



The ecotoxicological effects of microplastics on aquatic food web, from primary producer to human: A review

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ABSTRACT

The prevalence of microplastics in global waters raises the concern about their potential effects on aquatic biota. In aquatic environment, microplastics are almost ubiquitously present in all compartments from surface water to benthic sediment, making them accessible to a wide range of aquatic biota occupying different habitats. Exposure to microplastics may induce detrimental implications to the health of aquatic organisms. This review describes the wide occurrence of microplastics ingestion by aquatic fauna and evaluates the ecotoxicological effects of microplastics as well as the associated chemicals on aquatic biota including phytoplankton and fauna from both freshwater and marine environments. Trophic transfer of microplastics and associated contaminants along the aquatic food chain and potential impacts on human health are also discussed. Finally, this review emphasizes the current knowledge gaps and gives recommendations for the future work.

1. Introduction

Plastics consist of a large variety of polymer types, including polypropylene (PP), polyethylene (PE), polystyrene (PS), polyvinylchloride (PVC), polyethylene terephthalate (PET), polyamides (PA), and so on, which are mainly made from fossil fuels such as petroleum, natural gas, or coal, and are designed to meet the very different needs of end products. Thanks to their versatility, durable nature and high cost-effectiveness, plastics have played a crucial role in many strategic sectors, such as packaging, building and construction, transportation, electrical and electronic devices, agriculture, medical facilities, and sports (PlasticsEurope, 2017). The extensive application of plastics expedites the speed of world's plastic production, which has witnessed a sustained growth in the past decades and reached a yield of 335 million tonnes in 2016 (PlasticsEurope, 2017). The majority of plastics are intended for packaging that may become waste after a short service life (World Economic Forum et al., 2016). Due to the vast usage of plastic products, improper disposal of plastic waste, and refractory nature of plastic materials, plastic debris is accumulating at an uncontrolled rate in both terrestrial and marine ecosystems (Barnes et al., 2009; Rillig, 2012). It is estimated that at least 8 million tonnes of plastic waste ends into the world's oceans each year and by 2050 the weight of marine plastics would exceed that of fish (World Economic Forum et al., 2016). Rapid accumulation of plastic fragments in the natural environment has raised increasing global concerns (Auta et al., 2017; Cozar et al., 2014).

The released plastics are generally subjected to progressive fragmentation under the comprehensive function of environmental physico-chemical and biotic factors, such as mechanical abrasion, ultraviolet radiation, and biological degradation by microorganisms (Barnes et al., 2009; Cole et al., 2011). Breakdown of larger plastic debris can generate a myriad of secondary microplastics (< 5 mm in size), constituting the major source of microplastics in the aquatic environment (Jiang, 2018). In addition, plastics can also be originally manufactured in a microscopic size as primary microplastics, which are commonly applied as scrubbers in some personal care products, or as resin pellets for plastic production (Cheung and Fok, 2017; Cole et al., 2011). Primary microplastics may eventually end up in the water body via surface run-off, wastewater treatment plants discharge, or domestic and industrial drainage systems (Murphy et al., 2016). Numerous monitoring programs have demonstrated the pervasive presence of these micro-sized plastic particles in various aquatic ecosystems across the globe (Auta et al., 2017; Jiang, 2018).

Once entering into the aquatic systems, microplastics can widely disperse in different environmental compartments (surface water, water column and benthic sediment) due to varieties in shapes and polymer densities, which may affect their availability to the aquatic biota occupying different habitats or trophic levels (Cole et al., 2011; de Sá et al., 2018; Thompson et al., 2009). Evidence of microplastics ingestion has been observed in a long list of aquatic fauna ranging from small invertebrates to large predatory mammals (Bravo Rebolledo et al.,

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2013; Cole et al., 2013; Sanchez et al., 2014). Consumption of these tiny plastic particles can not only adversely impact the organisms that ingest them, causing mechanical injury and inflammatory responses (Wright et al., 2013), but also provides a viable route for introduction of some hazardous substances (including the endogenous plastic additives, pollutants absorbed from the ambient environment, and pathogenic microorganisms) into the aquatic food web (Crawford and Quinn, 2017; Tanaka et al., 2013; Zettler et al., 2013). Furthermore, the wide occurrence of microplastics ingestion by edible aquatic fauna poses a potential risk to food safety and human health (Van Cauwenberghe and Janssen, 2014).

A better understanding of the biological impacts of microplastics assists in properly assessing the environmental risks of this emerging contaminant. However, existing reviews on microplastics mostly emphasize on collating their source, occurrence, abundance, and analytical methods in different environmental compartments (Auta et al., 2017; Cole et al., 2011; Jiang, 2018; Wang and Wang, 2018). Although there have been several reviews regarding the toxic effects of microplastics on aquatic organisms, most of them are focused on the marine fauna (Auta et al., 2017; Carbery et al., 2018; Cole et al., 2011; Crawford and Quinn, 2017; Wright et al., 2013). In addition, there is an immense lack of knowledge on the trophic transfer process of microplastics and the associated contaminants from aquatic food web to human beings and the resulting implications for human health. This review collates what have been known about ecotoxicological effects of microplastics and associated compounds to aquatic biota involving both freshwater and marine organisms ranging from primary producers to various aquatic fauna. Potential risks of microplastics uptake to human health are also discussed. By summarizing these, we aim to characterize ecological risks of microplastics to aquatic biota and outline promising areas for future research.

2. Literature review

An extensive literature review was conducted using the ISI Web of Science (<http://apps.webofknowledge.com>) and ScienceDirect (<https://www.sciencedirect.com>) databases for studies up to 2018. The keyword queries included “microplastics”, “plastics” in combination with “organisms/biota”, “ingestion/uptake/transfer”, “effects/impacts/toxicity”. The retrieved publications were then previewed individually to remove duplicates and irrelevant papers. Ultimately, in total 43 literatures were selected and summarized based on the following criteria: environmental compartments (freshwater and marine water), biological groups of studied organisms, and observed ecotoxicological effects of microplastics on biota.

3. Occurrence of microplastics ingestion by aquatic fauna

In natural aquatic ecosystems, microplastics can float on the water surface, disperse in the water column of different depths, and accumulate in the sediment, making them accessible to a wide array of aquatic organisms occupying different habitats. The ubiquitous presence of microplastics, in addition to their similar size range and appearance as plankton, significantly increases the likelihood of microplastics ingestion by aquatic fauna (Cole et al., 2011). As is shown in Table 1, microplastics have been detected in digestive tracts or tissues of a considerable number of field collected marine animals, including crustaceans (Desforges et al., 2015), fish (Alomar and Deudero, 2017), bivalves (Van Cauwenberghe and Janssen, 2014), turtles (Hoarau et al., 2014), mammals (Bravo Rebolledo et al., 2013), seabirds (Tanaka et al., 2013), and so on. Freshwater suffers comparable levels of microplastics pollution to the oceans, while field studies concerning microplastics quantification within freshwater fauna are thus far highly limited. Existing evidence suggests that freshwater organisms also ingest microplastics (Faure et al., 2015; Su et al., 2018). The occurrence of microplastics consumption by both marine and freshwater organisms has also

been verified in laboratory studies (Table 3).

Microplastics uptake in most cases occurs accidentally due to the inability of aquatic living organisms in distinguishing microplastics from the natural prey items, while preying on lower trophic organisms that have been contaminated by microplastics can also result in introduction of microplastics into the aquatic food web (Auta et al., 2017; Carbery et al., 2018). There are many factors that affect the possibility of microplastics ingestion occurring. Compared with predators, filter, suspension and deposit feeders are generally believed to be additionally susceptible to microplastics uptake, because of their unselective feeding strategy (Wesch et al., 2016). The size of microplastics determines the aquatic taxa that ingest them, since organisms are more likely to consume particles with a similar size range as their natural preys (Cozar et al., 2014; Wright et al., 2013). The varying polymer densities of microplastics enable their pervasive vertical distribution in the aquatic environment from surface water to benthic sediment, thus influencing the bioavailability of these tiny particles to different aquatic organisms (Cole et al., 2011). For instance, pelagic species (e.g., zooplankton) are susceptible to low-density, floating plastics such as PE and PP, while benthic taxa (e.g., mollusc) are more likely to encounter high-density plastics, such as PVC and PET. The formation of biofilms on the surface of microplastics can not only affect the vertical transport of microplastics but also attract organisms with chemoreceptors to select prey by producing olfactory and gustatory cues (Carbery et al., 2018). Other factors such as the color, shape and abundance of microplastics are also likely to affect the bioavailability of microplastics in aquatic environments (Crawford and Quinn, 2017; Wright et al., 2013).

4. Ecotoxicological effects of microplastics on aquatic biota

The prevalence of microplastics in aquatic environments makes a broad range of aquatic taxa susceptible to these emerging pollutants. More than 690 species of aquatic fauna have been reported to ingest macro- or microplastics (Provencher et al., 2017). Once ingested, microplastics may induce uncertain consequences to the health of aquatic organisms (de Sá et al., 2018; Wright et al., 2013). Furthermore, although having not received enough attention, interactions between microplastics and aquatic primary producers might be another issue of concern, if taking into account the huge quantities of microplastics in global waters. Until recently, studies with regard to the biological impacts of microplastics were mostly conducted under controlled laboratory conditions.

4.1. Microplastics effects on aquatic primary producers

Up to now, knowledge about the ecotoxicological effects of an aquatic primary producers is highly limited. Existing studies on this issue have been restricted to the aquatic phytoplankton (microalgae), with most of them focusing on the growth dynamics of phytoplankton after exposure to microplastics (Table 2). It has been observed that microplastics exposure could result in a significant reduction on the growth of microalgae (Besseling et al., 2014; Casado et al., 2013; Sjollem et al., 2016), and with increasing exposure dosage, the inhibitory effects would be enhanced (Mao et al., 2018). However, the adverse effect of microplastics on algae growth seemed to be weakened as the particle size increased (Zhang et al., 2017).

Recently, some efforts have also been made to explore the physiological and biochemical response of aquatic phytoplankton to microplastics. Studies on freshwater microalgae demonstrated that microplastics exposure could not only cause a large variety of physical damages and oxidative stresses to the algae cells, but also affect the expression of genes involved in certain metabolic pathways (Lagarde et al., 2016; Mao et al., 2018). Zhang et al. (2017) reported that exposure to PVC microspheres resulted in significant reduction in the chlorophyll content and photosynthetic efficiency of *Skeletonema costatum*. Combined cultivation of *Chaetoceros neogracile* and microplastics

Table 1
Studies of microplastics ingestion by aquatic organisms in the natural environment.

Class	Species	Location	Microplastics load	Reference
Marine				
Crustacea	<i>Neocalanus cristatus</i>	Northeast Pacific Ocean	1 particle per 34 copepods	(Desforges et al., 2015)
	<i>Euphausia pacifica</i>		1 particle per 17 euphausiids	
Polychaete	<i>Arenicola marina</i>	French-Belgian-Dutch North Sea coast	1.2 ± 2.8 particles/g (wet weight)	(Van Cauwenberghe et al., 2015)
Mollusca	<i>Mytilus edulis</i>	North Sea and Atlantic Ocean	0.27 ± 0.3 particles/g (wet weight)	(Van Cauwenberghe and Janssen, 2014)
	<i>Crassostrea gigas</i>		0.47 ± 0.16 particles/g (wet weight)	
Fish	<i>Galeus melastomus</i>	Western Mediterranean Sea	0.34 ± 0.07 particles per individual	(Alomar and Deudero, 2017)
Turtle	<i>Caretta caretta</i>	South-West Indian Ocean	96.2% of the turtle-ingested debris were plastics	(Hoarau et al., 2014)
Mammal	<i>Megaptera novaeangliae</i>	North and west coast of Ireland	A total of 16 plastic particles were found	(Besseling et al., 2015)
	<i>Phoca vitulina</i>	The Netherlands	0.26 particles per individual	(Bravo Rebolledo et al., 2013)
Bird	<i>Puffinus tenuirostris</i>	North Pacific Ocean	0.04–0.59 g per bird	(Tanaka et al., 2013)
Freshwater				
Oligochaeta	<i>Tubifex tubifex</i>	River Irwell, England	129 ± 65.4 particles/g tissue (wet weight)	(Hurley et al., 2017)
Mollusca	<i>Corbicula fluminea</i>	Taihu Lake, China	0.2–12.5 particles/g (wet weight)	(Su et al., 2018)
Fish	<i>Gobio gobio</i>	Eleven French Rivers	12% of the collected fish contained microplastics	(Sanchez et al., 2014)
Bird	<i>Ardea cinerea</i>	Lake Geneva, Switzerland	4.3 ± 2.6 particles per bird	(Faure et al., 2015)
	<i>Cygnus olor</i> <i>Anas platyrhynchos</i>			

could induce formation of hetero-aggregates consisting of both algae cells and microplastic particles due to the release of extracellular sticky polysaccharides by the algae cells (Long et al., 2017).

It seemed that the toxicity of microplastics to phytoplankton varies with many factors, such as the particle size (Zhang et al., 2017), polymer type (Lagarde et al., 2016), concentration of microplastics (Mao et al., 2018), the exposure time, and the target species (Long et al., 2017). However, the environmental relevance and toxicity mechanisms are still unclear. In view of the important role phytoplankton plays in aquatic food webs and the rapid growth of microplastics quantities in aquatic environments, it is highly recommended to conduct further studies to elucidate how microplastics affect the survival, growth and function of these aquatic primary producers.

4.2. Effects of microplastics ingestion on aquatic fauna

The ecotoxicological effects of microplastics on aquatic fauna have been investigated by an increasing number of laboratory studies, using both marine and freshwater taxa representing different trophic levels of the aquatic food web (Table 3). Once microplastics are ingested by aquatic animals, perhaps the most direct effects are caused by accumulation of these inert particles in the digestive systems of the organisms (Wright et al., 2013). The ingested microplastics may accumulate in and even block the digestive tracts of aquatic animals, which thereby results in diminished feeding impetus due to false satiation (de Sá et al., 2018). A study using the copepod *Centropages typicus* demonstrated that feeding rate of the tested organisms kept decreasing with increasing addition of microplastics (Cole et al., 2013). Similar results were also reported by Welden and Cowie (2016) using the crustacean *Nephtys norvegicus* and Watts et al. (2015) using the shore crab *Carcinus maenas*.

Sustained decrement in feeding could in turn lead to a variety of detrimental effects on aquatic organisms, such as reduced body weight (Welden and Cowie, 2016), growth inhibition (Watts et al., 2015), impairment of the reproductive system (Lei et al., 2018), diminished mobility (Rehse et al., 2016), and even mortality (Rist et al., 2016). Microplastics ingestion can also induce other adverse impacts, including physical damage of digestive organs, oxidative stress, alteration in enzyme production and metabolism, and embedment in tissues (Lei et al., 2018; Welden and Cowie, 2016). In addition, as microplastics continue to breakdown into smaller particles, the possibility for these tiny plastics to penetrate into the circulatory systems and phagocytic cells of exposed organisms increases, which may thereby introduce additional harm to the organisms due to long-term retention of microplastics in their body and in the meanwhile facilitate the transfer of microplastics to higher trophic predators (Browne et al., 2008; Farrell

and Nelson, 2013). However, it seems that the actual effects associated with microplastics ingestion on aquatic animals vary with the exposed animals per se and physicochemical characteristics of microplastics (de Sá et al., 2018). Therefore, it is highly encouraged to conduct further research using an extended range of aquatic species and microplastics of differing size, shape, and composition, in order to clarify the actual effects of microplastics on a specific organism and the hidden interaction mechanisms.

4.3. Combined effects of microplastics and associated contaminants

The large surface-volume ratio and hydrophobicity enable microplastics to accumulate waterborne toxic contaminants (e.g., persistent organic pollutants and heavy metals) to a concentration considerably higher than that of the ambient water (Holmes et al., 2012; Mato et al., 2001). In addition, it is common that plastics are manufactured to contain some additives, such as alkylphenols, bisphenol A, polybrominated diphenyl ethers, and phthalates, for the purpose of improving performance of the end product (Barnes et al., 2009). Once leaching out, these plastic additives may induce toxic effects to the aquatic biota. Potentially harmful microorganisms colonizing the plastic might also threaten the aquatic foodweb (Zettler et al., 2013). Despite microplastics per se being biochemically inert, the leaching of plastic additives in addition to accumulation of other toxicants and pathogenic microorganisms makes microplastics a complex cocktail of harmful substances (Cole et al., 2011; Zettler et al., 2013). Uptake of contaminated microplastics by aquatic organisms provides a feasible way for introduction of these hazardous substances into the aquatic food web.

To date, a considerable number of studies concerning the combined effects of microplastics and other toxicants have been conducted using aquatic organisms across several groups (Table 4). Most of these studies were aimed at verifying whether or not the presence of microplastics could enhance the toxicity of other environmental pollutants to aquatic biota, because in the natural environment aquatic living organisms are simultaneously exposed to the complex mixture of microplastics and adhered substances. It has been demonstrated in laboratory studies that exposure to microplastic and toxic contaminants could result in bioaccumulation of the latter in aquatic animals that ingested microplastics (Avio et al., 2015; Khan et al., 2015). Field studies on African seabirds (*Puffinus gravis*) and Northern Pacific seabirds (*Puffinus tenuirostris*) also proved the possibility of microplastics ingestion to introduce plastic-derived chemicals into biological tissues (Ryan et al., 1988; Tanaka et al., 2013). Microplastics in combination with noxious chemicals could also induce other adverse implications on aquatic

Table 2
Studies of microplastics effects on microalgae.

Species	Microplastics		Exposure time	Biological effects	Reference
	Type	Size (µm)			
Marine					
<i>Dunaliella tertiolecta</i>	PS	0.05–6	25 & 250 mg/L 72 h	Significant inhibition on the algae growth with no effects on photosynthesis.	(Sjollema et al., 2016)
<i>Tisochrysis lutea</i> ; <i>Chaetoceros neogracile</i> ; <i>Heterocapsa triquetra</i>	PS	2	3.96 & 39.6 µg/L 30 d	Formation of hetero-aggregation for <i>C. neogracile</i> ; No effect on the algae growth and chlorophyll fluorescence.	(Long et al., 2017)
<i>Tetraselmis chuii</i>	PE	1–5	0.046–1.5 mg/L 96 h	No significant on the algae growth.	(Davaranpanah and Guilhaermimo, 2015)
<i>Skeletonema costatum</i>	PVC	1	0–50 mg/L 4 d	Inhibition on the algae growth; chlorophyll content and photosynthesis.	(Zhang et al., 2017)
Freshwater					
<i>Chlorella pyrenoidosa</i>	PS	0.1 & 1	10–100 mg/L 30 d	Inhibition on the algae growth from the lag to the earlier logarithmic phases; Resulting in reduced photosynthetic activity, unclear pyrenoids, distorted thylakoids and damaged cell membrane.	(Mao et al., 2018)
<i>Chlamydomonas reinhardtii</i>	PP & HDPE	400–1000	1 g/L > 78 d	No significant influence on growth and expression of genes involved in stress response; Enhanced expression of genes involved in sugar biosynthesis pathways.	(Lagarde et al., 2016)
<i>Scenedesmus obliquus</i>	PS	~0.07	44–1100 mg/L 72	Inhibition on algae growth;	(Besseling et al., 2014)
<i>Pseudokirchneriella subcapitata</i>	PS	0.055 & 0.1	0.1–1 mg/L 72	Reduction in Chlorophyll-a content. Inhibition on algae growth.	(Casado et al., 2013)

PS: polystyrene; PP: polypropylene; PE: polyethylene; PVC: polyvinylchloride; HDPE: high-density polyethylene.

biota, such as neurotoxicity (Avio et al., 2015), organ pathology (Rochman et al., 2013), metabolic abnormalities (Oliveira et al., 2013; Rist et al., 2016), and mortality (Browne et al., 2013). However, to what extent microplastics ingestion accelerates the transfer of the associated toxicants to aquatic biota is still controversial, especially in comparison with other exposure pathways (Koelmans et al., 2016). Although microplastics can potentially serve as vectors for pathogenic microbes, the resulting implications are currently unknown.

5. Trophic transfer of microplastics in aquatic food web

Despite few studies thus far attempting to track the transfer of microplastics through the aquatic food chain, existing evidence suggested that this phenomenon did occur. Microplastics have been detected in a large number of field collected aquatic organisms, including large predatory animals (Table 1). As aquatic predators tend to choose their prey purposively, bioaccumulation is likely to be an important pathway for introduction of microplastics into these animals. A study by Eriksson and Burton (2003) reported that microplastics were widely discovered in scats from the Antarctic fur seal *Arctocephalus tropicalis* and *Arctocephalus gazelle*, which was hypothesized to be due to fur seal's consumption of a pelagic fish *Electrona subaspera* that ingested microplastics. In the laboratory, Setälä et al. (2014) demonstrated the capability of copepods *Eurytemora affinis* and polychaete larvae *Marenzelleria* spp. to ingest 10 µm fluorescent PS microspheres and then transfer the ingested particles to pelagic mysid shrimps *Mysis mixta*. Mattsson et al. (2015) confirmed that PS nanoparticles could transfer along an artificial aquatic food chain from algae (*Scenedesmus* sp.), through zooplankton (*Daphnia magna*) to fish (*Carassius carassius*). Trophic transfer of microplastics was also observed to occur between mussels (*Mytilus edulis*) and crabs (*Carcinus maenas*), resulting in translocation of these tiny particles in the haemolymph and tissues of crabs (Farrell and Nelson, 2013).

It is known that environmental microplastics usually contain significant amounts of hazardous chemicals (e.g., the inherent plastic additives and absorbed contaminants) (Barnes et al., 2009; Mato et al., 2001), which might be released after ingestion, assimilated in tissues of aquatic biota, and transmitted along the aquatic food chain (Carbery et al., 2018; Rochman et al., 2013). This process has been verified by Batel et al. (2016) in the laboratory using a simple artificial freshwater food chain composed of brine shrimp (*Artemia* sp.) nauplii and zebrafish (*Danio rerio*) and finding that microplastics (1–20 µm fluorescent PE particles) and the absorbed chemical (benzo(a)pyrene) could accumulate in shrimp nauplii and subsequently be transferred to zebrafish. Unfortunately, such kind of research efforts are at present highly insufficient. Therefore, there is an urgent need to clarify the role of microplastics in bioaccumulation and biomagnification of the plastic-associated contaminants within the complex aquatic food webs using environmentally realistic scenarios. This shall assist in appropriately evaluating the actual ecological risks of environmental microplastics.

6. Implications for human health

Until recently, there is very little information with regard to the transfer of microplastics to human beings and potential implications for human health. Since humans are the ultimate consumer in the aquatic food web, introduction of microplastics into humans seems possible, due to consumption of the plastic-containing aquatic products (Van Cauwenberghe and Janssen, 2014). This hypothesis can be supported by the fact that a large variety of edible species including shellfish and fish have been found to be contaminated with microplastics (Table 1). Although for some organisms microplastics were generally found in their digestive tracts that are usually removed before consumption (Alomar and Deudero, 2017; Sanchez et al., 2014), there also exist plenty of species that are eaten whole. For instance, as commercially important crustaceans, *Nephrops norvegicus* from the Clyde Sea (Murray

Table 3
Studies of microplastics effects on aquatic fauna.

Class	Species	Microplastics		Exposure time	Biological effects	Reference
		Type	Concentration			
Marine						
Copepod	<i>Centropages typicus</i>	PS	4000–25,000 beads/mL	24 h	Significant reduction on algal ingestion	(Cole et al., 2013)
Crustacea	<i>Nephtys norvegicus</i>	PP	3000–5000 fibers per 1.5 g feed	> 8 months	Reduced feeding rate, body mass, metabolic rate and catabolism of stored lipids	(Welden and Cowie, 2016)
	<i>Carcinus maenas</i>	PP	Feed containing 0.3–1.0% plastics by weight	4 weeks	Reduced food consumption and energy available for growth.	(Watts et al., 2015)
Mollusca	<i>Mytilus edulis</i>	PS	110 particles/mL	14 d	Increase in energy consumption.	(Van Cauwenberghe et al., 2015)
Annelida	<i>Arenicola marina</i>	PS	110 particles/g sediment	14 d	No effect on cellular energy allocation; Increase in protein content.	(Van Cauwenberghe et al., 2015)
Fish	<i>Sparus aurata</i> & <i>Dicentrarchus labrax</i>	PVC & PE	1–100 mg/mL	1 or 24 h	No effects on the cell viability of head-kidney leucocytes; Negligible effects on the main cellular innate immune activities; No effects on the expression of genes related to immunity, oxidative stress, cellular protection to pollutants, and cell death.	(Espinosa et al., 2018)
Freshwater						
Crustacea	<i>Daphnia magna</i>	PE	12.5–400 mg/L	24 h	1 µm particles can cause immobilization while 100 µm particles have no observable effects.	(Rehse et al., 2016)
Fish	<i>Danio rerio</i>	PA, PP, PVC, & PS	0.001–10 mg/L	10 d	No or low lethality; Intestinal damage including cracking of villi and splitting of enterocytes.	(Lei et al., 2018)
Nematode	<i>Caenorhabditis elegans</i>	PA, PP, PVC, & PS	0.5–10 mg/m ²	2 d	Reduction in survival rate, body length and reproduction; Reduced calcium levels but enhanced expression of glutathione S-transferase 4 enzyme in the intestine.	(Lei et al., 2018)

PS: polystyrene; PP: polypropylene; PE: polyethylene; PVC: polyvinylchloride; HDPE: high-density polyethylene; PA: polyamide.

Table 4
Studies of combined effects of microplastics and other contaminants on aquatic biota.

Class	Species	Microplastics		Contaminants		Exposure time	Biological effects	Reference	
		Type	Size (µm)	Concentration	Type				Concentration
Microalgae	<i>Tetraselmis chuii</i>	PE	1–5	0.046–1,472 mg/L	Cu	0.02–0.64 mg/L	96 h	Reduction in microalgae population growth.	(Davarpanah and Guilhermino, 2015)
Crustacea	<i>Daphnia magna</i>	PS	0.05–10	5 mg/L	Phenanthrene	0.1 mg/L	14 d	0.05-µm PS increased the bioaccumulation of phenanthrene while 10-µm PS exhibited negligible effects.	(Ma et al., 2016)
	<i>Artemia</i> sp.	PE	1–20	~1.2 × 10 ⁶ particles per 20,000 nauplii	Benzo(a)pyrene	252 µg/L	3 & 6 h	Bioaccumulation and translocation in tissues.	(Batel et al., 2016)
Annelida	<i>Arenicola marina</i>	PS	400–1300	0–100 g/L sediment	PCBs	5.28 µg (ΣPCBs)/kg sediment (dry weight)	28 d	Reduction in feeding activity, body weight and energy efficiency.	(Besseling et al., 2013)
Mollusca	<i>Perna viridis</i>	PVC	1–50	21.6–2160 mg/L	Fluoranthene	10 ng Fluoranthene/g PVC	2 h/day for a period of 91 d	Significant reduction in filtration behavior, respiration rate, and byssus production;	(Rist et al., 2016)
	<i>Mytilus galloprovincialis</i>	PE & PS	< 100	20 g/L	Pyrene	0.5–50 µg/L	7 d	Declined survival time with increasing pollution. Increase in bioaccumulation of pyrene;	(Avio et al., 2015)
Fish	<i>Danio rerio</i>	PE	10–106	10–1000 particles/mL	Ag	1 µg/L	4 & 24 h	Decrement in granulocytes, lysosomal membrane stability, and antioxidant defences;	(Khan et al., 2015)
	<i>Pomatoschistus microps</i>	PE	1–5	18.4 & 184 µg/L	Pyrene	20 & 200 µg/L	96 h	Increase in nuclear anomalies; Changes of gene expression profile.	(Oliveira et al., 2013)
	<i>Oryzias latipes</i>	PE	< 500	Diet containing 10% of plastics by weight	PAHs, PCBs, & PBDEs	PAHs: 1.4–68 ng/g PE; PCBs: 0.3–2.9 ng/g PE; PBDEs: 0.017–0.54 ng/g PE	60 d	Reduction in Ag uptake and rise in the proportion of intestinal Ag.	(Rochman et al., 2013)
								Delay in pyrene-induced mortality; Increase in pyrene metabolites accumulation;	
								Inhibition in activities of acetylcholinesterase and isocitrate dehydrogenase.	
								Glycogen depletion in liver;	
								Single cell necrosis in liver;	
								Fatty vacuolation.	

PE: polyethylene; PS: polystyrene; PVC: polyvinylchloride; PCBs: polychlorinated biphenyls; PAHs: polycyclic aromatic hydrocarbons; PBDEs: polybrominated diphenyl ethers; ΣPCBs: total concentrations of all PCBs.

and Cowie, 2011) and *Crangon crangon* from the Southern North Sea and Channel area (Devriese et al., 2015) were reported to contain large quantities of microplastics. In addition, smaller microplastics are capable of penetrating into the tissues or circulatory systems of aquatic living organisms (Farrell and Nelson, 2013), thus increasing the difficulty in eliminating these particles. At the point of human consumption, *Mytilus edulis* from North Sea and *Crassostrea gigas* from Atlantic Ocean were detected with a microplastics load of 0.36 ± 0.07 and 0.47 ± 0.16 particles per gram soft tissue (wet weight), respectively (Van Cauwenberghe and Janssen, 2014). It is estimated that human consumers in European countries could ingest up to 11,000 plastic particles due to consumption of shellfish, which is a considerable exposure (Van Cauwenberghe and Janssen, 2014).

Knowledge concerning the transfer of plastic-associated chemicals to human beings is also in its infancy. Environmental microplastics can be viewed as a complex cocktail of toxicants (Thompson et al., 2009). Once microplastics are ingested by aquatic organisms, the plastic-associated chemicals are readily released under the specific condition of animal's gut and may subsequently transfer along the aquatic food chain (Batel et al., 2016). Although there has been a controversy about to what extent microplastics ingestion contributes to the bioaccumulation of the associated contaminants, it provides an additional exposure route for these harmful substances to human.

In terms of the potential implications of ingested microplastics on human health, an in vitro study demonstrated that exposure to PS microspheres (10 μm) could induce high production of reactive oxygen species in cerebral and epithelial human cells (Schirizzi et al., 2017). Recently, Deng et al. (2017) identified that upon exposure microplastics could accumulate in liver, kidney and gut of mice (*Mus musculus*) and cause several adverse effects in their livers, such as disturbance of energy and lipid metabolism, oxidative stress, and neurotoxic responses. This raises concern about the cellular toxicity of ingested microplastics to human liver cells. In addition, the very tiny plastic particles are capable of traversing cell membranes, which thus may assist in enhancing the bioavailability of plastic-derived toxicants (Vethaak and Leslie, 2016). However, with a lack of robust data quantifying the exposure levels of microplastics and the associated substances for human beings through trophic transfer and other exposure routes, it is difficult to reasonably evaluate the actual implications of microplastics to human health. In the context of increasing severity of microplastics pollution in both aquatic and terrestrial environments, there is still much work to be done to comprehensively understand the processes and mechanisms involved in the introduction and assimilation of microplastics in human bodies and the ecotoxicological effects on human health.

7. Conclusions and future perspectives

The ubiquitous distribution of microplastics in global waters makes a vast range of aquatic biota susceptible to microplastics exposure. Both field and laboratory studies have demonstrated the wide occurrence of microplastics ingestion by aquatic fauna at different trophic levels of aquatic food web. Microplastics exposure may induce a variety of adverse effects on aquatic biota from primary producers to top predators and even human beings. To date, microplastics toxicity studies are mainly focused on the possible harmful effects of ingested microplastics (including the associated toxicants) to aquatic fauna, especially the marine taxa. However, knowledge about impacts of microplastics exposure on aquatic primary producers, the trophic transfer process of microplastics and associated substances, and implications of consuming aquatic products for human health is much less known. In addition, most of the available studies regarding microplastics effects were conducted under laboratory conditions, which may be less relevant to the realistic environment. In order to better understand the ecological risks of microplastics to both aquatic organisms and humans, several research priorities are recommended below:

- (1) Use environmentally relevant concentrations in microplastics exposure studies.
- (2) Perform more studies to reveal the effects of microplastics on aquatic primary producers and influencing factors.
- (3) Pay more attention to the ecotoxicological effects of microplastics on higher order predators and freshwater organisms.
- (4) Comprehensively evaluate the synthetic effects of microplastics and environmental toxicants and identify the role of microplastics in trophic transfer of environmental contaminants.
- (5) Conduct further studies on the factors that affect the selectivity of aquatic organisms for microplastics, and the toxicity and fate of ingested microplastics in aquatic organisms.
- (6) Conduct extensive monitoring programs on the abundance of microplastics in aquatic products that are at the point of human consumption in order to calculate the amount of microplastics introduced into humans via consuming aquatic products.
- (7) Perform more in-vitro studies to discern the fate and behavior of microplastics and their associated contaminants in human's digestive tract.
- (8) Focus more efforts on the presence and toxicity of nanoplastics in aquatic organisms and evaluation of the implications for human health.
- (9) Conduct more studies to clarify the role of microplastics as vectors for pathogenic microorganisms and potential ecological risks.

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Declaration of interest

None.

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