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Review

Marine microplastic debris: An emerging issue for food security, food safety and human health

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ABSTRACT

Recent studies have demonstrated the negative impacts of microplastics on wildlife. Therefore, the presence of microplastics in marine species for human consumption and the high intake of seafood (fish and shellfish) in some countries cause concern about the potential effects of microplastics on human health. In this brief review, the evidence of seafood contamination by microplastics is reviewed, and the potential consequences of the presence of microplastics in the marine environment for human food security, food safety and health are discussed. Furthermore, challenges and gaps in knowledge are identified. The knowledge on the adverse effects on human health due to the consumption of marine organisms containing microplastics is very limited, difficult to assess and still controversial. Thus, assessment of the risk posed to humans is challenging. Research is urgently needed, especially regarding the potential exposure and associated health risk to micro- and nano-sized plastics.

1. Introduction

Plastics have been found worldwide in the marine environment, with estimates pointing to > 5 trillion plastic debris (over 250,000 tons) afloat at sea (Eriksen et al., 2014). A considerable amount of such plastic debris comes from continental sources entering the marine environment mainly through rivers (Lebreton et al., 2017), industrial and urban effluents, and runoff of beach sediments and neighbor fields. The other part results from direct inputs, such as offshore industrial activities (e.g. oil and gas extraction, aquaculture), loss of nets in fisheries and litter released during sea activities, including tourism. Among plastic litter, microplastics are of special concern regarding the environment as well as animal and human health mainly due to their small size, the lack of technology available to quantify the presence of the smallest microplastics in the environment, and their potential to cause adverse effects on the marine biota and humans.

Microplastics have been defined as small pieces of plastic less than five millimeters in size with no lower limit established (GESAMP, 2016). The microplastics present in the marine environment result from the fragmentation of larger plastic debris or may be introduced into the water and sediments already as micro- or nano-sized particles. Examples of microplastics are pre-production pellets and components of diverse products, such as fragments of fishing gear, packages and drink bottles, synthetic textiles, car tyres, paints, cosmetics and personal care products (e.g. facial cleaners, bath gels, toothpaste), and electronic equipment among others (Fendall and Sewell, 2009; Andrady, 2011; GESAMP, 2016). Consequently, microplastics encompass a very heterogeneous assemblage of particles that vary in size, shape, and chemical composition, among other properties (Hidalgo-Ruz et al., 2012; Andrady, 2017).

Microplastics have been found worldwide, are highly persistent in the environment and are, therefore, accumulating in different marine ecosystems at increasing rates (Woodall et al., 2014; van Sebille et al., 2015; Suaria et al., 2016; Cózar et al., 2017; Waller et al., 2017). Ocean

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Table 1
Summary of studies reporting the occurrence of microplastics in shellfish and fish of commercial interest as food.

Species name	Levels of mp	Size range	Parts	Types of debris	Location	Source
Shellfish						
Alectryonella plicatula	10.78 ± 4.07 particles/individual	5–5000 μm	Soft tissue	Fibers, fragments, pellets	China *From local fish market*	Li et al. (2015)
Amiantis umbonella	6 particles/individual	10–5000 μm	Soft tissue	Fibers, fragments, pellets, film	Coastal water of The Persian Gulf, Iran, Asia	Naji et al. (2018)
Amiantis purpuratus	6 particles/individual	10–5000 μm	Soft tissue	Fibers, fragments, pellets, film	Coastal water of The Persian Gulf, Iran, Asia	Naji et al. (2018)
Cerithidea cingulata	12 particles/individual	10–5000 μm	Soft tissue	Fibers, fragments, pellets, film	Coastal water of The Persian Gulf, Iran, Asia	Naji et al. (2018)
Crangon crangon	0.68 particles/g individual	200–1000 μm	Whole shrimp and peeled shrimp (abdominal muscle tissue)	Fibers	Belgium	Devriese et al. (2015)
Crassostrea gigas	0.6 particles/g individual	> 500 μm	Entire tissue	Fibers	California, USA *From local market*	Rochman et al. (2015)
	0.47 particles/g individual	5–25 μm	Soft tissue	Not specified	Atlantic Ocean *Market from Brittany, France*	van Cauwenberghe and Janssen (2014)
Cyclina sinensis	4.82 ± 2.17 particles/individual	5–5000 μm	Soft tissue	Fibers, fragments, pellets	China *From local fish market*	Li et al. (2015)
Eriocheir sinensis	13% ind. with MP	Not specified	Stomachs	Fragments, filaments	Baltic coastal	Wójcik-Fudalewska et al. (2016)
Meretrix lusoria	9.22 particles/individual	5–5000 μm	Soft tissue	Fibers, fragments, pellets	China *From local fish market*	Li et al. (2015)
Mytilus edulis	0.36 ± 0.07 particles/g	5–25 μm	Soft tissue	Not specified	North Sea	Van Cauwenberghe and Janssen (2014)
Mytilus galloprovincialis	4.33 ± 2.62 particles/individual	5–5000 μm	Soft tissue	Fibers, fragments, pellets	China *From local fish market*	Li et al. (2015)
	6.2–7.2 particle/g	760–6000 μm	Valves, hepatopancreas and gills	Filaments	Italy *From maricultured and natural stocks*	Renzi et al. (2018)
Mytilus spp.	3.2 ± 0.52 particles/individual	200 – > 2000 μm	Soft tissue	Fibers	Scottish coast	Catarino et al. (2018)
Modiolus modiolus	3.5 ± 1.29 particles/individual	200 – > 2000 μm	Soft tissue	Fibers	Scottish coast	Catarino et al. (2018)
Nephrops norvegicus	83% ind. with MP	Not specified	Stomach	Filaments	Clyde, UK	Murray and Cowie (2011)
Penaeus semisulcatus	7.8 particles/individual	< 100 – > 1000 μm	Muscle, skin	Fibers	Musa estuary, Persian Gulf	Abassi et al. (2018)
Patinopecten yessoensis	57.17 ± 17.34 particles/individual	5–5000 μm	Soft tissue	Fibers, fragments, pellets	China *From local fish market*	Li et al. (2015)
Perna perna	26.7% ind. with MP	Not specified	Digestive tract and entire tissue	Fibers	Santos Estuary, Brazil	Santana et al. (2016)
Pinctada radiata	11 particles/individual	10–5000 μm	Soft tissue	Fibers, fragments, pellets, film	Coastal water of The Persian Gulf, Iran, Asia	Naji et al. (2018)
Ruditapes philippinarum	5.72 ± 2.86 particles/individual	5–5000 μm	Soft tissue	Fibers, fragments, pellets	China *From local fish market*	Li et al. (2015)
Scapharca subcrenata	45 ± 14.98 particles/individual	5–5000 μm	Soft tissue	Fibers, fragments, pellets	China *From local fish market*	Li et al. (2015)
Sinonovacula constricta	14.33 ± 2.21 particles/individual	5–5000 μm	Soft tissue	Fibers, fragments	China *From local fish market*	Li et al. (2015)
Tegillarca granosa	5.33 ± 2.21 particles/individual	5–5000 μm	Soft tissue	Fibers, fragments	China *From local fish market*	Li et al. (2015)
Thais mutabilis	3 particles/individual	10–5000 μm	Soft tissue	Fibers, fragments, pellets, film	Coastal water of The Persian Gulf, Iran, Asia	Naji et al. (2018)
Fish						
Acanthurus gahhm	10; 100%	2700 μm (mean)	Gastrointestinal tract	Fibers, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. (2018)

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Table 1 (*continued*)

Species name	Levels of mp	Size range	Parts	Types of debris	Location	Source
Alepes djedaba	20; 100% (8.00 ± 1.22 item/10 g fish muscle)	< 100–5000 μm	Muscle	Fibers, fragments, pellets	Northeast of Persian Gulf	Akhbarizadeh et al. (2018)
Argyrosomus regius	5; 60%	217–4810 μm	Gastrointestinal tract	Fibers, fragments	Portuguese Coast **From local market*	Neves et al. (2015)
	51; 75%	> 9.07 μm	Gastrointestinal tract	Fibers, hard plastic, nylon	Mediterranean Sea	Güven et al. (2017)
Atherinopsis californiensis	7; 29%	> 500 μm	Gastrointestinal tract	Fibers, fragments	California, USA *From local market*	Rochman et al. (2015)
Brama brama	3; 33%	217–4810 μm	Gastrointestinal tract	Fibers	Portuguese Coast **From local market*	Neves et al. (2015)
Cetengraulis mysticetus	30; 3.3%	≤1100 μm	Gut	Fragment	Southeast Pacific Ocean	Ory et al. (2018)
*Clupea harengus*****	566; 2%	> 1000 μm	Gastrointestinal tract	Fibers, fragments	North Sea	Foekema et al. (2013)
	299, 21%	100 – > 5000 μm	Gastrointestinal tract	Fibers, fragments	Baltic Sea	Beer et al. (2018)
Cynoglossus abbreviatus	11; 12 (mean/individual)	< 100 – > 1000 μm	Muscle, gut, gills, liver, skin	Fibers, fragments	Musa estuary, Persian Gulf	Abassi et al. (2018)
Cynoscion acoupa	552; 51%	< 5000 μm	Gut	Filaments, hard microplastics	Goiana estuary, Brazil	Ferreira et al. (2018)
*Decapterus macrosoma*****	17; 29%	> 500 μm	Gastrointestinal tract	Fragments, styrofoam	Eastern Indonesia *From local market*	Rochman et al. (2015)
*Decapterus muroadsi*****	20; 80%	5000 μm	Gut	Fragments	South Pacific	Ory et al. (2017)
Dentex macrophthalmus	1; 100%	217–4810 μm	Gastrointestinal tract	Fibers	Portuguese Coast **From local market*	Neves et al. (2015)
Dicentrarchus labrax	40; 23%	≤1000–5000 μm	Gastrointestinal tract	Fibers, fragments	Mondego estuary, Portugal	Bessa et al. (2018)
Diplodus vulgaris	40; 73%	≤1000–5000 μm	Gastrointestinal tract	Fibers, fragments	Mondego estuary, Portugal	Bessa et al. (2018)
Engraulis encrasicolus	10; 80%	124–438 μm	Liver	Not specified	Mediterranean Sea	Collard et al. (2017)
	105; 15.24%	Not specified	Gastrointestinal tract	Fibers, fragments	Mediterranean Sea	Compa et al. (2018)
*Engraulis japonicus*****	64; 77%	10–500 μm	Gastrointestinal tract	Fragments, bead, filament, foam	Tokyo Bay	Tanaka and Takada (2016)
Engraulis mordax	10; 30%	> 500 μm	Gastrointestinal tract	Fiber, film, monofilament	California, USA *From local market*	Rochman et al. (2015)
Epinephelus areolatus	5; 20%	1800 μm (mean)	Gastrointestinal tract	Fibers, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. (2018)
Epinephelus chlorostigma	3; 33.33%	1900 μm (mean)	Gastrointestinal tract	Fibers, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. (2018)
Epinephelus coioides	20; 100% (7.75 ± 2.16 item/10 g fish muscle)	< 100–5000 μm	Muscle	Fibers, fragments, pellets	Northeast of Persian Gulf	Akhbarizadeh et al. (2018)
*Gadus morhua*****	80; 13%	> 1000 μm	Gastrointestinal tract	Fibers, fragments	North Sea	Foekema et al. (2013)
	74; 1.4%	< 5000 μm	Gastrointestinal tract	Fibers, fragments, film	Baltic Sea	Rummel et al. (2016)
	205; 2.4%	2800–4200 μm	Gastrointestinal tract	Fragments	Coast of Canada	Liboiron et al. (2016)
	302; 18.8%	< 5000 – > 20,000 μm	Stomach	Fibers, fragments, granule, film	Norwegian coast	Brate et al. (2016)
Lethrinus microdon	10; 20%	1480 μm (mean)	Gastrointestinal tract	Fibers, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. (2018)
Lipocheilus carnolabrum	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 thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. (2018)
Merlangius merlangus	50; 32%	1000–2000 μm	Gastrointestinal tract	Fibers, fragments, beads	English Channel	Lusher et al. (2013)

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Table 1 (*continued*)

Species name	Levels of mp	Size range	Parts	Types of debris	Location	Source
Merluccius merluccius	12; 29%	217–4810 µm	Gastrointestinal tract	Fibers	Portuguese Coast	Neves et al. (2015)
	3; 100%	10–5000 µm	Gastrointestinal tract	Fragments, line, film, pellet	Adriatic Sea	Avio et al. (2015)
	12; 16.7%	380–3100 µm	Stomach	Fragments, fibers, film, spheres	Spanish Atlantic	Bellas et al. (2016)
*Micromesistius poutassou*****	27; 51.9%	1000–2000 µm	Gastrointestinal tract	Fibers, fragments, beads	English Channel	Lusher et al. (2013)
Morone saxatilis	7; 29%	> 500 µm	Gastrointestinal tract	Fibers, film, foam	California, USA *From local market*	Rochman et al. (2015)
Mugil cephalus	30; 60% (wild)	< 2000 – > `5000 µm	Gastrointestinal tract	Fibers, fragments, sheet	Hong Kong Coast	Cheung et al. (2018)
	30; 16.7% (captive)	< 2000–5000 µm	Gastrointestinal tract	Fibers	Hong Kong *From fish farms*	Cheung et al. (2018)
Mullus barbatus	11; 64%	10–5000 µm	Gastrointestinal tract	Fragments, line, film, pellet	Adriatic Sea	Avio et al. (2015)
	207; 66%	> 9.07 µm	Stomach and intestine	Fibers, hard plastic, nylon	Mediterranean Sea	Güven et al. (2017)
	128; 18.8%	380–3100 µm	Stomach	Fragments, fibers, film	Mediterranean coast	Bellas et al. (2016)
Mullus surmuletus	4; 100%	217–4810 µm	Gastrointestinal tract	Fibers	Portuguese Coast	Neves et al. (2015)
	51; 35 and 49%	> 9.07 µm	Gastrointestinal tract	Fibers, hard plastic, nylon	Mediterranean Sea	Güven et al. (2017)
Odontesthes regia	9; 11.1%	Not specified	Gut	Fragments	Southeast Pacific Ocean	Ory et al. (2018)
Oncorhynchus tshawytscha	4; 25%	> 500 µm	Gastrointestinal tract	Fibers	California, USA *From local market*	Rochman et al. (2015)
Opisthonema libertate	40; 5%	≤3700 µm	Gut	Thread	Southeast Pacific Ocean	Ory et al. (2018)
Parascolopsis eriomma	5; 60%	1380 µm (mean)	Gastrointestinal tract	Fibers, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. (2018)
Platycephalus indicus	16; 100% (18.5 ± 4.55 item/10 g fish muscle)	< 100–5000 µm	Muscle	Fibers, fragments, pellets	Northeast of Persian Gulf	Akhbarizadeh et al. (2018)
	12; 21.8 (mean/individual)	< 100 – > 1000 µm	Muscle, gut, gills, liver, skin	Fibers	Musa estuary, Persian Gulf	Abassi et al. (2018)
Platichthys flesus	40; 13%	≤1000–5000 µm	Gastrointestinal tract	Fibers, fragments	Mondego estuary, Portugal	Bessa 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)
Rastrelliger kanagurta	10; 56%	> 500 µm	Gastrointestinal tract	Fragments, film, monofilament	Eastern Indonesia *From local market*	Rochman et al. (2015)
Rhizoprionodon lalandii	6; 33%	1000–5000 µm	Stomach	Pellets	Northeastern Brazil	Miranda and Carvalho-Souza (2016)
*Sardinella longiceps*****	10; 60%	500–3000 µm	Gut	Fragments	Indian Coast	Sulochanan et al. (2014)
*Sardina pilchardus*****	99; 19%	10–5000 µm	Gastrointestinal tract	Fragments, line, film, pellet	Adriatic Sea	Avio et al. (2015a, 2015b)
	7; 57%	> 9.07 µm	Gastrointestinal tract	Fibers, hard plastic, nylon	Mediterranean Sea	Güven et al. (2017)
	2; 100%	124–438 µm	Liver	Not specified	Mediterranean Sea	Collard et al. (2017)
	105; 14.28%	Not specified	Gastrointestinal tract	Fibers, fragments	Mediterranean Sea	Compa et al. (2018)
Saurida tumbil	4; 13.5 (mean/individual)	< 100 – > 1000 µm	Muscle, gut, gills, liver, skin	Fibers, fragments	Musa estuary, Persian Gulf	Abassi et al. (2018)
Sillago sihama	17; 14.1 (mean/individual)	< 100 – > 1000 µm	Muscle, gut, gills, liver, skin	Fibers, fragments	Musa estuary, Persian Gulf	Abassi et al. (2018)

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Table 1 (*continued*)

Species name	Levels of mp	Size range	Parts	Types of debris	Location	Source
Scyliorhinus canicula	20; 5%	1500 µm	Stomach	Micro-bead	North Sea	Smith (2018)
	72; 15.3%	380–3100 µm	Stomach	Fragments, fibers, film	Mediterranean coasts	Bellas et al. (2016)
*Scomberomorus cavalla*****	8; 62.5%	1000–5000 µm	Stomach	Pellets	Northeastern Brazil	Miranda and Carvalho-Souza (2016)
*Scomber japonicus*****	7; 71%	> 9.07 µm	Gastrointestinal tract	Fibers, hard plastic, nylon	Mediterranean Sea	Güven et al. (2017)
	35; 31%	217–4810 µm	Gastrointestinal tract	Fragments, fibers	Portuguese Coast	Neves et al. (2015)
	30; 3.3%	≤2100 µm	Gut	Fragment	Southeast Pacific Ocean	Ory et al. (2018)
*Scomber scombrus*****	13; 31%	217–4810 µm	Gastrointestinal tract	Fragments, fibers	Portuguese Coast	Neves et al. (2015)
	13; 30.8%	< 5000 µm	Gastrointestinal tract	Fibers, fragments, film	Baltic Sea	Rummel et al. (2016)
Siganus canaliculatus	3; 29%	> 500 µm	gastrointestinal tract	Monofilament	Eastern Indonesia *From local market*	Rochman et al. (2015)
Solea solea	533; 95%	< 100–500 µm	Gastrointestinal tract	Fibers, fragments	Adriatic Sea	Pellini et al. (2018)
Sparus aurata	110; 44%	> 9.07 µm	Gastrointestinal tract	Fibers, hard plastic, nylon	Mediterranean Sea	Güven et al. (2017)
Spratelloides gracilis	4; 40%	> 500 µm	Gastrointestinal tract	Fragments	Eastern Indonesia *From local market*	Rochman et al. (2015)
*Sprattus sprattus*****	515; 18.8%	100 – > 5000 µm	Gastrointestinal tract	Fibers, fragments	Baltic Sea	Beer et al. (2018)
Sphyraena jello	15; 100% (5.66 ± 1.69 item/10 g fish muscle)	< 100–5000 µm	Muscle	Fibers, fragments	Northeast of Persian Gulf	Akhbarizadeh et al. (2018)
Thalassoma rueppellii	12; 8.33%	1930 µm (mean)	Gastrointestinal tract	Fibers, film, fishing thread	Saudi Arabian Red Sea coast	Baalkhuyur et al. (2018)
Thunnus alalunga	131; 12.9%	< 5000 µm	Stomach	Fragments	Mediterranean Sea	Romeo et al. (2015)
Thunnus thynnus	34; 34.4%	< 5000 µm	Stomach	Fragments	Mediterranean Sea	Romeo et al. (2015)
Trachurus trachurus	56; 28.6%	1000–2000 µm	Gastrointestinal tract	Fibers, fragments, beads	English Channel	Lusher et al. (2013)
Trigla lyra	31; 19%	217–4810 µm	Gastrointestinal tract	Fragments, fibers	Portuguese Coast	Neves et al. (2015)
Xiphias gladius	56; 12.5%	< 5000 µm	Stomach	Fragments	Mediterranean Sea	Romeo et al. (2015)
Zeus faber	1; 100%	217–4810 µm	Gastrointestinal tract	Fibers	Portuguese Coast	Neves et al. (2015)
	42; 47.6%	1000–2000 µm	Gastrointestinal tract	Fibers, fragments, beads	English Channel	Lusher et al. (2013)
Clupea harengus *Limanda limanda* *Merlangius merlangus* *Sprattus sprattus*	400; 0.25% Two plastic particles were found in only 1 (*Sprattus sprattus*) out of 400 individuals	> 20 µm	Gastrointestinal tract	Spherical particles	North Sea	Hermsen et al. (2017)
Chelon subviridis *Johnius belangerii* *Rastrelliger kanagurta* *Stolephorus waitei*	30; Between 0 and 3 pigments and MP particles were isolated from each individual fish.	1–1000 µm	Eviscerated flesh (whole fish excluding the viscera and gills) and excised organs (viscera and gills)	Fragments, filaments, films	Malaysia **From local market*	Karami et al. (2017a)

[****Indicates that this species is included in the list of the most commonly caught marine species worldwide according to FAO, 2016].

gyres, estuaries and other coastal areas of heavily anthropogenic impacted regions are the ecosystems most polluted with these types of particles (Cózar et al., 2014; Eriksen et al., 2014; Galgani et al., 2015; Peters and Bratton, 2016; Frère et al., 2017).

Microplastics can be uptaken by a wide range of marine organisms by different processes (Lusher, 2015; GESAMP, 2016; Foley et al., 2018). Among these, ingestion is believed to be a main microplastics exposure route for several marine species. In some cases, microplastics are ingested because they are confounded with prey, but ingestion through passive water filtration and deposit feeding activity also occur (de Sá et al., 2015; Luís et al., 2015; Naji et al., 2018). After ingestion, microplastics absorption, distribution through the circulatory system, and entrance into different tissues and cells can occur, potentially resulting in several types of adverse effects (von Moos et al., 2012; Wright et al., 2013; Pedà et al., 2016; Avio et al., 2017; Chae and An, 2017; Foley et al., 2018). Such effects may be caused by the particles (e.g. physical damage or reaction to it and their chemical components) or chemicals added during the particle manufacturing or sorb to the microplastics during their use or permanence in the environment (Hartmann et al., 2017). Moreover, microplastics (Farrell and Nelson, 2013; Mattsson et al., 2017; Santana et al., 2017), as well as the chemicals they contain (Hartmann et al., 2017), can be transferred from marine prey to predators.

Microplastic ingestion has been observed in a range of animals of commercial interest that are consumed by humans as food, including fish (e.g. Atlantic cod, Atlantic horse mackerel; European pilchard, red mullet, European sea bass), bivalves (e.g. mussels, oysters), and crustaceans (e.g. brown shrimp) (Lusher et al., 2013; van Cauwenberghe and Janssen, 2014; Avio et al., 2015b; Devriese et al., 2015; Bellas et al., 2016; Brate et al., 2016; Güven et al., 2017; Bessa et al., 2018). In addition to animals from wild populations, those from aquaculture can also ingest microplastics (Cheung et al., 2018; Renzi et al., 2018). For example, bivalves cultured in estuaries and coastal lagoons are prone to ingesting microplastics because the water and sediments of many such areas are contaminated with these particles (Lusher et al., 2017). Furthermore, aquaculture systems where fish, shrimps or other farmed species are fed with feeding materials produced from fish and other animals (e.g. fishmeal) may be contaminated with microplastics present in these products (GESAMP, 2016). The presence of plastic debris has also been detected in seafood sold for human consumption, as well as in fish and shellfish purchased from markets (e.g. Li et al., 2015; Neves et al., 2015; Rochman et al., 2015; Karami et al., 2017a). This evidence raises concerns regarding the ingestion of microplastics by humans through the consumption of marine species contaminated with these particles as food and the potential effects on the human health.

Knowledge about the effects of microplastics on the human health through the consumption of fish and shellfish is still in its infancy and requires further investigation (Law and Thompson, 2014; Barboza and Gimenez, 2015; Rist et al., 2018). Therefore, our objective was to provide an overview of the evidence and potential risks associated with the presence of microplastics in the marine environment, integrating a dimension on the implications for human food security, food safety and health. Thus, the literature providing evidence of the presence of microplastics in human seafood and other food items was reviewed and discussed, and challenges and gaps in knowledge were identified.

2. Evidence of microplastics presence

2.1. Seafood

Despite the growing number of scientific investigations into the occurrence, transport, and distribution of microplastics in the marine environment and their adverse effects on marine life (Barboza and Gimenez, 2015), researchers have only recently begun to consider the potential effects on human health. Research has shown that shellfish (including crustaceans and bivalves), and a high variety of commercially important fish species are often contaminated with microplastics (Table 1), being a potential route through which human consumers become exposed to these particles and the chemicals they contain (Bouwmeester et al., 2015; GESAMP, 2016). For example, among the 25 species contributing mostly to global sea fishing (FAO, 2016), 11 were found to contain microplastics.

van Cauwenberghe and Janssen (2014) were among the first researchers to estimate the potential exposure of humans to microplastics through the ingestion of seafood contaminated by these particles. They calculated that in European countries with high shellfish consumption, consumers ingest up to 11,000 microplastic particles (size range 5–1000 μm) per year, whereas in countries with low shellfish consumption, consumers ingest an average of 1800 microplastics per year (Van Cauwenberghe and Janssen, 2014), which is still a considerable exposure. Considering shrimp consumption only, estimates indicate about 175 microplastic particles (size range 200–1000 μm) per person per year (Devriese et al., 2015). Regarding mussels consumed as food by humans, microplastics were found in *Mytilus edulis* and *M. galloprovincialis* from five European countries (France, Italy, Denmark, Spain and The Netherlands) (Vandermeersch et al., 2015). In commercial mussels from Belgium, the number of microplastic particles varied from three to five fibers per 10 g of mussels (de Witte et al., 2014). In other regions, several studies also report the presence of microplastics in marine molluscs consumed as food by humans. For example, a study of microplastics in commercial bivalves in China reported that the average number of microplastics (size range 5–5000 μm) varied from 2 to 11 items per gram and from 4 to 57 items per individual bivalve (Li et al., 2015). In five shellfish species (including gastropods and bivalves) of the Persian Gulf, 3.7 to 17.7 particles per individual were found (Naji et al., 2018). Concerning fish, microplastics were found in the Atlantic cod (*Gadus morhua*), the European hake (*Merluccius merluccius*), the Red mullet (*Mullus barbatus*) and the European pilchard (*Sardina pilchardus*) from several localities (e.g. Avio et al., 2015b; Brate et al., 2016; Liboiron et al., 2016; Rummel et al., 2016; Bellas et al., 2016; Compa et al., 2018). Rochman et al. (2015) demonstrated the presence of microplastics (size > 500 μm) in 9% and 28% of the gastrointestinal tracts from fish sold at markets in the USA and Indonesia, respectively, with an average number of plastic pieces of 0.5 per individual fish in the USA samples and 1.4 in the Indonesian samples. Miranda and Carvalho-Souza (2016) also found microplastics in the digestive tract of two important species of edible fish (*Scomberomorus cavalla* and *Rhizoprionodon lalandii*) caught along the eastern coast of Brazil, and Neves et al. (2015) detected microplastics in 19.8% of commercial fish from the Portuguese coast. Moreover, microplastics have been detected in the stomachs of commercially important fish from the Mediterranean (Romeo et al., 2015), and in the gastrointestinal tract and liver of anchovies and sardines that sometimes are totally consumed (i.e. the entire fish) (Avio et al., 2015b; Collard et al., 2017; Compa et al., 2018).

Although the occurrence of microplastics in the gastrointestinal tract of fish does not provide direct evidence for human exposure since this organ is usually not consumed (Wright and Kelly, 2017), generally seafood species that we eat whole (e.g. some molluscs and crustaceans, and small or juvenile phases of fish) pose a greater threat to seafood contamination than for example gutted fish or peeled shrimp. However, the presence of microplastics in the eviscerated flesh (whole fish excluding the viscera and gills) of two commonly consumed dried fish species (*Chelon subviridis* and *Johnius belangerii*) was significantly higher than excised organs (viscera and gills), evidencing that the evisceration does not necessarily eliminate the risk of microplastics intake by human consumers (Karami et al., 2017a). Moreover, the presence of microplastics was recently detected in the muscle of commercially important species of fish (Akhbarizadeh et al., 2018; Abassi et al., 2018) and of a crustacean (Abassi et al., 2018). These findings raise concerns about possible implications for human consumers.

Table 2
Summary of studies reporting the occurrence of microplastics in other food items and drinking water.

Item	Levels of mp		Size range	Types of debris	Location	Source
Other food items						
Beer	24; 100%	2–79 fibers L^{-1}, 12–109 fragments L^{-1} 2–66 granules L^{-1}	Not specified	Fibers, fragments, granules	Germany *From local supermarkets*	Liebezeit and Liebezeit (2014)
	12; 100%	0–14.3 particles/L	100–5000 μm	Fibers, fragments	USA *Purchased from Minneapolis, Duluth, Alpena, Michigan and Rochester (liquor stores, breweries)*	Kosuth et al. (2018)
Honey	19; 100%	166 ± 147 fibers/kg of honey 9 ± 9 fragments/kg of honey	10–20 μm	Fibers, fragments	Germany, France, Italy, Spain and Mexico *From local supermarkets or producers*	Liebezeit and Liebezeit (2013)
Sugar	5; 100%	217 ± 123 fibers/kg of sugar 32 ± 7 fragments/kg of sugar	10–20 μm	Fibers, fragments	*From local supermarkets*	
Salt	15; 100%	550–681 particles/kg of sea salts 43–364 particles/kg of lake salts 7–204 particles/kg of rock/well salts	45–4300 μm	Fragments, fibers, pellets, sheets	China *From local supermarkets*	Yang et al. (2015)
	17; 94%	1–10 particles/kg of salt	> 149 μm	Fragments, filaments, films	Australia, France, Iran, Japan, Malaysia, New Zealand, Portugal, South Africa *From local supermarkets*	Karami et al. (2017b)
	21; 100%	50–280 particles/kg of salt	10–3500 μm	Fibers	Spanish salt producers	Iñiguez et al. (2017)
	16; 100%	16–84 item/kg in sea salt 8–102 item/kg in lake salt 9–16 item/kg in rock salt	20–5000 μm	Fibers, fragments, films	Turkish *From local supermarkets*	Gündoğdu (2018)
	12; 100%	46.7–806 particles/kg of salt	100–5000 μm	Fibers, fragments	USA *Purchased from grocery stores and specialty shops in* Minneapolis (Salt ID – North Sea Salt; Celtic Sea salt; Sicilian Sea Salt; Mediterranean Sea Salt; Utah Sea Salt; Himalayan Rock Salt; Hawaiian Sea Salt; Baja Sea Salt; Atlantic Sea Salt; Pacific Sea Salt)	Kosuth et al. (2018)
Canned sardines and sprats	20; 20%	not specified	190–3800 μm	Fragments, filaments, films	Purchased from Australian and Malaysian markets and manufactured in Canada, Germany, Iran, Japan, Latvia, Malaysia, Morocco, Poland, Portugal, Russia, Scotland, Thailand, and Vietnam	Karami et al. (2018)
Drinking water						
Mineral water	38, 100%	2–44 particles/L in single-use plastic bottles 28–241 particles/L in returnable plastic bottles 4–156 particles/L in glass bottles 5–20 particles/L in beverage cartons	1–500 μm	Fragments	Grocery stores from Germany	Schymanski et al. (2018)
Tap water and bottle water*	159; 81%	0–61 particles/L	100–5000 μm	Fibers, fragments, films	Cuba, Ecuador, England, France, Germany, India, Indonesia, Ireland, Italy, Lebanon, Slovakia, Switzerland, Uganda, USA *From USA	Kosuth et al. (2018)

2.2. *Other products consumed as food by humans or used in human food preparation*

It should be highlighted that data on plastic fragments in food products are available in the European Commission's Rapid Alert System for Food and Feed (RASFF)'s portal and on the European Food Safety Authority's (EFSA) website. The RASFF and the EFSA report the presence of these contaminants, classified as foreign bodies, in a wide variety of human food items (RASFF, 2015; ESFA, 2016). The literature also provides several records of the presence of microplastics and other synthetic microparticles in human food and ingredients to prepare it, and in human drinking water. For example, microplastics were found in canned sardines and sprats (Karami et al., 2018), salt (Yang et al., 2015; Iñiguez et al., 2017; Karami et al., 2017b; Gündoğdu, 2018; Kosuth et al., 2018), beer (Liebezeit and Liebezeit, 2014; Kosuth et al., 2018), honey and sugar (Liebezeit and Liebezeit, 2013). Moreover, drinking water distributed in plastic bottles, glass bottles and beverage cartons obtained from grocery stores in Germany were also found to contain microplastics (Schymanski et al., 2018) as does tap water from different countries (Kosuth et al., 2018) (Table 2). Therefore, the occurrence of microplastics in other food items increases concern about the risks associated with ingestion and long-term exposure to multiple microplastic sources (Karami et al., 2018).

Despite the growing research interest in the occurrence of microplastics in seafood and other human food items, the information available is still limited to some regions around the world. More research is required to evaluate the presence of microplastics in consumed marine species, including edible tissues, especially from areas with high concentrations of these contaminants in the water and sediment. Qualitative and quantitative data are needed, including on the type, size, and components of microplastics. Novel approaches to identify, isolate and quantify very small microplastic particles in tissues, seawater and sediment samples, and harmonization and standardization approaches are required to improve exposure quantification. Moreover, quality assurance methods, standardization and harmonization during the processing of samples are fundamental to ensuring an adequate comparison of data (Wesch et al., 2017). Furthermore, in relation to the presence of microplastics in seafood and other food items, there is currently no regulatory framework (EFSA, 2016) that is needed to increase human food safety.

3. Implications for the environment and human food security

It is now well-known that microplastics are highly persistent in the environment and are accumulating in different ecosystems at increasing rates (Andrady, 2017). For this reason, microplastics are considered an emerging issue of great concern. However, uncertainty and variability in the data are considered as one of the main factors that hinder a realistic assessment of the environmental risks associated with these microparticles. Thus, the real environmental risks of microplastics remain uncertain (Koelmans et al., 2017b).

In recent years, laboratory experiments provided important results showing marine organisms ingest and uptake microplastics, that microplastics and the chemicals they contain induce adverse effects and are accumulated in a high number of species, that microplastics interact with the toxic effects of other environmental contaminants and other stressors, and that trophic transfer of microplastics and chemicals associated with them occurs. Several of the organisms that were investigated are keystone species in the ecosystems where they occur; thus their populations are crucial to the functioning of these ecosystems (Luis et al., 2015; Au et al., 2017).

Recent studies have documented the trophic transfer of microplastics in the wild (Welden et al., 2018) and in laboratory conditions (Farrell and Nelson, 2013; Setälä et al., 2014; Mattsson et al., 2017; Nelms et al., 2018), suggesting that micro- and nano-sized plastics can be transferred within different food webs. These findings raise concerns regarding the bioaccumulation and biomagnification of microplastics, increasing the risks and toxic effects mainly to top predators (Fonte et al., 2016; Carbery et al., 2018; Ferreira et al., 2018).

Regarding adverse effects, laboratory experiments have shown various effects on marine animals caused by exposure to microplastics, such as mortality (Luis et al., 2015; Gray and Weinstein, 2017), reduced feeding rate, body mass, and metabolic rate (Welden and Cowie, 2016), reduced allocation of energy for growth (Farrell and Nelson, 2013), decreased predatory performance (de Sá et al., 2015), changes in behavioral responses and reduced swimming performance (Barboza et al., 2018b), decreased fertilization and larval abnormalities (Martínez-Gómez et al., 2017), neurotoxicity due to acetycholinesterase inhibition and oxidative stress (Oliveira et al., 2013; Avio et al., 2015a; Ribeiro et al., 2017; Barboza et al., 2018a), intestinal damage (Pedà et al., 2016) and several other adverse effects (Wright et al., 2013; Foley et al., 2018). All this evidence indicates that in the wild, especially in areas with high concentrations of plastic debris (e.g. heavily industrialized and urbanized areas and oceanic gyres), populations may be negatively affected and at least some of them could decrease over time, with potentially adverse consequences for environmental health, biodiversity conservation, ecosystem services, and human food security (in terms of reduced food availability for the human population). Thus, to properly assess and manage the risks, more studies on the effects of microplastics are needed, with special focus on the long-term effects induced by the exposure to ecologically relevant concentrations of microplastics commonly found in the environment.

4. Implications for human food safety

In the marine environment, microplastics may act as vehicles for chemicals, including those intentionally added during their manufacturing process, as well as environmental contaminants that may be absorbed on to their surface during their use and permanence into the environment, such as styrene, toxic metals, phthalates, bisphenol A (BPA), polychlorinated biphenyls (PCB) and polycyclic aromatic hydrocarbons (PAHs) (Teuten et al., 2009; Ashton et al., 2010; Holmes et al., 2012; Bakir et al., 2012; Oliveira et al., 2013; Rochman et al., 2014; Massos and Turner, 2017; Barboza et al., 2018a; Hahladakis et al., 2018). It should also be stressed that a wide range of chemical products used in plastic manufacturing are recognized as very toxic to animals and humans (e.g. carcinogens, endocrine disruptors, neurotoxic chemicals) (Thompson et al., 2009; Rochman et al., 2013a; Galloway and Lewis, 2016; Hahladakis et al., 2018; Wright and Kelly, 2017). Moreover, pollutants and additives can be transferred from ingested microplastics to animal tissues and cause impairment of key functions that normally sustain health and biodiversity (Rochman et al., 2013b; Bakir et al., 2014). For example, plastic particles may be toxic to organisms due to physical damage caused by small particles adsorbed to membranes and also if they cross the membrane by altering cellular functioning (Bhattacharya et al., 2010; von Moos et al., 2012). Additionally, several of the chemicals associated with microplastics may accumulate and biomagnify in marine trophic webs (Amiard-Triquet et al., 1993; Kelly et al., 2007). This increases the risk of toxic effects of these chemicals, especially to top predators and humans consuming species contaminated with microplastics or with chemicals released from these particles after their ingestion (Koelmans et al., 2016; Hartmann et al., 2017; Hermabessiere et al., 2017). Phthalates and bisphenol A, for example, should receive particular attention because their toxicity has been proven in animal studies and because of their ubiquitous presence in the environment and the human body (Vom Saal et al., 2008; Koch and Calafat, 2009; Thompson et al., 2009; Koelmans et al., 2014). Regarding chemicals adsorbed to microplastics in the environment, the ability of these particles to adsorb very toxic metals has been demonstrated in some studies (Ashton et al., 2010; Holmes et al., 2012; Vedolin et al., 2018). Among these metals, mercury is of special relevance because it is a global pollutant, is a common contaminant in the marine environment occurring at increased concentrations in several regions, is highly toxic to animals and humans, is accumulated by a high number of organisms, and some of its organic forms, particularly methylmercury, biomagnify in trophic webs (Eagles-Smith et al., 2018).

In addition to chemicals, microbes and other organisms that have been found on plastic debris, generally described as the “plastisphere” (Zettler et al., 2013), are of particular concern regarding the spread of exotic invasive species and pathogens. Some of these communities have been found to include pathogenic organisms, such as *Vibrio spp*. (e.g. de Tender et al., 2015; Keswani et al., 2016; Kirstein et al., 2016), *Escherichia coli, Stenotrophomonas maltophilia, Bacillus cereus* (van der Meulen et al., 2014) and *Aeromonas salmonicida* (Virsek et al., 2017). Therefore, it has been suggested that plastic debris may increase the global risk of human and animal diseases via new contamination/infection routes, introduction of pathogens and their vectors into new areas through the environmental spread of microplastics or migrations of organisms contaminated with the pathogens mediated via microplastics (Keswani et al., 2016). Additionally, the “plastisphere” may also include exotic invasive species (pathogens or not) that may contribute to loss of biodiversity and other negative ecological and economic impacts (Zettler et al., 2013).

Available information on the presence of microplastics and their additives, associated pollutants and pathogens in fish and seafood, as well as the potential effects on human health, is still very scanty (Seltenrich, 2015; USEPA, 2015; GESAMP, 2016; Vethaak and Leslie, 2016). Although there is laboratory evidence that microplastics may increase the effects of chemical contaminants in fish, for example (Rochman et al., 2013b; Pedà et al., 2016; Barboza et al., 2018a; Rainieri et al., 2018), there is little evidence from field studies that the ingestion of microplastics affects the bioaccumulation of pollutants (Lohmann, 2017). As predicted by chemical partitioning models, the relative importance of contaminants exposure mediated by microplastics compared to other exposure pathways may be limited (Koelmans et al., 2013; Bakir et al., 2016; GESAMP, 2016). Indeed, to date, at the current observed microplastic concentrations, there is little evidence to suggest that microplastics may increase the chemical contamination of seafood when compared with other environmental sources (i.e., water, sediments, food web) (Koelmans et al., 2014; GESAMP, 2016; Koelmans et al., 2016; Lohmann, 2017; Pittura et al., 2018). This is confirmed by a recent field study with seabirds off the coast of Norway that showed only a negligible impact of ingested microplastics on tissue concentrations of POPs (Herzke et al., 2016).

Considering the high concentrations of additives or contaminants reported in microplastics and their potential release from the microplastics upon ingestion, the internationally peer-reviewed expert panel reports by EFSA (2016) and Lusher et al. (2017) calculate that microplastics may have a negligible effect on the exposure to some pollutants and additives considering the total dietary exposure of humans. However, given the uncertainties surrounding this issue (e.g. assumptions in modeling exercises, the analytical challenges of measuring micro- and nano-sized microplastics in environmental matrices including seafood), the contribution of plastic-derived chemicals to the human diet should receive continued attention in future research.

The transfer of pathogens from ingested plastics to humans is still speculative. It is currently unknown to what extent plastic debris is involved in the spread of infectious diseases to humans. However, the survival of these pathogenic organisms on plastic debris has not been extensively studied, and understanding pathogen transmission and infection disease risks via the consumption of seafood will require further studies.

Other critical issues regarding animal, ecosystem and human health are the toxicological interactions between microplastics and other environmental contaminants of concern, as well as the influence of alterations due to global climate changes, especially temperature variations, on such interactions. Several studies with marine organisms published in recent years have been showing that microplastics influence the toxicity (increasing, changing the type or the pattern of the effects) of a wide diversity of pollutants, such as polycyclic hydrocarbons (Oliveira et al., 2013), metals (Luis et al., 2015; Barboza et al., 2018a) and pharmaceuticals (Fonte et al., 2016). Moreover, temperature variation, especially temperature rise, has been found to influence such toxicological interactions (Ferreira et al., 2016; Fonte et al., 2016). The properties and concentrations of the microplastics and other chemicals tested, the conditions of the bioassays, and the tested species influence the findings reported. Therefore, more research on this topic is also needed.

5. Implications for human health

Even though scientific evidence demonstrates the presence of microplastics in several food products, there is no information available about the fate of microplastics in the human body following ingestion of the particles (Wright and Kelly, 2017; Rist et al., 2018). In this context, adverse effects on human health are still controversial and not well understood. Thus, several important questions remain open, such as if microplastics play a role in the development of cancer in marine animals and, by extension, in humans (Erren et al., 2015); what are the long-term effects of human exposure to microplastics considering the simultaneous exposure to such particles through several routes (Wright and Kelly, 2017), among several others.

Scientists speculate that microplastics with size bigger than 150 μm probably will not be absorbed while microplastics smaller than 150 μm may translocate from the gut cavity to the lymph and circulatory system, causing systemic exposure. However, the absorption of these microplastics is expected to be limited (≤0.3%). Only microplastics with size ≤ 20 μm would be able to penetrate into organs while the smallest fraction (0.1 > 10 μm) would be able to access all organs, cross cell membranes, the blood-brain barrier and the placenta – Fig. 1 (Browne et al., 2008; von Moos et al., 2012; Bouwmeester et al., 2015; Galloway, 2015; EFSA, 2016; Lusher et al., 2017). If so, it is possible that the distribution of microplastics in secondary tissues, such as liver, muscle, and brain, may occur (Wright and Kelly, 2017). Moreover, it is expected that micro- and nanoplastic interactions with the immune system may potentially lead to immunotoxicity and consequently trigger adverse effects (i.e. immunosuppression, immune activation and abnormal inflammatory responses) (Lusher et al., 2017; Wright and Kelly, 2017). Recently, in vitro studies with cerebral and epithelial human cells evidenced for the first time the potential of micro- (10 μm) and nano-plastics (40–250 nm) to cause cytotoxic effects at cell level in terms of oxidative stress (Schirinzi et al., 2017), reinforcing the scientific speculations on the possible consequences for human health.

Therefore, the knowledge in this field is still very limited and there is little evidence on the impact on human health from eating microplastics. A major challenge regarding this point is that we do not know the amounts of very small microplastics, including those with a size able to enter cells, in the water, sediments, organisms and air; thus the assessment of biota and human exposure is not possible. It should be noted that the microplastics encountered in the commercial species of all studies mentioned in Table 1 were limited to particles in the (upper) micro-size range. From these studies, it can be concluded that, in general, the prevalence of microplastics in seafood is typically low, suggesting that dietary exposure is likely to be low. However, it is worth noting that we are vulnerable to other exposures, such as airborne microplastics (Prata, 2018). In this regard, it has recently been demonstrated that the potential for human ingestion of fibers resulting from domestic dust during a meal may be higher than fiber intake through consumption of mussels (Catarino et al., 2018). Based on the above considerations, although there have been efforts in the attempt to estimate the human intake of microplastics, actual exposure will fall within vast margins and may, for this reason, remain difficult to quantify in practice (Santillo et al., 2017). Furthermore, our understanding of the risks that microplastics pose to human health is still in the early stages (Koelmans et al., 2017a); thus a proper risk assessment is not yet possible. In this way, adopting food safety risk analysis frameworks to evaluate hazards and risks to consumers posed by seafood contaminated with microplastics is of extreme necessity (Lusher et al., 2017). An analysis and assessment of the potential health risk of microplastics for humans should include the dietary exposure from a variety of foods across the total diet (GESAMP, 2016), and the best understanding of various parameters such as particle size, polymeric composition, particle shape, surface area, density, persistence, sorbed pollutants, additive content and toxicological consequences is a prerequisite to proper risk assessment (Hale, 2018).

Thus, the subsequent effects of microplastics on human health should be viewed with caution, since there is a large discrepancy between the current knowledge based on scientific evidence of the real implications for human health and the magnitude of the problem that has been addressed by the media (Wright and Kelly, 2017; Rist et al., 2018). The researchers face several challenges that need to be explored and clarified, and further research is needed to understand the effects of these particles on the human body. In this way, knowledge about the

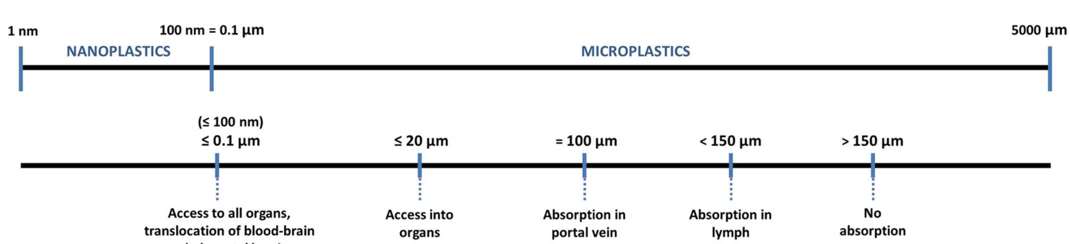

Fig. 1. Fate of micro- and nanoplastics in mammalian bodies (adapted from Lusher et al., 2017).

Box 1
Challenges and gaps of knowledge regarding microplastics and implications for human food security, food safety and health.

✓ Since microplastic concentrations are expected to increase in future, it will be increasingly important to regularly assess levels of microplastics in seafood and other food items.

✓ It is important to quantify the presence of microplastics in edible tissues of fish and shellfish. Also, the quantification in edible echinoderms, tunicates and algae also deserves investigation since in several countries they are widely consumed.

✓ Continuous monitoring programs will be required to evaluate the presence of microplastics in environmental compartments and thus avoid the reduction of global fish and shellfish stocks.

✓ Research also should focus on the contributing chemical and microbiological hazards and risks associated with ingested microplastics and in improving methods to evaluate the intake and translocation of these particles in humans.

✓ It is important to adopt food safety risk analysis frameworks to evaluate hazards and risks to consumers of fish, shellfish and food items contaminated with microplastics.

✓ There is a great need to study the assimilation of a range of microplastic sizes and compositions into human tissues and in the development of techniques capable of identifying the presence of microplastics in the human body (e.g. biopsies and tissue banks).

✓ Another area that deserves urgent attention is the presence of nano-sized plastics in seafood on which there is even less data in the literature.

✓ Research on analytical methods, toxicokinetics, and toxicity of micro- and nano-sized plastics is needed to improve the understanding of their potential impacts on seafood safety and human health.

real effects of microplastics on human health is an area for research that should be explored in the coming years.

6. Final remarks

The contamination of oceans by microplastics is of concern not only because of the ecological impacts but also because they may compromise food security, food safety and consequently human health. The presence of microplastics in species used for human consumption is a global problem and we are vulnerable to microplastic exposure through the consumption of seafood and other human food items, as well as through other routes such as air. Nevertheless, information on the occurrence of microplastics in these products is scarce, the exposure levels are in general largely unknown, and the potential effects on consumers are poorly understood. This information is necessary for providing a basis for a sound risk assessment. Understanding the processes and mechanisms involved in the entry and assimilation of microplastics in human tissues and their potential effects on human health is a priority research area and should be explored in the coming years. In this regard, we identified some challenges or knowledge gaps in this field (Box 1).

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