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Review

A review of microplastic pollution in aquaculture: Sources, effects, removal strategies and prospects

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ABSTRACT

As microplastic pollution has become an emerging environmental issue of global concern, microplastics in aquaculture have become a research hotspot. For environmental safety, economic efficiency and food safety considerations, a comprehensive understanding of microplastic pollution in aquaculture is necessary. This review outlines an overview of sources and effects of microplastics in aquaculture. External environmental inputs and aquaculture processes are sources of microplastics in aquaculture. Microplastics may release harmful additives and adsorb pollutants in aquaculture environment, cause deterioration of aquaculture environment, as well as cause toxicological effects, affect the behavior, growth and reproduction of aquaculture products, ultimately reducing the economic benefits of aquaculture. Microplastics entering the human body through aquaculture products also pose potential health risks at multiple levels. Microplastic pollution removal strategies used in aquaculture in various countries are also reviewed. Ecological interception and purification are considered to be effective methods. In addition, strengthening aquaculture management and improving fishing gear and packaging are also currently feasible solutions. As proactive measures, new portable microplastic monitoring system and remote sensing technology are considered to have broad application prospects. And it was encouraged to comprehensively strengthen the supervision of microplastic pollution in aquaculture through talent exchange and strengthening the construction of laws and regulations.

1. Introduction

Microplastics are synthetic solid particles or polymeric matrices with regular or irregular shapes (Frias and Nash, 2019), which generally refer to plastics smaller than 5 mm in size (Arthur et al., 2009). With the wide application of plastic products, primary microplastics intentionally produced in this size range and secondary microplastics formed through fragmentation or wear of plastic-containing articles are widely distributed in the environment (GESAMP, 2015). Microplastics can be introduced into aquaculture environments in various ways (Chen et al., 2021; Liu et al., 2019). Many studies have shown that there is a problem of microplastic accumulation in a large number of aquaculture environments (Bordós et al., 2019; Ma et al., 2020; F. Wang et al., 2020). These microplastics can accumulate in aquaculture products. For example, microplastics were found in commercial bivalves from fishery market, range from 4.3 to 57.2 item/individual (Li et al., 2015). As an important source of human protein, annual global aquaculture production has increased from less than 1 million ton in 1950–112 million tons in 2017 (FAO, 2017). The large scale of aquaculture determines that the microplastic pollution in aquaculture products will have a wide and far-reaching impact. The harm of microplastics in aquaculture is first manifested in aquaculture environment. Microplastic containing

Abbreviations: AN, acrylonitrile; BPA, Bisphenol A; CCD sensor, charge-coupled device sensor; COD, chemical oxygen demand; DEHP, diethylhexyl phthalate; EPDM, propylene - ethylene propylene diene monomer; EPS, expanded polystyrene; EVA, ethylene-vinyl acetate; HDPE, high density polyethylene; HOCs, hydrophobic organic pollutants; LDPE, low density polyethylene; Mt, million tonnes; MP, microplastic; NY, nylon; PA, polyamide; PAHs, polycyclic aromatic hydrocarbons; PAN, polyacrylonitrile; PCB, polychlorinated biphenyls; PE, polyethylene; PE-PP, poly(ethylene:propylene:diene); PES, polyethersulfone; PET, polyethylene terephthalate; PEVA, polyethylene-vinyl acetate; POM, polyoxymethylene; PP, polypropylene; PP:PE, poly (propylene-ethylene) copolymer; PS, polystyrene; PSA, poly (styrene co-acrylonitrile); PU, polyether urethane; PVC, polyvinyl chloride; ROS, reactive oxygen species; RY, rayon; SAR, synthetic aperture radar; UV, ultraviolet ray.

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chlorine (e.g. PVC) may release HCl to the water in the process of decomposition, resulting in acidification of the aquaculture environment (Gewert et al., 2015). The various organic additives in microplastics, such as BPA and phthalates, pose a threat to organisms as endocrine disruptors when leached in water (Do et al., 2022). In addition, microplastics can be released into the natural environment after accumulation in the aquaculture environment and then cause pollution diffusion (Cao et al., 2007). Secondly, microplastics are now known to enter aquaculture products through the water environment and have multiple adverse effects (Moore et al., 1998; Tabata and Ikada, 1990). For example, microplastics can slow down the growth rate of Japanese medaka and cause DNA damage (Pannetier et al., 2020), improve the absorption efficiency of *Oreochromis niloticus* to chemical contaminants (Zhang et al., 2019), stimulate the immune response, trigger antioxidant defenses and shorten intestinal villi of hybrid snakehead (Zhang et al., 2022). Microplastics and microplastic-related additives can also affect the immune system of aquaculture products and produce neurotoxicity, reducing the quality of aquaculture products (Tang et al., 2022, 2020). This indicates that microplastics will slow down the growth and propagation of aquaculture products, reduce the survival rate of aquaculture products, and ultimately cause economic losses to aquaculture. Finally, as consumers of aquaculture products, these microplastics have various effects on human health, including reducing digestive enzyme activity, affecting human digestive absorption function. In addition, microplastics also can promote the accumulation of other organic pollutants in aquaculture products, such as antibiotics and microplastic organic additives, and increasing the health risks they pose to human. These additives in microplastics have reproductive toxicity, teratogenicity and mutagenicity to human body, the intake of antibiotics will increase the human intestinal microflora resistance, threatening human health (Kuebler et al., 2020; Lim et al., 2021; Powell et al., 2010; Tan et al., 2020; Zhang et al., 2022b; Zhou et al., 2020). Therefore, microplastic pollution in aquaculture needs to be paid attention.

Based on the adverse effects of microplastics in aquaculture, countries around the world have taken some control measures against this emerging pollutant, including controlling the use of plastic fishing gears in aquaculture and increasing the recovery rate of these fishing gears, reducing or replacing the use of plastic packaging (Skirtun et al., 2022). Ecological interception of microplastics by aquatic plants is also a feasible method (Liu et al., 2022). However, we can also see that microplastic pollution has not been paid enough attention among aquaculture in countries, so that these measures have not been standardized in the industry, but only implemented in individual aquaculture bases. In addition, there is no unified standard for the analysis of microplastic pollution in aquaculture, which leads to the lack of representativeness and unity of the analysis processes and results. For example, the chemical digestion method widely used in aquaculture products will lead to the underestimation of microplastic abundance (Way et al., 2022). At the same time, aquaculture is a long-term dynamic process, and the existing sampling analysis processes are difficult to describe the change of microplastic pollution over time. Therefore, it is necessary to develop new monitoring and control methods for microplastic pollution in aquaculture. At present, the more promising measures include remote sensing technology (Martínez-Vicente et al., 2019) and portable sensor technology (Asamoah et al., 2019), which are helpful to establish a long-term detection network of microplastic pollution in aquaculture. As environmental problems in aquaculture, professional exchanges on environment and aquaculture can help to solve the current difficulties more effectively (Kusnierz et al., 2020). The governments' legislation on the detection process and limit value of microplastics in aquaculture is also an urgent direction (Lam et al., 2018). Clear provisions help to reduce microplastics in aquaculture and ensure the food safety.

In addition to the above problems, the current researches on the biological effects of microplastic pollution in aquaculture are mainly aimed at the pathological studies of biological individuals, and there are few studies on the impact of microplastics on the population of aquaculture products, which is difficult to evaluate the specific economic losses caused by microplastics in aquaculture. In addition, the current studies on the effects of microplastics on human body mainly focus on in vitro studies and mammalian replacement studies, so the effects of microplastics on human body still need to be carefully evaluated. This is also the focus of future researches on microplastic pollution in aquaculture. This review aims to systematically summarize the current situation, hazards and control methods of microplastic pollution in aquaculture, so as to deepen understanding of this field and provide feasible ideas for reducing microplastic pollution in aquaculture.

2. The sources of microplastics in aquaculture

Microplastic pollution is widespread in the global aquaculture environment and aquaculture products, which has a profound impact. The sources of microplastics in aquaculture can be divided into microplastics introduced from the external environment (including river, marine, land and atmosphere) and microplastics introduced in during aquaculture process (including the aging and wear of plastic fishing gears, feeding and packaging of aquaculture products). Fig. 1 summarizes the ways in which microplastics enter aquaculture environments.

2.1. Microplastics from the external environment (river, marine, land and atmosphere)

The sources of river microplastics include industrial effluents, human activities, sewage treatment plants, agricultural activity, etc (Kumar et al., 2021). In terms of industrial wastewater, textile wastewater is the main source of fibrous microplastics in rivers. Microplastics have been found in sewage discharged from a textile industrial area in Shaoxing city, China and have had an impact on the local freshwater environment, the abundance of microplastics in surface water samples in the nearby water environment was 2.1–71.0 items/L, and that in sediment samples was 16.7–1323.3 items/kg (d.w.) (Deng et al., 2020). In addition, there is a certain amount of microplastics in wastewater from the automotive, packaging and food industries (Gundogdu et al., 2018). Human activities also release microplastics into the environment. Microplastics are added to the daily necessities, including cosmetics, toothpaste and shampoo (Jiang, 2018). The washing of synthetic fiber clothing in daily life is also the source of microplastics. According to statistics, polyester fleece fabrics shed averaging 7360 fibers/m^2/L in one wash, synthetic fiber garments of acrylic, nylon, and other materials also shed different amounts of microplastics when washed (Carney Almroth et al., 2018). These microplastics will enter the river with domestic sewage. The above two kinds of sewage will form the non-point source pollution of river microplastics through the direct discharge of industrial areas and residential areas along river, while the wastewater from cities and large industrial areas is generally concentrated in sewage treatment plants, which led to the sewage treatment plant gathered complex sources of microplastics and become a point source of its emissions. Although the existing wastewater treatment process has a certain treatment effect on microplastics, the amount of microplastics entering rivers is still high due to the huge discharge of sewage (Sun et al., 2019). Studies of effluent from three wastewater treatment plants in Australia show that about 22.1×10^6 to 133×10^6 microplastics are discharged daily with treated wastewater (Ziajahromi et al., 2021). There are a large number of plastic products used in agricultural production, including plastic films, pipelines and so on. The weathering of these plastics will produce microplastics and these microplastics will transfer into rivers through wind and rain. The use of irrigation plastic pipes and their subsequent abandonment in the environment was identified as a source of microplastics of the river Ombrone (Guerranti et al., 2017). The introduction of these pathways leads to a high abundance of microplastics in rivers. It is estimated that about 3.3×10^5 tons of plastics are produced annually in the Yangtze River basin, while about 1.2×10^5 tons of plastics are

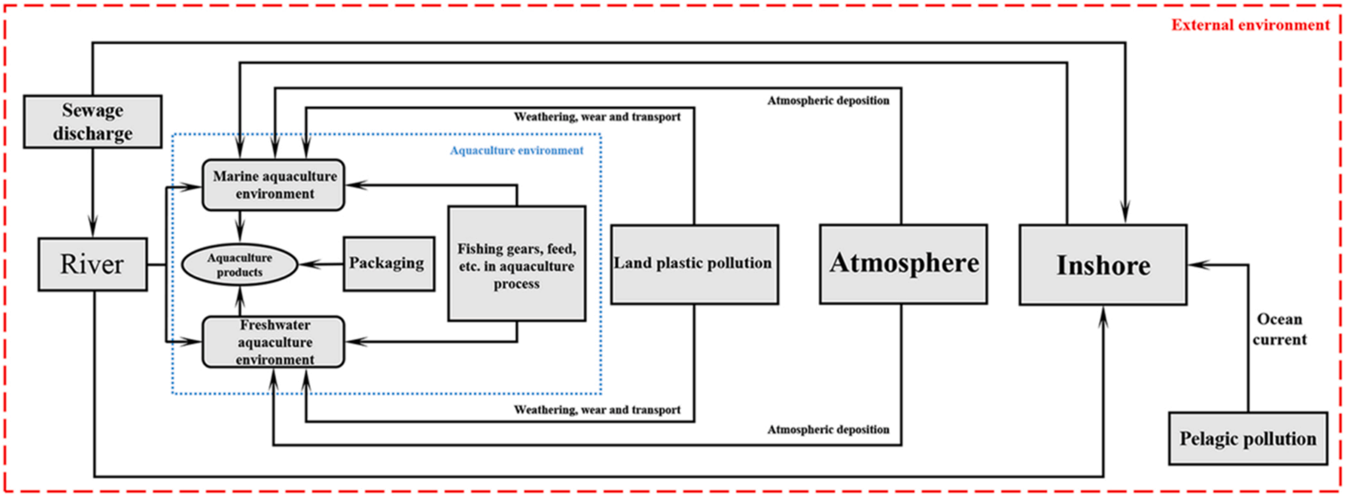

Fig. 1. Ways of microplastics introduced into aquaculture environments and aquaculture products.

produced annually in the Ganges River basin (Lebreton et al., 2017). The load of microplastics in the Dafeng River, where near developed oyster farming along the coast, was 8.3×10^8 particles/year (Q.R. Liu et al., 2021; S. Liu et al., 2021). As rivers are closely linked to freshwater and marine aquaculture environments, microplastics in rivers have a wide range of impacts on aquaculture environments. Multiple studies have demonstrated that microplastic pollution of aquaculture areas in estuaries and coastal areas near estuaries is associated with high abundance of microplastics in local rivers (Ma et al., 2020; Ta and Babel, 2020; Lam et al., 2022) Therefore, rivers as an important source of microplastic pollution in aquaculture should be taken seriously.

It is estimated that 92 % of 5.25 trillion particles in the global marine are microplastics (Eriksen et al., 2014). Marine microplastic pollution poses a serious threat to marine aquaculture. According to statistics, 4.8–12.7 million metric tons of plastic waste entered the marine from land in 2010 alone (Jambeck et al., 2015). Microplastics loaded by rivers are important sources of microplastics in the marine. It is estimated that between 1.15 and 2.41 million metric tons of plastic waste enters the marine per year from rivers (Lebreton et al., 2017). These plastic wastes entering the marine led to the production of large quantities of microplastics. In coastal areas, tourism, leisure and commercial fishing, shipping and the marine industry also produce large amounts of microplastics that are discharged into the marine (Cole et al., 2011). These microplastics pose a threat to coastal aquaculture. In addition, the development of the shipping industry has also increased the pollution of microplastics in the marine. The plastic parts in the hull, the wear of paint and other plastic wastes discarded on the ship will produce microplastics (Food and Nations, 2018). According to statistics, discharge of microplastics from cruise ships suggests 100 thousand tons of microplastics annually (Van Sebille et al., 2015). The microplastic pollution generated by the marine shipping industry will be transported through the marine current and affect the coastal aquaculture. According to statistics, about 15 % of the microplastics in the marine float in coastal areas, that is an important source of microplastics in coastal aquaculture (Yang et al., 2021). This is demonstrated by microplastic pollution from seawater farms in the Yellow Sea, the Bohai Sea and the Maowei Sea (Mohsen et al., 2019; Zhu et al., 2021).

Microplastics directly from land in aquaculture are mainly derived from wastes near the aquaculture environment. Plastic waste will form a large number of microplastic pollutants through weathering and photocatalytic decomposition in the process of stacking (Hartmann et al., 2019). Then these microplastics will migrate to the aquaculture environment through various ways, such as wind and rain (Dong et al., 2021). For example, due to the accumulation of garbage around, high microplastic abundances were found in the water of Marunda and Muara Kamal aquaculture ponds of 103.8 ± 20.7 particles/L and 90.7 ± 17.4 particles/L (Priscilla and Patria, 2019). And the existence of microplastics has been detected in the atmospheric environment (Allen et al., 2019). Microplastics have the risk of entering the aquaculture environment through atmospheric sedimentation. Research shows microplastics in the atmospheric fallout into the city ranging from 175 to 313 particles/m^2/day (Cai et al., 2017). Although the number of microplastics entering aquaculture environment through this way is limited, its accumulation will also affect aquaculture. In addition to normal atmospheric deposition, extreme weather also affects the abundance of microplastics in aquaculture environment. For example, typhoon can increase the abundance of microplastics in aquaculture environment by migrating terrestrial microplastics and releasing microplastics in water sediments (Wang et al., 2019). Study has found that typhoon increased the concentration of microplastics in the sediment of Sanggou Bay mariculture environment by approximately 40 % (Wang et al., 2019).

2.2. Microplastics produced during aquaculture (the aging and wear of plastic fishing gears, feeding and packaging of aquaculture products)

Fishing gears used in aquaculture will inevitably introduce microplastics into the aquaculture environment. Due to long-term immersion, erosion, wear and collision, the nets, fishing ropes, floating balls and other plastic products used for cage culture and raft culture can generate microplastics (Food and Nations, 2018), UV catalytic decomposition will accelerate this process (Song et al., 2017). Twisted rope, braided rope and filament which are widely used in aquaculture together may make up between 0.78 and 6.39 ± 2.33 cm^3 of estimated plastic volume per meter of beach, and potentially emit between 300 and 1277 ± 431 microplastic fragments per meter of beach (Wright et al., 2021). A study of coastal marine aquaculture in Weihai, China shows that the concentration of microplastics in the mariculture areas was 11.49 particles/m, much higher than that in other areas without mariculture (1.57 particles/m) (X. Zhang et al., 2021). These microplastics are considered to originate from fishing nets, ropes and foam floating balls in mariculture areas. The exposure of the plastic fencings to sunlight and the climbing of crab and crayfish on the fencing will promote the generation of microplastics (Xiong et al., 2021). Boring isopods would damage expanded polystyrene floats under aquaculture docks and expel copious microplastic particles (Davidson, 2012). Oyster rafts made of foam also produce microplastics under the water motion and weathering (Chen et al., 2022). Feed bags, ropes and floating polymers are used in the production process of salmon farming in Chilean, which can release microplastics into the marine aquaculture environment (Jorquera et al., 2022). At the same time, fishing gears would be lost in aquaculture for various reasons, such as washed away by waves (Chaves and da Silveira, 2016), or fall off from the ropes (Chen et al., 2018), etc. These fishing gears may uncontrolledly appear in aquaculture area and cause microplastic pollution to aquaculture (Food and Nations, 2018; Huntington, 2019).

Fish meal and shrimp meal are high protein feed ingredients in aquaculture, mainly from wild-caught fish and shrimp. Due to the widespread existence of microplastic pollution, wild fish and shrimp as contaminated feed will introduce microplastics into the aquaculture environment during the feeding process (Zhou et al., 2021). Microplastics have been widely found in aquaculture feeds. Roughly 50–100 mg/kg of polystyrene, 50–100 mg/kg of highly oxidized polyolefins and 12.9 mg/kg of polyester had been found in fish meal from Italy (Castelvetro et al., 2021a, 2021b). Hanachi et al. (2019) found that microplastics were contained in four kinds of fish meal, and their content was positively correlated with that of microplastics in cultured carp. And 10.7 n/100 g and 5.4 n/100 g microplastics were respectively detected in shrimp meals and fish meals from five countries (Yao et al., 2021). Packaging is the last procedure for aquaculture products to leave the aquaculture environment. Expanded polystyrene boxes, corrugated plastic boxes and plastic trays are commonly used packaging for aquaculture products (Margeirsson et al., 2011; Skirtun et al., 2022). Studies have shown that microplastic fibers may be released from plastic packaging of various materials, and the release abundance is the highest in polystyrene plastics (Du et al., 2020). Polystyrene packaging also has been found that would cause microplastic pollution to rainbow trout (Alak et al., 2021). In addition, the aging and poor management of plastic products such as rubber gloves, rubber shoes and rubber aprons widely used by aquaculture practitioners will aggravate the pollution of microplastics in aquaculture areas.

As can be seen from Tables 1 and 2, microplastics are ubiquitous in aquaculture waters and sediments, and their main sources are closely related to the natural and social environments. For example, the high abundance of microplastic in sea cucumber farms near Laizhou Bay in Bohai Sea is considered to be linked to 23 rivers that inject into Laizhou Bay. These rivers accumulate wastewater from coastal industries, agriculture and urban activities, resulting in the accumulation of microplastics in Laizhou Bay (Zhang et al., 2012). The high abundance of microplastics in Jiaozhou Bay sea cucumber farms is due to the pollution discharge of the high population city Qingdao (Mohsen et al., 2019). The small industrial and residential areas near the aquaculture area of Chao Phraya River Estuary, Thailand increased the abundance of microplastics nearby (Ta and Babel, 2020). It can also see from Tables 1 and 2 that fibrous microplastics almost were ubiquitously detected all the aquaculture environments, and it is speculated that the aging of plastic fishing gears such as fishing nets is an important reason for these fibers (Food and Nations, 2018). And the types of polypropylene and polyethylene microplastics are widely distributed, which is related to improper disposal of plastic products such as plastic fishing gears, bags, bottles, films, etc (Shim et al., 2018).

It can be concluded from Tables 3 and 4 that the proliferation of microplastics has a broad impact on the global aquaculture products. The accumulation of microplastic caused by aquaculture activities in closed or semi-closed freshwater aquaculture environment is particularly obvious. For example, the concentration of microplastics in the post-cultured water environment was significantly higher than that in the pre-cultured water environment during the aquaculture of Asian swamp eels (Lv et al., 2020). And the closed or semi-closed aquaculture environment increases the probability of microplastic intake in aquaculture products. Aquaculture products accumulate microplastics through the digestive system, gill and skin (Moore et al., 1998). Therefore, the abundance of microplastics in aquaculture products is generally higher than that in wild aquaculture products. For example, a study showed that the abundance of microplastics in cultured mussels was 1.4–1.7 times higher than that in wild mussels (Mathalon and Hill, 2014). Studies of reared sea bream have shown that microplastic intake increases rapidly once fish are placed in outdoor cages (Capó et al., 2022). The results in Tables 3 and 4 also show that the properties and characteristics of microplastics in aquaculture products are highly correlated with microplastics in aquaculture environment. For example, fiber microplastics widely present in aquaculture environments also exist in aquaculture products (Ta and Babel, 2020; Zhang et al., 2020). White polystyrene microplastics found in juvenile Pacific bluefin tuna dead during aquaculture are typical marine pollutants in aquaculture

Table 1
Microplastics pollution in non-marine aquaculture environments.

Site	Source	Abundance	Shape	Main composition	Reference
Chao Phraya River Estuary, Thailand	Sediment	48 ± 8 items/m^3	Fragments, fibers, and films	PP, PE, PP-PE, PS	(Ta and Babel, 2020)
	Surface water	39 ± 14 items/kg	Fragments, Fibers, and Films	PP, PE, PP-PE, PS	
Pearl River Estuary of Guangzhou, China	Fresh water	10.3–60.5 particles/L	Fibers, fragments, films	PP, PE	(Ma et al., 2020)
	Fresh water	33.0–87.5 particles/L	Fibers, fragments, films	PP, PE	
Experimental base of the Shanghai Academy of Agriculture Sciences, China	Sediment under the fresh water	27.1 ± 7.0 items/kg	Fragments and fibers	PP, PE	(Lv et al., 2020)
Rice-fish culture stations in Chongming, Shanghai, China	Fresh water	0.5 ± 0.1–0.9 ± 0.2 items/L	Films and fibers	PE, PP	(Lv et al., 2019)
Ciénaga Grande de Santa Marta lagoon complex, Colombian Caribbean	Lagoon water	0.00–0.22 items/L	Fibers fragments, films, foams and granules	PP, PE, HDPE, PS	(Garcés-Ordóñez et al., 2022)
	Sediment	0.0–3.08 items/kg	Fibers, films and fragments		
Mussel farm, Venice, Italy	Lagoon sediment	1237 n/kg d.w.	Irregular fragments, fibers, films and pellets/granules	PE, PP, PS	(Vianello et al., 2013)
Two aquaculture ponds in Hanoi city, Vietnam	Surface sediment	2767 ± 240–2833 ± 176 items/kg d.w.	Fibers and fragments	PE and PP	(Le et al., 2022)
Pearl-farming lagoons of French Polynesia	Surface water	0.9 ± 0.9–3.3 ± 2.3 item/m^3	Fragments and fibres	PP, PE, PS, PET and PU	(Gardon et al., 2021)
	Water column	82.6 ± 67.6–134.7 ± 224.0 item/m^3	Fragments and fibres	PE, PVC, PET and polyisoprene	
Pond breeding station, Hubei Province, China	Water	2.5 ± 0.1 particles/L	Fibers and fragments	PP:PE, PE, PET, cellophane and cellulose	(D. Zhang et al., 2021)
	Sediment	0.04 ± 0.02 particles/g d.w.	Fibers and fragments	PP:PE, PE, PET, cellophane and cellulose	
Crayfish cultivation field of rice-crayfish co-culture breeding station, Hubei province, China	Water	1.3 ± 0.1 particles/L	Fibers and fragments	PP:PE, PE, PET, cellophane and cellulose	(D. Zhang et al., 2021)
	Sediment	0.03 ± 0.01 particles/g d.w.	Fibers, fragments and microbeads	PP:PE, PE, PET, cellophane, PSA and cellulose	

Table 2
Microplastics pollution in marine aquaculture environments.

Site	Source	Abundance	Shape	Main composition	Reference
Xiangshan Bay, China	Marine sediment	73.94 ± 30.43 items/kg d.w.	Fibers	RY, PP, PA, AN, PET	(Wu et al., 2020)
Shandong Peninsula, China	Marine water	/	Fibers fragments and films	PE, PP	(Sui et al., 2020)
Andratx, Spain	Marine water	0.27 ± 0.14 items/m^2 (T_0)	/	/	(Capo et al., 2021)
The Yellow Sea and the Bohai Sea, China	Sediment	2.8 ± 1.30–46.8 ± 4.81 items per 50 g	Fibers, fragments and films	Cellophane, PET, PE	(Mohsen et al., 2019)
Maowei Sea, Beibu Gulf, China	Marine water	1.47–7.61 particles/L	Fibers, foam and film	PET, POM, PE	(Zhu et al., 2021)
Cultured ponds in Longjiao Bay, southeast China	Marine water	Mean value of 1594 ± 1352 particles/m^3	Fibers, granules, fragments, foams and films	PE, PET, PS	(Chen et al., 2020)
Weihai, China	Marine water	11.49 particles/m	Fragments and fibers	PE, PP, PS	(X. Zhang et al., 2021)
Lambert Channel and Baynes Sound, British Columbia, Canada	Marine sediment	Up to 25,000 n/kg dry sediment	Microbeads, microfibers and microfragments	/	(Kazmiruk et al., 2018)
Zhanjiang Bay, China	Marine water	0 n/m^3 to 2.65 n/m^3	Fragments, films, foams, fibers, and granules	PE, PP, EPS, olefin and rubber	(Chen et al., 2022)
Ma'an Archipelago marine ranching area, China	Marine water	0.2 ± 0.1–0.6 ± 0.2 items/L	Fibers, fragments and films	PE, PP, PE-PP,PS and PA	(Zhang et al., 2020)
	Sediment	30.0 ± 0.0–80.0 ± 14.1 items/kg d.w.	Fibers, fragments and films	Cellophane, PE and PP	

Table 3
Microplastics pollution in non-marine aquaculture products.

Site	Aquaculture Product	Source	Abundance	Shape	Main composition	Reference
The rice-fish culture stations in Chongming, Shanghai, China	Eel, loach and crayfish	Fresh water	average abundance 1.7 ± 0.5 items/individual	Fibers	PE, PP	(Lv et al., 2019)
The drinking water reservoirs for the City of Bloomington, McLean County, Illinois, the U.S.	Izzard shad and largemouth bass	Fresh water	1 to 49/No. Fish	/	/	(Hurt et al., 2020)
Huila region, Colombia	*Oreochromis niloticus*	Fresh water	44 % samples contain microplastics	Fragments, films and fibers	PET, PES, PE, PP	(Garcia et al., 2021)
The lagoon of Bizerte, Tunisia	*Mytilus galloprovincialis, Ruditapes decussatus, Crassostrea gigas Hexaplex trunculus, Bolinus brandaris* and *Sepia officinalis*	Lagoon water	703.95 ± 109.80 to 1482.82 ± 19.20 items/kg wet weight	Fibers, fragments and films	PP and PE	(Abidli et al., 2019)
Pearl-farming lagoons of French Polynesia	Pearl oysters	Lagoon water	23.0 ± 20.7 to 137.6 ± 89.4 MP/individual	Fragments and fibers	PP, PE, PS, PET and EVA	(Gardon et al., 2021)
Pond breeding station, Hubei province, China	Crayfish	Fresh water	0.92 ± 0.19 and 0.38 ± 0.13 particles/individual (non-cleansed and cleansed groups)	Mainly fragments	PP:PE, PE and cellulose	(Zhang et al., 2021a)
Rice-crayfish co-culture breeding station, Hubei province, China			0.75 ± 0.13 and 0.17 ± 0.07 particles/individual (non-cleansed and cleansed groups)	Mainly fibers		

areas, which have high abundance in this aquaculture area (Honryo et al., 2021).

3. Effects of microplastics on aquaculture

The adverse effects of microplastics and their loaded pollutants on aquaculture mainly reflect the impacts on aquaculture environment, aquaculture products and human health.

3.1. Effects of microplastics on aquaculture environment

Plastics are difficult to degrade in nature. Microplastics pollutants will exist stably for a long time and affect the water transmittance once they enter the aquaculture environment. Moreover, some plastics containing chlorine (such as PVC) may release HCl during photocatalytic decomposition, resulting in acidification of water environment (Gewert et al., 2015). Microplastics and additives have toxic effects on microalgae in water, which can affect the ecological balance of aquaculture environment (Zhang et al., 2022a). Compared with large plastic pollutants, microplastics have the characteristic of large specific surface area. And due to their surface hydrophobicity, microplastics can be loaded with HOCs, such as PAHs, organochlorine pesticides and PCB (Cai et al., 2017). At the same time, the surfaces of microplastics can be colonized by microorganisms forming biofilms, which can promote the release of HOCs into the water environment (Rummel et al., 2017). Therefore harmful additives in microplastics and pollutants loaded by microplastics can be released into the environment easily, which may increase the risk of aquaculture products ingesting toxins and pose a threat to humans. Microplastics also have some adverse effects on the microbial community of water environment. For example, antibacterial agents are added to some polymers during their manufacturing (Sui et al., 2020). These antibacterial agents can be released by microplastics, and the microorganism in the aquatic environment may produce drug resistance (Ta and Babel, 2020), which has the risk of causing the spread of infectious diseases. Microplastics may increase the abundance of antibiotic resistance genes in aquaculture environments, and increase potential risks of losing effectiveness for antibiotics (Lu et al., 2019). Microplastics also load a large number of viruses. Studies have shown that more than 1700 viruses are loaded in microplastics in water environments (H.X. Li et al., 2022; R. Li et al. 2022). This will worsen the aquaculture environment and reduce the production of aquaculture products, reduce the economic benefits of aquaculture. Microplastics

Table 4
Microplastics pollution in marine aquaculture products.

Site	Aquaculture Product	Source	Abundance	Shape	Main composition	Reference
Baynes Sound, British Columbia, Canada	Manila clam	Marine water	1.7 ± 1.2 particles/g	Fibers, films and fragments	/	(Davidson and Dudas, 2016)
Oshima Hatchery, Aquaculture Technology and Production Center, Kindai University, Japan	Pacific bluefin tuna (*Thunnus orientalis*)	Marine water	/	Chips, fibers and particles	PS, PEVA	(Okada et al., 2014)
Tenerife, Canary Islands, Spain	European sea bass (*Dicentrarchus labrax*)	Marine water	Between 0.6 ± 0.8 and 2.7 ± 1.85 particles per fish	Fibers, fragments, films and lines	PP, PE	(Granby et al., 2018)
The Yellow Sea and the Bohai Sea, China	Sea cucumber	Marine water	1.56 ± 0.96–24.2 ± 5.90/intestine	Microfibers	Cellophane, PET	(Mohsen et al., 2019)
Kalamukku, Kerala, India	*Rastrelliger kanagurta* , *Megalaspis cordyla* , *Sardinella longiceps* , *Sardinella gibbosa* , *Stolephorus indicus* , *Dussumieria acuta* , *Thryssa dussumieri* , *Sphyraena obtusata* and *Anontostoma chacunda*	Marine water	0.005 ± 0.02 items/g (in edible tissues) to 0.054 ± 0.098 items/g(in inedible tissues)	Fragments, fibers, foam	PE, PP, EPDM, PS	(Daniel et al., 2020)
Maowei Sea, Beibu Gulf, China	Oysters	Marine water	0.42 ± 0.09–2.44 ± 0.41 particles/g	Fibers, foam and film	PET, POM, PU	(Zhu et al., 2021)
LIMIA aquaculture facilities (Laboratorio de Investigaciones Marinasy Acuicultura), southwest coast of Mallorca, Andratx Bay	Sea bream (*Sparus aurata*)	Marine water	9.07 ± 5.21 items/fish(T_{60})	/	/	(Capó et al., 2022)
The Gulf of California eoregion, Mexico	*Litopenaeus vannamei*	Marine water	18.5 ± 1.2 microplastics /shrimp	Filaments, subangular, spheroidal	PA, PES, PS, PE, NY	(Valencia-Castañeda et al., 2022)
Ramalhete marine station, Faro, Portugal	Cuttlefish *(Sepia officinalis)*	Marine water	median 28.5/animal	Fibers, fragments and microfilm pieces	PP, LDPE, HDPE	(Oliveira et al., 2020)
Baja California, Mexico	Oysters	Marine water	0.22 ± 0.20 MPs org^{-1} to 0.38 ± 0.14 MPs org^{-1}	Fibers and fragments	PET, PAN, PE, PP, PS, PA and T. elastomer	(Lozano-Hernández et al., 2021)
Fish farms in Italy and Croatia	Sea bream *(Sparus aurata)* and common carp *(Cyprinus carpio)*	Marine water	0.48 items/specimen in sea bream and 0.11 items/specimen in ommon carp	Microfibers and microfragments	PET, PTFE	(Savoca et al., 2021)
Different aquaculture areas in Italy	Mussels *(Mytilus galloprovincialis)*	Marine water	Median 6.2–7.2 items/g	Filaments	/	(Renzi et al., 2018)
Oyster farm in Yantai, China.	Pacific oysters	Marine water	4.53 items/g wet weight	Fibers and fragments	Cellophane and polyester	(Zhu et al., 2020)
Ma'an Archipelago marine ranching area, China	*Muraenesox cinereus, Oplegnathus fasciatus, Raja porosa, Cynoglossus lighti, Sebastiscus marmoratus, Collichthys lucidus, Setipinna taty, Larimichthys crocea,* and *Chelidonichthys kumu*	Marine water	2.3 ± 1.5–7.3 ± 3.5 items/individual	Mainly fibers	cellophane, PA, PE and PE-PP	(Zhang et al., 2020)

accumulated in aquaculture environment will also enter the natural water through the discharge of aquaculture wastewater, expanding the pollution area of microplastics (Xiong et al., 2022). In summary, aquatic microplastics will bring a variety of pollution risks to aquaculture and its surrounding environment.

3.2. Effects of microplastics on aquaculture products

Microplastics have been found in a large number of aquaculture products (Food and Organization, 2020), such as fish, mussels, shrimp and crabs (Rezania et al., 2018). Microplastics cause multiple toxicological effects including oxidative stress in aquaculture products, as well as adverse effects on the behavior, growth and reproduction of aquaculture products, ultimately reducing the economic benefits of aquaculture products.

Microplastics have extensive and significant effects on fish metabolism, such as lipid metabolism, oxidative stress, carbohydrate metabolism and toxin excretion (Jacob et al., 2020). And the current academic research is more about its inducing effect on fish oxidative stress response (Jacob et al., 2020). Study has shown that microplastics can change the metabolic state of fish, promote the production of ROS, and then induce oxidative stress response (Jeong et al., 2017). The large production of ROS will also adversely affect the cholesterol level and enzyme activity related to lipid metabolism in fish (Cedervall et al., 2012; Karami et al., 2016; Wan et al., 2019). Microplastics have toxic effects on fish immune system. Studies have shown that PVC and PET microplastics with the sizes of 40–150 μm can cause oxidative damage to the cells of sea bream and sea bass (Espinosa et al., 2019). In terms of brain function, studies have shown that microplastic particles with particle sizes of 24 nm and 27 nm can affect the development of fish brain (Mattsson et al., 2015), for example, brain development slowdown, structural damage (LeMoine et al., 2018; Wan et al., 2019) and acetylcholinesterase activity decreased (Antao Barboza et al., 2018). And smaller particles may be located in blood vessels and tissues around the brain, causing harm to the brain (Schür et al., 2019). For some relatively large microplastic particles, it is generally believed that they will stay in the conjunctiva, blood vessels and tissues around the brain, thus affecting brain function (Schür et al., 2019). Larger particles (> 500 nm) can induce immune response, change fish metabolism and intestinal microbiota, and then lead to brain function damage (Borre et al., 2014; Chen et al., 2017). The effect of microplastics also can reduce heart and gills functions. For example, 51 nm PS microplastics can cause oxidative stress in zebrafish, which can lead to the decrease of heart rate in zebrafish (Pitt et al., 2018). At the same time, Karami et al. (2016) had proved microplastics which size 60 μm can cause tissue damage in the gills of the African sharptooth catfish and the *Clarias gariepinus*. Microplastics also have toxic effects on non-fish aquaculture products. For example, microplastics can lead to the mussel's digestive system inflammatory response (von Moos et al., 2012). Likewise, microplastics also can cause instability in phagocyte lysosome membrane of sea urchins and apoptosis (Romano et al., 2018). Triclosan and microplastics increased mussel (*Perna canaliculus*) oxidative stress markers including SOD activity and lipid peroxidation (Webb et al., 2020). Microplastics also can increased the immunotoxicity of sertraline to Tegillarca granosa (Shi et al., 2020).

Behavior, growth and reproduction are also the focus of the impact of microplastics on aquaculture products. Microplastics may affect the behavior of aquaculture products. Microplastics exist stably after being ingested by aquatic organisms, which may cause false satiety and affect the intake of aquatic organisms, or even cause gastrointestinal obstruction (Colferai et al., 2017). The non-digestibility of microplastics will increase the burden on the digestive system of fish when ingesting microplastics, resulting in the decrease of digestive enzyme activity and the increase of trypsin and chymotrypsin (Romano et al., 2018). And studies have shown that microplastics can reduce the feeding and swimming abilities of *Sebastes schlegelii* (Yin et al., 2018), exposure to PE microplastics decreased the swimming and predation ability of the common goby (Oliveira et al., 2013). Microplastics could impair the olfactory mediated behavioral responses of goldfish through a comprehensive mechanism that hampers odorant identification and other ways (Shi et al., 2021). In terms of growth, studies have found that microplastics significantly affect energy storage in *Sebastes schlegelii* (Yin et al., 2018). PET microplastics increase energy consumption and decrease growth rate of edible mussel (Détrée and Gallardo-Escárate, 2018). The accumulation of PS microplastics would significantly decreased the rates of respiration and excretion of Manila clam while significantly decreasing feeding and absorption efficiency, leading to a reduced amount of its energy available for growth and ultimately led to slower growth (Jiang et al., 2022). X.Q. Wang et al. (2022) studied the effect of polystyrene microplastics on loach juveniles, the results showed that the weight gain rate, and growth rate of loach juveniles were significantly reduced. Microplastics and their additives also have adverse effects on the reproduction of aquaculture products. For example, exposure to PS microplastics produced strong negative effects in energy uptake and allocation and reproductive health of oysters (Sussarellu et al., 2016). BPA released from microplastics can affect the reproductive organs and gonads of carp (Mandich et al., 2007). Microplastics and BPA may also exert toxic impacts on the gonadal development of whiteleg shrimp by interfering with metabolism and disrupting endocrine regulation (Han et al., 2022). Martinez-Gomez et al. (2017) found low fertilization (56–58 % success) in individuals exposed to PS-MPs. Microplastics can hamper the fertilization success of a broadcast spawning bivalve through reducing gamete collision and gamete fusion efficiency (Shi et al., 2022). Microplastics also have potential toxicological effects on embryos of aquatic products. Research suggests microplastics can delay hatching in fish, which may affect predatory escape behavior and the later larval developmental stages (Bonfanti et al., 2021).

The multiple adverse effects of microplastics on aquaculture products mean a decline in aquaculture production. For example, about 50 % of juvenile *Thunnus orientalis* died within 30 days of cage culture, while polystyrene microplastics and other inorganic substances were found in about one-third of the dead fish (Okada et al., 2014). The mortality rate of adult dagger blade shrimp exposed to > 50 μm spheres and fragments of microplastics reached 5–40 % (Gray and Weinstein, 2017). African catfish exposed to 2 g/L PE microplastics also showed 10 % mortality (Tongo and Erhunmwunse, 2022). The increase in mortality of aquaculture products and the decrease in reproductive efficiency mean the decrease in economic benefits of aquaculture. During 2001–2008, due to the high mortality rate of oyster aquaculture, the number of Charente-Marritime shellfish aquaculture enterprises in France decreased by 28 % (from 1260 to 910), and the number of related jobs decreased by 16 % (from 3520 to 2810 full time equivalent jobs), the economy was seriously affected (Girard and Pérez Agúndez, 2014). The larvae of aquaculture products are also important economic sources. The quantity and quality of fish seedlings are affected by many factors, and will have a profound impact on the subsequent aquaculture process (Hajirezaee et al., 2010). The reproductive effects of microplastics on aquaculture products may reduce the quantity and quality of aquaculture resources such as fish seedlings, thereby reducing the economic benefits of aquaculture.

3.3. *Effects of microplastics on human health*

Microplastics could transfer between trophic levels from herbivores to carnivores, which means microplastics were accumulated and amplificated in the food chain (Tang et al., 2021). Aquaculture product is an important source of risk for human intake of microplastics. Microplastics exist in approximately 80 % of the major food fish species (Walkinshaw et al., 2020). And the possibility of microplastic enter the human body through consumption of aquaculture had proved (Q.R. Liu et al., 2021; S. Liu et al., 2021). The health risk levels of MPs across commercial species from Fuzhou and Xiamen were higher than the hazard level IV (the hazard scores of plastic polymers based on chemical composition) (Fang et al., 2019), the potential risk assessment of microplastics in bivalves from the Daya Bay basing on polymer hazard index (PHI) was in the risk levels of II-III (H.X. Li et al., 2022; R. Li et al. 2022), and it is estimated that each person consumes about 3.3×10^2 to 3×10^3 microplastics per year from fish and about 2.6×10^3 to 1.6×10^4 microplastics per year from shellfish (Senathirajah et al., 2021). Intake of aquaculture products contaminated with microplastics can have adverse effects on human. Microplastics are resistant to chemical degradation. If ingested, they resist mechanical removal; their biological persistence and dose are important factors leading to their risk (Wright and Kelly, 2017). On digestive system, the study of Tan et al. confirmed the microplastic could interact with both lipid droplets and lipases, and revealed two mechanisms by which microplastics affect digestion and absorption: (i) Microplastics decreased the bioavailability of lipid droplets via forming large lipid-microplastics heteroaggregates due to the high microplastics hydrophobicity; and (ii) Microplastics adsorbed lipase, and reduced its activity by changing the secondary structure and disturbing the essential open conformation (Tan et al., 2020). The Peyer's patches of the ileum (third portion of the small intestine) are considered the major sites of uptake and translocation of particles (Powell et al., 2010). Studies have confirmed that non degradable particles such as aluminosilicate and TiO_2 accumulate in large quantities in the basal phagocytes of Peyer plaque (Powell et al., 2010). Both are non-degradable particles, microplastics will also deposit in this range and hijack the absorption pathway of endogenous particles, thus interfering with immune sensory and monitoring and damaging human immunity (Wright and Kelly, 2017).

Studies have shown that microplastics with a diameter of up to 130 μm can penetrate into mammalian blood vessels and lymph nodes at the villus tips of the desquamation zones (Wright and Kelly, 2017), then induce inflammation and immune response (Powell et al., 2010). Microplastics also cause hemolysis after entering the blood. Studies have shown that PS microplastics with diameter less than 5 μm can cause about 4 % hemolysis after entering the blood compared with controls (Hwang et al., 2020). The microplastics that enter the body can transfer with the blood and lymph circulation and then into various parts of the body. Study have shown that microplastics ranging in size from 2.15 to 103.27 μm have been found in 11 body fluids, including whole blood and cerebrospinal fluid, etc (Guan et al., 2023). After microplastics enter the circulatory system, they will flow into various organs through blood, thus affecting various organs in the human body. The experimental study of mammalian microplastics can be used as references. After being ingested by rats, nano polystyrene particles (202–535 nm) entering the lungs, causing lung inflammation (Wright and Kelly, 2017), and cerebral softening, micronecroses and scarring were observed in the brains of dogs after they ingested 5–110 μm PVC (Freedman, 1991). Microplastics can enter thoracic lymph nodes through macrophages and reach secondary target organs through systemic circulation, including liver, kidney, spleen, heart and brain, and cause different degrees of adverse effects on these organs (Kreyling et al., 2009). Microplastics such as PP, PE, PS and PU are also detected in human placenta and meconium (Braun et al., 2021), which suggests the presence of microplastics poses a potential health threat to developing fetuses.

It has been confirmed that some additives in microplastics do serious harm to human body. Including reproductive toxicity (e.g., DEHP and BPA), carcinogenicity (e.g., vinyl chloride and butadiene), and mutagenicity (e.g., benzene and phenol) (Powell et al., 2010). Microplastics can be loaded with pollutants including HOCs and heavy metals (such as cadmium, zinc, nickel and lead) (Rochman et al., 2014). In vitro studies showed that the release of Cr loaded on microplastics in human digestive system environment was higher than that in water environment, and gastric phase aroused the most bioaccessible Cr(VI) and Cr(III) (Liao and Yang, 2020), which means that the human inner environment promotes the release of pollutants loaded on microplastics and increases the health risks posed by microplastics.

4. Current countermeasures for microplastic pollution in aquaculture

At present, many studies have explored the treatment methods of microplastic pollution, such as membrane bioreactors (Lares et al., 2018), electro-coagulation (Perren et al., 2018) and zirconium metal-organic framework-based foam material filtration process for seawater (Chen et al., 2020), etc. The purification efficiency of these new technologies for microplastics is above 95 %, which can effectively reduce the microplastics entering the environment. However, most of these methods have not been widely applied and cannot directly reduce the microplastics introduce of aquaculture, so other schemes are needed to directly control the microplastic pollution in aquaculture.

4.1. Blocking external sources of microplastics in aquaculture: ecological interception

The so-called ecological interception refers to use the mitigation of water velocity of large-scale aquatic plants to intercept pollutants to improve water quality. Mangroves are aquatic flora commonly used for ecological interception. Pollutants in the water can be absorbed and accumulated in mangrove plants and soils under mangroves through physical, chemical and biological effects (Liu et al., 2022). Mangroves can maintain the steady state of aquaculture environment and reduce pollution levels in shrimp farming (Do and Thuy, 2022). Barbier et al. identified their role as nursery and breeding habitats for offshore aquaculture (Barbier et al., 2011). Cohen and Valenti also studied the possibility of developing low-cost aquaculture of seahorses in mangrove estuaries, and found that has great potential (Cohen and Valenti, 2019). Based on the application of mangrove in aquaculture, it can be considered that it has the potential to intercept microplastics pollution in aquaculture. Study shows that abundance of microplastics and proportion of fiber microplastics in mangrove edge was significantly higher than those in outside area (Duan et al., 2021). The abundance of microplastics in mangrove surface water ranged from 620 to 13, 100 n/m^3, and that in sediment ranged from 142 to 488 n/kg (Liu et al., 2022), which is much higher than the detection data near the seashore (103–2017n/m^3 in the surface seawater and 76–333 n/kg in the sediments) (Tang et al., 2018). Studies have shown that the greater the mangrove plant density, the stronger the interception effect on microplastics (Horstman et al., 2015). In addition, mangrove also has a certain degradation effect on microplastics. For example, Kathiresan found that the biodegradation rates of polyethylene plastics in mangrove soil for 9 months were 3.77 % and 4.21 %, respectively (Kathiresan, 2003). Auta et al. (2018) used *Bacillus* sp. and *Rhodococcus* sp. extracted from mangrove sediments to degrade polypropylene microplastics, the results showed that the degradation rates of the two microorganisms on microplastics reached 6.4 % and 4.0 % after 40 days, respectively. Auta et al. (2022) studied the degradation of polyethylene terephthalate and polystyrene microplastics in mangrove environment, the results showed that the degradation rates of polyethylene terephthalate and polystyrene were 16.4 % and 19 % respectively after 90 days in natural mangrove sediments, and the degradation value of polyethylene terephthalate microplastics increased to 18 % with the addition of artificial strains. In terms of freshwater aquatic plants, reed also showed the interception effect of microplastics similar to mangrove. Reed is an essential segment of fishpond biota, as they supply habitats and food sources for aquatic organisms and affect physical condition and biogeochemical cycles (Francova et al., 2021). Reed has a certain adsorption effect on microplastics (Plestenjak et al., 2021). A study by Yao et al. (2019) claimed that microplastics accumulate mainly at the edges of reed beds, where dense vegetation traps microplastics through leaves, roots, or biofilms attached to the reed surface. In the study of Yin et al. (2021) the average abundance of microplastics in sediments of reed farms was 511.2 ± 295.0 items/kg, higher than in surrounding waters. Therefore, due to its environmental protection and economic advantages, ecological interception is an effective method to control microplastic pollution in aquaculture environment. However, there may be no suitable aquatic flora near the specific aquaculture areas due to the diversity of aquaculture environment, so the application of this method is also limited by the local environment.

4.2. Reducing production of microplastics in aquaculture environment: application of environmental fishing gears and strengthening management of fishing gears

Various fishing gears are important sources of microplastics in aquaculture (Food and Nations, 2018). Therefore, the use of environmental materials to manufacture these fishing gears is the idea to reduce the microplastic pollution in aquaculture. For example, Skirtun et al. (2022) mentioned that in Scotland and the Netherlands, major farms are replacing plastic fishing gears with fishing gears made from biodegradable materials, such as biodegradable socks in off-bottom mussel culture, and Deroiné et al. (2019) developed a new generation of resistant and biodegradable monofilament, which helps reduce microplastic pollution in aquaculture environments It should be noted that degradable plastics also have the risk of microplastic pollution, but their impact on the aquaculture products is relatively weak. Khalid et al. (2021) have shown that exposure to bio-based biodegradable poly (l-lactide) microplastics at 100 μg/L concentration for 8 days do not cause significant oxidative stress, neurotoxicity and immunotoxicity to blue mussels. For comparison, the study of Paul-Pont et al. (2016) showed a reduced activity of catalase, lipid peroxidase, and enhanced glutathione S-transferase and superoxide dismutase activity in the digestive glands of *M. edulis* and *M. galloprovincialis* after an exposure of marine mussels to PS microbeads at 32 μg/L. However, biodegradable microplastics still have an impact on the lipid group of mussels (Khalid et al., 2021). This also means that it may be better to use non-plastic aquaculture tools and facilities as alternatives to similar products of plastic materials.

While reducing the application of ordinary plastic fishing gears in aquaculture, the management of existing plastic products in aquaculture should also be strengthened. Possible measures include improving the design of existing fishing gears. For example, mussel pegs have been replaced by continuous lines or loops in the Shetlands, this measure helps to reduce the loss of fishing gears in mussel farming, so as to reduce the probability of releasing microplastics from these fishing gears into water (Raedemaecker et al., 2020). The introduction of plastic waste management in aquaculture is also necessary. There are various consumer plastic products used by staff working at aquaculture farms, such as rubber gloves, protective clothing and packaging of food and beverages consumed (Sandra et al., 2019). If these plastic consumer goods are not properly disposed of, they may enter the aquaculture environment and cause microplastic pollution. Recycling and reuse of fishing gears in aquaculture are also necessary measures. For fishing gears that are no longer suitable for use, they can be recycled and reused in appropriate ways, so as to reduce the risk of microplastic pollution in aquaculture, but also reduce the generation of plastic waste, and produce certain economic benefits, improve the environmental protection enthusiasm of aquaculture practitioners. The existing examples under implementation include some organizations and agriculture farming communities to repurpose plastic facilities from fishery farms in North-Western Scotland and the Shetlands to construct the greenhouse, tunnels or farm fences from those fishery farms (Skirtun et al., 2022). Some companies and organizations are looking for innovative ways to upcycle plastic waste to produce sustainable consumer products like bracelets, bags and other textiles (Mowi, 2020), etc. All in all, these attempts are beneficial and worthy of attention by aquaculture practitioners.

4.3. Reducing microplastics in aquaculture products: purification of aquaculture products and improvement of packaging

Due to the limited effect of microplastic treatment methods, aquaculture products will still inevitably be polluted by microplastics. A feasible approach for aquaculture products that may be contaminated is to transfer them to clean water environments that strictly remove microplastics for purification for a certain period of time. This method is used to deal with aquaculture production reduction events such as harmful algal blooms (Mardones et al., 2021). And the water exchange and the recirculating pond based on this development is also to optimize the aquaculture environment and reduce the pollution of aquaculture products by exchanging purified water and polluted water (C. Wang et al., 2022). Purification has shown the potential to reduce microplastic pollution in aquaculture products. For example, the study of Birnstiel et al. proved that purification significantly reduced 28.95 % of microplastic in farmed mussels (Birnstiel et al., 2019). In the research of Solomando et al. on the effects of microplastics on *Sparus aurata*, several physiological indicators of *Sparus aurata* were abnormal after 90 days of microplastic diet intake, including activation of antioxidant and detoxification systems and liver and plasma inflammatory responses. These adverse reactions gradually disappeared in subsequent 30 days of purification, which means the effective discharge of microplastics in *Sparus aurata* (Solomando et al., 2021). The research of Solomando et al. on *Sparus aurata*'s gut also demonstrated that oxidative stress and pro-inflammatory responses in the gut of *Sparus aurata* caused by microplastics could gradually recover after purification (Solomando et al., 2020a, 2020b), which proved that purification is an effective method to alleviate the pollution of microplastics to aquaculture products.

As the main microplastic pollution source of aquaculture products after fishing, the microplastic pollution caused by packaging should be paid attention to. Studies have shown that microplastics have the possibility of polluting food through plastic packaging (Kedzierski et al., 2020). In terms of aquaculture products, Alak et al. studied the effects of different plastic packaging on the quality of rainbow trout fillets. The results showed that the most microplastics detected in rainbow trout fillets packed with polystyrene plates and wrapped films were fibers, fragments and pellets (Alak et al., 2021). Therefore, improving the packaging of current aquaculture products is also one of the ways to reduce the microplastic pollution in aquaculture products. Packaging improvements currently implemented in aquaculture include biodegradable mesh bags for clams, natural wooden trays for oysters, recycled modified atmosphere bags for vacuum sealed mussels and compostable cardboard fish boxes for salmons, etc (Skirtun et al., 2022). For plastic packaging that cannot be improved temporarily, the design can also be improved to reduce the amount of plastic. For example, some Belgian aquaculture producers reduce the use of 96 tons of plastic each year by reducing the weight of trays needed for the transport of aquaculture products by 20 % (Raedemaecker et al., 2020).

5. Suggestions and prospects on aquaculture microplastic pollution control

Researches on the impact of microplastics on the environment have yielded abundant achievements in the research on its influence in natural environment (Z.H. Wang et al., 2020; Xiang et al., 2022). However, efforts to monitor microplastics in artificial or semi-artificial aquaculture environments, develop pollution control standards and conduct international and cross-collaborative research have been insufficient. Therefore, it is necessary to discuss the control of microplastic pollution from these aspects to ensure the environmental safety of aquaculture.

5.1. Prospective monitoring methods for microplastics in aquaculture: new portable microplastic monitoring system and remote sensing technology

Current researches on the abundance of microplastic pollution in aquaculture mainly use the post-sampling analysis methods, which can obtain the microplastic pollution situation at a certain time, but it lacks the ability to analyze the abundance and distribution changes of microplastics in aquaculture environment. Aquaculture process is a long-term and dynamic process. Microplastic pollution may be completely different under different time and environmental conditions. Therefore, it is necessary to carry out long-term and continuous monitoring of microplastic pollution in the whole process of aquaculture in order to help formulate targeted countermeasures for microplastic pollution. For this purpose, monitoring instruments with small size, easy to use and real-time analysis are needed. Some studies have shown results that meet these requirements. Iri et al. designed a low-cost mobile Raman spectroscopy system suitable for the detection of microplastics in water. The system consists of a collimated laser module, a quartz colorimetric dish, a filter, a CCD sensor and a communication interface with a mobile phone, which can be used to detect the abundance of microplastics in water by hand. The system is not only portable, but also can be connected to mobile phones, convenient data storage, while low cost, less than $ 370. However, the shell of the system is made by 3D printing technology, which has a certain risk of introducing microplastics to the aquaculture environment, so it can also keep on improving (Iri et al., 2021). Asamoah et al. also developed a device for detecting microplastics in water by optical method. The setup consists of a portable handheld optical device which weighs 191 g, which can detect transparent and translucent plastic particles in water (Asamoah et al., 2019). Malyuskin conducted a feasibility study on the detection and quantification of microplastics in soil and water by vibrating microwave reflection method. Microwave reflection spectra of the sample are obtained by sweeping the frequency of the signal source and collecting the data, from which the microplastic concentration in the sample can be extracted using a suitable mathematical model (Malyuskin, 2020). Microwave sensor, with small size, low cost, rugged design for real-time, in-situ operation, is attractive for the in-situ microplastic detection and quantification in the flexible monitoring platforms (Aguzzi et al., 2019). Chaczko et al. proposed a system called 'SmartIC' based on Internet of Things, which is specially designed for in-situ monitoring of microplastics in aquatic environments. The system adopts intelligent machine learning algorithm and combines the feature selection technology of evolutionary algorithm, which can become an effective tool for dealing with the difficult positioning, detection and classification of pollutants in dynamic and continuous changing water environment (Chaczko et al., 2018). Due to their portability and low cost, these devices have broad application prospects in the construction of detection network for microplastic pollution in aquaculture environment. The research and application of such portable devices are helpful to study the dynamic distribution of microplastic pollution in aquaculture environment, and provide important reference for the prevention and control of microplastic pollution in aquaculture environment.

Remote sensing imagery with spatial resolution has provided an excellent ancillary tool to quantitatively explore the distributions of floating marine plastic debris (Moller et al., 2016). Martínez-Vicente et al. assessed the requirements for monitoring plastic debris using remote sensing from space (Martínez-Vicente et al., 2019), the results showed that near infrared spectroscopy and short wave infrared technology have recently demonstrated the potential for specific detection of marine plastic debris (Garaba and Dierssen, 2018). In addition, radar and laser radar also have the prospect of application in plastic debris detection. Compared with the traditional space remote sensing method, one of the obvious advantages of radar is that it can operate independently of solar illumination and in the case of cloud cover. The migration and potential accumulation areas of plastics can also be indirectly tracked by monitoring wind direction and ocean current (Li and Lehner, 2014; Romeiser et al., 2014). Davaasuren et al. developed a method for detecting marine microplastic pollution using SAR remote sensing. The goal of this method is to use SAR sensors to detect the surface oil on the ocean surface and the biofilm planted on the microplastics to determine the location of microplastic pollution that is not visible in the optical image (Davaasuren et al., 2018). Martínez-Vicente et al. pointed out because of the novelty of the field, observation requirements for marine plastic debris have to date not been considered in new remote sensing mission designs, which means that the application prospect of this type of equipment is very broad in the future (Martínez-Vicente et al., 2019). Remote sensing technology has been proved to be applied in many aspects of aquaculture (Quansah et al., 2007), includes monitoring of aquaculture conditions (Millie et al., 1992), sustainable management of aquaculture environments (Giap et al., 2003) and spatiotemporal changes in aquaculture areas (Tsai et al., 2006). Based on the wide application of remote sensing technology in plastic pollution monitoring and aquaculture, it is feasible to monitor the pollution of microplastics in aquaculture. Due to the comprehensiveness and traceability of remote sensing technology monitoring, it can monitor plastic debris in aquaculture environment to master the distribution of plastic debris and reduce the impact of secondary microplastic pollution on aquaculture. In addition, remote sensing method is also used to determine the precise location of aquaculture bases (Fan et al., 2019; Phonphan et al., 2018), which helps to determine the distribution of possible emission sources of plastic pollution around aquaculture environment, so that professionals can make more targeted responses to microplastic pollution.

5.2. Standardization of microplastic pollution control in aquaculture: from standardization of analytical process to improvement of relevant laws and regulations

There are problems in the analysis of microplastics in aquaculture, such as the inconsistent expression of analysis results and the uncertainty of analysis results caused by the defects of analysis methods. For example, different studies took different unit of measurement in the results description, such as items/kg, items L^{-1}, particles/m^3, items per 50 g, etc. Although this helps to express the results accurately, it is suggested to standardize the expression of microplastic analysis results so as to analyze the differences in microplastic pollution levels between different regions more conveniently. In addition, the existing microplastic analysis methods also have some problems. Chemical digestion is an important treatment method for microplastics in environmental and biological samples, which is widely used in the detection of microplastics in various samples in aquaculture (Da et al., 2022; Davidson and Dudas, 2016; Lin et al., 2021). At present, many studies have shown that the commonly used chemical digestion methods may cause the loss of microplastics in the detection (Catarino et al., 2017; Claessens et al., 2013; Cole et al., 2014). According to the estimating of Chloe Way et al. (2022) the abundance of microplastics in researches has been underestimated by about 14 %. The weathering of microplastics may also bring difficulties to the identification of microplastics (Fernández-González et al., 2021; Toapanta et al., 2021). Therefore, the existing microplastic pollution level in aquaculture is underestimated. Although there are some methods that have less impact on microplastics, these methods have some limitations, so that they haven't been widely used. For example, enzymatic digestion can digest the biological tissue on the surface of microplastics while maintaining the physical and chemical properties of microplastics (Tirkey and Upadhyay, 2021). However, enzymatic digestion also has the disadvantages of high cost and strict conditions, so the method has not been widely used (Fraissinet et al., 2021). In view of this, it is appealed to optimize the extraction methods and detection methods of microplastics in samples and to unify the expression of detection results in order to evaluate the pollution level of microplastics in aquaculture more accurately and conveniently.

At present, some laws and regulations have limited the use of plastic products, which helps to reduce the pollution of microplastics in the environment. But the current regulations to limit microplastic pollution are not perfect. For example, the Austrian Ordinance on Waste-Water Emission classifies plastics as filterable substances and sets a ceiling of 30 mg/L for plastics to be discharged into flowing water. This means that if the chemical plant discharges sewage at a flow rate of 100 L/s, more than 94.5 t of microplastics will be discharged each year, equivalent to about 2.7 million PET bottles (Lechner and Ramler, 2015). As microplastic pollution has been paid more and more attention by people around the world, countries have also begun to strengthen the restrictions on microplastic emissions. The United States Microbead-Free Waters Act aimed at reducing microplastic pollution was signed into law in December 2015 (McDevitt et al., 2017). The Canadian parliament passed legislation to prohibit the manufacture of microbeads in June, 2017. Australia has set up The Australia microplastics Working Group to seek voluntary agreements for the industrial phase-out of beads in personal care, cosmetics and cleaning products (EPA, 2016). In addition, comprehensive legislation restricting the inclusion of microplastics in cosmetics is being implemented in Canada and the UK (Xanthos and Walker, 2017). In Europe, the Netherlands took the lead in issuing a statement calling for a ban on microbeads within the EU (Xanthos and Walker, 2017). In Africa, Cape Verde has also implemented policies to limit microplastic production (Desai, 2018). As can be seen from the above policies and regulations, countries have begun to limit their initial microplastics manufacturing and emissions, which helps to reduce the pollution level of microplastics in aquaculture environment. Specific to aquaculture, EU Council Regulation 2377/90/EC sets the relevant limits for the use of aquaculture fish antibiotics in aquaculture (Okocha et al., 2018), the Norwegian Food Safety Authority (NFSA) regulates antibiotics use in aquaculture (Lulijwa et al., 2020), China has also initiated the twelfth 5-year plan on 2013 to control and prevent pharmaceutical chemicals posing environmental risks (Ahmad et al., 2022). However, unlike the pollutant indicators with accurate limits such as antibiotic, countries have not yet completed the establishment of pollution standards for microplastics in the environment. Therefore, countries should establish the limit standard of microplastics in the environment, which is particularly important for aquaculture. The policy regulations on the limit values of microplastics in aquaculture environment and aquaculture products help to reduce the economic risks of aquaculture and ensure people's food safety. At the same time, it is also convenient for environmental protection and food safety professionals to evaluate the microplastic pollution in aquaculture more accurately.

5.3. Cross-field cooperation: an effective way to solve microplastic pollution problem in aquaculture

The microplastic pollution in aquaculture needs the cooperation of professionals in aquaculture and environmental protection industries to find solutions. However, in general, these two types of professionals usually work in different areas: aquaculture professionals study and manage specific organisms, while environmental professionals assess and manage the chemical and physical conditions of the waters in which organisms live (Kusnierz et al., 2020), which means that environmental professionals focus on the quantification of regional chemical and physical contamination, and then compare with the threshold as a biological health indicator. In the study, environmental professionals generally need to consider a variety of biological groups in the aquatic environment (van Dam et al., 2014). But in aquaculture, people generally focus on specific typical commercial species, which can achieve the maximum economic benefits through the management of the species and its environment, which means that in some cases, aquaculture water quality is not up to standard from an environmental point of view, but from a fisheries point of view, it still has high productivity (Anders and Ashley, 2007). In this case, certain food safety risks may exist in aquaculture products. In the research of environmental protection professionals on aquaculture products, the method of sampling in groups to study the toxicological effect of microplastics on aquaculture products is often used, so it is difficult to highlight the impact of microplastics on the aquaculture products population, so it is difficult to analyze the economic impact of microplastic pollution. There have been precedents for cooperation among experts in different fields, such as the ecosystem-based management in the Great Lakes (Guthrie et al., 2019), which has achieved good results through cooperation between fisheries experts and water quality researchers. In addition, the methods of mathematical experts can also play a role in pollution control of microplastics. For example, the idea of complex network evolutionary game in mathematics is used to control plastic pollution in the ocean, thereby reducing the generation of microplastics (Xu et al., 2021). At present, there are also studies using artificial intelligence to photograph and identify plastic pollutants in the coastline and ocean, which greatly improves the efficiency of plastic pollutant identification (Kylili et al., 2020). In summary, microplastic pollution in aquaculture involves the intersection of multiple disciplines and fields, including environmental science, agriculture, biology, chemistry, mathematics and material science, etc (Gong and Xie, 2020). Therefore, it is necessary and useful for scholars in many fields to carry out cooperative research.

6. Conclusion

Due to the wide application of plastic products, microplastic has now entered the aquaculture environment in many ways. Human activities discharge microplastics to rivers and coastal area, which is the main external source of microplastic pollution in aquaculture. In addition, land waste weathering, atmospheric transport, ocean microplastic pollution will also introduce microplastics into aquaculture environment. Aquaculture fishing gears are the main internal source of microplastic pollution in aquaculture environment, and feed and packaging will also accumulate microplastics in aquaculture environment. For the aquaculture environment, the pollution of microplastics will cause the deterioration of the aquaculture environment, affect the material and energy cycle in the aquaculture environment, and affect the aquaculture benefit of aquaculture products. Microplastics in the aquaculture environment will also be released into the natural water environment after accumulation, resulting in broader environmental risks. Microplastics can cause oxidative stress in aquaculture products, affect the behavior of aquaculture products, growth and reproduction, and even lead to the death of aquaculture products, thereby reducing the economic benefits of aquaculture. The microplastics entering the human body through aquaculture products will also affect human health from multiple levels. At present, many countries have adopted some effective methods to control the pollution of microplastics in aquaculture, including ecological interception of microplastics in aquaculture environment, reducing or replacing the application of plastic fishing gears in aquaculture and purification of aquaculture products. In order to better control the pollution of microplastics in aquaculture, prospective technologies such as remote sensing and portable detection should be applied to the establishment and improvement of microplastic detection system in aquaculture. At the same time, countries should pay attention to the legislative provisions of the aquaculture environment and the limits of microplastics in aquaculture products, so as to ensure that aquaculture can implement environmental protection measures in accordance with the established standards, the standard system for microplastic pollution analysis should also be established to facilitate the assessment of microplastic pollution. In addition, environmental protection practitioners in various countries should enhance the communication between each other, and the exchange of practitioners in aquaculture, environmental protection industry and other industries also should be enhanced, which helps to find appropriate control measures of microplastic pollution in aquaculture.

CRediT authorship contribution statement

Haodi Wu: Conceptualization, Data curation, Writing – original draft, Writing – review & editing. **Jing Hou:** Project administration, Supervision, Validation, Writing – review & editing. **Xiangke Wang:** Supervision.

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.

Data Availability

No data was used for the research described in the article.

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