borealis*, and *B. acutorostrata*, respectively, have been detected with MPs particles (Baulch and Perry, 2014; Lusher et

al. 2015). A variety of synthetic polymers and particle morphologies have been found in the guts of *Megaptera novaeangliae* (Besseling et al. 2015). Ingestion of MPs and entanglement of plastic debris can cause both acute and chronic injury in cetaceans and increase contaminant exposure, leading to severe illness, and eventual death (Baulch and Perry, 2014). The presence of high levels of MP in the gastrointestinal tract of baleen whales could impede digestive processes and block the intestinal tract (Simmonds, 2012; Besseling et al. 2015). High concentrations of phthalates and OCs have been shown to impair antioxidant defences and other systems that prevent cellular damage in *B. physalus*, leading to oxidative stress and possible hormonal system abnormalities (Fossi et al. 2016). In addition, microscopic plastic particles have the potential to clog the filtration systems of organisms (Simmonds, 2012). The fate of MPs in the body of mammals is shown in Fig. 6.

Impacts on marine reptiles (sea turtles)

Plastic pollution is a serious threat to all living organisms in the oceans, including sea turtles (Duncan et al. 2021), which are susceptible to a variety of anthropogenic stressors, including ingestion and entanglement with plastics (Nelms et al. 2015). MPs deposits in sediments can reduce thermal diffusivity, increase heat capacity, and permeability, which can affect embryos of all seven turtle species (Alfaro-Núñez et al. 2015). Loggerhead turtles (*Caretta caretta*) have been observed to nest on beaches that are contaminated with plastics, causing hatchlings to get caught and increasing travel time to the ocean, potentially increasing predation and decreasing survival (Aguilera et al. 2018). Consumption of plastic may increase susceptibility to diseases such as fibropapillomatosis (FP), a neoplastic disease documented in all sea turtles species (Nelms et al. 2015; Alfaro-Núñez et al. 2014). Finally, consumption of plastic by sea turtles can damage the digestive system, clogging the digestive tract and reducing feeding, stimuli, and gastrointestinal capacity, leading to food dilution and starvation, and eventual death (Nelms et al. 2015).

Stranding has recently been recognized as a significant risk to numerous marine animals and is a major reason of turtle death in several locations (Camedda et al. 2014; Jensen et al. 2013; Casale et al. 2010). In addition, entanglement with abrasions or loss of limbs due to necrosis can limit the turtle's ability to feed competently or flee from pressure, resulting in death due to malnutrition or drowning (Nelms et al. 2015; Camedda et al. 2014). The list of the sea turtles entangled in plastic debris is given in Table 5.

Table 5. Entanglement of marine turtles in plastic debris.

Species	Ocean basin	Debris type	Pelagic juvenile	Neritic juvenile	Adult	Study area	References
Loggerhead (<i>Caretta caretta</i>)	Atlantic Ocean	Fishing	X	✓	✓	Northeastern (Boa Vista, Cape Verde Islands)	Lopez-Jurado et al. 2003
		Fishing/land-based	X	✓	✓	Northeastern (Terceira Island, Azores)	Barreiros and Raykov, 2014
	Mediterranean Sea	Land-based	X	✓	X	Tyrrhenian sea (Island of Panarea, Sicily)	Bentivegna, 1995
		Fishing/land-based	✓	✓	✓	Central Mediterranean (Italy)	Casale et al. 2010
Green (<i>Chelonia mydas</i>)	Indian Ocean	Fishing	X	✓	X	Northeastern (Darwin, Australia)	Chatto, 1995
		Fishing	n.a.	n.a.	n.a.	Northeastern (Australia)	Wilcox et al. 2013
Hawksbill (<i>Eretmochelys imbricata</i>)	Indian Ocean	Fishing	X	✓	X	Northeastern (Darwin, Australia)	Chatto, 1995
		Fishing	n.a.	n.a.	n.a.	Northeastern (Australia)	Wilcox et al. 2013
Olive ridley (<i>Lepidochelys olivacea</i>)	Indian Ocean	Fishing	n.a.	n.a.	n.a.	Northeastern (McCluer Island, Australia)	Jensen et al. 2013
		Fishing	n.a.	n.a.	n.a.	Northeastern (Australia)	Wilcox et al. 2013
		Fishing	X	X	✓	Northeastern (Australia)	Chatto, 1995
	Atlantic Ocean	Fishing	X	✓	✓	Southwestern (Brazil)	Santos et al. 2012
Flatback (<i>Natator depressus</i>)	Indian Ocean	Land-based	X	✓	X	Northeastern (Darwin, Australia)	Chatto, 1995
		Fishing	n.a.	n.a.	n.a.	Northeastern (Australia)	Wilcox et al. 2013
Multiple		Fishing	n.a.	n.a.	n.a.	Northeastern (Australia)	Wilcox et al. 2014

Impacts on coral

The first study on the consequences of MPs consumption in corals was published in 2015 by Hall et al. (2015). Blue MPs can be ingested by *Dipsastrea pallida* at feeding rates of 1.2-55 g plastic cm⁻²h⁻¹. Ingestion and exposure of MPs have negative effects on the symbiosis between corals and zooxanthellae (Huang et al. 2020). MP aging characteristics contribute to plastic ingestion by a variety of corals and have additional negative consequences. Table 6 summarizes what is known about the various effects of MPs on coral species.

Table 6. Impacts of microplastics on corals.

Species	MPs exposure				Impacts	References
	Polymer	Size	Concentration	Duration		
<i>Seriotopora caliendrum</i>	PS	3, 6 µm	–	30 h	MPs enter the tentacle layer, which is occupied by symbionts, disrupting and disrupting typical coral-symbiont connections.	Okubo et al. 2020
<i>Stylophora pistillata</i>	PE	106-125µm	5000, 50000 items/L	4 weeks	Photosynthetic efficiency is harmed; metabolite profiles of coral are altered in a minor but important way; and host-symbiont communication is affected.	Lanctôt et al. 2020
<i>Zoanthus sociatus</i>	LDPE, PVC	63-125µm	1, 10 mg/L (~0.5×10 ⁵ -4 ×10 ⁵ , ~ 0.7×10 ⁵ -1.5 × 10 ⁵ items/L)	96 h	High corals adherence and oxidative damage are caused, although photosynthetic efficiency is increased and no energetic expenditures are incurred.	Rocha et al. 2020
<i>Danafungiascruposa</i>	Virgin PE microbeads; biofouled PE and PP fragments collected from Great Pacific Garbage Patch	212-355, 600-710, 850-1000 µm microbeads; 200-500, 500-800, 800-1000µm	2996±5 beads/1.5L bag; 2997±6 beads/1.5L bag, 3005±35 biofouled fragments/1.5L bag, 1480±11 beads+ 1506±14 biofouled fragments/1.5L bag	2 days	Active swallowing and passive adherence to coral surfaces are the main mechanisms of interacting between corals and MPs; passive adhesion is the primary method; corals eat and store more biofouled MPs.	Corona et al. 2020
<i>Astroides calycularis</i>	PE obtained from plastic bags	2-3 mm	20 items	30 min; 30 min; 90 min	Coral eating efficiency is reduced, and plankton eating does not provide adequate energy.	Savinelli et al. 2020
Symbiodiniaceae algae (<i>Cladocopium goreaui</i>) inhabiting	PS	1 µm	5 mg/L (9.0×10 ⁹ items/L)	7 days	MP exposure prevents algae growth and density; greatly increases chlorophyll after 7 days without changing photocatalytic efficiency; suppresses	Su et al. 2020

in scleractinian corals

detoxifying activity, nutrient absorption, and photosynthetic efficiency; and increases oxidative stress, apoptosis level, and ion transportation.

<i>Stylophora pistillata</i>	Beach-collected foam PS containing brominated flame retardant hexabromocyclododecanes (HBCDD)	Leachate from 0.6g/L 0.5-1mm cubic fragments (sliced from >2 cm beach-collected macro debris) for 21 days	Leachate spiked with α -, β -, and γ -HBCDD	5 days	Photosynthetic capability, symbiont frequency, and chlorophyll content of corals are all affected to a lesser extent, as is coral polyp contraction.	Aminot et al. 2020
<i>Acropora tenuis</i>	PE microbeads; weathered PP collected from beach	1, 6 μ m PE microbead; 0.5, 1, 2 mm ² weathered PP	25-200 microbeads/L; 5-50 pieces/L	2.5 h; 24 h	Cause minor disruptions to coral fertilization, embryo abnormalities, and larval settling; do not significantly impede the success of important early-life coral activities.	Berry et al. 2019
<i>Acropora muricata</i> , <i>Pocillopora verrucosa</i> , <i>Porites lutea</i> , <i>Heliopora coerulea</i>	HDPE	1, 8 μ m	0.25 mg/L (200 items/L)	6 months	Bleaching, tissue damage, and parasites alter symbiont photosynthetic effectiveness but have no effect on symbiont concentrations or chlorophyll levels.	Reichert et al. 2019
<i>Lophelia pertusa</i> , <i>Madrepora oculata</i>	LDPE (with the natural formation of surface microbial biofilm preincubated for two months)	10×10 cm PE macroplastics; 500 μ m microbeads	–; 350 items/L	5 months	MP films reduce prey acquisition and growth rates in the coral <i>Lophelia pertusa</i> , causing the polyp "cap" structure to overgrow; had no effect on the growth and eating of the coral <i>Madrepora oculata</i> .	Mouchi et al. 2019

<i>Acropora formosa</i>	LDPE	<100, 100-200, 200-500 µm	0.05, 0.1 and 0.15 g/L	14 days	Bleaching and necrosis release zooxanthellae in considerable amounts.	Syakti et al. 2019
<i>Astrangia poculata</i>	Blue PE microbeads (with the formation of surface microbial biofilm incubated for 4-8 h; pre-spiked in the <i>Escherichia coli</i> cell cultures for 9 days)	170.5-23 0.8 µm	0.2 g/L; 10-25 microbeads with the <i>Escherichia coli</i> biofilm	90 min (feeding) +24 h (recovery in clean seawater); 4 weeks (<i>E. coli</i> biofilm microbead feeding)	Consumed MPs remain in the gastrovascular cavity's mesenterial tissues, reducing subsequent brine shrimp egg eating; co-ingestion of microbeads with <i>E. coli</i> cells results in coral mortality after four weeks.	Rotjan et al. 2019
<i>Montipora capitata</i> , <i>Pocillopora damicornis</i>	PE microbeads	150-180 µm	2000 items/L under 27°C or increased 30°C	10 days	Under heat stress, greatly limit <i>Artemia</i> nauplii feeding but not MP consumption.	Axworthy and Padilla-Gamiño, 2019
<i>Pocillopora damicornis</i>	PS	1 µm	50 mg/L (9×10 ¹⁰ items/L)	24 h	There are no noteworthy effects of symbiont zooxanthellae abundance; chronic MP exposure increases stress response and antioxidant enzyme activities; detoxifying and immune responses are suppressed.	Tang et al. 2018
<i>Lophelia pertusa</i>	LDPE (with the natural formation of surface microbial biofilm pre-incubated for two months)	10×10 cm LDPE macroplastics; 500 µm microbeads	–; 350 items/L	2 months	Lower coral skeletal development rates considerably; enhance polyp activities and decrease prey catch rates; MPs have no effect on polyp behaviour or prey capture rates, but they do lower calcification.	Chapron et al. 2018
<i>Montastraea cavernosa</i> , <i>Orbicella faveolata</i>	PE microbeads (with the natural formation of surface microbial biofilm pre-incubated for six weeks); Polyester microFibres	PE (90-106 µm, 212-250 µm, 425-500 µm, 850-1000 µm, 1.7-2.0 mm 2.4-2.8 mm);	30 mg/L	48 h	There are no calcification consequences.	Hankins et al. 2018

		Polyester (3-5 mm)				
<i>Acropora humilis</i> , <i>Acropora millepora</i> , <i>Pocillopora verrucosa</i> , <i>Pocillopora damicornis</i> , <i>Porites lutea</i> , <i>Porites cylindrica</i>	Pristine PE (with the natural formation of surface microbial biofilm during exposure periods)	37-163 µm	4000 items/L	4 weeks	Mucus formation, proliferation, involvement with tentacles or mesenterial filaments; bleaching and organ collapse.	Reichert et al. 2018
<i>Favites chinensis</i>	Fluorescent carboxylate microspheres; microbeads from commercial facewash	3, 6, 11 µm; 3-60 µm	–	2 days; 9 days	Intake of MPs and Artemia nauplii with MPs significantly reduces symbiotic algae's infectivity in the host and affects the commencement of symbiotic partnerships.	Okubo et al. 2018
<i>Astrangia poculata</i>	Microbe-free plastic mixtures (including HDPE,LDPE,PP,PET,P C,PVC,PS); Sunlight-weathered and biofouled plastic mixtures (including PS, LDPE,HDPE)	500-1000 µm; 125-1000 µm	–	24 h	Corals swallow different kinds of MPs due to phagostimulants in plastic leachates; corals consume more microbe-free MPs than biofouled MPs.	Allen et al. 2017
<i>Dipsastrea pallida</i>	Blue PP	10-2000 µm	0.395 g/L; 0.197 and 0.24 g/L	48 h; 12 and 3 h	MPs are mistaken for prey; swallowed MPs remain in the coral gut cavity's mesenterial tissue for more than 24 hours.	Hall et al. 2015

Impact on human health

Humans are vulnerable to the hazardous effects of MPs, which have been shown to contain toxins, neurotoxic chemicals, and endocrine disruptors (Rochman et al. 2013a; Wright and Kelly, 2017; Galloway and Lewis, 2016; Hahladakis et al. 2018). Ingestion, dermal absorption, and inhalation are the three ways by which plastics and their compounds can enter the human body. One of the most common pathways

through which MPs enter the human body is through the consumption of seafood and meals (Alfaro-Núñez et al. 2021; Smith et al. 2018; Wright and Kelly, 2017). Consequently, MPs act as a conduit for toxic contaminants from marine organisms into the human body (Fig. 7), and pose a major threat to human well-being (Smith et al. 2018). The existence of MPs in faeces of pregnant women was studied by Ar et al. (2020). All stool samples contained microplastics, according to their results. The number of microplastics detected ranged from 5 to 21, with fibres, fragments, and films being the most common. The length of MPs ranged from 0.2 to 4.9 mm. Ingested microplastics have been found to be excreted in faeces, but the residues are collected in the body and cause long-term health damage (Ar et al. 2020). The long term and detrimental effects of MPs in human health are still not fully understood and currently are being studied by many research groups worldwide.

Management Strategies To Control Mps In The Marine Environment

The following management strategies may be feasible and practical to control the loss of microplastics to the ecosystem during manufacture, use, and discarding (Prata et al. 2019):

- Control the production and consumption of environmentally harmful plastic items through bans or levies without compromising public health or food security.
- Reducing plastic consumption without unforeseen consequences by eliminating unnecessary packaging, labeling, raising awareness and education, and offering environmentally friendly alternatives to plastics where appropriate.
- Growing demand for recyclable materials through incentives, penalties, or taxes on recycled plastic.
- Adopt waste collection methods that reduce waste production and improve recyclability, such as door-to-door pickup and deposit-refund procedures, based on a "pay-as-you-throw" philosophy.
- Reduce and recycle waste generated during operations and provide accountability for waste and product impacts
- Reduce environmental impact of recycled plastics, use renewable energy in waste and recycling processing.
- Develop a life cycle analysis (LCA) for each product and process to improve eco-design, taking into account the expected end of life of the product.
- To optimize e-waste recyclability and, in the meantime, energy recovery
- To lessen the impact of plastics and MPs on the ecosystem, the different countries and organizations need to develop effective rules and laws.

Knowledge Gaps/ Future Research Recommendations

The opinions on what are "knowledge gaps" varies a lot, probably based on the field of interest of the researchers stating the gaps. In general, the consensus is that there are substantial knowledge gaps related to:

- More laboratory studies should be conducted on the most common forms (fibres and pieces) and sizes (800-1600 µm) of MPs detected in field samples of living material.
- Experimental studies on microplastics in soils and agriculture are very few compared to other fields in which microplastics have been studied.
- MPs content is likely to increase in the future, and it will become increasingly important to regularly monitor MP content in marine organisms and other foods.
- The amount of MPs in edible fish and shellfish tissue needs to be determined. Quantification of palatable echinoderms, tunicates and algae consumed in many countries should also be investigated.
- Continuous monitoring programmes are needed to assess the occurrence of MPs in ecological sections and to prevent depletion of global fish and shellfish stocks.
- Studies should focus on the chemical and microbial hazards and risks associated with MPs ingestion and on improving methods for assessing MPs ingestion and translocation to humans.
- It is critical to investigate the hazards and risks to consumers from MPs -contaminated fish, shellfish, and food using food safety risk assessment methods.
- The inclusion of a wide range of MPs -sizes and components in somatic cells and the development of new methods to detect the presence of MPs in the human body are urgently needed.
- Another urgent issue is the presence of nano-sized plastics in seafood, which has received less attention.

- Universal standardisation of methods and procedures to allow comparison of results between different sites, organisms and environments.
- Further studies on analytical techniques, toxic-kinetics and toxicology to improve our understanding of the potential impact of micro and nanoplastics on seafood quality and human health.
- Understanding the methods by which PE affects organisms other than fish and the effects of PS on organisms other than fish and tiny crustaceans.
- Investigate MPs ecotoxicity under more realistic conditions, such as mesocosms and multispecies exposures.
- Getting people to disclose unfavourable negative results.

Declarations

Declaration of competing interest

The authors claim that they have no known competing financial or personal interests that could have impacted the findings of this study.

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Figures

Figure 1

Plastic volume production by country around the world (Data source: World Population Review, 2021).

Figure 2

Litter on the seafloor of the Bay of Bengal, Bangladesh [Photo: Sharif Sarwar]. (2a) Plastic tea cup attaches to Gorgonia coral (2b) Discarded net covering live coral (2c) Plastic bottle (spark) on coral (2d) Discarded net covering coral (2e) Discarded net attached to Gorgonia soft coral (2f) Plastic packet (Mr. Twist) of the chip (2g) Discarded tore net over seaweed & coral (2h) Plastic bottle of cold drink (7up).

Figure 3

Figure 4

Total number of publications dealing with the effects of MP on marine organisms.

Figure 5

Co-authorship among authors who had a joint publication related to the effects of MP on marine organisms.

Figure 6

Micro- and nanoplastics in the mammalian body: What happens to them? (Modified from Lusher et al. 2017).

Figure 7

MPs ingestion routes in human body and possible effects.