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REVIEW ARTICLE

Microplastics: an emerging threat to food security and human health

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Abstract Microplastic presence in seafood and foodstuff have been documented globally in recent studies. Consequently, human exposure to microplastics through the ingestion of contaminated food is inevitable and pose a risk to food security and human health. In this review, microplastics and related xenobiotics are defined, global evidence of microplastic pollution in seafood is reviewed, the impacts to commercial marine species and food security are discussed, and the current knowledge of its direct effects on human health is reviewed. In addition, limited information regarding food security and scientific gaps are identified. Although microplastics in the marine environment and its effects on marine organisms have been well documented, more research is needed to completely understand the implications of microplastics over food security and human health. Further research must focus on monitoring and eliminating microplastics along the food supply chain and determining the extent to which food security is affected by microplastic pollution.

Keywords Microplastic · Food security · Human health · Seafood · Food contamination

Introduction

Plastics are synthetic organic polymers created by the process of polymerisation of monomers extracted from hydrocarbons (Rios et al. 2007). The annual production of plastic products in 2016 reached > 335 million tons worldwide (PlasticsEurope 2018). As a consequence, plastics are ubiquitous in modern days (Hitchcock and Mitrovic 2019) and thus, are one of the most common and persistent pollutants to date. Plastic debris enters the oceans in many ways and constantly accumulates in marine environments (Ryan et al. 2009). These pollutants are known for many detrimental impacts such as entanglement, ingestion, effects on reproduction, and translocation of non-native species (Derraik 2002). The sea-based sources of plastic (shipping or fishing) are lower than land-based sources (industries, riverine, tourism and urbanization) in comparison (Andrady 2011). Hence, larger coastal cities produce larger plastic marine pollution.

While the impact that large plastic waste has on the marine environment has been the subject of research for a long time (Cole et al. 2011), microplastic pollution has gained attention by scientists and public perception in the last decade. Microplastics are generally defined as small plastic pieces smaller than 5 mm in diameter (Andrady 2017) and can be primary or secondary. Primary microplastics are manufactured to be of a microscopic size (Cole et al. 2011), including preproduction resin pellets, microbeads in cosmetics, toothpaste and blasting, powders for textile coatings, and drug delivery media (Shim et al. 2018), while secondary microplastics derive from the degradation of larger plastics (GESAMP 2016) due to photolytic, mechanical fragmentation and biological degradation (Browne et al. 2009), including plastic fragments, microfibers from fabric and rope, coatings, and debris from tire wear (Shim et al. 2018). Microplastics are known to adsorb chemical pollutants in trace concentrations, such as heavy metals, polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB), organochlorine pesticides (OCP), and pharmaceuticals (Brennecke et al. 2016; Camacho et al. 2019; Li et al.

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2018c; Rochman et al. 2014) and leach industrial additives, like polybrominated diphenyl ethers (PBDEs), used as brominated flame retardants, lead heat stabilizers and phthalate plasticizers (Halden 2010; Lithner et al. 2011), resulting in a cocktail of contaminants (Rochman 2015). Due to their small size and spatial distribution in the marine environment, microplastics are highly bioavailable for many organisms. Ingestion of microplastics by marine animals has been widely reported in fish (Kumar et al. 2018; Pegado et al. 2018), bivalves (Li et al. 2018a; Su et al. 2018), and mammals (Bravo et al. 2013) sampled from the marine environment.

Although the distribution and effects of microplastics on the environment have been researched, the presence of microplastics in food and the implications for human health are still to be investigated. Fish and shellfish consumption can have health benefits due to their high protein content, omega fatty acids, nutrients and minimum saturated fats (Arts et al. 2001; Pieniak et al. 2010). However, marine food is highly susceptible to xenobiotics and emerging contaminants from the environment (Thompson and Darwish 2019). As for now, studies have reported the presence of microplastics in commercial shellfish from markets (Cho et al. 2019; Li et al. 2018b), canned fish (Karami et al. 2018), drinking mineral water (Schymanski et al. 2018), table salts (Renzi and Blašković 2018), honey and sugar (Liebezeit and Liebezeit 2013). Akhbarizadeh et al. (2018) found microplastics in the muscles of benthic and pelagic fish species from the Persian Gulf. Accordingly, microplastic uptake by commercial fish species should be considered as a potential pathway to human consumption.

The effects of microplastics on human health and how it compromises food security requires further research. For this reason, the aim of this review is to evidence the presence of microplastics in food and explain its implications to food security and potential risks to human health.

Microplastic presence in food

The increasing global concern about microplastic aquatic pollution is leading to an extensive number of studies assessing microplastics in the past years (Wang and Wang 2018), but researchers have recently focused on its implications to food security and human health. Many commercially relevant fish and shellfish species have been reported to be contaminated with microplastics. Ory et al. (2017) reported that 80% of the sampled *Decapterus muroadsi* (Carangidae) from the coast of Rapa Nui, in the South Pacific subtropical gyre, had ingested microplastics very similar to its natural prey, thus indicating one important pathway for microplastics to enter the food chain. Baalkhuyur et al. (2018) assessed microplastic ingestion in 26 different fish species from different habitats from the Saudi Arabian Red Sea coast. Microplastics were found in 14.6% of the sampled fish, and the highest concentration of ingested microplastics was observed in *Parascolopsis eriomma*, a species feeding on benthic invertebrates (Baalkhuyur et al. 2018). Concerning bivalves, Van Cauwenberghe and Janssen (2014) evidenced the presence of microplastics in two commercially grown bivalves, *Mytilus edulis* and *Crassostrea gigas*, containing an average of 0.36 $\pm$ 0.07 particles/g and 0.47 $\pm$ 0.16 particles/g respectively. These results indicate that European shellfish consumers can eat up to 11,000 microplastics annually (Van Cauwenberghe and Janssen 2014). A research on cultured oysters from the coast of China found that 84% of the sampled oysters were contaminated with microplastics, with an average of 0.62 particles/g (Teng et al. 2019).

Although scientists have focused on the presence of microplastics in organisms sampled from the environment, very few studies have reported microplastics in seafood species coming directly from markets and supermarkets (e.g. Cho et al. 2019; De Witte et al. 2014; Li et al. 2015, 2018b; Rochman et al. 2015; Van Cauwenberghe and Janssen 2014). Li et al. (2015) investigated microplastic pollution in nine commercial bivalves from a fishery market in China. Their results indicate that all the bivalve species had breathed microplastics with concentrations ranging from 2.1 to 10.5 particles/g, being *Scapharca subcrenata* the species with the highest concentrations (Li et al. 2015). Li et al. (2018b) also investigated the mussel *Mytilus edulis* from markets from six different locations around the UK and reported higher microplastic concentrations in pre-cooked mussels (1.4 particles/g) than in the ones supplied live (0.9 particles/g). This suggests that the pre-process of pre-cooked mussels could imply a higher exposure to microplastics coming from the process itself due to insufficient cleaning standards and not necessarily from the environment. Cho et al. (2019) surveyed the microplastic presence in four commercial bivalves from three major cities of South Korea. The mean concentration of microplastics in the four species was 0.15 $\pm$ 0.20 particles/g and it was estimated that the Korean population intakes 212 particles/person/year from shellfish consumption (Cho et al. 2019). All this evidence shows that trophic transfer of microplastics in aquatic organisms is making a pathway for wastes and contaminants into our diet (Fig. 1).

Although microplastic presence in the marine environment have been widely researched, terrestrial ecosystems have been overlooked. There is little information on microplastic degradation by organisms in the plant's rhizosphere (Wang et al. 2019). However, microplastics in soil could significantly alter plant biomass, tissue elemental

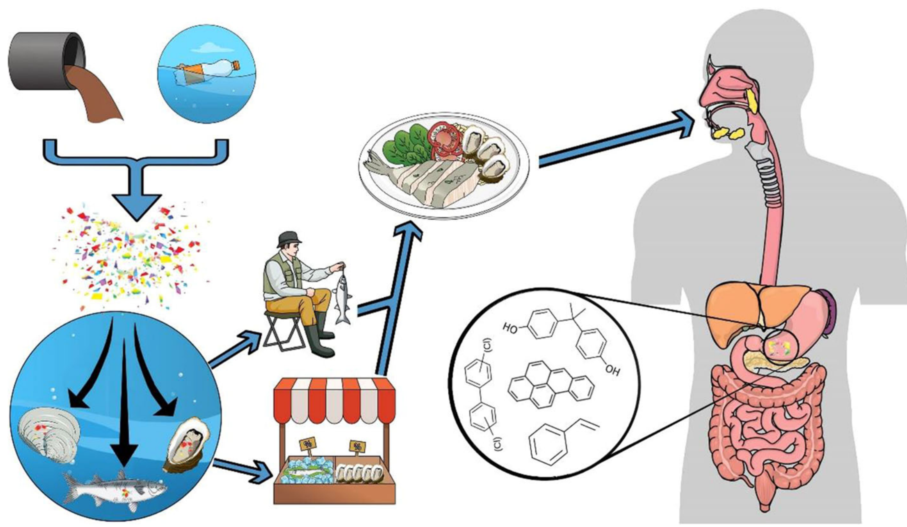

Fig. 1 A model showing how anthropogenic activity cause microplastics to enter the food web, make a path to our food and, ultimately, our organs

composition, root traits and microbial activities (de Souza Machado et al. 2019). The presence of microplastics haven been evidenced in terrestrial edible snails *Helix aperta*, *Helix aspersa* and *Helix pomatia* (Panebianco et al. 2019), hence contributing to the risk assessment of human exposure to microplastics deriving from food consumption.

Other products consumed as food or used for cooking have been evidenced to be contaminated with microplastics. Microplastics have been found in drinking mineral water (Schymanski et al. 2018), beer, tap water (Kosuth et al. 2018), table salts (Renzi and Blašković 2018), canned food (Karami et al. 2018), and honey and sugar (Liebezeit and Liebezeit 2013). These reports evidence how microplastics have become ubiquitous in human foodstuff and drinks. Low concentration but chronic exposure and intake of microplastics by humans pose a potential threat to human health.

Although some studies are mentioned, there is still knowledge gaps regarding the occurrence of microplastics in foodstuff. There is a lack of standardized methods, monitoring techniques and protocols and no regulatory framework for microplastics in seafood and foodstuff and hence more research is required globally.

Food security

According to the Food and Agriculture Organization of the United Nations (FAO), "food security is 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 2002). The four main pillars of food security are food availability, access, utilization and stability (FAO 2009). Each pillar is equally important for food security. In brief, these pillars are defined by Mc Carthy et al. (2018) as:

a. Food availability: This pillar refers to having a sufficient quantity of food as a minimum and considers imported or locally produced food. It also takes into account the current food stocks for a particular region and the provision for food aid coming from other countries.
b. Food access: This pillar considers the physical and economic access to food. The main factors within this pillar are the purchasing power of the region and its income level. Another factor to consider is local infrastructure.
c. Food utilization: This pillar encompasses the whole food supply chain and handling. It addresses the production, processing, distribution, retail and household stages of the food supply chain from a hygiene point of view.
d. Food stability: This pillar considers stability of food supply and access, commonly affected by the local political issues, economy and pricing. Also, regional weather pattern changes and climate change cannot be ignored.

The presence of microplastics in seafood compromises the pillars of food availability and utilization. After ingestion, marine organisms cannot break down synthetic polymers through enzymatic activity, meaning microplastics could be retained and not be digested (Guzzetti et al. 2018). This blocks food passages and parts of the intestinal tract (Tourinho et al. 2010), causing reduced feeding and disturbing food digestion in smaller organisms. In microalgae, microplastics have shown to cause a reduction in photosynthetic activity and growth (Sjollema et al. 2016). Ingested microplastics could potentially be adsorbed through the digestive system by translocation (Cole et al.

2011). Microplastics transfer through the food web (Setälä et al. 2014) and bioaccumulate in more complex organisms. Lu et al. (2016) exposed *Danio rerio* to micro- and nano-sized microplastics in different concentrations. Microplastics accumulated in gills, liver and gut, causing inflammation, lipid accumulation in the liver and oxidative stress instauration evidenced by the increase in superoxide dismutase and catalase enzymes (Lu et al. 2016). However, the specific effects of microplastic ingestion alone could significantly vary depending on the species and environmental conditions. A bigger concern to the marine biota is the pollutants absorbed or adhered to the microplastics and the leaching of toxic plastic additives. As mentioned before, microplastics are known to interact with heavy metals, PAHs, PCBs, OCPs, PBDEs and pharmaceuticals (Brennecke et al. 2016; Camacho et al. 2019; Fonte et al. 2016; Li et al. 2018c; Rochman et al. 2014). Some of these pollutants are considered toxic, endocrine disruptors, mutagens and biomagnify through trophic transfer (Cole et al. 2011). For example, styrene oligomers (SOs) are low molecular weight compounds derived from polystyrene (Kwon et al. 2017). Kwon et al. (2015) researched the concentration of SOs in sand and seawater from coastal regions around the world. Their results revealed that in Greece, Los Angeles (USA), and Costa Rica, SOs pollution in sand samples reached up to 31,400.0 μg/kg, 29,106.8 μg/kg, and 26,277.4 μg/kg respectively (Kwon et al. 2015). This indicates alarming levels of pollution with SOs and polystyrene. Considering the synergic interaction with other pollutants, microplastics act as a vector of many potentially toxic xenobiotics. The magnitude of microplastics impact on marine biota from an ecological level is still poorly understood. Nonetheless, microplastic presence and interaction with other organic and inorganic pollutants compromises the health and populations of different marine species. Consequently, the reduction of seafood species populations threatens the pillar of availability, especially in regions dependent on fishing as one of their main sources of food.

The physical properties of plastic materials can make a suitable habitat for diverse microbial communities (Zettler et al. 2013). Biofilms colonizing the plastic surface could become a reservoir for pathogens, faecal indicator organisms and algal bloom species (Keswani et al. 2016), and acting as vector for microorganisms. Recent studies have confirmed the presence of potentially harmful microbes colonizing microplastics from the environment. Kirstein et al. (2016) sampled microplastics from the North and Baltic seas using Neuston nets and later isolated bacterial colonies from the microplastics. Their results confirm the presence of a pathogenic *Vibrio parahaemolyticus* in various types of polymers (Kirstein et al. 2016). Importantly, ingestion of microplastics colonized by *V. parahaemolyticus* might compromise the survival of shrimp populations in natural waters and hatcheries conditions. Other pathogenic communities colonizing microplastics have been reported (e.g. Virsek et al. 2017). A laboratory research by Harrison et al. (2014) confirmed in a 14-day microcosm experiment that bacteria can colonize low-density polyethylene in little time. Uptaken microplastics by marine organisms are retained through the entire supply chain process, reaching markets and supermarkets (Cho et al. 2019; Li et al. 2018b; Rochman et al. 2015) and ultimately served for consumption. All this evidence suggests that the colonization of microplastics from the environment and its accumulation in seafood exposes humans to pathogenic microbes. Hence, microplastic exposure to environmental microbes compromises the pillar of food utilization.

Although there is a firm connection between microplastic pollution to seafood and the pillars of food availability and utilization, there still little information available to understand up to what extent microplastics could compromise food security. Further research should focus on a macroscale of the impacts of microplastics to make an understanding of the impact to food security.

Exposure and human health

The main sources of human exposure to microplastics are through inhalation, ingestion and skin contact. Inhaled airborne microplastics come chiefly from synthetic textiles, powdered synthetic rubber tires and city dust (Prata 2018); eating contaminated seafood, other kinds of food and drinking contaminated water are the main pathways to the gastrointestinal tract. Organisms that are eaten completely present a higher risk than eviscerated ones (Carbery et al. 2018). Although the human skin prevents microplastics and other contaminants to pass directly through, some possible entry routes are sweat glands, open skin injuries or hair follicles (Schneider et al. 2009). All three sources of exposure are key to account for the absolute microplastic exposure by humans, yet those coming from seafood and the environment could represent a higher threat due to weathering, leaching of plastics additives, residual monomers (Araujo et al. 2002), longtime interaction with other toxic pollutants (Brennecke et al. 2016; Camacho et al. 2019; Li et al. 2018c; Rochman et al. 2014) and pathogenic microorganisms from the environment (Virsek et al. 2017).

According to Catarino et al. (2017), microplastic ingestion through contaminated mussels is minimal compared to airborne household fibers that fall into our meal. However, estimating microplastic ingestion by humans depends on microplastic content, consumption habits and rates at a local level. For example, Cho et al. (2019)

estimated that the average Korean ingests 212 particles/person annually, via the consumption of oysters, mussels, manila clams and scallops, while Van Cauwenberghe and Janssen (2014) calculated that the European minor shellfish consumers ingest around 1800 microplastics annually and top shellfish consumers could ingest up to 11,000 microplastics per year. Chinese consumers could reach a higher annual dietary exposure (Li et al. 2015). Indeed, human exposure to microplastics varies significantly in globally every region.

Following microplastic ingestion, particles smaller than 150 μm may translocate to the lymph and circulatory system, but absorption is expected in less than 0.3% of the ingested particles (Barboza et al. 2018). Absorption happens through pinocytosis and vesicular phagocytic processes (Galloway 2015); Microfold cells in the Peyer's patches are the main site of uptake (Van Cauwenberghe and Janssen 2014) for nanoparticles to enter the circulatory system and through the lymphatic system (Galloway 2015). Only $\leq$ 20 μm particles could penetrate into certain organs (Barboza et al. 2018) and the smallest nano-sized plastic particles may access all organs and be transported across cellular membranes (Bouwmeester et al. 2015). Laboratory studies have demonstrated cellular uptake of nanoparticles using different human cell lines (e.g. Forte et al. 2016; Fuchs et al. 2016; Liu et al. 2018; Walczak et al. 2015). The direct effects of nanoparticles are cytotoxicity, inflammation, and production of reactive oxygen species (Elsaesser and Howard 2012). Brown et al. (2001) and Forte et al. (2016) conducted laboratory experiments with polystyrene nanoparticles in A549 lung cells and human gastric adenocarcinoma cells respectively, both showing induced pro-inflammatory responses. Larger polyethylene particles (0.3–10 μm) have shown to stimulate the production of cytokines, like IL-6, IL-1β, and TNF-α (Green et al. 1998), of which some are inflammatory factors.

One common plastic additive is bisphenol A (BPA), used as an antioxidant or stabilizing material (Yamamoto et al. 2001). BPA can cause endocrine disrupting effects (Halden 2010). It is able to migrate out of polycarbonates, adhering to food or drinks (Calafat et al. 2008), and consequently be ingested by humans. Studies have reported BPA contamination in tuna fish (Munguía-López et al. 2005), meat (Shao et al. 2007), and tap water (Colin et al. 2014), showing how this contaminant could reach highly consumed foods. Meeker et al. (2010) found that BPA concentrations in urine of 167 men were inversely associated with serum levels of inhibin B and estradiol:testosterone ratio, meaning a negative effect on hormones level. BPA could also contribute to obesity development by disturbing alpha and beta receptors in fat tissues (Michalowicz 2014), affecting fat tissue hormones level and interfering with the activity of lipoprotein lipase, aromatase and lipogenesis regulators (Vom Saal et al. 2012). It may induce breast and prostate cancer in mammals, possibly promoting the same types of cancer in humans (Michalowicz 2014). Research have shown that other chemical compounds present in plastics or adhered to microplastics, like residual low molecular weight styrenes, polyvinyl chloride monomer, PAHs, PCBs, OCPs, PBDEs, and pharmaceuticals, including their metabolites, could become carcinogenic, mutagenic and endocrine disruptors after being uptaken.

Conclusion and future research

Microplastic pollution in marine environments pose a risk to food security and human health. Research has proven the presence of microplastics in seafood and foodstuff around the world, meaning we are always exposed to microplastic ingestion. Nonetheless, little is known about its direct effects on human health. Future research should focus on microplastic monitoring techniques along the supply chain. There is a lack of information on the extent to which food security is affected by microplastic presence. Finally, plastic waste management must be improved, along with microplastic legislation.

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