Chapter 5
Marine Microplastics and Seafood: Implications for Food Security

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Abstract Seafood is an important food source, and this chapter addresses the food safety concerns related to plastic particles in different seafood. Here we focus on those species which are commonly consumed by humans, such as bivalves, gastropods, cephalopods, echinoderms, crustaceans, and finfish. The objectives of this chapter are to (1) outline the major sources, fate, and transport dynamics of microplastics in marine ecosystems, (2) provide a critical assessment and synthesis of microplastics in seafood taxa commonly consumed by humans, (3) discuss the implications of microplastics with regard to human health risk assessments, and (4) suggest future research priorities and recommendations for assessing microplastics in marine ecosystems in the context of global food security and ocean and human health.

5.1 Introduction

Seafood is an important food source – with fisheries and aquaculture production predicted to increase by about 17.5% from 171 million tonnes in 2016 to approximately 201 million tonnes in 2030 (FAO 2018). It is a necessity that these marine-based foods are carefully managed and are safe for human consumption. Food

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security is defined by the Food and Agriculture Organization (FAO) as "a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO 2017). In this chapter, the food safety concerns related to plastic particles in seafood will be addressed.

Global annual production of plastics is estimated to be approximately 300 million tonnes (Galloway 2015) and is still increasing steadily. Most plastic polymers are resistant to complete degradation and pose a potential risk to both human and environmental health. Of particular concern are microplastics, which are defined as particles <5 mm (GESAMP 2019) and which are the focus of this chapter.

Microplastics occur in different shapes and sizes and are formed from different polymers as well as additives, which reflects the diversity of sources and emissions to the environment (Rochman et al. 2019). The dominant microplastic polymers which are detected in the marine environment include polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polyamide, and polyvinylchloride (PVC) (Hantoro et al. 2019). Primary microplastics are manufactured intentionally for a range of commercial uses (e.g., microbeads) whereas secondary microplastics originate from parent material such as textiles and discarded plastic items and are either generated through the use of plastic products or fragmentation following their loss to different environmental compartments. Plastic debris can enter the ocean from ships and fishing gear, as well as from atmospheric deposition, river transport, stormwater, sewage effluents, etc. (Browne et al. 2011; Napper and Thompson 2016; Lebreton et al. 2017; Allen et al. 2019). Plastics and microplastics have been identified in the oceans, from coastal zones to offshore areas, such as oceanic gyres (Eriksen et al. 2014; Jiang et al. 2020;), as well as in remote areas including the Arctic (e.g., Cózar et al. 2017). The ubiquitous nature of plastics in the ocean is an obvious concern for marine ecosystems and their inhabitants. In particular, the progression from macro- to microplastics at sea is a result of physical erosion and UV action and increases the bioavailability of smaller-sized particles to a wide array of marine organisms (Browne et al. 2008; Wright et al. 2013). Plastics have long been reported associated with marine organisms, from the first study of plastic ingestion by fish (Carpenter et al. 1972) to mariculture sites where boring worms facilitate the generation of microplastics from polystyrene buoys (Jang et al. 2018). Many investigations have been conducted to further understand the interaction between marine organisms and microplastics with several studies focusing on microplastic uptake, ingestion, exposure, and metabolic dynamics (Roch et al. 2020). Fibers are routinely identified as the most common microplastic type reported in fish, accounting for 58–87% of the plastic morphologies observed (Walkinshaw et al. 2020). Fragments, films, and fibers are also frequently found in fish and shellfish while microplastics in the forms of spheres are less common. The physical impacts of microplastic ingestion on marine organisms can include oxidative stress, inflammation, and potentially starvation, while less is known regarding the chemical effects of ingestion. The bioavailability and potential toxicity of microplastics are size dependent, with smaller particles able to penetrate further into an organism (Browne et al. 2008), with the potential of the release of associated co-contaminants (Bakir et al. 2016; Batel et al. 2016). It is widely accepted that ingestion is the main route of microplastics uptake in marine biota; however, it has recently also been demonstrated that surface scavenging appears to be an alternative route, as demonstrated in mussels (Kolandhasamy et al. 2018). Microplastics can also be taken up through respiration via the gills (Watts et al. 2016; Franzellitti et al. 2019) and have additionally been demonstrated to be maternally transferred to eggs in zebra fish (Pitt et al. 2018).

Plastics in aquatic environments have been shown to affect an organism's health (such as behavioral changes and reduced growth rates); however, there is limited information on the effects of microplastics in seafood on human health. Lusher et al. (2017a) reported that more than 220 species of marine organisms including zooplankton, bivalves, crustaceans, fish, marine mammals, sea turtles, and seabirds had been shown to have ingested plastics, and more recently this number of species has increased to 690 (Carbery et al. 2018). Here we focus on those species which are commonly consumed by humans, such as bivalves, echinoderms, gastropods, cephalopods, crustaceans, and finfish. The specific objectives of this chapter are to (1) outline the major sources, fate, and transport dynamics of microplastics in marine ecosystems, (2) provide a critical assessment and synthesis of microplastics in seafood taxa commonly consumed by humans, (3) discuss the implications of microplastics with regard to human health risk assessments, and (4) suggest future research priorities and recommendations for assessing microplastics in marine ecosystems in the context of global food security and ocean and human health.

5.2 Fate and Transport of Microplastics in Marine Ecosystems.

The fate and transport of microplastics in the context of physical and biological oceanography has recently been reviewed by van Sebille et al. (2020), as well as by Thushari and Senevirathna (2020) with older reviews and critical papers developed by Andrady (2011), Wright et al. (2013), Galloway et al. (2017), and Wieczorek et al. (2019). The ocean can be both a source and sink for microplastics (Allen et al. 2020), and important themes within the cycling and degradation of microplastic particles (Weinstein et al. 2016) include the importance of transport from land via rivers (Lebreton et al. 2017; Hurley et al. 2018), the role of seafloor ocean circulation patterns as a driver of microplastic hotspots (Kane et al. 2020), and the concept of marine snow which has been identified as an important mechanism for transporting microplastic particles from the water column to the sediment (Porter et al. 2018). Moreover, fishing gear and other sources of macroplastics can degrade into microplastics via biological, chemical, and physical processes (Davidson 2012). Although settling of microplastic particles to the ocean floor is well-documented, recent research has shown that episodic events such as flooding (Hurley et al. 2018) and typhoons (Wang et al. 2019) are important drivers regarding the distribution and abundance of microplastics in coastal marine ecosystems.

5.3 Microplastic in Bivalves

Bivalves are by far the most investigated seafood species (Smith et al. 2018; Walkinshaw et al. 2020). Much of the investigations were performed for the purpose of uptake of microplastics from the environment, as filtering puts bivalves at an increased risk of microplastic intake from the water column (Li et al. 2019). Early investigations focused on blue mussels (*Mytilus* spp.), with wild and market brought samples presenting contamination levels of up to 7.2 microplastics per gram (Abidli et al. 2019; Bråte et al. 2018; Cho et al. 2019; De Witte et al. 2014; Li et al. 2015, 2016; Renzi et al. 2018a; van Cauwenberghe and Janssen 2014; van Cauwenberghe et al. 2015; Vandermeersch et al. 2015). Other bivalve species which have been investigated for microplastic uptake include clams (*Venerupis philippinarum*), oysters (*Crassostrea gigas*), and scallops (*Patinopecten yessoensis*) (Abidli et al. 2019; Cho et al. 2019, 2020; Davidson and Dudas 2016; Li et al. 2015; Rochman et al. 2015; van Cauwenberghe and Janssen 2014).

Microplastic fibers are often the most dominant morphology reported in bivalves. For example, fibers accounted for 80% of microplastics in mussels (*Mytilus edulis*, *Perna viridis*) from China (Qu et al. 2018), 90% of microplastics in Manila clams (*V. philippinarum*) from British Columbia (Davidson and Dudas 2016), and 99% in razor clams (*Siliqua patula*) and Pacific oyster (*Crassostrea gigas*) from Oregon, USA (Baechler et al. 2020a). One of the hypotheses behind the observed high abundance of this type of microplastic is that fibers are likely harder to remove from digestive tracts. Ward et al. (2019) reported that larger spheres are rejected at higher numbers (98%) than smaller spheres (10–30%). Fragments were most common in blue mussels and Pacific oyster from the French Atlantic coast (Phuong et al. 2018) as well as those from Korea, where EPS fragments likely originated from the high abundance of aquaculture facilities in the region (Cho et al. 2020). De Witte et al. (2014) reported that there was a high prevalence of fibers in blue mussels collected from quaysides related to fishing activities.

Microplastics in bivalves are likely dependent on several factors including, but not limited to, culture conditions and contamination levels in the environment, depuration procedures, filtration capabilities, as well as the tissues targeted for investigation. Some investigations, in distinct parts of the world, have found that bivalves sampled from highly contaminated areas or within the vicinity of urban sources of microplastics contained higher numbers of microplastics (Bråte et al. 2018; Qu et al. 2018; Cho et al. 2020). However, conversely, some investigations have reported no difference in microplastic exposure in bivalves related to sources (Covernton et al. 2019; Phuong et al. 2018).

There have been some reported differences between the occurrence of microplastics in market purchased (80%) and wild-caught individual bivalves (40%)

(Ding et al. 2018). Similarly, farmed mussels displayed higher concentrations of microplastics than wild mussels (75 items and 34 items per mussel, respectively) (Mathalon and Hill 2014), although no difference was observed for wild and cultured Manila clams (*Venerupis philippinarum*) in British Columbia (Davidson and Dudas 2016). The use of depurations procedures appears to reduce the number of microplastics identified in bivalve species (van Cauwenberghe and Janssen 2014 – *Mytilus edulis* and *Crassostrea gigas*; Birnstiel et al. 2019 – *Perna perna*), which would hold significance in the preparation of mussels for consumption. The seasonality of sampling could also play a role in observed microplastic concentrations in marine biota. A significant seasonal variation was observed during summer for oyster samples which contained more microplastics; however, this trend was not detected for razor clams (Baechler et al. 2020c).

Particle selection by bivalves, related to size and morphology, will influence which particles are internalized both pre- and post-ingestion (Ward et al. 2018). Gut retention times, which are known to vary between bivalve species and the age of individuals, have shown, in general, that as particle size decreases, accumulation increases (Browne et al. 2008; Ward and Kach 2009; Ward et al. 2019). Much of the work performed on bivalves is based on the sampling and processing of whole organisms, with no differentiation between and among tissue types; this makes it impossible to determine whether microplastics were internalized by individuals, had migrated from gills and guts to visceral tissue, or were in the process of being egested (e.g., as pseudofeces). Kolandhasamy et al. (2018) reported that microplastic fibers can accumulate on the foot and mantle of blue mussels.

Consequences of microplastic intake/uptake by bivalves indicate that microplastics can directly affect bivalve physiology but also indirectly change the structure of their habitats, impairing food resources and facilitate the efficient transfer of organic pollutants (Zhang et al. 2019a). Other observed implications include negative effects on filtration activity (Green et al. 2019; Xu et al. 2017), feeding behavior (Wegner et al. 2012), and reproduction (Sussarellu et al. 2016; Gardon et al. 2018). It is important to highlight that effects are mostly studied using uniform particles, mostly spheres so these may not be truly representative of environmentally relevant microplastic exposure regimes (see Gomes et al. 2021, Chap. 7, this volume).

5.4 Microplastics in Echinoderms

Sea urchins and sea cucumbers are the main echinoderms consumed as food item, and few studies have been conducted on the abundance of microplastics in these marine organisms. Of the heart urchins (*Brissopsis lyrifera*) analyzed, 40% were found to contain microplastics in their soft tissue, primarily in the form of flakes (90%, the remaining 10% as fibers). In most cases the number of particles present was 1/individual (Bour et al. 2018). It is noteworthy that this study was conducted for an ecological assessment of the influence of habitat, feeding mode, and trophic level on microplastic abundance in benthic and epibenthic organism and that this species is not commonly consumed. Feng et al. (2020) reported a higher prevalence of microplastics (in 90% of the individuals) in four species of sea urchins (*Strongylocentrotus intermedius*, *Temnopleurus hardwickii*, *Temnopleurus reevesii*, and *Hemicentrotus pulcherrimus*) harvested from 12 sites along the northern China coast. The average abundance of microplastics (predominantly as fibers) in soft tissue from sea urchins from all sites was 5 particles/individual (1.1 particles/g), considerably higher than reported in heart urchins from the Oslofjord, Norway (Bour et al. 2018). Higher detection rates and abundances were found in sea urchins from Dalian, China (Feng et al. 2020). The tissue of relevance in urchins with regards to seafood safety is the gonads, and while whole soft tissue of heart urchins was analyzed for microplastics (Bour et al. 2018), the abundance in urchins from the Yellow Sea was assessed in gonads, coelomic fluid, and the gut. Gonads and coelomic fluid contained significantly lower number of particles/individual than the gut in all four species of urchin; however, this difference was not evident when normalized to wet weight in three of the species, and it only remained significantly lower in *S. intermedius* (Feng et al. 2020).

Microplastic ingestion has been reported in several species of sea cucumber including *Holothuria grisea*, *Cucumaria frondosa*, *Holothuria floridana*, *Thyonella gemmata* (Graham and Thompson 2009), *Holothuria tubulosa* (Renzi et al. 2018b), *Holothuria mexicana*, *Actinopyga agassizi* (Plee and Pomory 2020), and *Apostichopus japonicus* (Mohsen et al. 2019). Sea cucumbers are commonly eaten in Asia, and farming is widespread to meet consumer demand. The body wall of sea cucumbers is typically eaten raw in Japan and boiled, pickled, or salted in China, and the internal organs (gonads, respiratory trees, and intestines) are also edible (Kiew and Don 2011). Iwalaye et al. (2020) reported microplastic particles in the intestines, coelomic fluid, and respiratory trees of the *Holothuria cinerascens* and that uptake was both via the feeding tentacles and the respiratory trees. The most abundant microplastics found in farmed sea cucumbers (*Apostichopus japonicus*) from eight locations in the Bohai Sea and Yellow Sea in China were cellophane microfibers (Mohsen et al. 2019).

5.5 Microplastics in Gastropods

Limited research has been carried out on microplastics in marine gastropods. Xu et al. (2020) analyzed nine species of gastropods from shores in Hong Kong for microplastics, with the highest abundance found in sea snails (*Batillaria multiformis*, 5.4 ± 1.2 particles/g wet weight) and the lowest observed in Chameleon nerite snails (*Nerita chamaeleon*, 1.50 ± 0.2 particles/g wet weight). The common periwinkle (*Littorina littorea*) sampled from four different locations in Galway Bay, Ireland, contained between 0.6 and 2.8 microplastics/g wet weight of soft tissue, and commercial common periwinkles, intended for human consumption, contained on average 2.2 microplastic s/g wet weight soft tissue (Doyle et al. 2019). Most of the microplastics (97%) recorded in periwinkles were fibers. Similarly, fibers accounted for more than half of the total microplastics present in the girdled horn shell (*Cerithidea cingulata*), whereas film was the most abundant microplastic (approximately 44%) in *Thais mutabilis* from the Persian Gulf region. The mean number of total microplastics was 13 and 20 particles/g wet soft tissue weight for *C. cingulata* and *T. mutabilis*, respectively (Naji et al. 2018). Lower levels of microplastic contamination were reported in periwinkles (*Littorina* spp.) from two sites on the eastern coast of Thailand with an average of 0.17 particles/g wet weight and 0.23 particles/g wet weight, with no contamination observed in periwinkles from Bangasaen, the third site investigated (Thushari et al. 2017).

5.6 Microplastics in Cephalopods

Cephalopods are the seafood phylum which have received the least focus with regard to microplastic contamination. Oliveira et al. (2020) investigated the levels of microplastics in the stomach, caecum/intestine, and digestive gland of cuttlefish (*Sepia officinalis*); however, tissue relevant for consumer exposure was not included in this study. Microplastic contamination in Indian squid (*Uroteuthis duvaucelii*) was found in 18% of the individuals examined, with an average of 0.2 microplastic particles/individual and 0.008 microplastic particles/g wet weight of edible tissue (Peng et al. 2020).

5.7 Microplastics in Crustaceans

Most biota-based studies have examined microplastics in the organisms' gut, which is not generally an organ consumed directly by humans. However, shellfish including crustaceans and mollusks are an exception since these are frequently eaten either whole or with their gut removed. The risk of ingesting microplastics from other tissues, such as muscle, depends on the ability to cross the intestinal barrier and subsequent accumulation (Zeytin et al. 2020).

To date, most literature on crustaceans which are commonly harvested for human consumption has focused on wild individuals, rather than those that are farmed. Investigations generally have not focused on crustaceans in the context of seafood safety but rather from an environmental contaminant perspective. For example, there have been numerous investigations into langoustine, *Nephrops norvegicus*, which are also commercially exploited. *N. norvegicus*, sampled from the Clyde Sea area, were shown to contain more microplastic fibers in their gut than individuals from the North Sea and Minch where only a small percentage of individuals contained microplastic, predominantly as single-strand fibers (Welden and Cowie 2016). Other commercially relevant species, such as spinous spider crabs (*Maja squinado*), shrimps, and prawns, have been observed to contain microplastics (Welden et al. 2018; Devriese et al. 2015; Zhang et al. 2019b; Cau et al. 2019).

Many crustaceans are harvested from coastal environments, which may be close to sources of microplastic contamination, including the influence of terrestrial plastic sources. As an example, shrimp (*A. antennatus*) from the Mediterranean had an average occurrence of microplastics equal to 39.2%; however, those in close vicinity to urban areas had 100% presence of microplastics (Carreras-Colom et al. 2018). The same % occurrence trend was observed between remote populations (<40%) of *N. norvegicus* compared to those sampled near Glasgow (84%) in the Clyde Sea (Welden and Cowie 2016).

Additionally, no spatial pattern was observed in a similar study of *N. norvegicus* in Irish waters (Hara et al. 2020). Both *N. norvegicus* and *Aristeus antennatus* were investigated in the Mediterranean Sea from depths between 270 and 660 meters (Cau et al. 2019). The authors reported a significant difference in the size and composition of microplastics identified between the two species and suggested that the nonselective feeding strategy of *N. norvegicus* likely led to a higher degree of exposure to microplastics and hence a higher measured abundance. Nonselective feeding is an example of direct uptake of microplastics from the environment. Organisms can also ingest microplastics which have been internalized by prey species, a concept commonly referred to as trophic transfer. Laboratory studies on this topic performed with shore crabs (*Carcinus maenas*) fed mussels which had been exposed to microplastics showed that polystyrene microspheres could accumulate in the foregut of the crabs (Watts et al. 2015).

Fibers and fragments are the most often reported particle type in crustaceans sampled from the wild, with fiber bundles reported across many species (Welden and Cowie 2016; Cau et al. 2019; McGoran et al. 2020). In most studies, stomachs were often the target organ of microplastics investigations, but other tissues are starting to be considered further, as these may have relevance for human exposure, especially when stomachs are removed prior to cooking and consumption. As an example, microplastics have been found in different tissues of wild-caught *Portunus gracilimanus* and *P. trituberculatus* (Zhang et al. 2019b).

5.8 Microplastics in Finfish

Evaluating microplastic occurrence and abundance in finfish is fundamental to understanding how plastics and their associated chemical compounds affect and potentially impact wild fisheries that are relied upon by humans as an important source of food and nutrition (Rochman et al. 2015; Barboza et al. 2018; FAO 2020; Lusher and Welden 2020). The topic of microplastics in the marine environment, including information on finfish, has been reviewed by several authors (Andrady 2011; Cole et al. 2011; Hidalgo-Ruz et al. 2012; Wright et al. 2013; Gall and Thompson 2015; Galloway et al. 2017; Baechler et al. 2020a, b; Thushari and Senevirathna 2020; Wang et al. 2020; Walkinshaw et al. 2020). Microplastics exposure in finfish is largely a result of plastics being mistaken for natural prey items, via ingestion of contaminated prey items or by passive uptake through gills (Lusher et al. 2016; Watts et al. 2015; Nelms et al. 2018; Roch et al. 2020). Trophic transfer of microplastics may also expose predaceous fish to microplastics (Farrell and Nelson 2013; Setälä et al. 2014; Lusher et al. 2016; Baechler et al. 2020a), and microplastics have frequently been detected in finfish gastrointestinal tracts (e.g., Lusher et al. 2017b,). The methodological challenges with identifying particles within fillet muscle tissue have limited the number of published studies thus far, although they have been identified albeit at extremely low concentrations (Zeytin et al. 2020).

Many species of edible demersal, pelagic, and reef fish, sampled from across the globe, have been found to contain microplastics (e.g., Bellas et al. 2016; Rummel et al. 2016; Bråte et al. 2016; Lusher et al. 2013; Tanaka and Takada 2016; Rochman et al. 2015; Neves et al. 2015; Critchell and Hoogenboom 2018; Abbasi et al. 2018; Su et al. 2018). The percentages of different fish species which have been found to contain microplastics in their gut vary greatly: 0.9% Peruvian anchovy, 2.8% Atlantic cod, 8.8% Atlantic herring, 9.4% Skipjack tuna, 24.5% Jack and Horse mackerel, 23.3% Pacific chub mackerel, 23.4% Yellowfin tuna, and 76.6% Japanese anchovy (Neves et al. 2015; Lusher et al. 2013; Güven et al. 2017; Ogonowski et al. 2017; Rummel et al. 2016; Hermsen et al. 2018; Rochman et al. 2015; Choy and Drazen 2013; Markic et al. 2018; Bråte et al. 2016; Liboiron et al. 2016; Tanaka and Takada 2016). Several studies have examined the microplastic particle prevalence in fish with different feeding ecology (Foekema et al. 2013; Lusher et al. 2013). Lusher et al. (2013) did not find any significant difference between the abundance of plastic ingested by pelagic and demersal fish. Of the 24 fish species examined from the Beibu Gulf, one of the world's largest fishing grounds, in the South China Sea, 12 species contained microplastics (Koongolla et al. 2020). The abundance of microplastics varied from 0.027 to 1 item per individual, and most was present in fish stomach (57.7%) and less in intestines and gills (34.6% and 7.7%, respectively). Nine of the 11 fish species sampled from Zhoushan fishing grounds in the East China Sea were found to contain microplastics, with 23 different polymer types identified, and the highest number of items was 8 in a single individual (Zhang et al. 2019a). It is challenging to compare all the studies listed above, as many different methods have been utilized by researchers to determine the presence or absence of microplastics across these species. Some trends in the methods used have previously been described, with visually searching the most common method (Lusher et al. 2017b); however, the lack of standards and incomplete reporting of data, and quality control procedures have also been highlighted (Hermsen et al. 2018). Differences in sampling and analytical methods may lead to different values being observed and are important to consider when evaluating trends across regions, ecosystem types, and species.

The microplastic content of wild fish has been more widely studied than aquaculture species. A recent review of microplastics in seafood found that data were lacking for four of the ten most cultured aquatic food species, namely, grass carp, whiteleg shrimp, bighead carp, and catla (Walkinshaw et al. 2020).

5.9 Co-contaminants Associated with Microplastics in Seafood

The role of marine microplastics as vectors for major ocean pollutants was recently reviewed by Ziccardi et al. (2016), Santillo et al. (2017), and Amelia et al. (2021). Plastics are inherently complex in size, morphology, and polymer composition and may contain a range of additives, including plasticizers, stabilizers, pigments, fillers, and flame retardants which may leach out into the environment including air, water, and food, and in general, microplastics are now considered to represent a suite of co-contaminants (Rochman et al. 2019). More than 50% of plastics are associated with hazardous monomers, additives, and chemical byproducts (Lithner et al. 2011). Plastics have been shown to accumulate various organic and inorganic co-contaminants from the surrounding water column (Rochman et al. 2013, 2015). The high surface area to volume ratio of small particles and hydrophobic nature facilitate the sorption of chemicals on the plastic surface, forming a complex mixture of contaminants available to marine organisms (Rochman et al. 2013). Laboratory studies have demonstrated that continuous exposure to contaminated plastics can lead to the accumulation of plastic-associated co-contaminants in fish (Rochman et al. 2013; Wardrop et al. 2016).

Both field and modeling studies suggest that transfer of environmental pollutants through microplastics are negligible compared to other routes of uptake (Gouin et al. 2011; Bakir et al. 2016; Espinosa et al. 2018; Koelmans et al. 2016; Ziccardi et al. 2016; Lohmann 2017; Smith et al. 2018). Nonetheless, caution is warranted as many of the chemicals sorbed onto microplastics are known to be potent toxicants to humans and marine biota, triggering adverse effects such as endocrine disruption, neurological disorders, and reduced reproductive success (GESAMP 2016). An example of this is the investigation by Barboza et al. (2020a) who reported significantly higher concentrations of bisphenols in fish with microplastics compared to individuals with no microplastics. However, none of the fish species investigated (European seabass *Dicentrarchus labrax*, Atlantic horse mackerel *Trachurus trachurus*, and Atlantic chub mackerel *Scomber colias*) contained bisphenol A levels which would lead to an exceedance of the Tolerable daily Intake established by the European Food Safety Authority (EFSA) (Barboza et al. 2020a).

5.10 Microplastic Uptake and Toxicity in Humans

The uptake of microplastics is dependent on size, morphology, solubility, and surface charge and chemistry. Microplastics <130 μm in diameter can potentially translocate into human tissue (EFSA 2016), and particles sized 1.5 μm and below can penetrate capillaries (Yoo et al. 2011). Proposed mechanisms for uptake of microplastics include endocytotic and paracellular transfer across epithelial tissues (Wright and Kelly 2017). It is estimated that 90% of ingested microplastics are excreted from the body (EFSA 2016); however, the remaining microplastics may be detrimental to human health, and further research is required to develop a more comprehensive understanding regarding public health aspects of microplastic pollution.

Oxidative stress and subsequent inflammation are both thought to be the main mechanisms of particle toxicity (Feng et al. 2016). Other potential biological responses to microplastic exposure include genotoxicity, apoptosis, and necrosis, which could ultimately lead to tissue damage, fibrosis, and carcinogenesis (Wright and Kelly 2017). The extent of potential adverse effects is dependent on particle size, and nanoparticles have been found to generate more reactive oxygen species (ROS) than larger particles and are more likely to be translocated (Stone et al. 2007). Consequently, potential health effects of microplastics largely depend on particle characteristics, and it is envisaged that nanoplastics are likely more deleterious than microplastics (Feng et al. 2016).

5.11 Consequences of Microplastics in Marine Animals

More than 690 marine species from different trophic levels have been reported to contain plastic debris; however, the transfer of microplastics and associated co-contaminants, from seafood to humans, and the implications for seafood safety have received limited attention to date (Carbery et al. 2018; Lusher et al. 2017a; Walkinshaw et al. 2020). Most studies conducted have considered the environmental rather than the potential human health impacts of micro- and nanoplastics. Effects of micro- and nanoplastic exposure reported in marine organisms include reduced growth, impacted energy metabolism, feeding behavior, and locomotion, effects on the immune system, and hormonal regulation, physiological stress, oxidative stress, inflammation, aberrant development, cell death, general toxicity, and altered lipid metabolism (Kögel et al. 2019). In humans, it is evidenced that consumers may be exposed to microplastics from seafood consumption; however, the risks remain unclear (Smith et al. 2018; VKM 2019).

Shellfish and small fish that are consumed whole are the seafoods which are likely to give the highest exposure risk since the gastrointestinal tract, which generally contains the highest microplastic concentrations, are consumed (van Raamsdonk et al. 2020). In contrast most fish species are filleted, and most crustaceans have their digestive tracts removed before consumption, thereby reducing microplastic exposure. Similarly, bivalves, shellfish, and other lower trophically positioned marine organisms are probably the most important seafood source of dietary exposure to microplastics (Walkinshaw et al. 2020). It has been estimated that the average European shellfish consumer may ingest up to 11,000 microplastics per year based on levels in mussels and oysters (van Cauwenberghe and Janssen 2014). A systematic review and meta-analysis of microplastic contamination in seafood reported a maximum annual consumption of 55,000 microplastic particles, with mollusks from Asia being the most heavily contaminated (Danopoulos et al. 2020).

The presence of several types of microplastics in human stool from different countries has been reported, with PP and PET being the most abundant types (Schwabl et al. 2019), indicating human exposure. However, there is currently no indisputable evidence on the effects of microplastics on human health (Toussaint et al. 2019). Potential health impacts can result directly such as tissue damage but also indirectly from environmental contaminants associated with microplastics or associated microorganisms (Oberbeckmann et al. 2015).

While the focus of the scientific literature has primarily been on human exposure to microplastics from seafood consumption, much less data is available on the occurrence of microplastics in other food groups, so their relative contribution is unknown which is important from a risk assessment perspective (Wright and Kelly 2017). Data on microplastics in foods (Kwon et al. 2020) other than seafood include sugar, salt, honey, and drinking water and beer (Karbalaei et al. 2018), whereas there are significant data gaps for plant- and terrestrial animal-derived foods (van Raamsdonk et al. 2020). To date there are also limited data on microplastic levels in freshwater fish (Collard et al. 2019) and terrestrial foods (e.g., vegetables, poultry). In addition to food and drinking water, inhalation is a potential route of exposure, and atmospheric fallout is thus also an important source of microplastic exposure (Dris et al. 2016; Allen et al. 2019). Catarino et al. (2018) concluded that the potential for microplastic ingestion from shellfish consumption was minimal, especially when compared to general air exposure from household dust (123–4620 particles/year/capita and 13,731–68,415 particles/year/capita from food versus dust, respectively). Similarly, Rist et al. (2018) highlighted that food and beverages likely only constitute a minor exposure pathway to human microplastic exposure. Based on the current knowledge on microplastics in seafood, there is no evidence that food safety is compromised (Gamarro et al. 2020).

The extent to which microplastics present in foods contribute to human exposure is not well understood, especially as studies evaluating microplastics and associated chemical exposure to humans are not consistent (Rist et al. 2018; Barboza et al. 2020a, b). Human exposure estimates in the USA to microplastics in food (seafood, sugars, salts, honey), drinking water, alcohol, and air found that inhalation was the main route of exposure for adults whereas drinking water was the main source for children (Cox et al. 2019). However, this study did not include major food groups such as meats, grains, and vegetables due to a lack of empirical data.

5.12 Challenges and Priorities in Marine Microplastic Research

Risk characterization including information on the particle size-dependent toxicokinetics and dynamics of microplastics is needed to calculate evidence-based guidance or tolerable weekly intakes to support realistic human health and exposure risk assessments. Discrepancies exist in the sampling, extraction, identification, and quantification of microplastics (Collard et al. 2019), and there is a need for harmonization of current procedures (Hartmann et al. 2019; Cowger et al. 2020). An effective risk assessment of the human health effects of microplastics requires reliable human exposure data which is currently limited (Toussaint et al. 2019). Knowledge gaps regarding the uptake and potential human health effects of microplastic exposure have been highlighted (EFSA 2016; Wright and Kelly 2017; van Raamsdonk et al. 2020).

Importantly, there is currently still a lack of harmonized and proven methods for microplastics which can compromise the level to which microplastic contamination in seafood species (and other foods) can be compared. Some recommendations have been presented which focus on the methods that – thus far – have proven efficient at isolating microplastics from biota tissues (e.g., Dehaut et al. 2019; Lusher et al. 2020; Ribeiro et al. 2020). The field of microplastic research has been moving very rapidly, with several advancements in methods emerging in parallel. It is therefore of great urgency to coordinate an effort to compare the field and laboratory-based methods to one another to determine the level of comparability and overall effectiveness. This is easier said than done. Currently, laboratory comparisons have been limited to scientific approaches conducted by individual research groups (e.g., Catarino et al. 2017; Karlsson et al. 2017; Thiele et al. 2019; Yu et al. 2019; Jaafar et al. 2020; Ribeiro et al. 2020), rather than between different institutions. Some interlaboratory efforts have been made, but these have generally focused on clean water samples, rather than complex matrices such as seafood material and biological tissues (e.g., ongoing EU-JRC and SCCWRP intercalibration exercises). Similarly, there are different reporting criteria that have been applied to the study of microplastics in biota, and the quantification of the microplastics is not standardized which presents some important challenges to this subdiscipline of environmental chemistry. Different measurement units are often used (e.g., numbers per weight or per individual) highlighting the need for harmonization and standardization.

Moving forward, methods will need to be adopted that are truly reproducible and that can be validated and compared using standard reference materials. This requires that validation and feasibility assessments are undertaken while also supporting initiatives that promote scientific discovery and method development. There are several methods that are promising, and utilizing these novel approaches will allow for the development of more robust and comparable methods across different sectors/regions within the sphere of microplastic research. Unfortunately, several methods are focused on the larger fraction of microplastics (e.g., >100 μm), and method development is still required for accurately detecting smaller microplastics (<20 μm) and nanoplastics (<1 μm). Methods that focus on smaller fractions are needed to support risk characterization and exposure assessments in marine biota and humans.

5.13 Future Recommendations and Conclusions

Microplastics are ubiquitously found in seafood, and the importance of standardized and harmonized methods for the effective biomonitoring of farmed and wild seafood species including bivalves and finfish has become evident (Lusher et al. 2017b; Hartmann et al. 2019; Ribeiro et al. 2020). Lower trophically positioned organisms may be at the highest risk of contamination from microplastics, and currently there is insufficient evidence to conduct realistic and meaningful human health risk assessments. Moreover, several seafood species from wild fisheries and aquaculture are not well studied in the context of global food security including commonly consumed taxa (Lusher et al. 2017a; Walkinshaw et al. 2020). Microplastic pollution and exposure to plastics and their associated co-contaminants via seafood consumption will likely serve as effective themes to help link the IOC-UNESCO's Decade of Ocean Science for Sustainable Development (2021–2030) with the UN Decade of Action on Nutrition (2016–2025) and to gather critical stakeholders and develop important sustainable development strategies to support ocean and human health. In conclusion, the effects of microplastics on food security are still largely unknown, and further research and robust biomonitoring efforts on seafood are required to elucidate potential impacts.

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