Impacts of Microplastics on Marine Organisms and in Human Health

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Abstract

The ubiquitous presence of microplastics (MPs) across all oceans has emerged as a significant marine hazard as worldwide plastic production continues to grow. Now and during the next 20-30 years will be the time to confront the implications of the plastic industry's rise, which has resulted in the large-scale global production of millions of plastic-based items, varying from a single pen to automobiles. Inappropriate management, lack of awareness of the detrimental effects, reckless universal use, and the indiscriminate disposal of plastic based synthetic materials, has turned Earth into a "plastic planet”. It is critical to have a throughout understanding of MPs' potential from sink to source as well as the processes that govern their distribution and uptake and exchange in ecosystems, to properly comprehend their potential consequences and ecological harm. The goal of the present study was to identify the scenarios of microplastics structure, functions and subsequent impact to the marine organisms. Diversified origins of MPs in the oceans and their negative effects on marine animals have been discussed critically in this review. Because of their small size, these plastic particles are easily ingested by a wide range of marine life (e.g., fish, Mollusca, Arthropoda, Annelida, Echinodermata, Nematoda, phytoplankton, zooplankton, algae, birds, Mammalia, marine reptiles, and coral), putting their health at risk. The ability of MPs to absorb a variety of dangerous hydrophobic chemicals from the environment directly transfers these toxins into the food chain. As a result, many laws and rules have been created to address the major issue of MP pollution in the marine ecosystem and it must be improved and implemented worldwide. To avert future dangers, it is critical to stop producing it and replace it with environmentally suitable alternatives.

Main Text

Introduction

Microplastics (MPs) reported all over the world are extremely non-biodegradable in the environment and, as a result, swiftly accumulate in many marine habitats (Woodall et al. 2014; van Sebille et al. 2015; Suaria et al. 2016; Cózar et al. 2017; Waller et al. 2017; Bhuyan et al. 2020; Alfaro-Núñez et al. 2021). In the marine ecosystems, the number of MPs continues to climb, due to the constant elevation in plastics manufacture, which reached 335 million tons in 2016 (Plastics Europe, 2017). In 2019, over 350 million tons of plastic were manufactured, according to Plastics Europe (2020). Nearly 4.8-12.7 million tons of plastic were dumped into the oceans in 2010, with this number anticipated to rise by an order of magnitude by 2025 (Jambeck et al. 2015). By 2100, the mass of floating MPs would have increased from 2.5×10^7 to 1.3×10^8 tonnes, resulting in a 50-fold rise in total MP mass (Everaert et al. 2018). High levels of MP (>10-10^4 items/m^3) were identified in garbage areas in the midst of vast ocean basins (Cózar et al. 2014), as well as the North Sea, the Mediterranean Sea, the Black Sea, and the South China Sea (Waldschläger et al. 2020).

MPs have been reported in world's oceans, estuaries, and other coastal regions of highly anthropogenically-populated locations (Cózar et al. 2014; Eriksen et al. 2014; Galgani et al. 2015; Peters and Bratton, 2016; Frère et al. 2017). Many countries of the world are the major contributor of plastic in the ocean (Fig. 1). Both primary and secondary MPs have been detected in many species after they have been released into the ocean. MPs have been found in the stomachs of a wide spectrum of marine wildlife including fish (Rummel et al. 2016; Alfaro-Núñez et al. 2021), phytoplankton (Long et al. 2015), polychaete worms (Mathalon and Hill, 2014), tubifex worms (Hurley et al. 2017), amphipods (Thompson et al. 2004), cetaceans (Besseling et al. 2015; Lusher et al. 2015a), seabirds (Amelineau et al. 2016), molluscs (Alfaro-Núñez et al. 2021, Brillant and MacDonald, 2002; Browne et al. 2008), crustacean (Alfaro-Núñez et al. 2021), echinoderms (Graham and Thompson, 2009), zooplankton (Cole et al. 2013; Desforges et al. 2015; Sun et al. 2017), mammals (Fossi et al. 2012) and corals (Hall et al. 2015). MPs have been found to reduce feeding activity (Besseling et al. 2013; de Sá et al. 2015), cause oxidative stress (Della Torre et al. 2014), genotoxicity (Della Torre et al. 2014), neurotoxicity (Oliveira et al. 2012, 2013; Luis et al. 2015; Ribeiro et al. 2017), growth delay (Della Torre et al. 2014; Lee et al. 2013; Au et al. 2015; Cole et al. 2015; Mazurais et al. 2015; Li et al. 2016) in marine organisms.

Water and sediments of many oceans, estuaries, and coastal lagoons are contaminated with MPs and thus bivalves raised in these places are at risk of consuming them (Lusher et al. 2017). The quantity of MP particles per 10 g of mussels in commercial mussels from Belgium ranged from three to five (de Witte et al. 2014). MPs have been found in red mullet (*Mullus barbatus*), European hake (*Merluccius merluccius*), Atlantic cod (*Gadus morhua*), European pilchard (*Sardina pilchardus*) and Gilthead seabream (*Sparus aurata*) from several different places (Avio et al. 2015a; Brate et al. 2016; Bellas et al. 2016; Liboiron et al. 2016; Rummel et al. 2016; Compa et al. 2018; Jovanović et al. 2018; Solomando et al. 2020; Alomar et al. 2021). Nearly 9 % and 28 % of MPs (size > 500 μm) were found in the gastrointestinal tracts of fish sold at markets in the United States and Indonesia, respectively (Rochman et al. 2015). As regional example, Brazil's eastern coast, Miranda and Carvalho-Souza (2016) discovered MPs in the digestive tracts of two significant edible fish species (*Scomberomorus cavalla* and *Rhizoprionodon lalandii*). MPs were identified in 19.8% of commercial fish collected off the Portuguese coast by Neves et al. (2015). MPs have also been found in the stomachs of economically important Mediterranean fish, as well as in the gastrointestinal system and liver of anchovies and sardines (Romeo et al. 2015; Avio et al. 2015a; Collard et al. 2017; Compa et al. 2018).

MPs can be absorbed by marine species through their gills and digestive tract (Boerger et al. 2010; Denuncio et al. 2011; de Stephanis et al. 2013; Jantz et al. 2013; Lusher et al. 2013; Rebolledo et al. 2013; Watts et al. 2014; de Sá et al. 2015; Jovanović et al. 2018; Solomando et al. 2020; Alomar et al. 2021). It could be ingested due to a lack of ability to identify MPs from prey (de Sá et al. 2015) or ingestion of organisms from lower trophic levels that contain these particles (e.g., plankton with MPs) (Browne et al. 2008; Fendall and Sewell, 2009; do Sul and Costa, 2014). MPs can also adhere directly to organisms (Dabrunz et al. 2011; Cole et al. 2013). MPs are potentially accessible to a wide range of creatures by ingestion due to their small size, which overlaps with the size range of their prey (Galloway et al. 2017). Several marine organisms are being exposed to MPs by ingestion. MPs have been reported to be ingested by cod, pilchard, horse mackerel, mussels, red mullet, oysters, shrimp, and sea bass (Lusher et al. 2013; van Cauwenberghe and Janssen, 2014; Avio et al. 2015a; Devriese et al. 2015; Bellas et al. 2016; Brate et al. 2016; Güven et al. 2017). MPs are consumed when they are mistaken for prey, but they can also be ingested by deposit-feeding and active filtration systems (de Sá et al. 2015; Naji et al. 2018).

After ingestion, MPs get absorbed, distributed through the circulatory system and into numerous tissues and cells, where it can have a range of deleterious consequences (von Moos et al. 2012; Wright et al. 2013a; Pedà et al. 2016; Avio et al. 2017; Chae and An, 2017; Foley et al. 2018). MPs particles and other toxic compounds contained by the prey get passed off to predators in the ocean (Farrell and Nelson, 2013; Mattsson et al. 2017; Santana et al. 2017; Hartmann et al. 2017). MPs in aquatic organisms exhibited a median concentration of 400 µg/L (Cormier et al. 2019; Hamed et al. 2019; Limonta et al. 2019; Peixoto et al. 2019; Qiao et al. 2019; Wang et al. 2019; Yin et al. 2019; Chae and An, 2020; Choi et al. 2020; Li et al. 2020; Pannetier et al. 2020), while 0.003 µg/L median ambient concentration (from environmental samples) were recorded in three research studies encompassing 13 locations (Goldstein et al. 2012; Lacerda et al. 2019). This is the equivalent as exposing organisms to MP quantities almost 100000 times greater than what they would be exposed to in the natural habitat.

Several investigations on the ingestion of MPs by commercially significant marine species have recently been undertaken around the world, with MPs being discovered often; 36.5-63.5% in the Portuguese coast (Neves et al. 2015), 14.6% in the Saudi Arabian 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 the 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 Beibu Gulf, 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 marine edible species containing MPs puts human health at risk (Bhuyan et al. 2020). MPs were documented in 11 of the 25 species that contribute the most to global fisheries (FAO, 2016). Consumers in European nations with high shellfish intake absorb up to 11000 MP particles (size ranged between 5-1000 µm) per year. Consumers in low-shellfish-consumption countries consume an average of 1800 MPs per year, which is still a significant amount (Van Cauwenberghe and Janssen, 2014). Estimates suggest that each person consumes roughly 175 MP particles (size varied between 200-1000 µm) each year just on shrimp intake (Devriese et al. 2015). MPs were discovered in *Mytilus edulis* and *Mytilus galloprovincialis* mussels from five European nations (Vandermeersch et al. 2015).

The presence of MPs in the gastrointestinal tract of fish does not imply that humans have been exposed since this organ is rarely eaten (Wright and Kelly, 2017; Alfaro-Núñez et al. 2021). Whole seafood species (such as molluscs, crustaceans, and juvenile fish) have a higher risk of infection than gut fish or sliced shrimp. MPs were found in substantially larger concentrations in the eviscerated flesh of two commonly eaten dried fish species (*Chelonsub viridis* and *Johnius belangerii*) than in the removed organs, indicating that evisceration does not always minimize the danger of MPs ingestion by humans (Karami et al. 2017). MPs have also been found in the commercially valuable fish species' muscle (Abassi et al. 2018; Akhbarizadeh et al. 2018; Alfaro-Núñez et al. 2021) and a crustacean (Abassi et al. 2018; Akhbarizadeh et al. 2018; Alfaro-Núñez et al. 2021). The implications for human customers are highlighted by these findings.

Microplastics (MPs)

MPs are the most common types of plastic debris (minuscule particles, fibres, and granules) found in the ocean water (Thompson et al. 2009; Cole et al. 2011; Betts, 2008; Fendall and Sewell, 2009; Hidalgo-Ruz et al. 2012; Bhuyan et al. 2020). The high level of MP's pollution in the oceans is directly associated with these family of products being inexpensive, versatile, robust and durable, which is linked to the high amounts of plastics manufactured, used and easily discarded (Alfaro-Núñez and Bermudez, 2018). Plastics ultimately found in the sea floor (Fig. 2). Primary and secondary MPs are the two types of MPs found in the sea (Auta et al. 2017). Tiny plastic fragments are released into the environment directly through the home and industrial effluents, spills, and sewage discharge are known as primary MPs. Fragments (Rummel et al. 2016), fibres (Rummel et al. 2016), pellets (Nobre et al. 2015), film (Kang et al. 2015; Lusher et al. 2015a), and spheres are among the basic MP particle forms (Li et al. 2016). Personal care and cosmetics goods, detergents and facial scrubs, children's products, insecticides, skin care products, and medications (Zitko and Hanlon, 1991; Patel et al. 2009; Cole et al. 2011; Duis and Coors, 2016; Fendal and Sewell, 2009), ship-breaking and air-blasting residue materials are primary MPs (Andrady, 2011; Cole et al. 2011). Secondary MPs are created as bigger plastic particles already existing in the environment gradually get fragmented due to inorganic deposition, microbial treatment, structural disintegration, and photo-degradation (Browne et al. 2007; Andrady and Neal, 2009; Andrady, 2011; Cole et al. 2011; Duis and Coors, 2016). Polyethylene (PE), polystyrene (PS), polypropylene (PP), polyester (PES), polyvinylchloride (PVC), polyamide (PA), acrylic polymers (AC), polyether (PT), cellophane (CP), polyurethane (PU), and polyethylene terephthalate (PET) are synthetic polymers commonly encountered as MPs in the ocean (Rocha-Santos and Duarte, 2015). MPs, both primary and secondary, are found at high concentrations in marine ecosystems, resulting in a significant risk to marine life and biological processes (Bhuyan et al. 2020).

Organisms studied worldwide

Fish, amphibians, birds, mammals, reptiles, crustaceans, molluscs, echinoderms, annelid worms, cnidaria, porifera, and rotifera were the focused creatures under research. Zooplankton was included in the category of "small crustaceans," whereas all other crustacean species were included in the category of "big crustaceans." The majority of research yet has focused on fish; further information on the impacts of MPs on other taxa, particularly invertebrates, is needed (De Sá et al. 2018, Alfaro-Núñez et al. 2021).

Characteristics of microplastics

Plastics have a variety of properties that allow them to be used in a wide range of applications, from construction to medical (Bockhorn et al. 1999; Bhuyan et al. 2020). Corrosion resistance, weak electric and thermal conductance, longevity, and transporting additional resources and manufacturing at a cheap cost are some of the notable features. Existence of plastics in the environment is problematic due to these qualities. Our current knowledge on the wider scale effects of large plastic fragments and their consequence fragmentation into MP's on marine diversity is still limited (Alfaro-Núñez and Bermudez, 2018).

It is also to annotate that throughout the manufacturing process of plastics; they get molecularly missed with other chemical compounds that give them the aforementioned specialized properties, turning out to be harmful when consumed (Andrady and Neal, 2009; Fries et al. 2013). Plastics in the environment may potentially absorb other toxic chemicals (Zarfl and Matthies, 2010; Velzeboer et al. 2014). MP particles have a great potential for collecting environmental pollutants such as polycyclic aromatic hydrocarbons and metals due to their enormous surface area to volume ratio (Rios et al. 2007; Betts, 2008; Ashton et al. 2010).

Although plastic can eventually degrade into smaller pieces down to nanoplastics, it remains intact as plastic polymers (the main blocks that hold the plastic structure together) and attracts persistent organic pollutants (POPs) such as dioxins and 1,1-dichloro-2,2-bis (*p*-chlorophenyl) ethylene also known as DDE, besides of the toxic chemicals MPs already contain (e.g., bisphenol A (BPA) and flame retardants) (Alfaro-Núñez and Bermudez, 2018). Polyethylene (PE) accounts for 28% of total output in Europe, followed by polypropylene (PP) at 19%, polyvinylchloride (PVC) at 10%, and polystyrene at 7% (Plastics Europe, 2020). The density of different plastic polymers determines MP behaviour in the aquatic environment (Nizzetto et al. 2016). Moreover, MPs come in a variety of forms (e.g., spheres, fibres, film, irregular). MPs disperse differently in distinct compartments (water surface, water column, and sediment) of the aquatic environment because of differences in shape and density, affecting their availability to species at various trophic levels and in various ecosystems (Betts, 2008; Thompson et al. 2009; Cole et al. 2011).

Behaviour and fate of microplastics

MPs are resistant to biodegradation and can endure for hundreds of years into the ecosystems, posing an eminent threat to the environment and wildlife. These are primarily let into the marine environment because of human activities (Duis and Coors, 2016; Clark et al. 2016; Bhuyan et al. 2020). The abundance of MPs and the increase in human population density have been shown to exert a very logic positive correlation, which will lead to an increase in plastic trash accumulating within a marine setting (Rochman et al. 2013a). Physical and chemical features along with hydrodynamic and environmental conditions might impact their transit dynamics, influencing their development and dispersal in various marine environments as a result (Rocha-Santos and Duarte, 2015). MPs have been found in ecosystems of the intertidal zone (Claessens et al. 2011; Stolte et al. 2015; Mathalon and Hill, 2014), surface waters (Lusher et al. 2014; Lusher, 2015; Lusher et al. 2015a), deep-sea sediments (Woodall et al. 2014; Van Cauwenberghe et al. 2015; Alomar et al. 2017), and Polar regions (Ivar do Sul et al. 2013).

MPs can be consumed by virtually most living organism in the ocean and have been well documented in a diverse group of marine creatures with different feeding strategies within the food web (Table 1). MPs can affect phytoplankton, zooplankton, echinoderms, deposit and suspension-feeders (Browne et al. 2008; Cole et al. 2013; Avio et al. 2015a; Nelms et al. 2015; Batel et al. 2016; Caron et al. 2016; Fossi et al. 2016;

Ferreira et al. 2016). MPs can be taken straight off the water by giant marine life, or indirectly through the eating of many other animals that can absorb or metabolize them. A vast number of species of fish, seabirds, marine mammals and turtles have been documented to become entangled or to ingest pieces of plastics like ropes, fish nets, plastic bags, etc., this may result in ulceration or starvation, and finally in death of the animal (Alfaro-Núñez and Bermudez, 2018). MPs can be stored within the organism or transported across bodily tissues (Browne et al. 2008; Van Cauwenberghe and Janssen, 2014; Avio et al. 2015a), or they can be excreted or ingested through pseudo-feces (Browne et al. 2008; Van Cauwenberghe and Janssen, 2014; Thompson et al. 2004; Avio et al. 2015a). MPs that accumulate in the environment can have a variety of negative effects on the organisms that consume them. Internal or external traumas, digestive system blockages resulting in pseudo-satiety, and physiological stress, modification of nutrition and growth retardation, loss infertility, fecundity, and progeny survival rate are only a few examples (Wright et al. 2013b; Nelms et al. 2015; Cole et al. 2015; Sussarellu et al. 2016; Ogonowski et al. 2016; Welden and Cowie, 2016). MPs can also serve as a vehicle for the entry of harmful substances into marine species (Wang et al. 2016; Brennecke 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**
Coryphaena hippurus	87%	150-5000 µm	Digestive tract	Fibres	Ecuador	Alfaro-Núñez et al. 2021
Centropomus robalito	60%	150-5000 µm	Digestive tract	Fibres	Ecuador	Alfaro-Núñez et al. 2021
Cynoscion stolzmanni	73%	150-5000 µm	Digestive tract	Fibres	Ecuador	Alfaro-Núñez et al. 2021
Cynoscion analis	73%	150-5000 µm	Digestive tract	Fibres	Ecuador	Alfaro-Núñez et al. 2021
Alopias pelagicus	87%	150-5000 µm	Digestive tract	Fibres	Ecuador	Alfaro-Núñez et al. 2021
Mugil cephalus	60%	150-5000 µm	Digestive tract	Fibres	Ecuador	Alfaro-Núñez et al. 2021
Peprilus medius	53%	150-5000 µm	Digestive tract	Fibres	Ecuador	Alfaro-Núñez et al. 2021
Larimus argenteus	80%	150-5000 µm	Digestive tract	Fibres	Ecuador	Alfaro-Núñez et al. 2021
Hemanthias peruanus	60%	150-5000 µm	Digestive tract	Fibres	Ecuador	Alfaro-Núñez et al. 2021
Urotrygon chilensis	80%	150-5000 µm	Digestive tract	Fibres	Ecuador	Alfaro-Núñez et al. 2021
Diapterus brevirostris	80%	150-5000 µm	Digestive tract	Fibres	Ecuador	Alfaro-Núñez et al. 2021
Selene peruviana	73%	150-5000 µm	Digestive tract	Fibres	Ecuador	Alfaro-Núñez et al. 2021
Chloroscombrus orqueta	60%	150-5000 µm	Digestive tract	Fibres	Ecuador	Alfaro-Núñez et al. 2021
Diplectrum maximun	67%	150-5000 µm	Digestive tract	Fibres	Ecuador	Alfaro-Núñez et al. 2021
Lethrinus microdon	10; 20%	1480 µm (mean)	Gastrointestinal tract	Fibers, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. 2018
Lipocheilus camolabrum	7; 28.57%	1870 µm (mean)	Gastrointestinal tract	Fibers, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. 2018
Lutjanus kasmira	10; 16.67%	2160 µm (mean)	Gastrointestinal tract	Fibers, film, fishing	Saudi Arabian Red Sea coast	Baalkhuyur et al. 2018

				thread		
Parascolopsis eriomma	5; 60%	1380 µm (mean)	Gastrointestinal tract	Fibers, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. 2018
Plectorhinchus gaterinus	6; 33.33%	3310 µm (mean)	Gastrointestinal tract	Fibers, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. 2018
Pristipomoides multidens	10; 20%	3800 µm (mean)	Gastrointestinal tract	Fibers, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. 2018
*Sprattus sprattus*****	515; 18.8%	100 - > 5000 µm	Gastrointestinal tract	Fibers, fragments	Baltic Sea	Beer et al. 2018
*Clupea harengus*****	299, 21%	100 - > 5000 µm	Gastrointestinal tract	Fibers, fragments	Baltic Sea	Beer et al. 2018
Mugil cephalus	30; 16.7% (captive)	< 2000–5000 µm	Gastrointestinal tract	Fibers	Hong Kong From fish farms	Cheung et al. 2018
Cynoscionacoupa	552; 51%	< 5000 µm	Gut	Filaments, hard MPs	Goiana estuary, Brazil	Ferreira et al. 2018
Odontesthes regia	9; 11.1%	Not specified	Gut	Fragments	Southeast Pacific Ocean	Ory et al. 2018
*Scomber japonicus*****	30; 3.3%	<2100 µm	Gut	Fragment	Southeast Pacific Ocean	Ory et al. 2018
Soleasolea	533; 95%	< 100-500 µm	Gastrointestinal tract	Fibers, fragments	Adriatic Sea	Pellini et al. 2018
Scyliorhinus canicula	20; 5%	1500 µm	Stomach	Micro-bead	North Sea	Smith, 2018
Engraulis encrasicolus	10; 80%	124-438 µm	Liver	Not specified	Mediterranean Sea	Collard et al. 2017
*Sardina pilchardus*****	2; 100%	124–438 µm	Liver	Not specified	Mediterranean Sea	Collard et al. 2017
Argyrosomus regius	51; 75%	> 9.07 µm	Gastrointestinal tract	Fibers, hard plastic, nylon	Mediterranean Sea	Güven et al. 2017
Mullus barbatus	207; 66%	> 9.07 µm	Stomach and intestine	Fibers, hard plastic, nylon	Mediterranean Sea	Güven et al. 2017
Mullus surmuletus	51; 35 and 49%	> 9.07 µm	Gastrointestinal tract	Fibers, hard plastic, nylon	Mediterranean Sea	Güven et al. 2017
Sardina	7; 57%	> 9.07	Gastrointestinal tract	Fibers, hard	Mediterranean	Güven et al.

*pilchardus*****		μm		plastic, nylon	Sea	2017
*Scomber japonicus*****	7; 71%	> 9.07 μm	Gastrointestinal tract	Fibers, hard plastic, nylon	Mediterranean Sea	Güven et al. 2017
Sparus aurata	110; 44%	> 9.07 μm	Gastrointestinal tract	Fibers, hard plastic, nylon	Mediterranean Sea	Güven et al. 2017
*Gadus morhua*****	302; 18.8%	< 5000 μm- > 20,000 μm	Stomach	Fibers, fragments, granule, film	Norwegian coast	Brate et al. 2016
Merluccius merluccius	12; 16.7%	380–3100 μm	Stomach	Fragments, fibers, film, spheres	Spanish Atlantic	Bellas et al. 2016
Mullus barbatus	128; 18.8%	380–3100 μm	Stomach	Fragments, fibers, film	Mediterranean coast	Bellas et al. 2016
Scyliorhinus canicula	72; 15.3%	380-3100 μm	Stomach	Fragments, fibers, film	Mediterranean coasts	Bellas et al. 2016
Merluccius merluccius	3; 100%	10–5000 μm	Gastrointestinal tract	Fragments, line, film, pellet	Adriatic Sea	Avio et al. 2015a
Mullus barbatus	11; 64%	10–5000 μm	Gastrointestinal tract	Fragments, line, film, pellet	Adriatic Sea	Avio et al. 2015a
*Sardina pilchardus*****	99; 19%	10–5000 μm	Gastrointestinal tract	Fragments, line, film, pellet	Adriatic Sea	Avio et al. 2015a,b
Brarna brama	3; 33%	217-4810 μm	Gastrointestinal tract	Fibers	Portuguese Coast *From local market	Neves et al. 2015
Merluccius merluccius	12; 29%	217–4810 μm	Gastrointestinal tract	Fibers	Portuguese Coast	Neves et al. 2015
Dentex macrophthalmus	1; 100%	217-4810 μm	Gastrointestinal tract	Fibers	Portuguese Coast *From local market	Neves et al. 2015
Mullus surmuletus	4; 100%	217–4810 μm	Gastrointestinal tract	Fibers	Portuguese Coast	Neves et al. 2015
Scomber	35; 31%	217-4810	Gastrointestinal tract	Fragments,	Portuguese Coast	Neves et al.

*japonicus*****		µm		fibers		2015
*Scomber scombrus*****	13; 31%	217-4810 µm	Gastrointestinal tract	Fragments, fibers	Portuguese Coast	Neves et al. 2015
Trigta lyra	31; 19%	217-4810 µm	Gastrointestinal tract	Fragments, fibers	Portuguese Coast	Neves et al. 2015
Zeus faber	1; 100%	217-4810 µm	Gastrointestinal tract	Fibers	Portuguese Coast	Neves et al. 2015
Argyrosomus regius	5; 60%	217-4810 µm	Gastrointestinal tract	Fibers, fragments	Portuguese Coast *From local market	Neves et al. 2015
Thunnus thyrmus	34; 34.4%	< 5000 µm	Stomach	Fragments	Mediterranean Sea	Romeo et al. 2015
Xiphias gladius	56; 12.5%	< 5000 µm	Stomach	Fragments	Mediterranean Sea	Romeo et al. 2015
*Sardinella longiceps*****	10; 60%	500–3000 µm	Gut	Fragments	Indian Coast	Sulochanan et al. 2014
*Clupea harengus*****	566; 2%	> 1000 µm	Gastrointestinal tract	Fibers, fragments	North Sea	Foekema et al. 2013
*Gadus morhua*****	80; 13%	> 1000 µm	Gastrointestinal tract	Fibers, fragments	North Sea	Foekema et al. 2013
Merlangius merlangus	50; 32%	1000-2000 µm	Gastrointestinal tract	Fibers, fragments, beads	English Channel	Lusher et al. 2013
*Micromesistius poutassou*****	27; 51.9%	1000–2000 µm	Gastrointestinal tract	Fibers, fragments, beads	English Channel	Lusher et al. 2013
Trachurus trachurus	56; 28.6%	1000-2000 µm	Gastrointestinal tract	Fibers, fragments, beads	English Channel	Lusher et al. 2013
Zeus faber	42; 47.6%	1000-2000 µm	Gastrointestinal tract	Fibers, fragments, beads	English Channel	Lusher et al. 2013
Shellfish						
Species	**MP levels (particles/ind.)**	**Size range**	**Parts**	**Debris types**	**Location**	**References**
Saccostrea palmula	0.71 ± 0.29	734–1585 µm	Digestive tract	Fibres, fragments	Galapagos Islands	Jones et al. 2021
Holothuria kefersteini	0.99 ± 0.34	165.5 – 952 µm	Digestive tract	Fibres, fragments	Galapagos Islands	Jones et al. 2021
Dosidicus gigas	93%	150-5000	Digestive tract	Fibres	Ecuador	Alfaro-Núñez

		µm				et al. 2021
Penaeus occidentalis	20%	150-5000 µm	Digestive tract	Fibres	Ecuador	Alfaro-Núñez et al. 2021
Modiolus modiolus	3.5 ± 1.29	200 - > 2000 µm	Soft tissue	Fibres	Scottish coast	Catarino et al. 2018
Amiantis purpuratus	6	10-5000	Soft tissue	Fibres, fragments, pellets, film	Coastal water of The Persian Gulf, Iran, Asia	Naji et al. 2018
Cerithidea cingulata	12	10-5000 µm	Soft tissue	Fibres, fragments, pellets, film	Coastal water of The Persian Gulf, Iran, Asia	Naji et al. 2018
Thais nuitabilis	3	10-5000 µm	Soft tissue	Fibres, fragments, pellets, film	Coastal water of The Persian Gulf, Iran, Asia	Naji et al. 2018
Pinctnda radiate	11	10-5000 µm	Soft tissue	Fibres, fragments, pellets, film	Coastal water of The Persian Gulf, Iran, Asia	Naji et al. 2018
Mytilus gallopravincialis	6.2-7.2 particle/g	760-6000 µm	Valves, hepatopancreas and gills	Filaments	Italy From maricultured and natural stocks	Renzi et al. 2018
Pernapema	26.7% ind. with MP	Not specified	Digestive tract and entire tissue	Fibres	Santos Estuary, Brazil	Santana et al. 2016
Eriocheir sinensis	13% ind. with MP	Not specified	Stomachs	Fragments, filaments	Baltic coastal	Wojcik-Fudalewska et al. 2016
Crangon crangon	0.68 particles/g individual	200-1000 µm	Whole shrimp and peeled shrimp (abdominal muscle tissue)	Fibres	Belgium	Devriese et al. 2015
Crassostrea gigas	0.6 particles/g individual	> 500 µm	Entire tissue	Fibres	California, USA From local market	Rochman et al. 2015
Cyclina sinensis	4.82 ± 2.17	5-5000 µm	Soft tissue	Fibres, fragments, pellets	China From the local fish market	Li et al. 2015
Alectryonella plicatola	10.78 ± 4.07	5-5000 µm	Soft tissue	Fibres, fragments, pellets	China From the local fish market	Li et al. 2015
Meretrix ktsoria	9.22	5-5000 µm	Soft tissue	Fibres, fragments, pellets	China From the local fish market	Li et al. 2015

Mytilus gallopravincialis	4.33 ± 2.62	5-5000 µm	Soft tissue	Fibres, fragments, pellets	China From the local fish market	Li et al. 2015
Patinopecten yessoensis	57.17 ± 17.34	5-5000 µm	Soft tissue	Fibres, fragments, pellets	China From the local fish market	Li et al. 2015
Ruditapes philippinarum	5.72 ± 2.86	5-5000 µm	Soft tissue	Fibres, fragments, pellets	China From the local fish market	Li et al. 2015
Scapharca subcrenata	45 ± 14.98	5-5000 µm	Soft tissue	Fibres, fragments, pellets	China From the local fish market	Li et al. 2015
Sinonovacula constricta	14.33 ± 2.21	5-5000 µm	Soft tissue	Fibres, fragments	China From the local fish market	Li et al. 2015
Tegillarea granosa	5.33 ± 2.21	5-5000 µm	Soft tissue	Fibres, fragments	China From the local fish market	Li et al. 2015
Crassostrea gigas	0.47 particles/g individual	5-25 µm	Soft tissue	Not specified	Atlantic Ocean Market from Brittany, France	van Cauwenberghe and Janssen, 2014
Mytilus edulis	0.36 ± 0.07 particles/g	5-25 µm	Soft tissue	Not specified	North Sea	Van Cauwenberghe and Janssen, 2014
Nephrops norvegicus	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 being used in a wide range of products (e.g., furniture, textiles, and so on) in our daily lives (Gago et al. 2018). MP contamination is largely caused by abrasion and fibre release from synthetic garments. The washing of a single polyester clothing resulted in the shedding of >1900 MP fibres and microbeads, resulting in >hundred fibres/l of sewage water (Browne et al. 2011). In compared to fabrics made entirely of acrylic or polyester, polyester-cotton blends lose far fewer fibres (Napper and Thompson, 2016; Bhuyan et al. 2020).

Polyester is a polyethylene terephthalate fabric that is widely used because to its strength, physical features, and distinctive wear characteristics (Carr, 2017). Polyester, which accounts for about half of the world fibre industry, is mostly utilized in garment fabrics and other processed textile commodities (Carr, 2017). Polylactide (polyamide), nylon (polyamide), rayon (semi-synthetic), acrylic, and polypropylene are some of the other synthetic textile fibres. In the production of synthetic fibres, 60 percent synthetic fibres, 30-percentage cotton, and 10% non-synthetic fibres, such as animal wool, are employed (Carr, 2017). 35% of MP fibres are formed from laundering synthetic textiles and 28% through tire erosion particles. These are the two most common primary MP items introduced into the world's oceans (Boucher and Friot, 2017). MP fibres are released into the environment throughout the manufacturing process; while laundering finished products access the oceans when textiles and no laundering materials disintegrate (Bhuyan et al. 2020).

Construction site bruising of insulation materials are also among the listed sources of MPs (Sundt et al. 2014; Mishra et al. 2019; Waldschläger et al. 2020). MPs include pre-production granules and elements in a wide range of products, including fishing gear fragments, packaging and liquor cans, synthetic textiles, vehicle tyres, coatings, skincare, and beauty products, and electronic devices (Fendall and Sewell, 2009; Andrady, 2011; GESAMP, 2016). Sources and transportation of MPs in the ocean are depicted in Fig. 3.

Transformation of microplastics

Microplastics deterioration

Weathering effects such as UV-light radiation, wind, salinity, etc., and biofouling are aging procedures that can change the physicochemical characteristics of MPs in the ocean (Vroom et al. 2017). MPs disintegrate as a result of these processes, shrinking in size and forming an uneven form and surface, eventually increases their overall surface area (Lambert et al. 2017). As soon as MPs enter the oceans, a layer of organic and inorganic compounds occurs. This can result in 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; Zettler et al. 2013). The bulk of existing research use immaculate, "virgin" MPs in their trials, which does not represent MPs found in the marine environment (Mazurais et al 2015). MPs were forced to age by soaking them in natural seawater for three weeks, during a biofilm was thought to grow on their surface. This shows that the weathering and biofouling processes increase MP bioavailability.

Density transformation by biotechnology

The buoyancy of plastic debris can be affected by biofouling. As the plastic sinks, it becomes accessible to marine wildlife at higher depths in the water column, resulting in greater density and impartial/damaging buoyancy (Bhuyan et al. 2020). According to Kooi et al. (2017), biofouling causes a size-dependent vertical migration of MPs, with maximum concentration at depths in the middle. This results in a lesser quantity of MP on the water surface and preventing its accumulation on the seabed. As a result, the zooplankton, which travels through the vertical zones, comes in contact with these MPs as they pass through. MPs can also be transported to deeper water through faecal pellet digestion and upward migration during the day. Other marine organisms that eat faeces pellets contribute to the vertical flux of particulate matter that regarded as the part of the biological pump (Cole et al. 2016). According to the research, low-density MPs detected in faecal pellets affects their sinking rates due to decreased density, which could have an impact on CO_2 sequestration in the deep ocean (Cole et al. 2016). Moreover, coprophagia nature makes those lower-density faeces pellets accessible to a variety of species. MPs can also be integrated into the secretion of mucus, which are employed by species like *Bathochordaeusstygius* to concentrate food particles via active filter feeding, often known as "houses" (Katija et al. 2017). When these dwellings become congested, they get discarded and sink quickly, exposing another biological transport mechanism that transports MPs from surface water to the seafloor (Katija et al. 2017).

Aggregations

MPs' hydrophobic characteristics allow them to get collected and become incorporated into marine aggregates like marine snow. Depending on the plastic-type, an increase in overall particle size gets generated that might affect density. As a result, they become bioavailable to species of various sizes and those found in various strata of the water column. Externally, MPs have been observed accumulating on copepod antennae, limbs, swimming appendages, eating equipment, and furca (Cole et al. 2013). This could cause blockage, which would decrease motility, intake, reproduction, and mechanoreception even further. The formation of these aggregations has also been observed within the digestive system (Vroom et al. 2017; Cole et al. 2013).

Economic loss due to microplastics management

Due to a multitude of causes, notably economic forces, MPs may have an impact on health (Oliveira et al. 2019). The yearly economic consequences of lost marine capital are projected to be between $33,000 to $2500 bn/ton of MP trash in 2011 (Beaumont et al. 2019). Reduced tourism as a result of plastic litter could jeopardize the survival of many communities and, as a result, their health (Clapp and Swanston, 2009). For example, the Azores archipelago in the North-East Atlantic lost 710,698€ (0.02% of GDP) in 2016 due to troubles sourced by marine litter, such as mends, lost output, and clean-up operations (Rodríguez-Torres et al. 2020). Lost funds could be diverted to social and environmental objectives such as long-term sustainability by eliminating the ecological and economic repercussions of marine litter, as well as the lesser-known effects of MPs.

Substrate of pathogen

Pathogenic microorganisms that cause infections can be detected on the surface of MPs and benefit from the aggressions that these particles produce. MPs in the environment, for example, have been discovered to contain *Vibrio* sp., a type of bacterium linked to foodborne illnesses (Letchumanan et al. 2019; Kirstein et al. 2016). Ingestion of MPs can cause respiratory problem of the marine organisms, having 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 micro particles that had been kept in river water for fourteen days *in situ*, pointing to the existence of human diseases (Murphy et al. 2020). MPs have been linked to the spread of antimicrobial genes or pathogenic microorganisms (Hu et al. 2019) since these particles have been demonstrated to increase the frequency of *in vitro* resilience plasmid transfer from *E. coli* to wild bacterial colonies (Arias et al. 2019). Moreover, MPs may cause an increment in the density and severity of toxic algal blooms, which may have detrimental consequences for other organisms at sea (Yokota et al. 2017) potentially affecting food supplies. For example, the count of antibiotic-resistant bacteria in MPs particles in a marine aquaculture system was 100-5000 times greater than in the ambient water, implying a concern to human and fish welfare (Zhang et al. 2021).

Materials and methods

Study sites

Data was gathered from many countries throughout the world. Results from the publications of various scientists and researchers are featured.

Data collection

The initial phase included the identification of related studies. To conduct a systematic literature review, we created the following specifications for our database:

- **Searching database**

- Scopus, Web of Science, Google Scholar, PubMed, Dimension

- **Searching conditions**

- English-language journal articles
- Impact of MPs on marine organisms-related journals, book chapters, conference proceedings
- Available on the internet (No time limitation)

- **Searching strings**

Data was collected using 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 mollusks” or “Impacts of microplastics on marine Arthropoda” or “Impacts of microplastics on marine Annelida” or “Impacts of microplastics on marine Echinodermata”, etc.

Impacts of microplastics on marine organisms

The bulk of natural nano- and microparticles are less than 100 nm in size (Rosse and Loizeau, 2003), are abound in seawater. In general, those microscopic particles have discernible influence on marine species

(Table 2). MPs, on the other hand, cannot be broken down or assimilated once consumed since marine organisms lack the necessary enzyme pathways to break down the synthetic polymers, and hence might be classified as bioinert substances (Andrady, 2011). Ingestion of MPs has long been known to cause a variety of issues. MPs are known to harm aquatic organisms in a variety of ways, including effects on growth and development (Lee et al. 2017; Lo and Chan, 2018), decreased feeding efficiency, intestinal blockage (Wright et al. 2013a), changes in swimming behaviour (Webber and Haines, 2003; Vieira et al. 2009), and interference with reproductive success (Frederick and Jayasena, 2011). MPs' ability to engross and absorb metals and POPs (e.g., polychlorinated biphenyls, polycyclic aromatic hydrocarbons, dichloro-diphenyl-trichloroethane and polybrominated diphenyl ethers) from the ecosystem is a matter of concern (Bowmer and Kershaw, 2010; Rochman et al. 2014 a,b; Gewert et al. 2015). The type of polymeric materials (e.g., glassy or rubbery), weathering and residency period of plastic trash in seawater, as well as the bio colonization on their surface may enhance the capacity of MPs absorption (Wang et al. 2016). MPs can acquire POPs at greater levels than bigger plastics due to their increased surface area to volume ratio (Cole et al. 2011), which is harmful for the environment (Gewert et al. 2015). Hirai et al. (2011) and Ogata et al. (2009) estimated an average worldwide concentration of POPs in marine plastic pellets of 1-10,000 ng/g.

MPs can collect and store metals, the majority of which come from a variety of sources, including industrial effluents, waste incineration, and antistatic coatings (Rochman et al. 2013b; Holmes et al. 2012; Brennecke et al. 2016). Because of the pervasiveness of plastic trash and the little size of MPs, both primary and contaminated MPs can be swallowed by a variety of marine animals, potentially causing hazardous effects. One or more sources, such as leftover monomers and additives in plastics, products resulting from partial breakdown, or substances adsorbed to them, can induce these effects. Furthermore, the number of MPs consumed, and the duration spent in tissue or organs inside an organism are critical factors in determining their possible impacts (Wright et al. 2013a; Wang et al. 2016). MPs alone or in conjunction with other marine contaminants have been shown to pose a significant health risk of many marine biotas in multiple studies.

Impacts of microplastics on Mollusca

There is a historic financial association between humans and molluscs. Molluscs provide several commercial benefits, such as fisheries and mariculture, but they can also cause substantial economic loss and thus, produce misery in communities depending of this income (Levin, 2013). They are a diverse group that can be found in a variety of aquatic habitats settings. They play a crucial role in ecosystem engineering, reshaping aquatic bottom conditions while also providing habitat, security, and food for a variety of other taxa (Fernández Pérez et al. 2018).

Impacts on bivalve

Potential human health consequences from MP fibres associated marine bivalves’ ingestion have recently allured a lot of attention. Molluscs are a group of filter-feeding animals that are vital to both the environment and the economy. These sessile animals filter a significant amount of water that gets absorbed and deposit a wide spectrum of marine toxins that humans can tolerate in their tissues until certain level. Bioindicator organisms such as *Mytilus galloprovincialis* and *Mytilus edulis* are widely used to assess aquatic environment health and monitor marine pollution (Sureda et al. 2011; Torre et al. 2013; Faggio et al. 2016; Savorelli et al. 2017; Bat and Arici, 2018; Bat et al. 2018; Capillo et al. 2018). Molluscs and other benthic species, such as annelid worms, are prone to be impacted by MPs due to their habitats and food intake. Filter-feeding species with strong bioaccumulation potential can be found in large numbers in molluscs. Since several of these species (e.g., *M. edulis*) are widely consumed as seafood, they might serve as a source of MPs or other environmental toxins for people (Van Cauwenberghe and Janssen, 2014; Wegner et al. 2012; Mincarelli et al. 2021). The main effect of contaminants bio accumulating within mussels is cell destruction in reaction to oxidative damage (Pagano et al. 2016, 2017; Messina et al. 2014; Sureda et al. 2018; Sehonova et al. 2018).

Mincarelli et al. (2021) exposed blue mussels to plastic softener Di-2-ethylhexyl phthalate (DEHP) for 7 days with both single and combined stress factors, +3 °C high temperature and two environmental concentrations. Males were found to be more vulnerable to high temperatures, as evidenced by a large increase in spawning gonads outside of the breeding season and greater gene expression of the antioxidant catalase and the oestrogen receptor genes. DEHP exposure, on the other hand, affected the oestrogen-related receptor gene expression in females, despite the gametogenesis cycle being more durable in females than in males (Mincarelli et al. 2021).

In laboratory studies, *M. edulis* was discovered to ingest and accumulate polystyrene microspheres (2 µm in diameter) and tubules (4-16 µm in diameter) in its gastrointestinal canal within 12 hours of contact with MPs and seawater (Browne et al. 2008). Polystyrene microspheres (3 m and 9.6 µm in size) were also discovered in the haemolymph and haemoglobin, indicating that MPs had transferred from the stomach to the circulatory system. MPs were translocated into the haemolymph and haemocytes of *M. edulis* within three days and remained there for more than 48 days, posturing substantial health risks. Early granulocytoma development (inflammation), a rising in haemocytes, and a significant reduce in lysosomal membrane stability (LMS) were also detected (Browne et al. 2008). Furthermore, the amount of energy allocated to immunological functions may be lowered, causing injury to all normal physiological processes. Result is the deterioration of individual fitness and ecosystem. Furthermore, the constant consumption and accumulation of MPs in bivalves may have long-term consequences. After confirming that *M. edulis* can ingest and amass both primary and polluted MPs. Mussels treated with MPs and pyrene exhibited a larger concentration of pyrene in their digestive glands than mussels treated solely with pyridine, according to Avio et al. (2015b).

Table 2. Effects of microplastics on aquatic biota.

Classes	Species	Exposure time (hrs)	MPs Type (size μm)[a]	MPs Tested Concentration	Effects[b]	Ref.
Annelida	*Arenicola marina*	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. 2013a
		744	PE, PVC (1.4-707)	0.2-20 g of MPs Kg^{-1} of wet sediment	↑ Metabolic rates	Green et al. 2016
Echinodermata	*Lytechinus variegatus*	24	PE	200 ml of MPs L^{-1}	↑Anomalous larvae development	Nobre et al. 2015
	Paracentrotuslividus	6-48	PS (0.04-0.05)	1-50 μg ml^{-1}	↑ MPs accumulation ↑ Malformations ↑ Disruption of cell membrane ↑ *Cas8* (related with apoptotic processes) ↑ Oxidative stress ↑ *Abcb1* 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	

	Tripneustesgratilla	120	PE (10-45)	300 MPs ml^{-1}	↓ Growth	Kaposi et al. 2014
Rotifera	*Brachionuskoreanus*	288	PS (0.05-6)	0.1 – 20 μg ml^{-1}	↓ Growth rate ↓ Fecundity ↓ Lifespan ↑ Reproduction time	Jeong et al. 2016
Mollusca	*Crassostrea gigas*	1440	PS (2-6)	0.023 mg L^{-1}	↑ Microalgae consumption ↑ Absorption efficiency ↑ Maintenance costs ↓ Oocyte number ↓ Sperm velocity	Sussarellu et al. 2016
	Mytilus edulis	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
	Mytilus galloprovincialis	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)	Ribeiro et al. 2017

					↑ SOD activity (digestive gland) ↓ CAT activity (digestive gland) ↑ GPx activity after 3 days exposure (digestive gland) ↓ GPx activity after the remaining time (digestive gland) ↓ GST (digestive gland) ↓ AChE activity (gills) ↑ LPO levels (digestive gland) Genotoxicity	
Crustacea	*Hyalella azteca*	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	
	Carcinus maenas	1-24	PS (8)	10^6-10^7 MPs L^{-1}	↓ Hemolymph sodium ions ↑ Hemolymph calcium ions ↑ Oxygen consumption	Watts et al. 2016
	Tigriopus japonicus	2 generation test	PS (0.05-0.5)	0.125-25 µg ml^{-1}	↑ Mortality ↓ Survival ↓ Fecundity	Lee et al. 2013
	Centropagestypicus	24	PS (0.4-3.8)	$40x10^3$-$1x10^6$ MPs ml^{-1}	↓ Ingestion rates	Cole et al. 2013
	Nephrops norvegicus	5760 (feeding test)	PP (3000-5000)	5 MPs $feeding^{-1}$	↓ Feeding rate ↓ Body mass ↓ Metabolic rate	Welden and Cowie, 2016
	Palaemonetes pugio	3h	PE,PS,PP (30-165)	50 000 MPs L^{-1}	↑ Mortality	Gray and Weinstein 2017
	Gammarus fossarum	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-		↓ Wet weight gain	

			250)			
	Artemia franciscana	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
	Daphnia galeata	120	PS (0.05)	5 mg L^{-1}	↑ Mortality ↓ Reproduction Abnormal development	
	Daphnia magna	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
	Amphibalanusamphitrite	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
	Calanus helgolandicus	24, 216	PS (20)	65-75 MPs ml^{-1}	↓ Predatory performance ↓ Reproductive output ↓ Survival	Cole et al. 2015

					Energetic depletion	
	Paracyclopina nana	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
	Parvocalanuscrassirostris	144, 576	PES (5-10)	10000-80000 MPs mL^{-1}	↓ Egg production ↓ Population size ↑ *H3* (gene involved in chromatin structure of eukaryotic cells)	Heinder et al. 2017
Fish	*Dicentrarchuslabrax*	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 mucose and submucosa/mucosa Occurrence of rodlet cells in the intestinal mucosa	Peda et al. 2016
	Pomatoschistusmicrops	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
	Sparus Aurata	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	Espinosa et al. 2017

			↓ *prdx5* and *hsp90* (genes related to stress) ↑ *prdx1, prdx3,* and *ucp1* (genes related to stress)

PE-Polyethylene; PS-Polystyrene; PP-Polypropylene; PVC-Polyvinylchloride; PLA-Biodegradable plastic; AC-Acrylic; PES-Polyester.

De Witte et al. (2014) discovered that *M. edulis* samples collected throughout the Belgian coast and purchased from stores contained 0.26 to 0.51 fibres per gram of tissue, with variations attributing to environmental availability. Mathalon and Hill (2014) found about 30 and 70 fibres per individual of *M. edulis* collected from a Nova Scotia harbour and purchased from an aquaculture site, respectively. Li et al. (2015) found greater quantities of fibres (up to about 5 per g) in a variety of bivalves from a Chinese fisheries market.

The feeding capacity of Pacific oyster (*Crassostrea gigas*) larvae was unaffected by different sizes of polystyrene microbeads (Cole and Galloway, 2015). This could be due to the simplicity of oyster's intestinal tract, which allows for the retention of fewer MPs as they are ingested more easily. The Pacific oyster *C. gigas* (Revel et al. 2020; Alfaro-Núñez et al. 2021) and the blue mussel *Mytilus* sp. exhibited no detrimental effects (Revel et al. 2019), however the black-lip pearl oyster *Pinctada margaritifera* had issues with energy balancing and breeding (Gardon et al. 2018; Revel et al. 2019).

Experiments on the marine mussel *M. galloprovincialis* subjected to PE MPs revealed a number of negative effects in molluscs, including immunological response, oxidative damage, and cytotoxicity (Avio et al. 2015a). Enzymatic changes were reported in the marine mollusc *M. galloprovincialis* after exposure to PS and PE MP (Avio et al. 2015a). Two mollusc species showed additional ecotoxicological consequences after being exposed to PS MPs. Elevation in neurotoxicity and genotoxicity were documented in a study using *Scrobicularia plana* (Ribeiro et al. 2017). Ingestion of PS MPs in *M. edulis* resulted in 25% increase of energy consumption (Van Cauwenberghe et al. 2015). This was most likely the result of the need to assimilate inactive material while maintaining metabolic equilibrium (von Moos et al. 2012). After a three-day exposure, the transfer of MP from the gut to the haemolymph was shown to last for 48 days in *M. edulis* (Browne et al. 2008). MPs' longevity in mussel tissues poses a risk of toxicity to their predators as well as in humans (Van Cauwenberghe and Janssen, 2014; De Witte et al. 2014). MP exposure influenced homeostasis in mussels *Mytilus* sp., leading to increased energy expenditure (Détrée and Gallardo-Escárate, 2018), reduction in attachment strength (Green et al. 2018), impact on key metabolism enzymes, and antioxidant indicators are up regulated (Détrée and Gallardo-Escárate, 2017). Changes in immunological indicators, oxidative stress, neurotoxicity, and genotoxicity, as well as transcriptional effects, were observed in mussels with high levels of pyrene. MPs in mussels are of growing concern, not only because of their vital role in the trophic chain but also as a part of the benthic ecological system (Browne et al. 2008). Bivalves such as *M. galloprovincialis* and *M. edulis* are heavily exploited in the food industry. *Ostrea edulis* was stressed by MPs, both conventional and biodegradable (Green, 2016).

Impacts on gastropods

Non-filter-feeding, larger-sized creatures like gastropods feed on predetermined amounts of MP fibres to assure retention through uptake and effect analysis (Watts et al. 2015; Jabeen et al. 2018; Grigorakis et al. 2017; Ehlers et al. 2020). *Radix balthica* ate a biofilm comprising MP fibres while feeding (Ehlers et al. 2020). Following that, MP fibres were gradually ingested through the faeces in a fibre-free media, which took three days to complete (Ehlers et al. 2020). However, an in-depth investigation of whole tested organisms after chemical digestion found fibres that were retained within the snails' body six days after contact (Ehlers et al. 2020). This shows that certain ingested fibres can remain in the bodies of snails, even though most MP fibres are expelled in a few days of consumption (Ehlers et al. 2020).

Planorbella campanulata were subjected to exceptionally high levels of polyester textile materials in the marine environment, and fibres accumulated in the snail's mouth, resulting in greater death rates than control snails (Philips et al. 2020). As a result, impact on the quality in local hot spots with high fibre concentrations may cause food intake blockage and snail mortality (Philips et al. 2020). In addition, in the polyester fibre treatment, snails produced more progeny. This was thought to be a result of death generating a surge in offspring or estrogenic effects from chemicals evaporation from the fibres (Philips et al. 2020). Ingestion of polystyrene microbeads by the veligers of the marine gastropod *Crepidula onyx* resulted in slower development rates as well as premature settling on the seabed (Lo and Chan, 2018), which may have a negative impact on post-settlement effectiveness. Moreover, those individuals subjected to microbeads only during the larval stage grew at a slower rate 65 days after the MPs were removed. This emphasizes the potential for harmful long-term consequences of early-life exposure on development. The adult stage on the other hand, were unaffected at environmentally relevant MP concentrations.

Impacts on Arthropoda

Decapods come into contact with MPs in the water column at their gill surfaces during ventilation or by ingestion while foraging. Filter and deposit-feeding decapods passively ingest MP fibres, whereas selective feeding decapods aggressively feed on them. Isopods and predatory crabs' consumption of MP fibres was studied by including fibres in their food (Watts et al. 2015; Hamer et al. 2014). When the number of eaten fibres was measured in different parts of the gastrointestinal tract and in the faeces, there were no signs of aggregation within the digestive system (Watts et al. 2015; Hamer et al. 2014).

In another study, langoustine (*Nephrops norvegicus*) unmolten individuals were fed with a meal comprising polypropylene fibres for 2 months, accumulating fibres in their intestinal tract (Welden and Cowie, 2016). In the stomachs of molten animals, however, there were no leftover MP fibres. The presence of MP fibres in the shed gut lining suggests that *N. norvegicus* can lose MP fibres during ecdysis (Welden and Cowie, 2016). The ability of Atlantic ditch shrimp (*Palaemonvarians*) to vomit swallowed polyacrylic threads was discovered as another technique to expel ingested fibres (Saborowski et al. 2019). Crustaceans that ingest MP fibres appear to be able to expel the fibres in a number of different ways.

MPs of various shapes and sizes were exposed to dagger blade grass shrimp (*Palaemonetes pugio*) in the water column (Gray and Weinstein, 2017). Due to water flow, all MPs stuck to the gill region, and shrimps that are picky in their foraging swallowed the MPs. Considering the brief exposure period, the shrimps died within the first three hours of treatment and during the subsequent 96-hour depuration time. The varied sizes of polypropylene fibres tested induced mortality, and the mortality rates for fibres were higher than fragments of various sizes (Gray and Weinstein, 2017).

The high deadliness of MP fibres has been linked to damage the intestinal tissues caused by entangling (Gray and Weinstein, 2017). The greater toxicity of fibres, on the other hand, could be linked to their weathered state. After a 96-hour exposure, virgin 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 fibre plastics used or the degree of degradation of the fibres, revealing the impact of fibre characteristics on decapods (Leads et al. 2019; Gray and Weinstein, 2017). In a later 2-day challenge assay with bacteria (*Vibrio campbellii*), the polyester-exposed shrimp did not perish, which was linked to the polyester fibres being eliminated rather quickly within 48 hours, reducing their immunotoxicity (Leads et al. 2019).

For 41 days, Pacific mole crabs (*Emerita analoga*) were treated in the water column to ecologically appropriate levels of 1 mm polypropylene fibres (Horn et al. 2019). When compared to control crabs, exposed individuals had a higher mortality rate. Chemical digestion of the entire crabs was assessed to measure fibre intake. The crabs' mortality rate increased as the number of fibres consumed increased. This showed that Pacific mole crabs and other non-selective feeders cannot sense the difference between plastic and food, putting them at peril as ambient fibre levels rise (Horn et al. 2019). Likewise, exposed *E. analoga* had lower egg clutch retention and higher heterogeneity in embryonic development rates. Ingested MP fibres may impair reproduction, or the colour associated with these fibres leached (Horn et al. 2019).

MP fibres and spheres were introduced to water fleas (*Ceriodaphnia dubia*) is mounting, ranging between two and three orders of magnitude above ambient values (Ziajahromi et al. 2017). Water fleas did not consume polyester fibres from the water, but tactile contact with the fibres was linked to lower development, reproduction, and aberrant swimming behaviour. At concentrations of 4.3×10^3 fibre/l and beyond, fibres produced bodily impairment such as carapace and antenna abnormalities. When water fleas were uncovered to MP fibres for 48 hours in an acute bioassay, their survival was impacted dose-dependently. The lethal concentration (LC_{50}) for 50% of the organisms was as big as 1.3×10^4 polymer materials per litter (Ziajahromi et al. 2017). Despite the fact that this is four times higher than ambient values (Song et al. 2015; Ryan et al. 2020; Luo et al. 2019) the findings suggest that localized high MP fibre contamination can have a significant impact on zooplankton.

Besides the acute toxicity, *Hyalella azteca* subjected to high fibre concentrations showed growth that has slowed dramatically, with >50% lower weight than control animals (Au et al. 2015). MP fibres retained in the digestive system of amphipods were substantially bigger than spherical or naturally occurring foodstuffs (Au et al. 2015), explaining the growth inhibition that was reported due to less energy being available. In experimental amphipods, however, MP fibres did not aggregate, and it was possible to digest the polypropylene fibres completely (Au et al. 2015). Au et al. (2015) studied the effects of PP MPs on *H. azteca,* and found that PP MPs were more harmful than PE MPs. PS MPs were found in the estuarine mysid *Neomysis integer* (Setälä et al. 2014) and the crab *Uca rapax* (Setälä et al. 2014).

Similar to amphipods, the water flea *Daphnia magna* was discovered to be dead after consuming polyester fibres present in the water column for 48 hours (Jemec et al. 2016). The survival of the species was not dose-dependent, showing that MP fibres have diverse effects on various aquatic creatures. However, there was a decreased in mortality rate when *D. magna* were ex-fed with algae before being exposed (Jemec et al. 2016). When *D. magna* and *Artemia franciscana* were subjected to high concentrations of polyester fibres for 48 hours, no acute mortality was found despite the presence of MP fibres in their guts (Kokalj et al. 2018). MPs caused immobility (Rehse et al. 2016), mortality (Aljaibachi and Callaghan, 2018), and reproduction impairment (Pacheco et al. 2018) in the planktonic crustacean *D. magna*, with transgenerational impacts of lower growth and reproduction (Martins and Guilhermino, 2018).

Individual fitness in several crab species was impacted by exposure over a lengthy period of time to MP fibres. Since crabs (*Carcinus maenas*) had a meal incorporating polypropylene fibres (0.3-1.0 percent by weight) for 4 weeks, they consumed lower food and had much reduced energy available for development (Watts et al. 2015). These crabs can select more desirable food items in the wild than other species. MP fibre pollution is expected to have direct ecological consequences for this organism (Watts et al. 2015). Fibres can be excreted by a variety of decapods quickly and efficiently, thus they stay unaffected. On the other hand, some species are more susceptible to exposure of MP fibre and remain under threat as MP fibre concentrations rise.

Impacts on fish

Fish is a major source of protein for humans. Hence, the presence of MPs in fish and their possible consequences deserve special consideration (Wang et al. 2020). MPs have been found in a wide range of fish species caught in the oceans, and seas (Pazos et al. 2017; Alomar et al. 2017; Jabeen et al. 2017; Morgana et al. 2018; Bessa et al. 2018; Alfaro-Núñez et al. 2021). MPs are mostly consumed by fish as a result of misperception of MP particles for natural prey, in advertent ingestion when foraging, and due to direct ingestion of animals harbouring MPs (Boerger et al. 2010; Lusher et al. 2013; Ory et al. 2017). In the field, fish ingested MP fibres at various life stages from larvae to mature (Steer et al. 2017; Mizraji et al. 2017; Kühn et al. 2018; Gove et al. 2019). Fibres served as the most common among MP shape in larvae and juveniles, raising concerns on younger life stages, becoming more susceptible to MP fibres ingestion especially. According to fibre dispersion patterns, uptake of MP fibres by fish from the Mediterranean Sea was positively related to coastal human population, river inputs, and shipping lanes (Sbrana et al. 2020).

MPs were detected in the fish (*Priacanthus hamrur*, *Sciades sona*, *Carangoides chrysophrys*, *Harpadon nehereus*, *Otolithoides pama*, *Setipinna tenuifilis*, *Coilia neglecta*, *Anodontostoma chacundam*, *Sardinella* *brachysoma* and *Megalaspis cordyla*) of the Bay of Bengal, Bangladesh (Ghosh et al. 2021). There were 215 MPs retrieved in total, with an average abundance of 2.20 MPs per individual. Fibres, films, pieces, foams, and granules were discovered among the MPs (Ghosh et al. 2021). For example, in wild North Atlantic fish's muscle and liver (*Scomber colias*, *Trachurus trachurus, Dicentrarchus labrax*), a strong association was discovered between the quantity of ingested MPs and total bisphenol content (Barboza et al. 2020).

Fish through direct or indirect ingestion from the seawater can absorb MP fibres when they come into contact with them at their gills. In a study of *Pomatoschistus microps*, adverse effects of MPs with chromium (VI) included neurotoxicity and death (Luis et al. 2015). PE MPs have been shown to cause neurotoxicity in fish (Luis et al. 2015; Oliveira et al. 2012, 2013), as well as a loss in predatory performance and efficiency in *P. microps* (de Sá et al. 2015). Mortality was reported in the European bass (*D. labrax*) (Mazurais et al. 2015). MPs are neurotoxic, affect energy-related enzymes, cause detrimental effects on swimming performance, and cause oxidative stress and lipid peroxidation in juvenile European seabass (*D. labrax*) (Barboza et al. 2018a,b,c).

MP particles were found in 149 (71%) of 210 fish from 14 different species (in at least twenty specimens for each of all fish species analysed) across the Tropical Eastern Pacific and Galapagos (Alfaro-Núñez et al. 2021). The authors concluded that this value was higher than those previously reported, allowing to conclude that MPs debris in the form of fish feed, may accumulate over time and space.

Oryzias lapites, a Japanese medaka fish, chemical contaminants (PAHs, PCBs, and PBDEs) were shown to accumulate in the body, as evidenced by bioaccumulation. Liver stress and early tumour formation were reported after being exposed to both pieces of primary and marine plastic for a short time (Rochman et al. 2013b). After exposure, structural damage in the gills including epithelial denudation on gill arches, fusion of main lamellae, and increased mucus production were visualized through scanning electron microscopy (Hu et al. 2020). Polyethylene with absorbed chemical pollutants from the ocean water bodies may disrupt the endocrine system function in adult *O. lapites* fish (Rochman et al. 2014a). Males had their choriogenin (ChgH) gene expression down regulated, while females had their vitellogenin (VTgI), ChgH, and oestrogen receptor (ER) gene expression down regulated. The main concern should be the long-term impacts of exposure during an organism's early development phases, which could jeopardize the propagative success and threaten biota (Rochman et al. 2014a).

Blue MP particles were enriched in the guts of a predatory fish Amberstripe scad (*Decapterus muroadsi*), likely because of the false interpretation of the MPs to their natural prey bluefish copepods (Ory et al. 2017). Similarly omnivorous fish species (*Girella laevifrons*) piled up large quantities of red MP fibres instead of their feed red algae (Mizraji et al. 2017). In specimens with a higher amount of MP fibres in their digestive system, the body conditions were shown to be worse (Mizraji et al. 2017), suggesting that ingested fibres may directly affect fitness. In the wild, a reduction in predatory activity may decrease the ability of juvenile gobies to catch prey and flee predators. As a result, there is a chance that individual health and thus population fitness will be under threat, with implications in juvenile development rates and species survival.

MPs significantly reduced the swimming velocity and resistance time of young European seabass, *D. labrax* (Barboza et al. 2018d). Additionally, behavioural abnormalities such as sluggish and irregular swimming activity were noticed. These findings demonstrate the importance of assessing the combined effects of MPs and other environmental pollutants, with a focus on behaviours in fish and other marine species, as well as the use of fish responses as a susceptible endpoint to determine the effects of MP contamination (Barboza et al. 2018d).

Impacts on Annelida

Annelids are marine worms that irrigate and provide oxygen, promoting the growth of useful plants and algae. The fundamental ecological role of the marine worm in oceanic reefs is to provide nutrition for aquatic species higher up the food chain (von Palubitzki and Purschke, 2020). Species inhabiting sediments may be affected by MPs, with serious consequent alterations such as change of gut microbiota, growth suppression, and collembolans reproduce in the soil (Zhu et al. 2018), depending on the degrees and concentrations of exposure. In reaction to large dosages of HDPE, PLA, and PVC in sandy sediments, *Arenicola marina* respiration rates rise (Green et al. 2016). A decrease in energetic reserves was also found, which could be attributable to inflammatory responses in tissues, as well as reduced feeding for mistaken fill or the deposition of MPs in digestive cavities (Wright et al. 2013a). As a result, stress may affect the health and behaviours of the polychaete *A. marina*, such as feeding behaviour and sediment reworking, negatively impacting ecological processes (Green et al. 2016). Furthermore, *A. marina* collected nonylphenol and triclosan from polyvinyl chloride (PVC) when exposed to high levels of plastic, resulted in compromised immunological systems, physical stress, and death (Browne et al. 2013). Exposure to PS MPs has ecotoxicological effects in the polychaete *A. marina*, including lower feeding activity and lysosomal membrane stability (Besseling et al. 2013). When *A. marina* was exposed to PS MPs, Van Cauwenberghe et al. (2015) detected an increase in energy consumption. The lipid stores of *A. marina* exposed to sediment PVC were depleted, and an inflammatory reaction was seen (Wright et al. 2013a).

Impacts on Echinodermata

Echinoderms are a vital component of the ocean food web, as well as a source of food and medication for humans (PiRuby, 2018). PE MPs have been proven to alter *Tripneustes gratilla* larval growth without influencing its subsistence in echinoderms (Kaposi et al. 2014). For *Lytechinus variegatus* larvae, Nobre et al. (2015) confirmed these findings. It may be relevant to highlight that all these investigations were carried out at concentrations of MP that are greater than those associated in the water bodies. In the echinoderm *Paracentrotus lividus*, Della Torre et al. (2014) described the effects of PS MPs on gene expression, counting an up-regulation of the Abcb1 gene, which is involved in shield and multi-drug confrontation (Shipp and Hamdoun, 2012).

MPs affected the oceanic planktotrophic pluteus larvae of the sea urchin *P. lividus* (Messinetti et al. 2018). When sea urchins, *Lytechinus variegatus*, were exposed to leachate generated from virgin 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 stages of life to both internal and exterior MP exposure, as well as the unknown long-term effects for organisms' ontogeny (Nobre et al. 2015).

Impacts on Nematoda

Nematoda is one of the most diversified taxonomic groups on the planet. Sea nematodes play important role in marine ecosystem since they recycle carbon and nutrient, required for other marine organisms (Yeates et al. 2009). Systemic inflammation permeability and reactive oxygen species (ROS) development with rising MP levels have been observed in the nematode *Caenorhabditis elegans*, 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 testing carried out at MP concentrations that are relevant to the environment, revealing 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) is anticipated to be 6650 particles m^{-3}, which is expected to be exceeded in hotspot sites on occasion (Everaert et al. 2018).

Impacts on phytoplankton

Phytoplankton is the main pillar of the whole food chain in the sea, representing the main source of nutrition to a big proportion of the ocean's biodiversity. The consequences of MPs on microalgae are also becoming an increasing issue of global concern. Microalgae are a major source of energy for most marine ecosystems, as they feed a variety of creatures ranging from tiny zooplankton to molluscs and crustaceans. These species are the next in the food web to be preyed upon. Phytoplankton has been credited for producing half of the Earth's photosynthetic activity and, as a result, a major portion of new biomass converted into chemical energy by the solar energy, underpins the trophic networks. Because of their relevance, there is concern about the micro and nanoplastics' detrimental impacts on them.

It is well known that the algae cells of the *Chlorella* and *Scenedesmus* genera can aggregate and absorb nanoplastic beads (0.02 m) due to their shape and motility, resulting in reduction of photosynthesis and development of oxidative damage (Bhattacharya et al. 2010). The physico-chemical characteristics of plastics, as well as the algae's physical and metabolic features, appear to be responsible for this adsorption; in particular, a strong attraction between algae and plastic particles with a positive charge has been described (Bhattacharya et al. 2010). When exposed to different types of plastic things of varying sizes, Sjollema et al. (2015) found no suppression of photosynthesis in the marine flagellate *Dunaliella tertiolecta*. Uncharged polystyrene beads inhibited microalgae development by 45 percentage, but only at high concentrations (250 mg/L). The negative effect increased as particle size reduced (Sjollema et al. 2015).

Impacts on zooplankton

Zooplankton is considered as an important food source for different secondary marine organisms' consumers. It acts as a pathway for MPs to enter the food web and move up the higher trophic levels (Botterell et al. 2019). Zooplankton can exhibit a variety of feeding behaviours according to their species, life stage, and prey obtainability (Greene, 1985; Cole et al. 2013). Prey selection is influenced by the size of the hunter in comparison to the prey, both of their swimming behaviours, and the vulnerability of each prey type to the predator once encountered (Greene, 1985). A combination of mechano- and chemoreceptors also aids in the choice of appropriate prey items (Cole et al. 2013; Friedman and Strickler, 1975). MPs are likely ingested as a result of indiscriminate feeding techniques, such as suspension feeding, in which prey is frequently fed non-selectively (Cole et al. 2013). A few zooplankton species can modify their eating habits to prefer one type of algae to another, as well as plastic beads (Ayukai, 1987; Frost, 1977). Additionally, when exposed to MPs and algal prey, the copepod *Calanus helgolandicus* preferred smaller-sized algal prey (Cole et al. 2015). This change in feeding behaviour indicates that copepods are changing their feeding habits to avoid ingesting MPs. MPs have not been found in all zooplankton species. Cole et al. (2013) reported MP ingestion in *Parasagitta* sp. (Chaetognatha) and *Siphonophorae* sp. (Cnidaria) over a range of sizes. However, both species are raptors, and active feeders need an animal prey response, which could explain why immotile MP 'prey' did not tempt them (Table 3).

Table 3. Impacts of microplastics in marine copepods.

Species	MPs Type	Size(nm)	Concentration	Effects	References
Acartia clause *Calanus helgolandicus* *Centropages typicus* *Temora longicomis*	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
Acartia tonsa *Calanus helgolandicus*	Polystyrene beads, fibers, 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
Acartia sp. *Eurytemora ajfinis* *Limnocalanus macrurus*	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, *E. ajfinis* ingests microspheres.	Setala et al. 2014
Calanus finmarchicus	Nylon MP granules or fibers	10-30 or 10 x 30	50 MPs/mL	-Exposure to polyester fibers reduces algal intake rates by *C. finmarchicus* by 40% on average, although no effect is seen with nylon granules. -*C. finmarchicus* revealed to nylon MPs molt considerably faster than control *C. finmarchicus*.	Cole et al. 2019
Calanus finmarchicus *Calanus glacialis* *Calanus hyperboreus*	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
Calanus finmarchicus *Pseudocalanus* sp. *Acartia longiremis*	Polystyrene beads Polystyrene fragments	15 and 30 < 30	50-200 beads/ fragments/mL	- Both *A. longiremis* and *C. finmarchicus* can eat MPs, albeit *A. longiremis* only eats the smaller (15-µm) particles and *C. finmarchicus* eats both sizes, whilst *Pseudocalanus* spp. cannot eat any MPs. - Copepods consume older MPs than new ones.	Vroom et al. 2017
Calanus helgolandicus	Fluorescent PE microspheres Nylon fibers Polyethylene terephthalate fibers Nylon fragments	10-32	100 MPs/mL	- Copepods exposed to MP fibers 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
Calanus helgolandicus	Polystyrene beads	20	75 MPs/ mL	-Microbead exposure reduces algal cell intake by 89 percent and carbon biomass ingestion by 60 percent in *C. helgolandicus*, respectively. -Long-term exposure to polystyrene beads reduces reproductive output considerably, but has no effect on egg formation rates, breathing, or longevity.	Cole et al. 2015

Paracyclopina nana	Polystyrene microbeads	0.05, 0.5, 6	10 ng/mL	- The 0.05 µm pellets can be found everywhere over *P. nana*'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
Parvocalanus crassirostris	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
Pseudodiaptomus Annandalei	Monodisperse Polystyrene microspheres	0.5, 2, and 10	20, 200, and 2 x 10^3 µ/L	- MPs of three sizes were consumed by *P. annandalei*. MPs with diameters of 0.5 and 2 micrometers were consumed at higher rates than MPs with diameters of 10 micrometers. - *P. annandalei* ingested MPs through fecal pellets.	Cheng et al. 2020
Temora turbinata *Tignopus fulvus* *Tignopus japonicus*	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 10s 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 ephyryae. - 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
Tignopus japonicus	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
Tigriopus japonicus	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
Tigriopus japonicus	Polyethylene and polyamide-nylon 6 MPs	10–30 and 5–20	0,12.5, 25, 50,100, 200, and 400 mg/L	- In *T. japonicus*, MPs had a deleterious effect on eating, reproduction, and longevity. - MPs had no effect on the body size of *T. japonicus* 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; Sun et al. 2018; Desforges et al. 2015). The majority of laboratory studies have used microbeads to expose copepods to MPs, proving that they can be consumed by a variety of copepods, including *Centropages typicus*, *Calanus helgolandicus*, *Acartia clause*, *Temora longicornis* (Cole et al. 2013), *Limnocalanus macrurus, Eurytemora affinis*, *Acartia* sp. (Zhang et al. 2019). Choi et al. (2018) reported that sheepshead minnow (*Cyprinodon variegatus*) larvae readily ate irregular polyethylene forms (6-350 m). 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 MP pieces (30 m) as well as microbeads.

In the Northern South of the China Sea, East China Sea, and North East Pacific, microfibres are the most common type of fibre regularly swallowed by marine copepods (Sun et al. 2017, 2018; Desforges et al. 2015). This may be explained by the fact that copepods have a higher bioavailability of micro-fibres, or that they meet the highest frequencies of microfibres in situ, as opposed to other morphologies. Several studies in marine copepods, including *C. helgolandicus* (Coppock et al. 2019), *C. finmarchicus* (Vroom et al. 2017), and *A. tonsa* (Vroom et al. 2017), have demonstrated the selectivity and impacts of different-shaped MPs (Botterell et al. 2020).

Copepods (*C. helgolandicus*) contact to nylon pieces or fibres in the water bodies with algae reduced their food ingestion in the suspended fibres treatments but not in the fragment's treatments (Coppock et al. 2019). In addition, copepods in the treatments of exposure ate fewer algae that were comparable in size of unpleasant nylon fibres, indicating that avoidance behaviour was at work (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, Cole et al. (2015) and Lee et al. (2013) found a reduction in survival and productiveness. In the small crustaceans *A. franciscana* and *Paracyclopina nana*, Gambardella et al. (2017) and Jeong et al. (2017) found some changes in enzymes. *Calanus finmarchicus* juvenile and adult ate the MP pieces readily, according to Choi et al. (2018). In comparison to spherical MPs, irregularly shaped MPs harmed the larvae's swimming behaviour, reducing the total distance travelled and maximum velocity.

Effects on feeding capacity

MP ingestion is a regular problem for copepods, whether in a controlled laboratory setting or in the wild (Welden and Cowie, 2016; Espinosa et al. 2019; Choi et al. 2018). Because zooplankton is a taxonomically diverse group, they use variety of feeding strategies including invasion eating and suspended feeding (Strickler, 1982). MPs have been proven to clog in feeding appendages limiting food intake and potentially blocking or damaging the alimentary canal (Cole et al. 2013). Herbivory behaviour was significantly reduced in copepods prone to environmental algal congregations with the addition of polystyrene microbeads (Cole et al. 2013, 2015). In numerous marine organisms, decreased energy input causes physiological harm, including intestinal obstruction in the alimentary system (Welden and Cowie, 2016; Espinosa et al. 2019; Choi et al. 2018). MP exposure has been shown to suppress the copepod's feeding activity in several earlier studies (Coppock et al. 2019; Cole et al. 2013, 2015, 2019). The copepod *C. typicus* upon exposure to natural algal accumulations with and without PS (7.3-m) microbeads at a concentration of >4000 beads/mL reveals MP treatment to decrease grazing on algal cells considerably (Cole et al. 2013).

According to another study, exposure to 20-m PS MPs limited the copepods feeding activity and reduced algal cell ingestion by 89 percentage and carbon biomass ingestion by 60 percentage in *C. helgolandicus*, respectively (Cole et al. 2015). The copepods' grazing on algae of uniform shape (i.e., *Prorocentrum micans*) and size (i.e., *T. rotula*) was significantly reduced when C. helgolandicus was exposed to four varying sizes of MPs at a concentration of 100 plastics/mL, but such exposure did not cause a shift in algal selection; for example, exposure to nylon fibres significantly reduces the copepods' grazing behaviour (Coppock et al. 2019). The naturally vital cold-water copepod *C. finmarchicus* was exposed to nylon MP fibres (10-30 m; 50 plastics/mL), which resulted in obvious shifts in the copepod's feeding, as evidenced by a 40% reduction in ingested biomass and a significant decline in ingestion rates for the largest algae *S. trochoidea* (2934 m) and *T. rotula* (1924 m) (Cole et al. 2019). Surprisingly, a recent study found that PS MPs significantly reduce (by about 50%) the filtration and digestion rates of *P. annandalei* after 24 hours of exposure as compared to that of control group (Cheng et al. 2020). MPs can alter copepods' total energetic input by altering eating capacity, such as grazing rate and prey choice, causing energy to be redistributed away from critical life aspects like growth and reproduction, limiting individual fitness.

Effects on growth, development, and reproduction

Decline in feeding capabilities result in energy deficit. For early larval phases, this could harm their growth and development until they reach adulthood (Cole et al. 2015; Heindler et al. 2017; Jeong et al. 2017; Lee et al. 2013; Zhang et al. 2019). Limited food availability has been linked to reduce egg production in copepods in several studies (Teixeira et al. 2010; Williams and Jones, 1999; White and Roman, 1992). A substantial number of egg sacs failed to mature, according to Lee et al. (2013). MP intake has been found to lengthen the nauplius phase of the copepod *T. japonicus* by reducing algal prey eating (Lee et al. 2013). Long-term exposure to polystyrene microbeads has also been demonstrated to reduce the fertility of *C. helgolandicus*, a copepod species (Cole et al. 2015). They discovered that exposure to 20m PS MPs (75 plastics/mL) for nine days does not affect egg production rate, oxygen consumption, or survival in *C. helgolandicus*, but they conclude that MP ingestion can cause copepod irradiation, as indicated by a reduction in egg size and hatching efficiency in the treated copepods.

The effects of MPs on eggs development and colony size for the calanoid copepod *P. crassirostris* have been investigated by Heindler et al. (2017). The main findings revealed that egg production is reduced in a concentration-dependent method after 5 days of exposure to MPs; in the meantime, exposure to microplastic particles for six days reduces population size by 75% compared to the control, while populations exposed for longer periods (24 days) have more severe depletion (Heindler et al. 2017). The fertility of the marine copepod *T. japonicus* was considerably reduced when it was exposed to 0.5- and 6-µm PS microbeads (Lee et al. 2013; Zhang et al. 2019). As a result, MP contamination can reduce a marine copepod's development and reproduction, posing a threat to the function and structure of the marine environment by potentially altering population numbers and reproduction (Lee et al. 2013; Zhang et al. 2019).

Effects on lifespan

Inadequate nutrients or a damaged digestive system due to clogging might result in a steady loss of energy and eventually to cause death. Over two generations, copepods including nauplius were exposed to MPs and resulted in a higher mortality rate (Lee et al. 2013). This could affect recruitment in subsequent generations, resulting in a reduction in population size, and as a result, a reduction of food was recorded in higher trophic levels. Other studies, on the other hand, found no substantial effects on survival (Cole et al. 2015; Kaposi et al. 2014). *Tripneustes gratilla* larvae were exposed to MPs for 5 days and showed no significant influence on their survival. However, this species' ability to egest the bulk of MPs from their stomachs in a matter of hours likely helped to reduce the negative effects of MP ingestion (Kaposi et al. 2014). After nine days of exposure to polystyrene microbeads (75 beads mL^{-1}), Cole et al. (2015) discovered no significant influence on *C. helgolandicus* survival. In contrast, Lee et al. (2013) used chronic exposures that lasted an average of 14 days, and the longer MP exposure time probably amplified the effect on death rate.

Impacts on algae

Algae capture and utilise energy from sunlight, and use carbon dioxide (CO_2), water to make organic matter. They are regarded as an essential component of a healthy 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 (McHugh, 2003). 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
Skeletonema costatum	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
Tetraselmis chuii	fluorescent red polyethylene	96h	Growth inhibition	No significant growth rate inhibition	Davarpanah and Guilhermino, 2015
Oxyrrhis marina	virgin and fluorescent polystyrene	60 min	Uptake and motility	Increased uptake; bio-fouling formation	Lyakurwa, 2017
Rhodomonas baltica	virgin and fluorescent polystyrene	60 min	Uptake and motility	Increased uptake; bio-fouling formation	Lyakurwa, 2017

Impacts on birds

Plastic ingestion has an impact on seabirds all over the world. Wilcox et al. (2015) estimated that by 2050, plastic would be found in the gastrointestinal tracts of 99 percentage of all types of seabirds and that 95 percentage of individual members of avian species would have ingested plastic (>5 mm). Nevertheless, the consequences have been estimated to be less severe in seabirds and hardly die as a result of MP consumption (Lusher, 2015). Moreover, young seabirds consumed more MPs than adult seabirds, according to research by (Kuhn and van Franeker, 2012; Provencher et al. 2014; Acampora et al. 2014). Young northern fulmars (*Fulmarus glacialis*) have been reported with greater amount of plastic in their stomachs than mature birds, according to Kuhn and van Franeker (2012). Investigation on seabirds off the coast of Norway verified this, with ingested MPs having just a minor impact on tissue POP concentrations (Herzke et al. 2016). MPs have also been discovered in the vomits and faeces of wild Eurasian dippers *Cinclus cinclus* (D'Souza et al. 2020), as well as in confined grey seals *Halichoerus grypus* and their wild food Atlantic mackerel *Scomber scombrus* (Nelms et al. 2018).

Impacts on Mammalia

Cetacean species such as baleen whales can consume MPs (Simmonds, 2012). MPs can be collected from the seawater column by macro filter feeders because of their non-selective feeding behaviour. MPs particles have been recorded in the stomachs of Franciscana dolphins (*Pontoporia blainvillei*), True's beaked whales (*Mesoplodon mirus*), and two baleen whale species, Sei and Minke whales (*Balaenoptera borealis* and *B. acutorostrata*), respectively (Denuncio et al. 2011; Baulch and Perry, 2014; Lusher et al. 2015a). The guts of the humpback whale, *Megaptera novaeangliae*, were found to contain a variety of synthetic polymer (PP, PE, PET, PVC, and nylon) and particle morphologies (sheets, fragments, and threads) (Besseling et al. 2015). Ingestion of MPs and plastic debris tangling can induce both acute or chronic injury in cetaceans, as well as increasing pollutant loads, ending in severe disease, and eventually mortality (Baulch and Perry, 2014). The existence of large levels of MP in baleen whales' gastrointestinal tracts could impede digestion processes and block the intestinal tract (Simmonds, 2012; Besseling et al. 2015). Furthermore, these microscopic plastic particles have the potential to clog organisms' filtration systems (Simmonds, 2012). The fate of MPs in the mammalian bodies showed in Fig. 4.

The baleen whale *B. physalus*, one of the world's largest filter feeders, has been reported to swallow MPs (Fossi et al. 2012; 2016). This massive marine animal can filtrate up to 70.000 L of water at a time, putting it at risk of ingesting MPs both directly from the sea and passively via planktonic food trophic transfer (Lusher et al. 2015a, b; Fossi et al. 2012, 2016). Large concentrations of phthalates and OCs have been shown to affect antioxidant defences and other systems that prevent cell damage in *B. physalus*, consequence in oxidative stress and possible endocrine system abnormalities (Fossi et al. 2016). This data indicates that whales in the wild are more toxicologically vulnerable than originally thought.

Impacts on marine reptiles (sea turtles)

Plastic pollution is a severe hazard 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). MP build-up in sediments can reduce thermal diffusivity; increase heat capacity, and permeability, all of which can affect egg embryo of all seven turtle species (Alfaro-Núñez et al. 2015). Undeniably, loggerhead sea turtles (*Caretta caretta*) have been observed nesting on beaches polluted with plastic materials in the United States (Martin et al. 2019; Garrison and Fuentes, 2019) and Cyprus (Duncan et al. 2018), resulting in hatchling attachment and extended travel time to the sea (Aguilera et al. 2018), potentially increasing predation and decreasing survival. List of the marine turtles entangled in plastic debris is presented in the (Table 5).

When contaminated prey such as molluscs and crustaceans consume and assimilate MPs in their tissues, this is known as indirect ingestion. When MPs is combined with normal food or a situation of mistaken identity occurs, unintentional ingestion might occur (Caron et al. 2016; Nelms et al. 2015). Ingestion of plastic by sea turtles can damage the digestive system and clog the intestinal tract, as well as reduce the eating stimuli and gastrointestinal capacity, resulting in food dilution and starvation, and eventually causing death (Nelms et al. 2015). The large volumes of buoyant polymers accumulating in their guts may affect swimming behaviour and buoyancy control, affecting predatory action, the ability to evade predators, and the ability to survive human threats (e.g., ship assaults and fisheries). Furthermore, adverse consequences such as decreased development rates, fecundity, and productiveness were detected, suggesting that MPs pose a threat to the constancy and survival of marine turtle populations (Nelms et al. 2015; Caron et al. 2016).

Table 5. Entanglement of marine turtles in plastic debris.

Species	Ocean basin	Debris type	Pelagic juvenile	Neritic juvenile	Adult	Study area	References
Loggerhead (*Caretta caretta*)	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 (*Chelonia mydas*)	Indian Ocean	Fishing	X	✓	X	Northeastern (Darwin, Australia)	Chatto, 1995
		Fishing	n.a.	n.a.	n.a.	Northeastern (Australia)	Wilcox et al. 2013
Hawksbill (*Eretmochelys imbricata*)	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 (*Lepidochelys olivacea*)	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 (*Natator depressus*)	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

Finally, plastic consumption can have an impact on turtle health, affecting immune system function and potentially increase vulnerability to diseases such as fibropapillomatosis (FP) (Nelms et al. 2015). Entanglement fishing gear (e.g., ghost net) has recently been recognized as a significant risk to numerous sea animals and is one of the leading causes of turtle mortality in several places (Camedda et al. 2014; Wilcox et al. 2013; Jensen et al. 2013; Casale et al. 2010). Furthermore, entanglement with abrasions or the loss of extremities due to necrosis might reduce the turtle's ability to feed competently or flee pressures, which can result in death due to malnutrition or drowning (Nelms et al. 2015; Camedda et al. 2014). Turtle habitats may be harmed by plastic debris/trash; this has an impact on the temperatures and porosity of the substrate on natural nesting habitats (Nelms et al. 2015). These changes can have an impact on hatchling sex ratios and propagative success, as well as limiting or degrading the habitat accessible for reproduction owing to chemical contaminants. This results in decline in turtle population yield (Nelms et al. 2015; Carson et al. 2011).

Impacts on coral

MP ingestion and exposure have negative impacts on coral-zooxanthellae symbiosis (Huang et al. 2020). MP aging characteristics contribute to plastic ingestion by a variety of corals and have additional negative consequences (e.g., intestinal obstruction, pathogen transmission, and toxic substances). The first study of the consequences of MPs consumption by corals was published in 2015 by Hall et al (2015). Blue PP MPs (10-2000μm) can be swallowed by scleractinian corals *Dipsastrea pallida* at feeding rates of 1.2-55 g plastic $cm^{-2}h^{-1}$ and may be kept in the coral intestinal cavity's mesenterial tissues for more than 24 hours, according to their findings. Most of the ingested MPs may be ejected via cleaning methods (e.g., direct contact, mucus formation) after 1-2 days, according to subsequent research, but the potential implications of retained MPs on corals remain significant (Rotjan et al. 2019; Hankins et al. 2018; Allen et al. 2017). Table 6 summarizes what is known about the various effects of MPs on coral species.

Table 6. Impacts of MPs on corals.

Species	MPs exposure				Impacts	References
	Polymer	Size	Concentration	Duration		
Seriotopora caliendrum	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
Stylophora pistillata	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
Zoanthus sociatus	LDPE, PVC	63-125µm	1, 10 mg/L (~0.5×10^5-4 $\times 10^5$, ~ 0.7×10^5-1.5 × 10^5 items/L)	96 h	Cause high coral adhesion and oxidative stress, but increase photosynthetic efficiency and not induce energetic costs	Rocha et al. 2020
Danafungiascruposa	Virgin PE microbeads; biofouled PE and PP fragments collected from Great Pacific Garbage Patch	212-355, 600-710, 850-1000 µmmicrobeads; 200-500, 500-800, 800-1000µm	2996±5 beads/1.5L bag; 2997±6 beads/1.5L bag, 3005±35 biofoule 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	Corona et al. 2020

					store more biofouled MPs.	
Astroides calycularis	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 (*Cladocopium goreaui*) inhabiting in scleractinian corals	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 detoxifying activity, nutrient absorption, and photosynthetic efficiency; rises oxidative stress, apoptosis level, and ion transport; and increases oxidative stress, apoptosis level, and ion transportation.	Su et al. 2020
Stylophora pistillata	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 macrodebris) for 21 days	Leachate spiked with α-, β-, and γ-HBCDD	5 days	Coral photosynthetic capacity, symbiont density, and chlorophyll concentration are all affected to a lesser extent, as is coral polyp contraction.	Aminot et al. 2020
Acropora tenuis	PE microbeads; weathered PP collected from beach	1, 6 μm PE microbeads; 0.5, 1,	25-200 microbeads/	2.5 h; 24 h	Cause minor disruptions to coral	Berry et al. 2019

		2 mm2 weathered PP	L; 5-50 pieces/L		fertilization, embryo abnormalities, and larval settling; do not significantly impede the success of important early-life coral activities.	
Acropora muricata, *Pocillopora verrucosa*, *Porites lutea*, *Heliopora coerulea*	HDPE	1, 8 µm	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
Lophelia pertusa, *Madrepora oculata*	LDPE (with the natural formation of surface microbial biofilm preincubated for two months)	10×10 cm PE macroplastics; 500 µmmicrobeads	--; 350 items/L	5 months	MP films reduce prey acquisition and growth rates in the coral *Lophelia pertusa*, causing the polyp "cap" structure to overgrow; had no effect on the growth and eating of the coral *Madrepora oculate*.	Mouchi et al. 2019
Acropora formosa	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
Astrangia poculata	Blue PE microbeads (with the formation of surface microbial biofilm incubated for 4-8 h; pre-spiked in the *Escherichia coli* cell cultures for 9 days)	170.5-230.8 µm	0.2 g/L; 10-25 microbeads with the *Escherichia coli* biofilm	90 min (feeding) +24 h (recovery in clean seawater); 4 weeks	Consumed MPs remain in the gastrovascular cavity's mesenterial tissues, reducing subsequent	Rotjan et al. 2019

				(*E. coli* biofilm microbead feeding)	brine shrimp egg eating; co-ingestion of microbeads with *E. coli* cells results in coral mortality after four weeks.	
Montipora capitata, *Pocillopora damicornis*	PE microbeads	150-180 µm	2000 items/L under 27°C or increased 30°C	10 days	Under heat stress, greatly limit Artemia nauplii feeding but not MP consumption.	Axworthy and Padilla-Gamiño, 2019
Pocillopora damicornis	PS	1 µm	50 mg/L (9×10^{10} items/L)	24 h	There are no significant 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
Lophelia pertusa	LDPE (with the natural formation of surface microbial biofilm pre-incubated for two months)	10×10 cm LDPE macroplastics; 500 µmmicrobeads	--; 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
Montastraea cavernosa, *Orbicella faveolata*	PE microbeads (with the natural formation of surface microbial biofilm pre-incubated	PE (90-106 µm, 212-250 µm, 425-500 µm, 850-1000	30 mg/L	48 h	There are no calcification consequences.	Hankins et al. 2018

	for six weeks); Polyester microfibers	µm, 1.7-2.0 mm 2.4-2.8 mm); Polyester (3-5 mm)				
Acropora humilis, *Acropora millepora*, *Pocillopora verrucosa*, *Pocillopora damicornis*, *Porites lutea*, *Porites cylindrica*	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
Favites chinensis	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
Astrangia poculata	Microbe-free plastic mixtures (including HDPE,LDPE,PP,PET,PC,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 plastics due to phagostimulants in plastic leachates; corals consume more microbe-free MPs than biofouled MPs.	Allen et al. 2017
Dipsastrea pallida	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 prone to the hazardous effects of MPs, which have been well documented to contain poisons, neurotoxic chemicals, and endocrinal disruptors (Rochman et al. 2013a; Thompson et al. 2009; 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 may enter the human body. Ingestion of contaminated food and/or drinking water is one of the most common ways for plastic components to enter the human body. Humans swallow between 39,000 and 52,000 plastic particles every year on average (Cox et al. 2019). Consumer plastics such as plastic bottles leach BPA, NP, and di-(2-ethylhexyl) phthalate (DEHP) (Erythropel et al. 2014; Cox et al. 2019). In the same way, marine organisms unknowingly consume plastics and MPs, as well as trophic and seawater plastic-derived EDCs (Thompson, 2006). Plastic waste may enhance the human and animal infections that pose a global threat by providing new sources of pollution routes, allowing pathogens to spread to new places via the ecological spread of MPs, or allowing pathogen-infected organisms to migrate via MPs (Keswani et al. 2016).

Fish and other seafood are key sources of protein, minerals, and vitamins for human health and play a crucial role in marine ecology. One of the most common routes for MPs to enter the human body is through the consumption of marine seafood and meals (Wright and Kelly, 2017; Smith et al. 2018; Alfaro-Núñez et al. 2021). As a result, MPs operate as a conduit for hazardous contaminants from marine organisms to the human body, posing a major hazard to human well-being (Smith et al. 2018). Bivalves could potentially be an important source of MPs for humans because their soft bodies are eaten fully and may comprise higher levels of MPs (Everaert et al. 2018). MPs were reported in mussels at an average concentration of 0.36 particles g ww^{-1}, according to Van Cauwenberghe et al. (2015). The latter results show that consumers today can intake up to 864 MP particles per year based on a consumption of 2.4 kg mussels' y^{-1}. This unwanted absorption can range from 1550 to 9474 MPs per year for an average European who consumes a lot of shellfish, depending on their (low-high) consumption pattern (EFSA, 2011). Everaert et al. (2018) reported that by 2100, the body load of mussels will have increased to 15.8 MP particles g/ww, based on the expected (relative) rise in PECt and the accumulation factor. By 2100, higher accumulation in bivalves will result in increased human consumption: small consumers would consume 6.6×10^4 particles per year, while top consumers would consume 4.4×10^5 particles per year (Everaert et al. 2018).

Interactions between MPs and the immune system may cause immunotoxicity, resulting in deleterious outcomes (such as immunosuppression, immunological stimulation, and aberrant provocative responses) (Wright and Kelly, 2017; Lusher et al. 2017). A preliminary study *in vitro* with cerebral and epithelial living organisms showed that micro- (10 µm) and nano-plastics (40-250 nm) can trigger cytotoxicity at the cell level in terms of oxidative damage (Schirinzi et al. 2017), validating scholarly theories on the potential health effects.

MPs and their additives along with associated contaminants and microorganisms that infect fish and shellfish, along with their potential impacts on people health, are unknown (Vethaak and Leslie, 2016;

USEPA, 2015; GESAMP, 2016; Seltenrich, 2015). Even if laboratory research suggest that MPs may exacerbate the impacts of unwanted pollutants in fish (Pedà et al. 2016; Rochman et al. 2013b; Rainieri et al. 2018; Barboza et al. 2018d), field investigations show that MP intake has minimal influence on toxin bioaccumulation (Lohmann, 2017). When compared to other environmental sources (such as water, sediments, and the food chain), there is no evidence that MPs will result in increased seafood contamination at the current MP level (Koelmans et al. 2014, 2016; GESAMP, 2016; Lohmann, 2017; Pittura et al. 2018).

The presence of microplastics in the faeces of pregnant women was investigated by Ar et al. (2020). All the stool samples included microplastics, according to the findings. The number of microplastics discovered ranged from 5 to 21, with fibre, fragments, and films being the most common. Microplastics range in length from 0.2 to 4.9 mm. It has been determined that ingested microplastics are excreted in the faeces, but the residue will be collected in the body and cause long-term health hazards (Ar et al. 2020).

The ensuing impacts of MPs on human health should be considered with caution, as there is a significant gap between current scientific understanding of the true ramifications for people's health and the severity of the problem as reported in the media (Rist et al. 2018; Wright and Kelly, 2017; Alfaro-Núñez and Bermudez, 2018). The researchers must overcome many challenges, and additional research is required to properly appreciate the impact of these particles on the body.

Future research recommendations

- More laboratory investigations with the most prevalent forms (fibres and pieces) and size (800-1600 μm) of MPs discovered in field samples of living material should be conducted.
- MPs level are likely to rise in the future, and it will become progressively vital to monitor MP levels in ocean organisms and other foods frequently.
- The amount of MPs in consumable fish and shellfish tissues must be determined. Also worth investigating is the quantification of palatable echinoderms, tunicates, and algae, which are widely consumed in numerous countries.
- To assess the prevalence of MPs in ecological sections and avoid the depletion of world fish and shellfish stocks, programmes of continual monitoring will be needed.
- Studies should concentrate on the chemical and microbial hazards and risks related with ingested MPs as well as enhancing methodologies for assessing MP intake and translocation in people.
- It's vital to examine the dangers and risks exposed to consumers by MP-contaminated fish, shellfish, and food using food safety risk assessment methods.
- The incorporation of a wide range of MP sizes and components into body cells, as well as the development of new methods to identify the existence of MPs in the human body, are both critically required.

- Another pressing concern is the presence of nano-sized plastics in seafood, which has received even less attention.
- Universal standardisation of methodologies and procedures to be able to compare results between different locations, organisms and environments
- More study on analytical techniques, toxicokinetics, and toxicology is aimed at improving our understanding of the potential impacts of micro- and nano-sized plastics on seafood quality and people's health.
- Understand the methods through which PE impacts creatures other than fish, as well as the effects of PS MPs on organisms other than fish and tiny crustaceans.
- Examine MPs' ecotoxicity under more realistic conditions, such as mesocosms and multispecies exposes.
- Inspire people to publish 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 producing countries of the world (Data source: World Population Review, 2021).

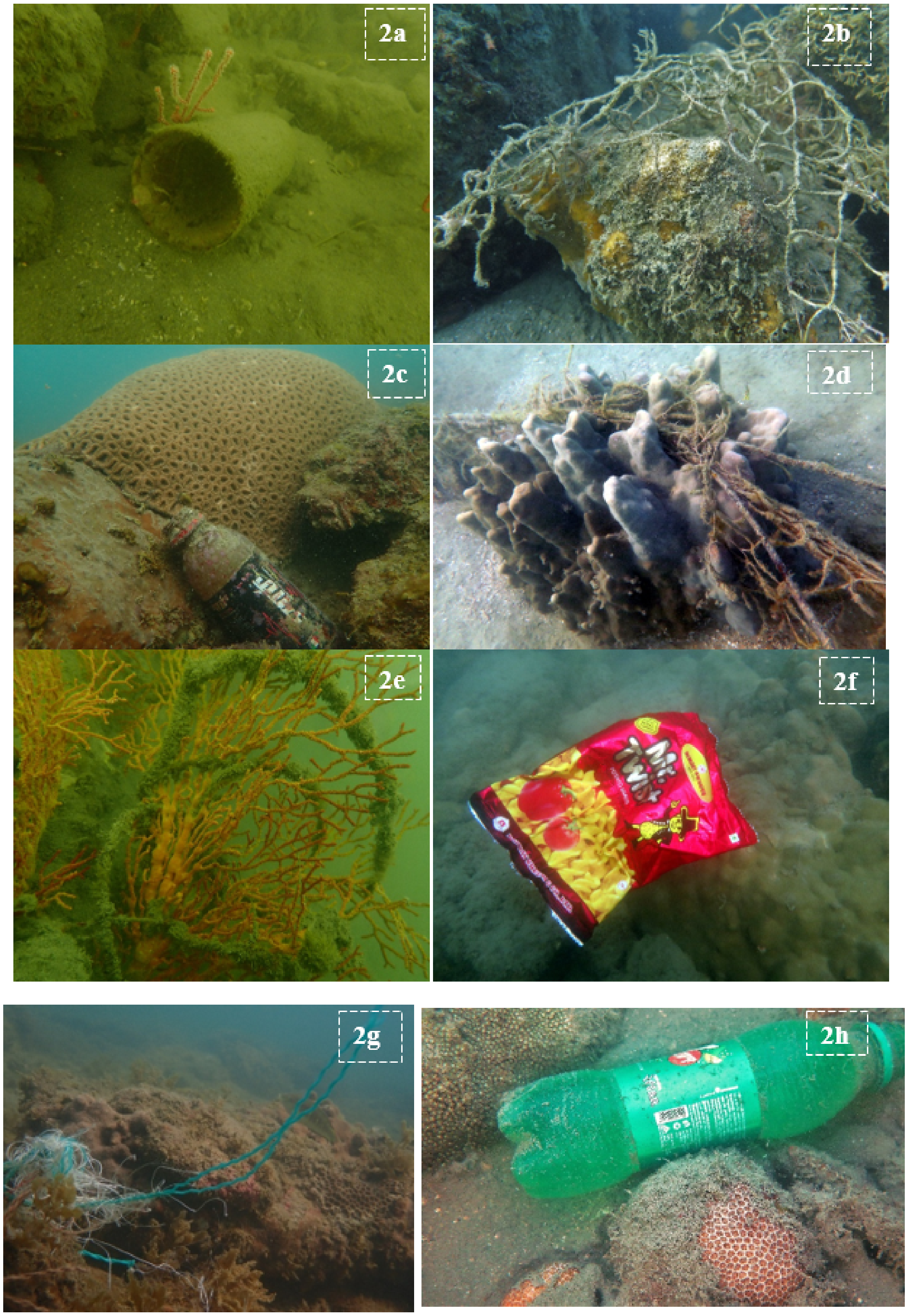

Figure 2

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).

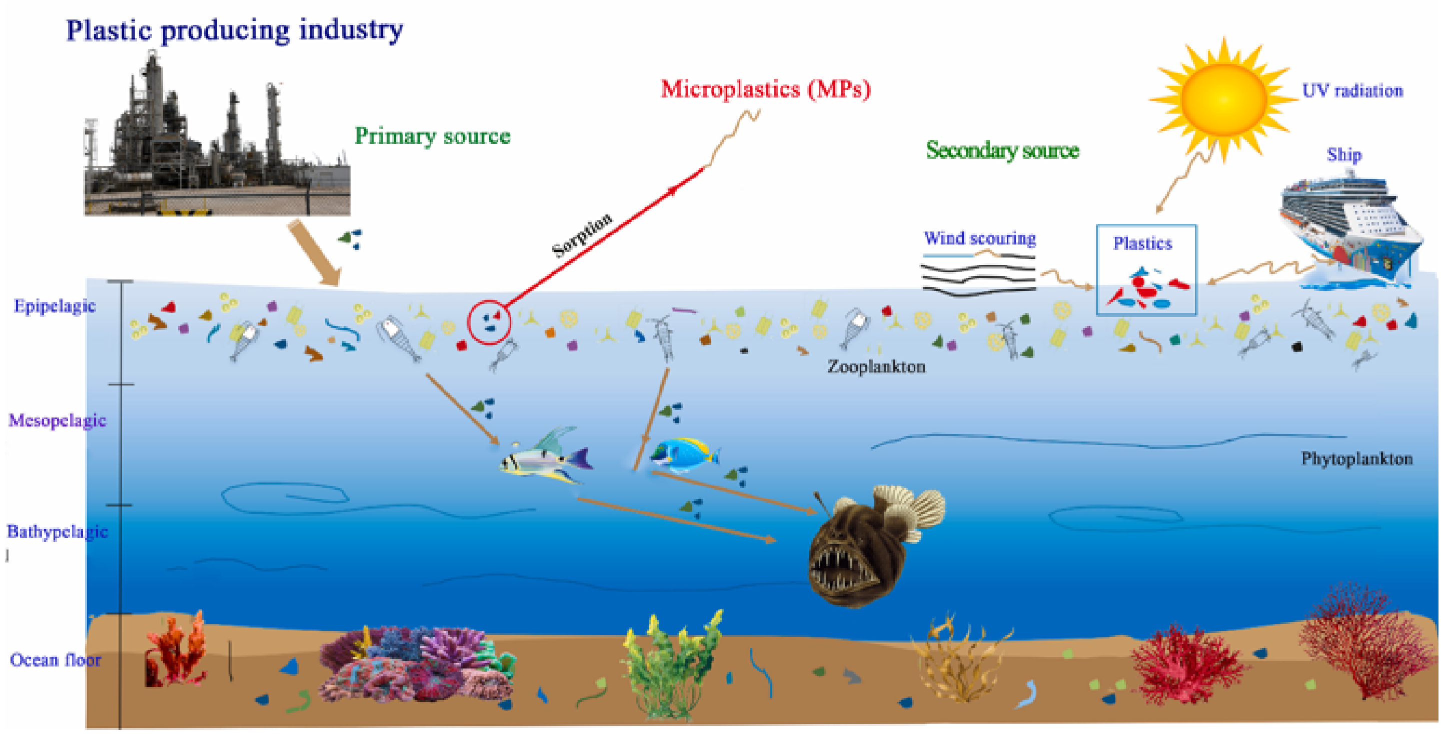

Figure 3

Source and transportation of MPs in the ocean.

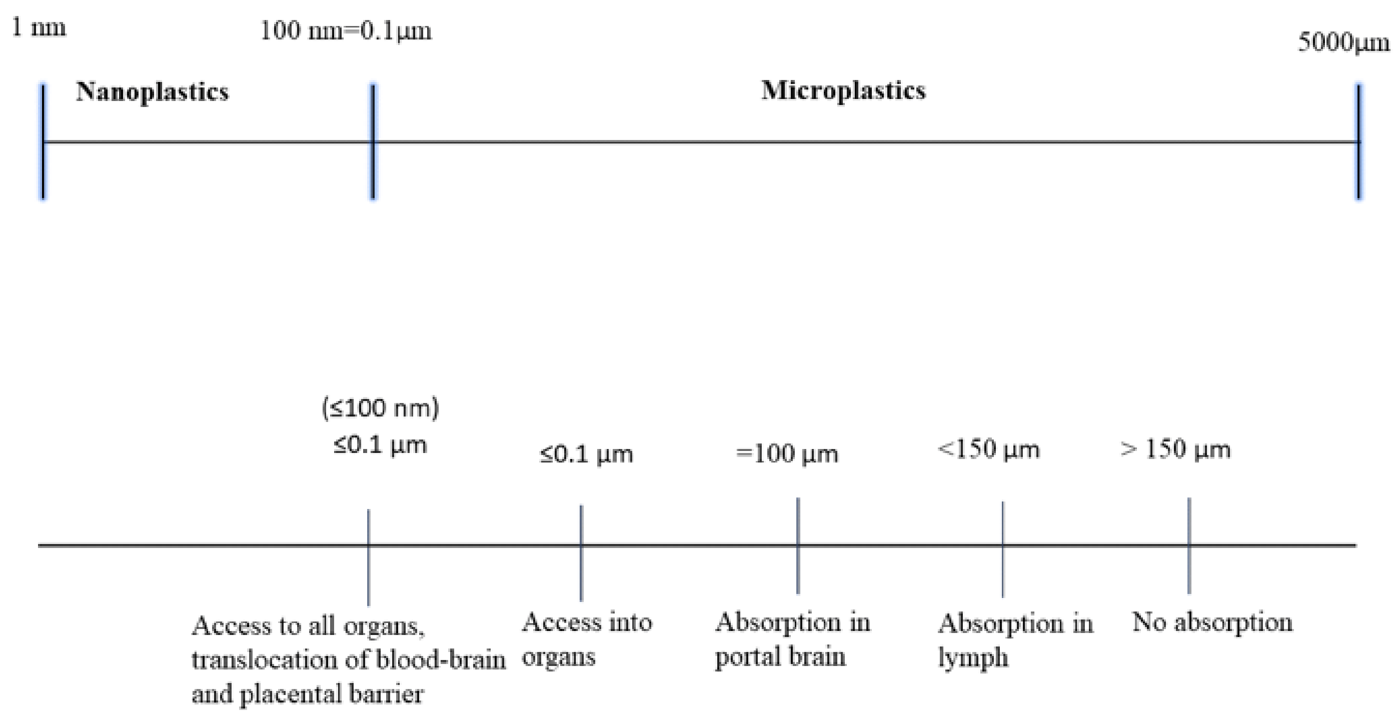

Figure 4

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