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Review

Occurrence and ecological impact of microplastics in aquaculture ecosystems

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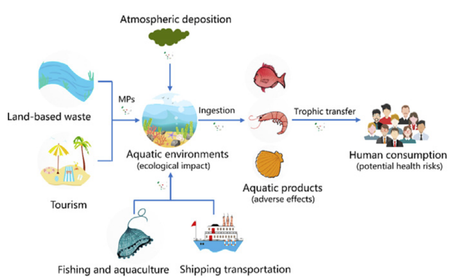
HIGHLIGHTS

- Microplastics are ubiquitous in aquaculture environments and species.
- Microplastics in the aquaculture species can cause a series of adverse effects.
- Aquaculture product consumption is a source of human ingestion of microplastics.
- Microplastics in the aquaculture systems need to be reduced to ensure food safety.

GRAPHICAL ABSTRACT



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ABSTRACT

Extensive applications of plastic in human life has caused substantial microplastic pollution in the global environment, which, due to plastic's ubiquitous nature and everlasting ecological impact, has caused worldwide concern. In aquatic ecosystems, microplastics are ingested by aquatic animals, affecting their growth and development and resulting in trophic transfer to higher organisms in the food chain. Therefore, consumption of aquatic products is a main primary source of human exposure to microplastics. Recently, aquaculture production has experienced tremendous growth and will exceed production from fish catch soon. Because they constitute an important source of protein in the human food supply, aquaculture products contaminated with microplastics directly affect food quality and safety. The present review summarizes documented studies regarding the occurrence and distribution of microplastics in various aquaculture systems and species and compares microplastic pollution in aquaculture species and captured species. Microplastics in aquaculture environments mainly come from exogenous imports, such as plastic waste and debris from the land, tourism, shipping transportation and atmospheric deposition. In addition, the use of plastic gear and equipment, aquaculture feed and health products, and special aquaculture environments contribute to a higher accumulation of microplastics. We also discuss the adverse effects of microplastics in aquaculture species and the potential health risks of microplastics to humans through the food chain. In summary, this review highlights the effects of microplastic pollution in aquaculture, particularly the ecological impacts on aquaculture species and associated human health implications, and calls for restricted control of microplastics in aquaculture ecosystems.

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Contents

1. Introduction

Plastic products have brought great convenience to modern life, due to their advantageous properties and low price. Since the 1950s, global annual plastic production has continuously increased, such that approximately 359 million tons of plastic were generated in 2018 (Plasticseurope, 2019). However, due to improper management and low biodegradability, plastic waste has become one of the most serious environmental issues (Krüger et al., 2020). It is estimated that 79% of plastic waste is released into the environment, 12% is incinerated, and only 9% is recycled (Geyer et al., 2017). Given the plastic products in various industries and fields, plastic waste is ubiquitously present in all spheres of the environment. Due to multiple factors, such as sunlight, microbes or mechanical abrasion, plastics in the environment can be degraded slowly into smaller pieces. Plastic particles <5 mm in diameter are defined as microplastics (MPs, secondary microplastics) (Thompson et al., 2009; Andrady, 2011). Microplastics are also intentionally manufactured (primary microplastics) for various application, including microbeads used in domestic cleaning and industrial and medical products (Cole et al., 2011). Due to their tiny size, microplastics can be ingested/inhaled and bioaccumulated by organisms, mistakenly and inadvertently, leading to potential health risks (Von Moos et al., 2012; Wright et al., 2013; Cole et al., 2015). Therefore, microplastics have gained global attention in recent years, and the number of studies in this area have rapidly increased (Campanale et al., 2020).

Microplastics have been detected in all types of environments around the world, including terrestrial ecosystems, (land, island, city and beach), aquatic ecosystems, (marine, river, lake, reservoir and pond) and the atmosphere (Duis and Coors, 2016; Auta et al., 2017; Peng et al., 2017; Li et al., 2018b; Chen et al., 2020c). Because of improper disposal, approximately 4.8−12 million tons of plastic waste enters the ocean every year (Jambeck et al., 2015). The major sources of microplastics in the ocean are the decomposition of marine plastic waste, import of river-based and land-based waste, plastic waste from marine tourism and shipping, devices of fishing and aquaculture, atmospheric deposition and other sources (Dong et al., 2020). In the freshwater environment, microplastics are mainly attributed to discarded plastic waste, effluent from domestic, industrial and wastewater treatment plants, shipping, fishing, aquaculture and import of land-based waste through runoff (Liu et al., 2019; Yan et al., 2019). Terrestrial microplastics may originate from agricultural films and from the processing, production, and transportation of plastics and the poor management of plastic waste (including discards and landfills) (Dong et al., 2020). Atmospheric microplastics are produced by the production, use and wear of plastic textile fiber, waste landfills and incineration, exhaust emission, abrasion of roads and tires, degradation of plastics and dust resuspension (Dris et al., 2016; Chen et al., 2020b). In summary, the sources of microplastics are varied and vast, such that ubiquitous and persistent microplastic pollution threatens the health of organisms in diverse environments.

Microplastics can be swallowed by biota and accumulate in their digestive systems. Microplastics have been detected in a variety of organisms, particularly in aquatic organisms like zooplankton, bivalves, shrimp, fish, and whales (Harmon, 2018; Rezania et al., 2018). For example, the abundance of microplastics in benthic and pelagic fish species from the northeastern Persian Gulf was 5.66−18.5 items/10 g fish muscle, while 4.3 to 57.2 items/individual microplastics were found in 9 commercial bivalves from a fishery market in China (Li et al., 2015; Akhbarizadeh et al., 2018). Once microplastics are ingested by organisms, a series of adverse physiological effects can occur that affecting feeding and behavior, inhibit growth and development, and cause reproductive toxicity, immune toxicity, and genetic damage (Harmon, 2018). For instance, microplastics have been found to increase the death rate of *Daphnia magna* and reduce their reproductive ability, while exposure to microplastics can cause oxidative stress, immune responses and cell apoptosis in *Mytilus galloprovincialis* (Ogonowski et al., 2016; Détrée and Gallardo-Escárate, 2017). In addition, microplastics can be vectors for leaking monomers, additives, multiple pollutants and microorganisms absorbed from the environment (Wang et al., 2016; Verla et al., 2019). By attaching to microplastics, the contaminants can enter and accumulate in tissues, thereby increasing their toxicity effects to the organisms. Through the food web, microplastics and contaminants can also transfer and bioaccumulate in high trophic organisms, posing serious potential health risks (Carbery et al., 2018; Nelms et al., 2018).

Aquatic products are an important source of human food. Global fish production in 2018 have reached approximately 179 million tons, of which 156 million tons were used for human consumption, accounting for 17% of the global population's intake of animal proteins, and 7% of all proteins (Fao, 2020). In recent years, world aquaculture production of farmed aquatic animals has consistently increased, reaching 82 million tons in 2018, accounting for 46% of total production, up from 25.7% in 2000. In addition, some countries are purposefully producing more aquatic animals from aquaculture than fishing with the goal of achieving a sustainable aquaculture industry. This is particularly the case in China, where they produced more farmed aquatic food than the rest of the world combined since 1991 and the aquaculture products account for 76.5% of total aquatic production in 2018 (Fao, 2020). Thus, the aquaculture industry can provide a large amount of animal-protein-containing food for human consumptions (Zhou et al., 2020), improving the economy and reducing hunger and poverty in local regions (Naylor et al., 2000; Fao, 2020). However, current aquaculture environments, such as oceans, rivers, lakes and ponds, are polluted with a plethora of contaminants, including microplastics that will enter aquatic products or adsorb on their surface and are consumed by human, posing serious health risks (Harmon, 2018). Therefore, the quality of aquatic products is closely related to food safety and human health (Waring et al., 2018; Garrido Gamarro et al., 2020; Zhou et al., 2020). It is imperative that we reveal pollution in aquaculture environments and products as well as the associated adverse effects on humans. This review summarizes current distributions and characteristics of microplastics in aquaculture animals and ecosystems and discuss the sources and potential health risks to animals and humans, raising concerns about the relationship between microplastics and aquaculture products. Suggestions for future research and protecting of aquaculture environments and products are also included.

2. Microplastics in aquaculture environments

Microplastics have been identified in more than 100 species, including many commercial fish, which has raised serious human food safety concerns (Lusher et al., 2017). As a result, published research regarding microplastics in global aquatic environments is increasing rapidly. Microplastics have been detected in oceans, coasts, shores, rivers and lakes. For example, concentrations of microplastics ranges from 33 to 83 particles/L in Jinhae Bay of South Korea; approximately 500 particles per 0.0125 m^3 have been detected in the sediment of the northern coast of Taiwan; and MPs range from 7850 to 10,950 particles m^{-3} with an average of 8902 particles m^{-3} in the Pearl River estuary of China (Song et al., 2015; Kunz et al., 2016; Yan et al., 2019). Although these aquatic environments are important to aquaculture productions, most of these studies only considered aquaculture activities as sources of microplastics in aquatic environments, without actually investigating microplastics in the aquaculture environments. Studies reporting microplastics detection in aquaculture environments and products remain limited. The results of several studies regarding microplastics occurrence and implications for aquatic organisms and food safety are summarized in Table 1.

Due to the wide use of plastic products and the ubiquitous presence of microplastics, there is no doubt that all aquaculture systems are contaminated by microplastics in the studies summarized in Table 1. For instance, 16.4/m^3 of microplastics were found in the mussel-farming region in Jurujuba Cove, while the total average abundance of microplastics in Xiangshan Bay was 8.9 ± 4.7 items/m^3 in seawater and 1739 ± 2153 items/kg in sediment (Castro et al., 2016; Chen et al., 2018). In the mariculture zone of the Maowei Sea, the abundances of microplastics range from 1.2 to 10.1 particles/L, and a mean value of 1594 ± 1352 particles/m^3 of microplastics was found in the shrimp-culturing farm in Longjiao Bay (Zhu et al., 2019; Chen et al., 2020a). In addition, microplastics were also observed in freshwater aquaculture environments, such as the fish ponds in the Carpathian Basin (13.79 ± 9.26 particles/m^3), rice-fish coculture system in Shanghai (0.4 ± 0.1 items/L), eel culture stations in Shanghai (1.0 ± 0.4 items/L) and scallop aquaculture areas in Shandong (Bordós et al., 2019; Lv et al., 2019, 2020; Sui et al., 2020). The microplastics in these studies appeared most commonly as fibers, making this shape dominant component in the data. In the Ma'an Archipelago, fibers were the most dominant type of microplastics in both surface water (70.0 ± 27.0%) and sediment (92.0 ± 9.0%), while fibers accounted for 94.66% of microplastics in the surface water of Xiangshan Bay (Wu et al., 2020; Zhang et al., 2020b). Fiber microplastics in the environment predominantly originate from plastic textiles, such as cloth, fishing nets and lines, the annual production of which reached 60 million metric tons (Gasperi et al., 2018). During the production and consumption of plastic textiles, fiber debris is released into the environment. For example, studies estimate that approximately 1900 fibers are released into domestic wastewater per wash, which may eventually enter freshwater environments (Browne et al., 2011). In addition, fragments, films and granules in aquaculture environments come from the degradation of plastic products like plastic bags, bottles, containers, agricultural films, fishing gear, etc (Shim et al., 2018). Pellets or microbeads mostly originate from primary microplastics, which are used in personal care products (toothpaste, facial scrubs and skin cleaners), domestic cleaning products, and medical and industrial applications; the foam widely used in packaging materials and fishing gear is also a source of microplastics in aquaculture environments (Di et al., 2019; Yuan et al., 2019). Regarding chemical composition, polypropylene (PP) and polyethylene (PE) were microplastics detected in these studies, because of their high production and wide application. The production of PP and PE accounted for 49% of global plastic products in 2018, including use in food packaging, plastic bags, bottles, containers, pipes, automotive parts, agricultural film, houseware, etc (Plasticseurope, 2019). Due to plastic's wide use and improper waste management, microplastics eventually contaminate every facet of the human environment, including aquaculture.

Researchers shows that the concentration of microplastics in aquaculture environments is generally higher than in surrounding environments because of rapidly expanding aquaculture activities (Chen et al., 2018; Priscilla and Patria, 2019). Microplastics can be released into aquaculture environments from plastic fishing gear as well as fish feed and medicine (Lv et al., 2020; Zhou et al., 2020). In addition, geography and weather influence microplastics accumulation and distribution in aquaculture environments (Chen et al., 2018; Wang et al., 2019). Aquaculture areas are mostly enclosed or semi-enclosed aquatic environments, which prevent the transfer of microplastics to other areas, causing the accumulation of microplastics in the water column and sediment (Chen et al., 2018). Aquaculture regions located in areas with high anthropogenic activities contribute substantially to the increase in microplastics observed environmentally and biologically. For example, researchers have reported that the water in aquaculture ponds in Marunda and Muara Kamal contain high microplastic abundances of 103.8 ± 20.7 particles/L and 90.7 ± 17.4 particles/L, respectively, because these ponds are close to a river mouth where large amounts of trash accumulate (Priscilla and Patria, 2019). Studies have revealed that weather conditions, such as wind and rain, can affect the microplastics abundances in aquatic environments. During rain, microplastics in the land can be transported into aquatic systems via surface runoffs (Liu et al., 2019; Ma et al., 2020). Wind is another predominant means of transporting microplastics (Chen et al., 2018). Researchers have reported that typhoons increased the average concentrations of microplastics in seawater and sediments by approximately 40%, and the shapes, colors and types of microplastics were also changed (Wang et al., 2019).

3. Source of microplastics in aquaculture environments

Microplastics in the environment originate from the breakdown of plastic waste and tiny plastic particles intentionally manufactured for their microsizes (Andrady, 2011; Cole et al., 2011). Microplastics in the environments are transported over long distances by wind, currents and other forces, distributing them widely around the world in the atmosphere, land, rivers, lakes, estuaries, offshore, and in pelagic, polar and deep seas (Auta et al., 2017; De Souza Machado et al., 2018; Li et al., 2018b; Allen et al., 2019). MPs in aquaculture environments mostly come from 1) land-based plastic waste, 2) disposal plastic waste from tourism, 3) shipping transportation, 4) fisheries and aquaculture and 5) atmospheric deposition (Fig. 1).

Table 1
The concentrations and characteristics of microplastics in the aquaculture systems.

Site	Source	Abundance	Size	Shape	Composition	Color	Reference
Xiangshan Bay, China	seawater	8.9 ± 4.7 items/m^3	Ave: 1.54 ± 1.53 mm.	fiber, film, fragment, foam	PE, PP, PS, PA, PET, cellulose	N/A	Chen et al. (2018)
	sediment	17.39 ± 21.53 items/kg	Ave: 1.33 ± 1.69 mm	fiber, film, fragment, foam	PE, PP, PET, Rubber, cellulose		
Xiangshan Bay, China	sediment	33-113 items/kg, Ave: 74 items/kg	345–4998 μm, Ave: 1830 μm	fiber, film, fragment	Cellulose, PA, AN, PP, PET	N/A	Wu et al. (2020)
Fish farms in Mediterranean, Spain	sediment	0 to 213 items	0.128–5 mm	fiber, fragment, pellet	PE, PP, PA, cellulose	black, transparent, blue, yellow, red	Krüger et al. (2020)
Fish ponds in Changzhou, China	freshwater	13 to 27 items/L	<0.1–5 mm	fiber, film, fragment, pellet	PE, PP, PS, PA, PET	transparent, white, green, yellow, gray	Wang et al. (2020)
Maowei Sea, China	seawater	1.2–10.1 items/L, Ave: 4.5 ± 0.1 items/L	<0.25–5 mm	fiber, flake, foam, fragment	PES, PP, PE, PA, PS, POM, PU, PBT	white, yellow, blue, green, red, black	Zhu et al. (2019)
Fish ponds in Carpathian basin, Europe	freshwater	3.52–32.05 items/m^3, Ave: 13.79 ± 9.26 items/m^3	N/A	N/A	PE, PP, PS, PTFE, PAC, PES	N/A	Bordós et al. (2019)
	sediment	0.46 to 1.62 items/kg, Ave: 0.81 ± 0.37 items/kg					
Fish ponds in Guangzhou, China	freshwater	42.1 items/L	<0.1–3 mm	fiber, film, granule, fragment, pellet	PP, PE	blue, purple, transparent, white, black, green, yellow, red	Ma et al. (2020)
Rice-fish co-culture system in Shanghai, China	freshwater sediment	0.4 ± 0.1 items/L 10.3 ± 2.2 items/kg	<1–5 mm	fiber, film, granule, fragment	PE, PVC, PP	black, transparent, blue, white	Lv et al. (2019)
Mussels farming in Jurujuba Cove	seawater	16.4/m^3	<1–5 mm, dominant: < 1 mm	fragment, fiber, sheet, pellet	PE, PP	blue, green, red, yellow, orange, black	Castro et al. (2016)
Eel culture stations, Shanghai	water soil	1.0 ± 0.4 items/L 27.1 ± 7.0 items/kg	<0.1–5 mm	film, fiber, fragment, granule	PE, PP, EA	yellow, green, white, black, blue, translucent	Lv et al. (2020)
Milkfish ponds in Muara Kamal	water sediments	103.8 ± 20.7 items/L 111680 ± 13204 items/kg	N/A	fiber, film, fragment, granule	N/A	N/A	Priscilla and Patria. (2019)
Milkfish ponds in Marunda	water sediments	90.7 ± 17.4 items/L 82480 ± 11226 items/kg					
Shrimp-culturing farm in Longjiao Bay, China	seawater	250-5150 items/m^3, mean: 1594 items/m^3	0.3–5 mm (92.03%) <0.3 mm (7.97%)	fiber, fragment, foam, film, granule	PE, PET, PS, PP, PC, PA, PAA	granule, fibers, white, yellow, black	Chen et al. (2020a)
Artificial reefs in Ma'an Archipelago, China	seawater sediment	0.2 ± 0.1–0.6 ± 0.2 items/L 30.0 ± 0.0–80.0 ± 14.1 items/kg	1–5 mm 0.05–1 mm (dominant)	fibers, fragments, films	PA, PE, PP, PS, cellulose, cellophane	blue, transparent, black, red, green, yellow, white	Zhang et al. (2020b)
Eight sea cucumber farms along the Bohai Sea and the Yellow Sea in China	sediment	20 - 1040 items/kg	<1 mm (82%) 1–5 mm (18%)	fibers, fragments, films	cellophane, polyester, PET, PE, PP, PA, PVA, PAN	blue, transparent, black, red, purple, brown	Mohsen et al. (2019)

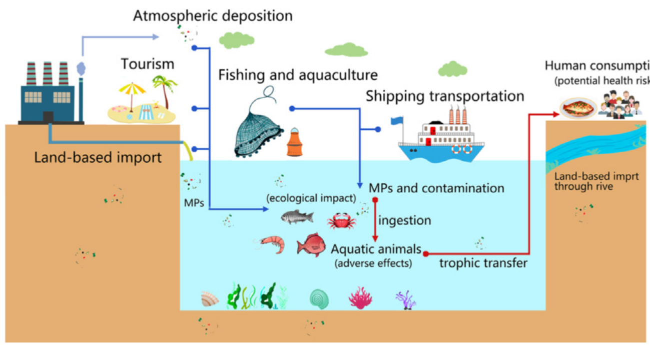

Fig. 1. Sources and behavior of MPs in aquaculture systems.

Land-based plastic waste is the main source of microplastics in the aquatic environment (Lebreton et al., 2017; Schmidt et al., 2017). Plastics are produced on land, and most of them are used on land. However, a large amount of plastic waste and land-sourced microplastics eventually enter aquatic environments (Thompson, 2015; Auta et al., 2017). Rivers provide a freshwater aquaculture environment and are also considered a pathway for MPs from land to the marine environments (Lebreton et al., 2017). It is estimated that approximately eight tons of plastic waste enter the ocean every year, 80% of which is from land-based sources (Jambeck et al., 2015; Wang et al., 2020). In addition, industrial, agricultural and domestic wastewater contains microplastics, which are also major contributor of microplastics in aquatic environments (Piehl et al., 2018; Liu et al., 2019; Lv et al., 2019). For example, over 700,000 fibers can be generated from an average 6-kg wash load of acrylic fabric, and showering with a body scrub may flush 100,000 microplastic beads into the wastewater system (Committee, 2015; Napper and Thompson, 2016). Although the abundance of microplastics in wastewater declines sharply after treatment by wastewater treatment plants (WWTPs), effluents discharged from WWTPs still poses a serious threat to the aquatic environment (Liu et al., 2019).

The development of tourism has also contributed to the spread of plastic waste to aquatic environments (Zhou et al., 2020). Many plastic products, such as plastic bags, mineral water bottles, and food packaging bags, are carried by tourists and discarded around or in rivers, lakes, coasts, beaches and oceans (Wang et al., 2018; Di et al., 2019). Sunlight, temperature changes, and freshwater/seawater erosion break down these plastic products into microplastics that enter aquatic environments. Shipping transportation also contributes substantially to microplastics pollution in aquatic environments via plastic waste discarded from ships (Wang et al., 2018; Fao, 2020). Studies have estimated that approximately 5 million tons of plastic waste has contaminated the ocean as a results of ship transportation worldwide in 2005 (Unep, 2005). Meanwhile, large amounts of primary microplastics are added to gasoline, diesel and other fuels to enhance and improve their quality. During the shipping process, incomplete burning of plastic particles releases into the atmosphere and water environments (Gasperi et al., 2018). In addition, shipping accidents also spill plastic products into aquatic environments.

Plastic products are inseparable from fishing and aquaculture activities. Most fishing gear, such as fishing nets, lines, buckets and other devices, are made of plastic or contain plastic ingredients (Zhou et al., 2020). As they are used and discarded, these devices can release microplastics into surrounding environments. For example, during benthic dredging and trawling operations, the wear and tear of fishing ropes and nets increase the content of microplastics in marine fishery waters (Fao, 2020). In addition, due to long-term use and insufficient maintenance of fishing gear, a large number of plastic fishing gear is lost and abandoned in aquatic environments every year (Macfadyen et al., 2009). For instance, the quantity of lost and discarded fishing gear has reached more than 4000 tons in Norwegian commercial fishing areas (Deshpande et al., 2020). In aquaculture environments, plastic fishing gear is the predominant and most important source of microplastics. Plastic products such as fishing nets, fishing ropes, and floating balls are used in offshore cages and raft culture. Their aging and damage cause a large number of plastic fragments to enter the aquatic environments (Fao, 2020). Due to long-term immersion, erosion, abrasion and collision in water, plastic debris is generated from plastic equipment and accumulates in the water. In addition, feeds and medicinal products contribute to microplastics in aquaculture environments (Lv et al., 2019, 2020). Artificial feeds contain large amounts of microplastics, as MPs can be introduced into feeds during production, transportation, storage and feeding (Zhou et al., 2020). Meanwhile, a large amount of zooplankton, invertebrates, small fish and aquatic plants in natural environments contain microplastics, and are used to make artificial feed or are directly used as natural food in aquaculture (Fao, 2020). For example, fragment-shape-dominated microplastics with a mean particle size of 452 ± 161 μm were found in four fish meal and positive relationships were found between microplastics in fish meal and cultured carp in the study (Hanachi et al., 2019). Another study showed that microplastic concentrations in the water increased significantly from pre-rearing to post-rearing (Lv et al., 2020). Furthermore, fish medicine, antibiotics and other chemicals, which are used to treat and prevent diseases and improve the quality of water and products, are attached to microplastics and are, therefore, another source of microplastics pollution in aquaculture environments (Fao, 2020; Zhou et al., 2020).

Microplastics have been found in the atmosphere and can be transported through the atmosphere over long distances (Allen et al., 2019). Affected by gravity and various weather conditions, microplastics in the atmosphere are deposited on land surfaces and in aquatic environments (Dris et al., 2015). Similar degradation patterns of microplastics from atmospheric fallout and lakes indicate that some microplastics in the aquatic environment may be derived from atmospheric fallout, and studies have shown that microplastics in the atmosphere are a significant source of MPs in aquatic ecosystems (Dris et al., 2015; Cai et al., 2017). Increasing cumulative production and accumulation pose a dangerous threat to aquaculture systems and the health of aquaculture products and humans through the food chains.

4. Microplastics in aquaculture products and their adverse effects

Microplastics have been found in many species including commercial species such as fishes, mussels, shrimp and crabs (Rezania et al., 2018). For example, synthetic fibers ranged from 200 to 1000 μm were detected in shrimp from coastal waters of the southern North Sea and channel area with an average value of 1.23 ± 0.99 items/individual, while the abundance of microplastics in six species of commercial fish from estuarine areas of Guangdong varied from 1.0 to 17.0 items/individual (Devriese et al., 2015; Zhang et al., 2020a). Similarly, 0.7 to 2.9 items/g were found in the tissue of wild mussels sampled from the U.K. coastal environment (Li et al., 2018a). However, such studies detecting microplastics in commercial fishes are mainly focused on fishes in wild environments, so that information regarding microplastics in aquaculture species remains limited. Meanwhile, concerns regarding the ubiquitous presence of microplastics and their risk to food safety are rising. To aid our knowledge of the occurrence, distribution and adverse effects (including human health risks) of microplastics in aquaculture

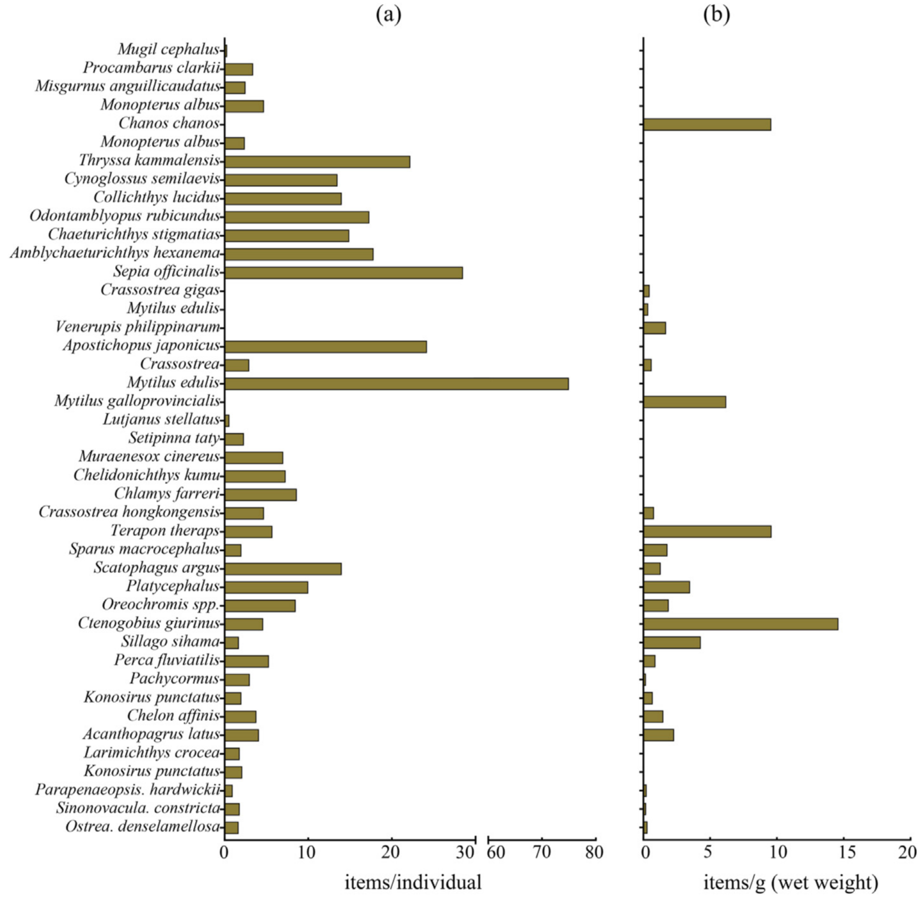

Fig. 2. MPs detected in aquaculture species. (a) items/gram (ww); (b) items/individual.

products, related studies have been collected, analyzed, and summarized in Table S1.

Microplastics have undoubtedly been found in all aquaculture products investigated (Fig. 2) in a range of aquaculture environments, including bays, artificial reefs, coastal areas, rivers, lakes, ponds, fishing farms, net cages and rice-fish coculture systems. For example, in a study quantifying microplastics in cultured oysters from 17 sites along the coastline of China, the average abundance of microplastics in oysters was 0.62 items/g (wet weight) or 2.93 items/individual (Teng et al., 2019). In Jakarta Bay, researchers found microplastics in milkfish (*Chanos chanos*) from aquaculture ponds at Muara Kamal and Marunda (Priscilla and Patria, 2019). Another study found that mullets obtained from fish farms in Hong Kong had ingested microplastics with an average of 0.2 items per mullet, and the most common plastic items were smaller than 2 mm (Cheung et al., 2018). In the rice-fish coculture ecosystem in Shanghai, a specific aquaculture environment, the average microplastic abundance was 1.7 $\pm$ 0.5 items/individual in the three animals (eel, crayfish and loach), and the abundance of microplastics increased significantly from the non-rice period to the rice-planting period (Lv et al., 2019).

Studies have also compared microplastics in aquaculture animals and wild species. The average microplastic abundance in aquaculture mussels (*Mytilus edulis*) was higher than in wild mussels from Halifax Harbor, Nova Scotia (Mathalon and Hill, 2014). On Vancouver Island, significantly higher numbers of microplastics were also observed in farmed blue mussels and Pacific oysters compared to their wild counterparts (Murphy, 2018). Meanwhile, no significant difference was observed in microplastic concentrations detected in cultured and wild clam (*Venerupis philippinarum*) in Baynes Sound (Davidson and Dudas, 2016). Similar results were reported in demersal fish in Hong Kong (Chan et al., 2019). Another study showed that wild mullets from the eastern coast of Hong Kong have a higher risk of microplastic ingestion than their captive counterparts from fish farms (Cheung et al., 2018). In general, the concentrations of microplastics detected in aquaculture products are higher than those in their wild counterparts from surrounding environments, because of the special environments and frequent activities associated with aquaculture (Chen et al., 2018; Priscilla and Patria, 2019). Enclosed or semi-enclosed aquaculture environments prevent the transportation of microplastics to other systems, and the use of aquaculture gear and food can quickly increase the abundance of microplastics in the environment.

Microplastics can be detrimental to the growth and development of aquatic organisms. Polystyrene (PS) microplastics in sediments have been shown to significantly inhibit the growth of sandworms (*Arenicola marina*) to extents that are positively correlated to surrounding concentrations of microplastics (Besseling et al., 2013). Studies have also found that microplastics inhibit the feeding and growth of sea urchins (*Tripneustes gratilla*), and significantly affect energy storage in *Sebastes schlegelii* (Kaposi et al., 2014; Yin et al., 2018). Polyethylene terephthalate (PET) microplastics with particle sizes of 1–50 μm can disrupt the homeostasis of the blue mussel, resulting in increased energy consumption and decreased growth rates (Détrée and Gallardo-Escárate, 2018).

In addition, microplastics ingestion affects the feeding and behavior of aquatic species. Studies have shown that microplastics can significantly reduce the feeding and swimming abilities of *S. schlegelii* (Yin et al., 2018) and that exposure to polyethylene microplastics decreased the swimming ability and predation ability of the common goby (*Pomatoschistus microps*) (Oliveira et al., 2013). Meanwhile, microplastics can induce a series of immune responses after entering the tissues and organs of aquatic animals. Studies have shown that polyvinyl chloride (PVC) and PET microplastics with particle sizes of 40–150 μm can cause oxidative damage to the white blood cells of sea bream (*Sparusaurata*) and sea bass (*Dicentrarchus labrax*) (Espinosa et al., 2018). Microplastics (<80 μm) can also enter the mussel's digestive system, leading to an inflammatory response (Von Moos et al., 2012). Likewise, exposure of sea urchins to amino-polystyrene nanoplastics (10 and 25 μg/ml) can cause instability in phagocyte lysosome membrane and apoptosis (Marques-Santos et al., 2018).

Furthermore, microplastics can affect reproduction in aquatic organisms. Exposure to PS microplastics produced strong negative effects in energy uptake and allocation and reproductive health of oysters (Sussarellu et al., 2016). Microbeads can also penetrate the cell membranes of marine copepods (*Paracyclopina nana*) and cause cellular damage, leading to reduced reproduction and growth rates (Jeong et al., 2017). In addition to the particle toxicity caused by microplastics, the leakage of monomers and additives from microplastics and the absorption of contamination and microorganisms from environments can induce more serious health risks to aquatic species (Wang et al., 2016; Verla et al., 2019). For example, bisphenol A (BPA) is mainly used as a monomer for epoxy resin and polycarbonate and is also used as an additive in the production of other plastics (PE, PP and PVC) (Campanale et al., 2020). As a significant endocrine disruptor, BPA can create cytotoxic effects in living tissues and may be involved in reproductive abnormalities.

In 2018, 39 countries produced more aquatic animals than fisheries, and another 22 countries accounted for more than 30% of worldwide aquaculture production (Fao, 2020). Global aquaculture production reached 82 million tons, accounting for 46% of global fish production. There is no doubt that total aquaculture production will exceed total wild capture in the future, reinforcing the importance of aquaculture products in the human food and protein supply. However, both aquaculture environments and products are contaminated by microplastics (Zhou et al., 2020). Studies show that microplastics can affect feeding ability and inhibit growth and development, which may influence the quality of aquaculture products. Food safety is an even more important concern (Lusher et al., 2017; Garrido Gamarro et al., 2020). Microplastics are present in mussels, oysters and other aquaculture species and are the main source of human consumption via food. The risk of microplastic ingestion is reduced by the removal of the gastrointestinal tract in most commercial species (Lusher et al., 2017). Thus, more concern exists regarding aquaculture products that are mostly consumed whole, with the digestive system included. The number of microplastics ingested per person per year can reach 11,000 due to shellfish consumption (Smith et al., 2018). Attached contamination, leaking monomers and additives also pose a health risk to humans. *In vitro* studies have shown that microplastics can cause cytotoxic and inflammatory effects in human cells by inducing reactive oxygen species formation, altering expression level of associated proteins and activating inflammatory gene transcription (Wright and Kelly, 2017; Yong et al., 2020). It is clear from this evidence that we must prioritize the quality and safety of aquaculture products to protect ecological and human health interests.

5. Conclusion

Microplastics have been found in various environments and species including aquaculture systems and products, and are closely related to food supply and safety (Zhou et al., 2020). Source of microplastics in global aquaculture environments are extensive and predominantly originate from land-based transportation, tourism, shipping, fishing, aquaculture and atmospheric deposition (Dong et al., 2020). Among these, plastic waste from terrestrial ecosystems, fishing gear and products are the most important input sources of MPs for aquaculture systems (Schmidt et al., 2017; Fao, 2020). The variabilities of MP sources and aquaculture environments determine the varied microplastic concentrations and distributions in each aquaculture system. In order to control microplastic pollution in these areas, it is important to detect and analyze the MPs that currently contaminate them. And when detecting MPs in aquaculture environments, it is necessary to clarify the sources and fates of microplastics within them. For example, in aquaculture environments like pools, using filtered water and recycling discarded plastic fishing gear and garbage can significantly reduce the microplastics concentrations (Birnstiel et al., 2019). In addition, once ingested, microplastics can inhibit aquatic organisms' growth, development, feeding and behavior, and cause reproductive toxicity, immune toxicity, and genetic damage (Harmon, 2018). The mechanisms underlying the detrimental effects of microplastics remain unclear, particularly at the molecular and genetic levels. Moreover, toxic environmental contaminants can attach to the surfaces of microplastics and pose additional health threats to the organisms that consume them. More research is required to reveal the mechanisms behind the particle toxicity of microplastics, the adsorption/desorption processes by which environmental pollutants attach to microplastics, and their combined toxicity and associated mechanisms. Furthermore, experimental data have not yet confirmed that microplastics have a negative impact on human health, although *in vitro* studies have shown that microplastics can harm human health by inducing oxidative stress, cytotoxicity and inflammation (Yong et al., 2020). Because the consumption of aquaculture products is an important source of microplastics in humans (Lusher et al., 2017; Waring et al., 2018), it is important that we detect the microplastics in aquatic products and determine their adverse effects on humans. In addition, clarification regarding the relationship between microplastics, aquaculture products and their potentially detrimental impacts on human and ecological health is needed in order to better evaluate the quality and safety of aquaculture products, control the input of microplastics to aquaculture environments and promote the sustainable and healthy development of aquaculture.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Akhbarizadeh, R., Moore, F., Keshavarzi, B., 2018. Investigating a probable relationship between microplastics and potentially toxic elements in fish muscles from northeast of Persian Gulf. Environ. Pollut. 232, 154–163.
Allen, S., Allen, D., Phoenix, V.R., Le Roux, G., Durántez Jiménez, P., Simonneau, A., et al., 2019. Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nat. Geosci. 12 (5), 339–344.
Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62 (8), 1596–1605.
Auta, H.S., Emenike, C.U., Fauziah, S.H., 2017. Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions. Environ. Int. 102, 165–176.
Besseling, E., Wegner, A., Foekema, E.M., Van Den Heuvel-Greve, M.J., Koelmans, A.A., 2013. Effects of microplastic on fitness and PCB bioaccumulation by the lugworm arenicola marina (L.). Environ. Sci. Technol. 47 (1), 593–600.
Birnstiel, S., Soares-Gomes, A., Da Gama, B.a.P., 2019. Depuration reduces microplastic content in wild and farmed mussels. Mar. Pollut. Bull. 140, 241–247.
Bordós, G., Urbányi, B., Micsinai, A., Kriszt, B., Palotai, Z., Szabó, I., et al., 2019. Identification of microplastics in fish ponds and natural freshwater environments of the Carpathian basin, Europe. Chemosphere 216, 110–116.
Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., et al., 2011. Accumulation of microplastic on shorelines woldwide: sources and sinks. Environ. Sci. Technol. 45 (21), 9175–9179.
Cai, L., Wang, J., Peng, J., Tan, Z., Zhan, Z., Tan, X., et al., 2017. Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: preliminary research and first evidence. Environ. Sci. Pollut. Res. Int. 24 (32), 24928–24935.
Campanale, C., Massarelli, C., Savino, I., Locaputo, V., Uricchio, V.F., 2020. A detailed review study on potential effects of microplastics and additives of concern on human health. Int. J. Environ. Res. Publ. Health 17 (4).
Carbery, M., O'connor, W., Palanisami, T., 2018. Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health. Environ. Int. 115, 400–409.
Castro, R.O., Silva, M.L., Marques, M.R.C., De Araújo, F.V., 2016. Evaluation of microplastics in Jurujuba Cove, Niterói, RJ, Brazil, an area of mussels farming. Mar. Pollut. Bull. 110 (1), 555–558.
Chan, H.S.H., Dingle, C., Not, C., 2019. Evidence for non-selective ingestion of microplastic in demersal fish. Mar. Pollut. Bull. 149, 110523.
Chen, B., Fan, Y., Huang, W., Rayhan, A.B.M.S., Chen, K., Cai, M., 2020a. Observation of microplastics in mariculture water of Longjiao Bay, southeast China: influence by human activities. Mar. Pollut. Bull. 160, 111655.
Chen, G., Feng, Q., Wang, J., 2020b. Mini-review of microplastics in the atmosphere and their risks to humans. Sci. Total Environ. 703, 135504.
Chen, G., Fu, Z., Yang, H., Wang, J., 2020c. An overview of analytical methods for detecting microplastics in the atmosphere. TrAC Trends Anal. Chem. (Reference Ed.) 130, 115981.
Chen, M., Jin, M., Tao, P., Wang, Z., Xie, W., Yu, X., et al., 2018. Assessment of microplastics derived from mariculture in Xiangshan Bay, China. Environ. Pollut. 242, 1146–1156.
Cheung, L.T.O., Lui, C.Y., Fok, L., 2018. Microplastic contamination of wild and captive flathead grey mullet (*Mugil cephalus*). Int. J. Environ. Res. Publ. Health 15 (4).
Cole, M., Lindeque, P., Fileman, E., Halsband, C., Galloway, T.S., 2015. The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod Calanus helgolandicus. Environ. Sci. Technol. 49 (2), 1130–1137.
Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62 (12), 2588–2597.
Committee, E.A., 2015. Environmental impact of microplastics [online]. https://spark.adobe.com/page/qW03f/.
Davidson, K., Dudas, S.E., 2016. Microplastic ingestion by wild and cultured manila clams (*Venerupis philippinarum*) from Baynes Sound, British columbia. Arch. Environ. Contam. Toxicol. 71 (2), 147–156.
De Souza Machado, A.A., Kloas, W., Zarfl, C., Hempel, S., Rillig, M.C., 2018. Microplastics as an emerging threat to terrestrial ecosystems. Global Change Biol. 24 (4), 1405–1416.
Deshpande, P.C., Philis, G., Brattebø, H., Fet, A.M., 2020. Using Material Flow Analysis (MFA) to generate the evidence on plastic waste management from commercial fishing gears in Norway. Resour. Conserv. Recycl. X. 5, 100024.
Détrée, C., Gallardo-Escárate, C., 2017. Polyethylene microbeads induce transcriptional responses with tissue-dependent patterns in the mussel Mytilus galloprovincialis. J. Molluscan Stud. 83 (2), 220–225.
Détrée, C., Gallardo-Escárate, C., 2018. Single and repetitive microplastics exposures induce immune system modulation and homeostasis alteration in the edible mussel *Mytilus galloprovincialis*. Fish Shellfish Immunol. 83, 52–60.
Devriese, L.I., Van Der Meulen, M.D., Maes, T., Bekaert, K., Paul-Pont, I., Frère, L., et al., 2015. Microplastic contamination in brown shrimp (*Crangon crangon*, linnaeus 1758) from coastal waters of the southern North Sea and channel area. Mar. Pollut. Bull. 98 (1), 179–187.
Di, M., Liu, X., Wang, W., Wang, J., 2019. Manuscript prepared for submission to environmental toxicology and pharmacology pollution in drinking water source areas: microplastics in the Danjiangkou Reservoir, China. Environ. Toxicol. Pharmacol. 65, 82–89.
Dong, H., Chen, Y., Wang, J., Zhang, Y., Zhang, P., Li, X., et al., 2020. Interactions of microplastics and antibiotic resistance genes and their effects on the aquaculture environments. J. Hazard Mater. 403, 123961.
Dris, R., Gasperi, J., Rocher, V., Saad, M., Renault, N., Tassin, B., 2015. Microplastic contamination in an urban area: a case study in Greater Paris. Environ. Chem. 12 (5), 592–599.
Dris, R., Gasperi, J., Saad, M., Mirande, C., Tassin, B., 2016. Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? Mar. Pollut. Bull. 104 (1), 290–293.
Duis, K., Coors, A., 2016. Microplastics in the aquatic and terrestrial environment: sources (with a specific focus on personal care products), fate and effects. Environ. Sci. Eur. 28 (1), 2.
Espinosa, C., García Beltrán, J.M., Esteban, M.A., Cuesta, A., 2018. *In vitro* effects of virgin microplastics on fish head-kidney leucocyte activities. Environ. Pollut. 235, 30–38.
Fao, 2020. The State of World Fisheries and Aquaculture 2020. https://doi.org/10.4060/ca9229en.
Garrido Gamarro, E., Ryder, J., Elvevoll, E.O., Olsen, R.L., 2020. Microplastics in fish and shellfish – a threat to seafood safety? J. Aquat. Food Prod. Technol. 29 (4), 417–425.
Gasperi, J., Wright, S.L., Dris, R., Collard, F., Mandin, C., Guerrouache, M., et al., 2018. Microplastics in air: are we breathing it in? Current Opinion in Environmental Science & Health 1, 1–5.
Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Science Advances 3 (7), e1700782.
Hanachi, P., Karbalaei, S., Walker, T.R., Cole, M., Hosseini, S.V., 2019. Abundance and properties of microplastics found in commercial fish meal and cultured common carp (Cyprinus carpio). Environ. Sci. Pollut. Control Ser. 26 (23), 23777–23787.
Harmon, S.M., 2018. Chapter 8 - the effects of microplastic pollution on aquatic organisms. In: Zeng, E.Y. (Ed.), Microplastic Contamination in Aquatic Environments. Elsevier, pp. 249–270.
Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., et al., 2015. Plastic waste inputs from land into the ocean. Science 347 (6223), 768–771.
Jeong, C.-B., Kang, H.-M., Lee, M.-C., Kim, D.-H., Han, J., Hwang, D.-S., et al., 2017. Adverse effects of microplastics and oxidative stress-induced MAPK/Nrf2 pathway-mediated defense mechanisms in the marine copepod *Paracyclopina nana*. Sci. Rep. 7 (1), 41323.
Kaposi, K.L., Mos, B., Kelaher, B.P., Dworjanyn, S.A., 2014. Ingestion of microplastic has limited impact on a marine larva. Environ. Sci. Technol. 48 (3), 1638–1645.
Krüger, L., Casado-Coy, N., Valle, C., Ramos, M., Sánchez-Jerez, P., Gago, J., et al., 2020. Plastic debris accumulation in the seabed derived from coastal fish farming. Environ. Pollut. 257, 113336.
Kunz, A., Walther, B.A., Löwemark, L., Lee, Y.-C., 2016. Distribution and quantity of microplastic on sandy beaches along the northern coast of Taiwan. Mar. Pollut. Bull. 111 (1), 126–135.
Lebreton, L.C.M., Van Der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nat. Commun. 8 (1), 15611.
Li, J., Green, C., Reynolds, A., Shi, H., Rotchell, J.M., 2018a. Microplastics in mussels sampled from coastal waters and supermarkets in the United Kingdom. Environ. Pollut. 241, 35–44.
Li, J., Liu, H., Paul Chen, J., 2018b. Microplastics in freshwater systems: a review on occurrence, environmental effects, and methods for microplastics detection. Water Res. 137, 362–374.
Li, J., Yang, D., Li, L., Jabeen, K., Shi, H., 2015. Microplastics in commercial bivalves from China. Environ. Pollut. 207, 190–195.
Liu, X., Yuan, W., Di, M., Li, Z., Wang, J., 2019. Transfer and fate of microplastics during the conventional activated sludge process in one wastewater treatment plant of China. Chem. Eng. J. 362, 176–182.
Lusher, A., Hollman, P., Mendoza, J., 2017. Microplastics in Fisheries and Aquaculture: Status of Knowledge on Their Occurrence and Implications for Aquatic Organisms and Food Safety (FAO Fisheries and Aquaculture Technical Paper).
Lv, W., Yuan, Q., He, D., Lv, W., Zhou, W., 2020. Microplastic contamination caused by different rearing modes of Asian swamp eel (*Monopterus albus*). Aquacult. Res. 51 (12), 5084–5095.
Lv, W., Zhou, W., Lu, S., Huang, W., Yuan, Q., Tian, M., et al., 2019. Microplastic pollution in rice-fish co-culture system: a report of three farmland stations in Shanghai, China. Sci. Total Environ. 652, 1209–1218.
Ma, J., Niu, X., Zhang, D., Lu, L., Ye, X., Deng, W., et al., 2020. High levels of microplastic pollution in aquaculture water of fish ponds in the Pearl River Estuary of Guangzhou, China. Sci. Total Environ. 744, 140679.
Macfadyen, G., Huntington, T., Cappell, R., 2009. Abandoned, Lost or Otherwise Discarded Fishing Gear.
Marques-Santos, L.F., Grassi, G., Bergami, E., Faleri, C., Balbi, T., Salis, A., et al., 2018. Cationic polystyrene nanoparticle and the sea urchin immune system: biocorona formation, cell toxicity, and multixenobiotic resistance phenotype. Nanotoxicology 12 (8), 847–867.

Mathalon, A., Hill, P., 2014. Microplastic fibers in the intertidal ecosystem surrounding Halifax harbor, Nova Scotia. Mar. Pollut. Bull. 81 (1), 69–79.

Mohsen, M., Wang, Q., Zhang, L., Sun, L., Lin, C., Yang, H., 2019. Microplastic ingestion by the farmed sea cucumber *Apostichopus japonicus* in China. Environ. Pollut. 245, 1071–1078.

Murphy, C. (Year). "A Comparison of Microplastics in Farmed and Wild Shellfish Near Vancouver Island and Potential Implications for Contaminant Transfer to Humans").

Napper, I.E., Thompson, R.C., 2016. Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions. Mar. Pollut. Bull. 112 (1), 39–45.

Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., et al., 2000. Effect of aquaculture on world fish supplies. Nature 405 (6790), 1017–1024.

Nelms, S.E., Galloway, T.S., Godley, B.J., Jarvis, D.S., Lindeque, P.K., 2018. Investigating microplastic trophic transfer in marine top predators. Environ. Pollut. 238, 999–1007.

Ogonowski, M., Schür, C., Jarsén, Å., Gorokhova, E., 2016. The effects of natural and anthropogenic microparticles on individual fitness in Daphnia magna. PloS One 11 (5), e0155063.

Oliveira, M., Ribeiro, A., Hylland, K., Guilhermino, L., 2013. Single and combined effects of microplastics and pyrene on juveniles (0+ group) of the common goby *Pomatoschistus microps* (Teleostei, Gobiidae). Ecol. Indicat. 34, 641–647.

Peng, J., Wang, J., Cai, L., 2017. Current understanding of microplastics in the environment: occurrence, fate, risks, and what we should do. Integrated Environ. Assess. Manag. 13 (3), 476–482.

Piehl, S., Leibner, A., Löder, M.G.J., Dris, R., Bogner, C., Laforsch, C., 2018. Identification and quantification of macro- and microplastics on an agricultural farmland. Sci. Rep. 8 (1), 17950.

Plasticseurope, 2019. Plastics - the Facts 2019 an Analysis of European Plastics Production, Demand and Waste Data.

Priscilla, V., Patria, M.P., 2019. Comparison of microplastic abundance in aquaculture ponds of milkfish chanos chanos (forsskål, 1775) at Muara kamal and Marunda, jakarta bay. IOP Conf. Ser. Earth Environ. Sci. 404, 012027.

Rezania, S., Park, J., Md Din, M.F., Mat Taib, S., Talaiekhozani, A., Kumar Yadav, K., et al., 2018. Microplastics pollution in different aquatic environments and biota: a review of recent studies. Mar. Pollut. Bull. 133, 191–208.

Schmidt, C., Krauth, T., Wagner, S., 2017. Export of plastic debris by rivers into the sea. Environ. Sci. Technol. 51 (21), 12246–12253.

Shim, W.J., Hong, S.H., Eo, S., 2018. Chapter 1 - marine microplastics: abundance, distribution, and composition. In: Zeng, E.Y. (Ed.), Microplastic Contamination in Aquatic Environments. Elsevier, pp. 1–26.

Smith, M., Love, D.C., Rochman, C.M., Neff, R.A., 2018. Microplastics in seafood and the implications for human health. Current Environmental Health Reports 5 (3), 375–386.

Song, Y.K., Hong, S.H., Jang, M., Han, G.M., Shim, W.J., 2015. Occurrence and distribution of microplastics in the sea surface microlayer in Jinhae bay, South Korea. Arch. Environ. Contam. Toxicol. 69 (3), 279–287.

Sui, M., Lu, Y., Wang, Q., Hu, L., Huang, X., Liu, X., 2020. Distribution patterns of microplastics in various tissues of the Zhikong scallop (*Chlamys farreri*) and in the surrounding culture seawater. Mar. Pollut. Bull. 160, 111595.

Sussarellu, R., Suquet, M., Thomas, Y., Lambert, C., Fabioux, C., Pernet, M.E.J., et al., 2016. Oyster reproduction is affected by exposure to polystyrene microplastics. Proc. Natl. Acad. Sci. Unit. States Am. 113 (9), 2430–2435.

Teng, J., Wang, Q., Ran, W., Wu, D., Liu, Y., Sun, S., et al., 2019. Microplastic in cultured oysters from different coastal areas of China. Sci. Total Environ. 653, 1282–1292.

Thompson, R.C., 2015. Microplastics in the marine environment: sources, consequences and solutions. Marine Anthropogenic Litter. Springer, Cham, pp. 185–200.

Thompson, R.C., Moore, C.J., Vom Saal, F.S., Swan, S.H., 2009. Plastics, the environment and human health: current consensus and future trends. Phil. Trans.: Biol. Sci. 364 (1526), 2153–2166.

Unep, 2005. Marine Litter, an Analytical Overview.

Verla, A.W., Enyoh, C.E., Verla, E.N., Nwarnorh, K.O., 2019. Microplastic–toxic chemical interaction: a review study on quantified levels, mechanism and implication. SN Applied Sciences 1 (11), 1400.

Von Moos, N., Burkhardt-Holm, P., Köhler, A., 2012. Uptake and effects of microplastics on cells and tissue of the blue mussel Mytilus edulis L. After an experimental exposure. Environ. Sci. Technol. 46 (20), 11327–11335.

Wang, F., Wang, B., Duan, L., Zhang, Y., Zhou, Y., Sui, Q., et al., 2020. Occurrence and distribution of microplastics in domestic, industrial, agricultural and aquacultural wastewater sources: a case study in Changzhou, China. Water Res. 182, 115956.

Wang, J., Lu, L., Wang, M., Jiang, T., Liu, X., Ru, S., 2019. Typhoons increase the abundance of microplastics in the marine environment and cultured organisms: a case study in Sanggou Bay, China. Sci. Total Environ. 667, 1–8.

Wang, J., Tan, Z., Peng, J., Qiu, Q., Li, M., 2016. The behaviors of microplastics in the marine environment. Mar. Environ. Res. 113, 7–17.

Wang, W., Yuan, W., Chen, Y., Wang, J., 2018. Microplastics in surface waters of dongting lake and Hong lake, China. Sci. Total Environ. 633, 539–545.

Waring, R.H., Harris, R.M., Mitchell, S.C., 2018. Plastic contamination of the food chain: a threat to human health? Maturitas 115, 64–68.

Wright, S.L., Kelly, F.J., 2017. Plastic and human health: a micro issue? Environ. Sci. Technol. 51 (12), 6634–6647.

Wright, S.L., Thompson, R.C., Galloway, T.S., 2013. The physical impacts of microplastics on marine organisms: a review. Environ. Pollut. 178, 483–492.

Wu, F., Wang, Y., Leung, J.Y.S., Huang, W., Zeng, J., Tang, Y., et al., 2020. Accumulation of microplastics in typical commercial aquatic species: a case study at a productive aquaculture site in China. Sci. Total Environ. 708, 135432.

Yan, M., Nie, H., Xu, K., He, Y., Hu, Y., Huang, Y., et al., 2019. Microplastic abundance, distribution and composition in the Pearl River along guangzhou city and Pearl River estuary, China. Chemosphere 217, 879–886.

Yin, L., Chen, B., Xia, B., Shi, X., Qu, K., 2018. Polystyrene microplastics alter the behavior, energy reserve and nutritional composition of marine jacopever (*Sebastes schlegelii*). J. Hazard Mater. 360, 97–105.

Yong, C.Q.Y., Valiyaveetill, S., Tang, B.L., 2020. Toxicity of microplastics and nanoplastics in mammalian systems. Int. J. Environ. Res. Publ. Health 17 (5).

Yuan, W., Liu, X., Wang, W., Di, M., Wang, J., 2019. Microplastic abundance, distribution and composition in water, sediments, and wild fish from Poyang Lake, China. Ecotoxicol. Environ. Saf. 170, 180–187.

Zhang, C., Wang, S., Pan, Z., Sun, D., Xie, S., Zhou, A., et al., 2020a. Occurrence and distribution of microplastics in commercial fishes from estuarine areas of Guangdong, South China. Chemosphere 260, 127656.

Zhang, D., Cui, Y., Zhou, H., Jin, C., Yu, X., Xu, Y., et al., 2020b. Microplastic pollution in water, sediment, and fish from artificial reefs around the Ma'an Archipelago, Shengsi, China. Sci. Total Environ. 703, 134768.

Zhou, A., Zhang, Y., Xie, S., Chen, Y., Li, X., Wang, J., et al., 2020. Microplastics and their potential effects on the aquaculture systems: a critical review. Rev. Aquacult. 13 (1), 719–733.

Zhu, J., Zhang, Q., Li, Y., Tan, S., Kang, Z., Yu, X., et al., 2019. Microplastic pollution in the Maowei Sea, a typical mariculture bay of China. Sci. Total Environ. 658, 62–68.