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Microplastics in fishmeal: A threatening issue for sustainable aquaculture and human health

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ABSTRACT

Plastic pollution is a global concern, leading to the abundance of macro- and microplastics (MPs) in the marine environment and subsequent accumulation in many marine organisms, particularly small pelagic and oceanic fish species. These small fishes are usually considered as the non-target catch or by-products of marine capture fisheries. However, these by-catch fishes convert into fishmeal due to their excellent nutritional value, and thereby, it used as the primary ingredient of artificial feeds for aquaculture and livestock animal production. The fishmeal and fish feed facilitates MPs' entry into the aquaculture systems when the MPs−contaminated feeds are supplied to cultured fish for regular feeding. Thus, MPs get access to interact with the elements of the culture pond ecosystem and leading to subsequent alterations in the physiological and behavioral attributes of cultured fishes. Consequently, MPs may accumulate in the edible portions of cultured fishes, which may cause severe physiological disorders in fish consumers. Thus, human exposure to MPs becomes a significant threat to global public health. Therefore, this review discussed the factors associated with MPs' introduction to the aquaculture systems via fishmeal. In addition, this article enlightened the possible consequences of MPs on the pond ecosystem, cultured fish physiology, and consumer health. We hypothesized that the growing concern among people about MPs might be impacted the demand for aquaculture goods. This study recommended taking necessary steps towards improving the MPs' screening process during fish feed production and focusing on more exclusive studies to elucidate the impacts of MPs on sustainable aquaculture production.

1. Introduction

Fishmeal is a valorized product of by-catch or by-products of marine capture fisheries, which is a nutritionally enriched source of high-quality animal protein with higher digestibility, palatability, attractive flavour, growth-promoting, and immune-boosting effects. As a result, fishmeal use in developing artificial feed for livestock animals and aquatic organisms, including fish and shrimp, is rapidly increasing globally (Cashion et al., 2017; Miles and Chapman, 2006). It was estimated that about 3.72 million tonnes of fishmeal were used in 2007 only for aquaculture feed production (Tacon et al., 2011). The World Bank reported that, in 2010, the aquaculture feed industries utilized about 73% of total fishmeal globally, while 20% for pigs, 5% for poultry, and 2% for other livestock animal feed production were used (World Bank, 2013). Fishmeal is mainly produced with small pelagic species, by-catches, excess allowable catch quotas trimmings, and fish processing wastes (Cashion et al., 2017; FAO, 2019; Newton et al., 2014; Péron et al., 2010; Shepherd and Jackson, 2013). However, several recent findings have demonstrated that due to the rapid increase of plastic pollution in the marine water bodies (Hanachi et al., 2019; Lusher et al., 2017), the abundance of microplastics (MPs) in fishmeal is sharply increasing (Foekema et al., 2013; Lusher et al., 2013; Tanaka and Takada, 2016).

MPs (<5 mm) are generally recognized as the breakdown products of

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macroplastics or polymers (Hanachi et al., 2019). Primary MPs are sourced from the plastics−manufactured as small plastic particles (e.g., manufacture of resin pellets, cosmetic scrubbers, or blasting abrasives), and secondary MPs are defined when these plastics are formed as fragments of larger plastic products (Andrady, 2011; Cole et al., 2011; Gregory, 1996; Mato et al., 2001). Macroplastics are subjected to wave action, sand grinding as well as several degrading processes (photo-degradation, thermal degradation, and biodegradation) and converted to MPs as the final products (Barnes et al., 2009; Klein et al., 2018). The small size range of MPs facilitates them to accumulate in different trophic levels of marine food web systems through direct/indirect ingestion by marine organisms, including fish. Though the incidence of MPs detection in seafood is now a well-known issue, there is a lack of knowledge about MPs' presence and their impacts on freshwater aquaculture systems. However, the introduction of MPs in aquaculture waterbodies could occur in many different routes. In general, it is thought that fishing equipment (boat, net, rope, and many others) (Lusher et al., 2017), agricultural runoff, sewage discharge, atmospheric deposition, and heavy rainfall (Eriksen et al., 2013; Thiele et al., 2021) are the primary reasons for MPs introduction in the aquaculture system. It was also suspected that there might be a relationship between MP-containing fishmeal and MPs introduction in aquaculture systems. Interestingly, several recent studies have been confirmed that the MPs abundance in fishmeal and fish feed is the key reason for MPs introduction in freshwater aquaculture systems, as evident by the detection of MPs in various fish feeds, culture waterbodies, and aquaculture fish tissues (Gündoğdu et al., 2021; Hanachi et al., 2019; Rahman et al., 2022; Wang et al., 2022; Wu et al., 2022). The increasing MPs accumulation into the freshwater fish body is also supported by the correlation between MPs uptake rate and their presence in feedstuffs, while fish usually refuses to intake free MPs from surroundings (Parker et al., 2021). In Fig. 1, we have illustrated the conceptual transmission routes of MPs from marine to freshwater aquaculture waterbodies via fishmeal and fish feed, and subsequent consequences of MPs accumulation in the aquaculture systems.

The introduction of MPs in aquaculture ponds has significant impacts on the physiology of farmed fish, the cultural environment, and consumer health. For example, several studies identified MPs in the fish gastrointestinal (GI) tract, body tissue, gills, and skin (Abbasi et al., 2018; Akhbarizadeh et al., 2017; Baalkhuyur et al., 2018; Rochman et al., 2013; Wang et al., 2021; Wang et al., 2021; Welden et al., 2018), which further contributed to reduced feeding and growth performance (Barboza et al., 2020; Jabeen et al., 2018; Peda et al., 2016; Wang et al., 2020), metabolic disorders (Lu et al., 2016), respiratory failure or gill infection (Jabeen et al., 2018; Movahedinia et al., 2012), fecundity reduction (Zhang et al., 2008), and neurological impairment (Vieira et al., 2009) in fish. Besides, it is reported that MPs also allow pathogenic microorganisms to aggregate toxic substances in aquatic water bodies due to having their larger surface areas (Lithner et al., 2011; Xu et al., 2020). Moreover, aged MPs may facilitate initial adherence and biofilm formation of pathogenic microorganisms. The bacterial biofilm protects the microorganisms from hydrodynamic shear force and provides a suitable ecological niche for several gene expressions related to pathogenicity, denitrification, and others (Shan et al., 2022).

It is a concerning issue that MPs are found in the edible portions of many commercial species (Rahman et al., 2022; Wu et al., 2020); thereby, it might be a severe threat to fish consumer health. Exposure to MPs may lead to chronic inflammation and oxidative stress, which are responsible for developing several chronic complexities, including cardiovascular disease, chronic kidney disease, acute lung injury, diabetes, and neuro-inflammation (Prata et al., 2020). In addition, MPs may play critical roles in carcinogenicity, chemotoxicity, and antimicrobial resistance among gut microbiota (Campanale et al., 2020; Lu et al., 2019). However, the global public awareness about the health risks associated with MPs is growing day by day. Thus, the increasing evidence of MPs' presence in farmed fish may affect consumer demand and acceptability for cultured fish (Lusher et al., 2017). Therefore, the review aims to illustrate the future impacts of plastic pollution on sustainable aquaculture and raise awareness worldwide to take necessary initiatives to mitigate the risk of MPs contamination in aquaculture goods. This review discussed the factors associated with MPs transmission in fishmeal, their detrimental effects on the aquaculture pond ecosystem, and the physiological attributes of cultured fish species. Further, the article portrayed the possible adverse effects of MPs' exposure to consumers and the consequences on demands for aquaculture products.

2. Factors associated with MPs' transmission to fishmeal

Fishmeal is mainly produced from small marine fishes such as menhaden, herring, anchovies, and sardines (Boyd, 2015). The majority of commercial fishmeal is derived from small oily fish such as blue

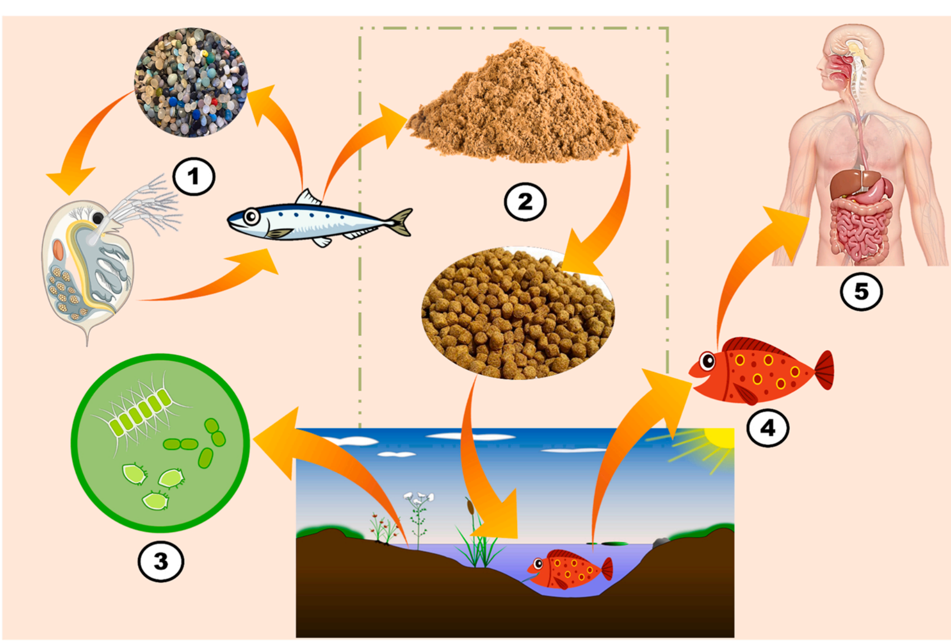

Fig. 1. Conceptual transmission routes of microplastics from marine to human. 1) Available microplastics from the marine environment are directly engulfed by small marine fish or indirectly intake after accumulating in zooplankton; 2) MPs are transferred into fish feed via fishmeal prepared from small marine trash fish and entered into the pond aquaculture system during regular feeding; 3) MPs are released in pond water and interact with the natural fauna of that aquaculture pond ecosystem; 4) MPs are also accumulated in farmed fish body tissue and organs, and leads to significant changes in fish physiology; 5) Human exposure of MPs after ingesting MPs containing fish muscle and subjected to many physical complications.

whiting (*Micromesistius poutassu*), Peruvian anchovies (*Engraulis ringens*), and lesser sand eels (*Ammodytes tobianus*) (Salin et al., 2018). However, the increasing plastic pollution in marine water bodies leads to the availability of MPs in marine organisms (Karami et al., 2017). Several studies identified various categories of MPs in these commercial fishmeal-producing species, as shown in Table 1. The most frequently recovered plastic polymers in fishmeal are polypropylene (PP), polystyrene (PS), and polyethene (PE), which are well-known for their extensive degradation in both terrestrial and marine environments (Andrady and Neal, 2009; Duis and Coors, 2016). Bakir et al. (2020) documented the occurrence of MPs in many pelagic fish species, such as *Sardinops sagax* (72%), *Etrumeus whiteheadi* (72%), and *Engraulis encrasicolus* (57%), and the concentration of MPs were 1.58, 1.38, and 1.13 items/individual, respectively. They also estimated the occurrence of various types of MPs, such as microfibers (80%), poly(ethylene:propylene:diene) (33%), polyester (20%), polyethylene (20%), polyamide (20%), and polypropylene (7%). In addition, Hanachi et al. (2019) reported that in fishmeal, the most abundant MPs were PP (45%) in types and fragments particles (67%) in shapes, while other types and shapes of MPs were also found in significant amounts, i.e., PE (19%), polyethene terephthalate (PET) (8%), and rayon (4%), and film (19%), pellets (8%), and fiber (6%), respectively. The relatively high concentrations of MPs in various types of fishmeal can be explained by their widespread presence in aquatic environments and their consumption by pelagic and demersal fish, as Hanachi et al. demonstrated in their current research.

MPs are found in almost all marine habitats and are about the same size as sediments and some planktonic species, making them bioavailable to various aquatic organisms, including fish (Wang et al., 2020). Due to the smaller size of MPs (<5 mm), fish may inadvertently intake MPs by mistaking them with natural prey (e.g., plankton) or because the MPs already might have been embedded in or adhered to the prey. MPs' small size, appealing colouration, and buoyancy cause misleading selection and ingestion by fish (Jovanović, 2017). Several factors are involved with the entry of MPs into the fish body. Among them, the feeding behavior of fish may directly influence the MPs uptake in fish. For example, predatory species may accumulate MPs in a roundabout way simultaneously as they consume MPs−contaminated prey, potentially leading to bioaccumulation at the highest trophic stages (Lusher et al., 2017). In contrast, filter and deposit-feeders are thought to be more vulnerable to MPs ingestion than predatory species (Wesch et al., 2016).

In contrast, Mizraji et al. (2017) reported that omnivorous fish consumed more MPs than herbivorous and carnivorous fish by analyzing the relationship between the feeding habits of intertidal fish and the likelihood of MPs uptake. Furthermore, the type of habitat of fish species may affect MPs ingestion amount. For example, it is reported that pelagic fish intake more MPs than fish species of other habitats, regardless of whether they are predators (Jovanović, 2017). For example, Phaksopa et al. (2021) reported that pelagic species are more prone to MPs exposure because of higher MPs ingestion by pelagic fish species (14.47%) than the demersal species (12.63%). On the other hand, MPs aggregation may be influenced by several factors, including species, time, distance, and exposure systems (Ding et al., 2018). In addition, MPs' size and shape may determine the MPs' uptake in fish (Auta et al., 2017). For example, myctophid fish most often consumed MPs in the size range of 1–2.79 mm, which corresponds to the size range of plankton species, the primary food source of these fishes (Boerger et al., 2010). In addition, Oliveira et al. (Oliveira et al., 2020) found the presence of MPs (size ranging from 1 to 3 mm) after analyzing the stomach content of neotropical omnivore fish species. In summary, the feeding behavior, habitat of fishes, and the size and shape of MPs act as the key factors of MPs accumulation in fishmeal.

Table 1
Presence of MPs in various common marine fish species used in fishmeal production.

Fish species	MPs concentration	MPs size range	Method of Analysis	References
Mugil cephalus	3.7 ± 1.0/fish	< 2–25 mm	Stereomicroscopy, digital camera, μ-FT-IR Spectroscope	(Jabeen et al., 2017)
Hyporhamphus intermedius	3.7 ± 2.2/fish			
Liza haematocheila	3.3 ± 0.3/fish			
Coilia ectenes	4.0 ± 1.8/fish			
Lateolabrax japonicas	2.1 ± 0.3/fish			
Argyrosomus regius	2.47/fish	0.1–2.5 mm	Stereomicroscopy, FT-IR spectroscopy	(Güven et al., 2017)
Sprattus sprattus	2.0/fish	300–400 μm	FT-IR spectroscopy	(Hermsen et al., 2017)
Atherinopsis californiensis	1.6 ± 3.7/fish	0.01–2.1 mm	Dissecting microscope	(Rochman et al., 2015)
Spratelloides gracilis	1.1 + 1.7/fish	–		
Stellifer brasiliensis	0.33 ± 0.08 /fish	> 1 mm	Stereomicroscopy	(Dantas et al., 2012)
Siganus canaliculatus	0.3 ± 0.6/fish	–	μ-Raman spectroscopy, EDX	(Karami et al., 2017)
Johnius belangerii	3.0/fish	–		
Trachurus mediterraneus	28 ± 19.5/fish	–	Microscopy	(Miliou et al., 2016)
Clupea harengus	–	124–438 mm	Polarized light microscopy	(Collard et al., 2017)
Alosa fallax	1.0/fish	2.11 ± 1.67 mm	Stereoscopic microscope/FT-IR	(Neves et al., 2015)
Gadus morhua	n.d.– 2/fish	1000 mm	FT-IR spectroscopy	(Markic et al., 2018)
Tunnus albacares	n.d.– 5/g	100 mm	ATR-FT-IR spectroscopy	(Chagnon et al., 2018)
Pollachius virens	0.28/fish	2.7 mm	Microscope, FT-IR spectroscopy	(de Vries et al., 2020)
Engraulis encrasicolus	2.5 ± 0.3/fish	GF/A	Microscope, FT-IR spectroscopy	(Kazour et al., 2019)
Clupea harengus	1.0/g	–	Visual inspection under a microscope	(Ogonowski et al., 2017)
Sardinops sagax	0.044 ± 0.025/g	0.7 mm	Zeiss Microscopy, μ-FT-IR spectroscopy	(Wu et al., 2020)
–	5.5 ± 1.6/g fishmeal	500–1000 μm	μ-FT-IR microspectroscopy	(Wang et al., 2022)
Sardinops pilcardus, Sardinella aurita, Scomber japonicas	253.3 ± 43.4/kg	–	Confocal Raman microscopy system, Leica microscope	(Gündoğdu et al., 2021)
Engraulis japonicus, Sardinops spp.	337.5 ± 34.5/kg			
Heteropneustes fossilis	0.33–1.57/gm	7–15 μm	Light microscope	(Rahman et al., 2022)
Harpadon nehereus, Trichiurus lepturus	41.33/g and 46.00/g		ATR-FT-IR	(Hasan et al., 2022)
Engraulis encrasicolus	9.06/fish	–	Light microscope	(Santonicola et al., 2021)

Note: Fourier Transformed Infrared Spectrometry (FT-IR); Scanning Electron Microscope (SEM); Energy Dispersive X-ray Spectroscopy (EDX); Attenuated Total Reflectance (ATR).

3. Introduction of MPs in aquaculture and their impacts on culture ecosystem

The development of various wastes can invade the aquatic ecosystem through the food chains and, after long-term accumulation, ultimately enter the human body. Besides, toxic compound contamination has adverse impacts on the human body and the natural environment (Dong et al., 2020). Primarily, it is considered that MPs can enter the aquatic ecosystem through agricultural runoff, sewage discharge, atmospheric deposition, heavy rainfall, and feedstuffs (Eriksen et al., 2013; Thiele et al., 2021). However, many recent studies determined that fishmeal is the main route of MPs' entry into the aquaculture environment (partly returning microplastics that were previously taken out, but also potentially adding new ones) since a proportion of fishmeal is thrown as aquaculture feed, illustrated in Fig. 1. It is estimated that about 180–310 million pieces of microplastics or 10–1670 kg of microplastics might be put into the coastal water bodies per year (Thiele et al., 2021) due to the use of 2.5 million tonnes of fishmeal annually for marine aquaculture (Cashion et al., 2017). The influence of MPs on aquatic environments is not yet fully known, but the adverse effects of MPs on marine and freshwater biota are increasingly recorded. Scherer et al. (2018) reported that MPs uptake by freshwater organisms might adversely impact the interactions between biotic and abiotic elements of freshwater ecosystems. The microscopic size of MPs allows aquatic organisms to ingest them from multiple trophic stages under various feeding strategies (Cole et al., 2013). As a result, MPs can reach higher trophic levels in the food chain, and the carnivorous species might have a substantial risk of MPs exposure by consuming fishmeal compared to lower trophic level organisms (Gündoğdu et al., 2021). In fact, the harmful effect of plastic debris on biota can be attributed to the sheer mechanical disruption capacity of MP in the GI tracts of organisms and the leaching of monomers and additives, as some of these are poisonous and carcinogenic or endocrine-disrupting (Lithner et al., 2011). Moreover, many studies demonstrated that MPs adversely affect the growth, feeding habits, and reproduction of zooplankton; even MPs may lead to significant loss of natural food resources by causing higher zooplankton mortality (Issac and Kandasubramanian, 2021).

MPs' smaller size and large surface area facilitate their bioavailability in various aquatic species like amphiboids, fishes, crustaceans, lugworms, and turtles, which can lead to the spread of toxic effects across the food chain (Xu et al., 2020). In addition, the broad surface area of MPs makes them powerful transporters of various microbes, including antibiotic-resistant pathogens, making them likely to be continuously introduced into aquaculture ecosystems. The large surface of MPs also facilitates the absorption of organic matter and inorganic nutrients that encourage viruses, bacteria, and other microorganisms to bind with MPs (Shan et al., 2022; Xu et al., 2020). MPs can also support microbes to tolerate environmental distress by facilitating biofilm formation, thus providing a stable habitat for microorganisms (Shan et al., 2022). The survival and long-term drift of surface microorganisms are assisted by the buoyancy and resilience of the MPs present in the pond ecosystems (Jiang et al., 2018).

Moreover, it has been explored that MPs increase the exposure rate of heavy metals in the aquatic environment (Brennecke et al., 2016). The most known toxic heavy metals are mercury, lead, chromium, and selenium. Heavy metal exposure reduces the aquaculture population, leading to organism deformities and alterations in the ecosystem (Sonone et al., 2020). Besides, long-term MPs exposure slowly reduces the soil quality, which directly affects the aquaculture system by altering water-environmental interactions and existing microbiota profile (Zhou et al., 2021, 2020). However, more extensive research is required to elucidate the impacts of microplastics on pond ecosystems and associated organisms.

4. Effects of MPs on farmed fish physiology

Since MPs are microscopic and comparatively smaller than natural feedstuffs, thus, fish quickly swallow these particles accidentally by mistaking them for natural prey (Crawford and Quinn, 2016; Jovanović, 2017). Walkinshaw et al. (2020) suspected that a herbivore aquaculture fish species, grass carp (*Ctenopharyngodon idella*), might intake MPs by being mistaken for similar-sized prey (aquatic weeds). However, it is considered that ingestion of MPs−carrying foodstuffs is primarily responsible for MPs' entry into the fish body (Parker et al., 2021; Su et al., 2019). For example, Wang et al. (2022) determined the MPs-contaminated fishmeal ingestion as the primary route of MPs introduction in aquaculture organisms. Primarily, they identified six types of MPs, including cellophane, PP, and PET, in fishmeal. Further, they showed that MPs became deposited in cultured *Salmon salar* and *Procambarus clarkia* at a higher concentration after ingesting the MPs−containing fishmeal. However, some MPs may be stored throughout the GI tract after ingestion, whereas the remainings were presumably extracted. MPs detention in the GI tract may lead to lower food intake resulting from false food satiation (Barboza et al., 2020), trigger the entire digestive system blockages (Wang et al., 2020), and create structural and functional injuries, which may have effects on fish nutrition and growth (Jabeen et al., 2018; Peda et al., 2016).

Besides, some hard MPs with pointed edges cause mechanical damage and ulceration by entering the intestinal lining. Mbugani et al. (2022) showed that dose-dependent MPs ingestion significantly damaged the small intestine, altered villi height-width, epithelial cell height and functional patterns of villi, epithelial, goblet and cryptic glandular cells, leucocytic infiltration, and blood congestion in *Oreochromis urolepis* larvae. Peda et al. (2016) tested the effects of MPs on GI tracts, and they demonstrated that fish fed a diet containing MPs displayed structural histopathological changes in the distal intestines, including lamina propria expansion, mucosal epithelium separation from lamina propria, villi contraction and swelling, intestinal absorptive cells vacuolation as well as the rise in goblet cells and serosa structures loss. Several previous studies reported that gastrointestinal MPs are temporary, but these are likely to be passed to the liver (Jovanović, 2017). Various stress symptoms, including glycogen deficiency, lipid starvation, and single-cell necrosis, are found in the MPs−affected fish liver (Rochman et al., 2013). MPs may also translocate into the liver and induce hepatotoxicity in fish through the agglomeration of smaller-sized MPs and endocytic/phagocytic uptake in the intestine (Collard et al., 2017; Collard et al., 2017). A zebrafish model study demonstrated that MPs induced inflammation, oxidative stress, lipid, and energy metabolism disturbance, lipid accumulation, and metabolic alterations in the fish liver after 7 days of exposure to polystyrene MPs. The study also discovered that lipid metabolic substances such as triglycerides and fatty acids (monounsaturated fatty acid, linoleic acid, FA-αH2, FA-ω-CH3, and fatty acyl chains) have significantly changed after MPs exposure. It also interrupted the synthesis and transportation of phospholipid and hampered lipid metabolism by altering choline, phosphorylcholine, and cholesterol levels (Lu et al., 2016). MPs exposure in zebrafish also reduced branched−chain amino acids (BCAAs), which play a vital role in fatty acid metabolism and fatty acid accumulation prevention (Newgard, 2012).

On the other hand, a few studies claimed that fish gills could be an entry route for MPs (Imhof and Laforsch, 2016; Wesch et al., 2016). Gill filaments trapped MPs could cause respiratory issues, including hypoxia (Movahedinia et al., 2012). Besides, MPs may cause gill infection through rupturing gill filaments (Jabeen et al., 2018; Movahedinia et al., 2012), resulting in hypoxia, respiratory problems, and death (Barboza et al., 2020). In addition, MPs could increase the indicating factors of oxidative stress, including superoxide dismutase and catalase activity (Lu et al., 2016). Vieira et al. (2009) reported that lipid peroxidation of cellular membrane induced oxidative stress that poses cellular damage to many organs of fish, including gills, muscles, and the brain. They revealed that lipid peroxidation in the muscle could obstruct muscle (e.g., cellular energy production) and neuromuscular activities, resulting in energy deficiency, movement coordination difficulties, reduced swimming performance, and various negative consequences. Barboza et al. (2020) discovered that MPs increased oxidative stress-mediated over-expression of acetylcholinesterase (AchE) activity in the fish brain, which causes neurological alterations (neurotoxicity), enhanced demand for energy, discord, confusion, and visual deficiency. These phenomena may decrease individual fish fitness and make them vulnerable to disease and non-pathogenic agents. In contrast, Oliveira et al. (2013) found that MPs with pyrene altered neuro and neuromuscular functions, including regulating physiological and behavioral processes by inhibiting AChE activity. The study also showed that MPs reduce intracellular energy production by inhibiting the $NADP^{+}$−dependent isocitrate dehydrogenase (IDH) enzyme. Apart from these, Parker et al. (2021) listed the outcomes of several MPs studies on dose-dependent exposure to freshwater fishes and discussed that MPs exposure altered morphological and physiological attributes such as feeding, swimming behavior, metabolisms, signalling, and many others. In addition, heavy metal−induced lipid peroxidation in the brain may cause movement behavioral abnormalities in fish (Shafiq-ur-Rehman, 2003). Likewise, de Sá et al. reported (2015) that MPs caused the alterations of predatory feeding behavior of juvenile common goby (*Pomatoschistus microps*, Gobiidae), which indicates the negative influences of MPs on the trophic level and food web systems. A conceptual illustration of the effects of MPs on fish physiology is given in the following Fig. 2. However, more in-vitro and in-vivo studies are required to elucidate the knowledge of MPs impacts on freshwater fish embryonic development, growth parameters, respiration, breeding behavior, and immune systems.

5. MPs associated consumer health risks

Plastic is an inert material, but it has a range of properties, including size, form, chemical composition, and hydrophobicity, affecting cells and tissues and impacting the cytotoxicity of particles (Wright and Kelly, 2017). The improved surface area/volume ratio of MPs, combined with their hydrophobicity, results in a high tolerance for a wide variety of hydrophobic and persistent organic contaminants, antibiotics, and heavy metals that humans may consume as a consequence of MPs absorption (Campanale et al., 2020). Exposure of MPs in the human body typically occurs via ingestion of fish and mussels, as shown in Table 2 (Hollman et al., 2013; Prata et al., 2020). The most evidence found MPs' presence in the GI tract of wild and farm animals (Zazouli et al., 2022). Thus, it was thought that removing the GI tract from fish might reduce MP exposure to humans (Toussaint et al., 2019). However, it is reported that removing the GI tract from fish could not completely eliminate the risk of humans' exposure to MPs (Karami et al., 2017). Most bivalves and a few small fish species are eaten−whole, thus, exposing the consumers to MPs (Lusher et al., 2017). Examples include *Gobio gobio* (Sanchez et al., 2014), *Penaeus vannamei*, *Macrobrachium rosenbergii* (Li et al., 2021), *Konosirus punctatus* (Wang et al., 2021), and *Harpadon nehereus, Trichiurus lepturus* (Hasan et al., 2022), which are generally wholely-eaten. A few studies reported the presence of MPs in cultured *Litopenaeus vannamei* and *Macrobrachium rosenbergii* (Reunura and Prommi, 2022) and the edible portion of farmed fishes, such as *Monopterus albus* (Lv et al., 2020), *Oreochromis niloticus* (Garcia et al., 2021), and *Heteropneustes fossilis* (Rahman et al., 2022). A recent study detected MPs in about 73.3% of freshwater fish species in Bangladesh. Among the experimental fish species, many are well-recognized as aquaculture species, such as *Labeo rohita*, *L. bata*, *L. calbasu*, *Cyprinus carpio*, *O. mossambiscus*, *Anabas testudineus*, and *H. fossilis* (Parvin et al.,

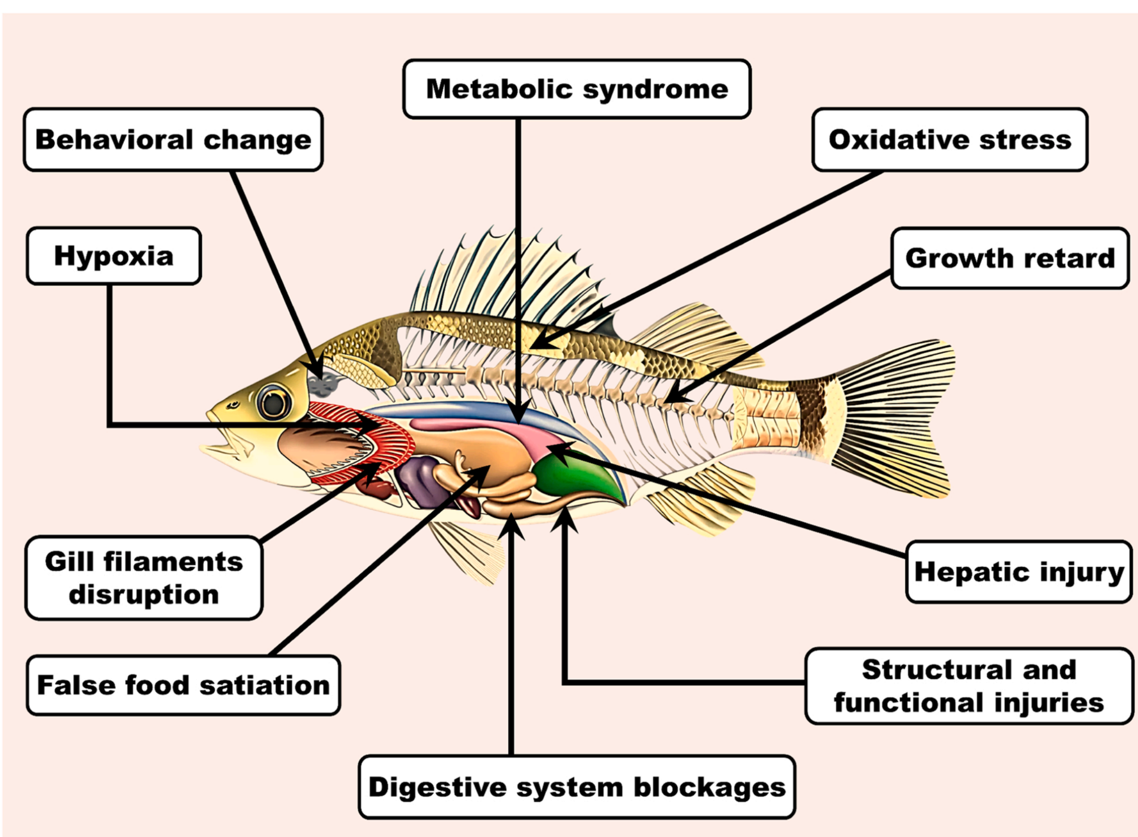

Fig. 2. Physiological alterations in fish after exposure to MPs. This figure shows MPs' impacts on different organs of the fish body. In addition, this figure illustrates how MPs alter fish physiological attributes, such as changes in feeding rate, growth rate, metabolic activities, and histopathological characteristics.

Table 2
An estimation of microplastics exposure due to ingestion of seafood items.

Food	Reference intake	Derived MP intake	Country	Reference
Fish muscle	300 g/ week (adults) 50 g/ week (children)	169–555 MP/ week (adults) 28–92 MP/ week (children)	Iran	(Akhbarizadeh et al., 2018)
Fish Crustaceans Mollusks	15.21 kg/ year 2.06 kg/ year 2.65 kg/ year	31–8323 MP/ year 206–17,716 MP/ year 0–27,825 MP/ year	Globally	(Danopoulos et al., 2020)
Mollusks	72.1 g/ day (top consumers) 11.8 g/ day (minor consumers)	11,000 MP/ year (top consumers) 1800 MP/ year (minor consumers)	Europe	(Van Cauwenberghe et al., 2015)
Bivalves	3.01 g/day	212 MP/ year	Korea	(Cho et al., 2019)
Shellfish	4.03 g/day	283 MP/ year	Korea	(Cho et al., 2019)
Mussels	82 g/ year	123 MP/ year	UK	(Catarino et al., 2018)
Mussels	3.08 kg/ year	4620 MP/ year	France/ Belgium	(Catarino et al., 2018)
Mussels	225 g	7 µg 0.1 µg/ kg bw/ day	Globally	(Chain, 2016; Lusher et al., 2017)

Note: The table is adapted from Garrido Gamarro and Costanzo (2022).

2021). However, there is a lack of literature on the health risks of MPs-contaminated cultured fish intake; hence, the general adverse effects of MPs on the human body may explain the possible consumer health issues associated with MPs contaminated farmed fish consumption. We have illustrated the possible human health risk related to MPs in Fig. 3.

Since fish are used as food, it is assumed that MPs contaminated fish ingestion may significantly impact human health (Barboza et al., 2020; Sonone et al., 2020). As MPs play the role of a carrier of heavy metals, MPs–contaminated fish consumption may facilitate heavy metal–mediated multiple illnesses such as obesity, diabetes, cancer, and Alzheimer's disease (Bakulski et al., 2020; Campanale et al., 2020; Chen et al., 2009; Cortés et al., 2021; Huat et al., 2019; Javaid et al., 2021; Liu et al., 2021). A recent in-vivo study showed that co-exposure of MPs and iron facilitated an increased iron accumulation in C57BL/6 mice brain that subsequently exacerbated the cognitive impairment by altering brain iron homeostasis and inducing neuronal ferroptosis (an iron-dependent non-apoptotic cell death). The study also demonstrated that MPs-iron co-exposure significantly downregulated the expressions of neuronal nuclei (NeuN), and synaptotagmin and synaptosomal-associated protein 25 (SNAP-25), which are well-recognized biomarkers for mature neurons and functional synapses degeneration in Alzheimer's disease (Liu et al., 2022). Moreover, many studies reported that MPs–contamination could cause oxidative stress, inflammatory lesions, cardiopulmonary complications, endogenous metabolites alterations, genotoxicity, and increased absorption or translocation in all biological systems (Barboza et al., 2020; Kannan and Vimalkumar, 2021; Smith et al., 2018). It is suspected that plastic may interact with the immune system and lead to oxidative stress and deformation of DNA (Fonseca et al., 2017). Melzer et al. (2010) demonstrated that intake of bisphenol A, a chemical used in plastic production, leads to oxidative damage and inflammations that result in cardiovascular disease and type 2 diabetes through damaging endothelial cells and upregulation of lipid levels in serum and pancreatic

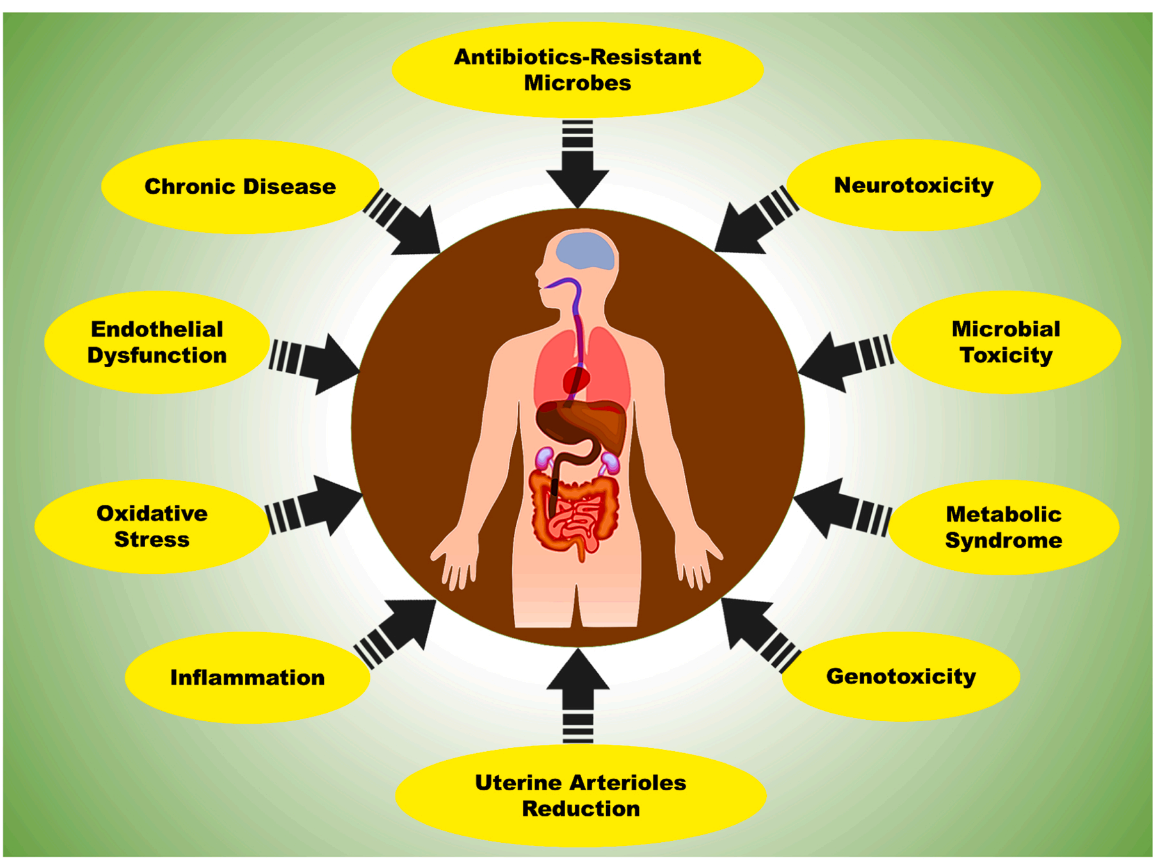

Fig. 3. Adverse impacts of MPs on human health. Microplastics act as the carrier of heavy metals and pathogens, which show various toxicity and induce many pathophysiological factors. These pathophysiological mediators subsequently cause many physiological disorders and chronic complications.

β-cell dysfunction and insulin resistance, respectively (Fig. 3). In addition, the inability of the immune system to clear plastic particles may cause chronic inflammation and a high chance of neoplasia (Prata et al., 2020). Plastic particles may enter the GI tract through contaminated foods, causing inflammation, increased permeability, and alteration in the structure and metabolism of gut microbes (Salim et al., 2014). The MPs adsorption by specialized M-cells or dendritic cells after ingestion, subsequently covering the intestinal lymphoid tissue and Peyer's patches and showing higher adherence to the gastrointestinal mucus (Ensign et al., 2012). Though there is a lack of evidence on MPs toxicity in humans, it is reported that nanoplastics translocate through the cell membrane and penetrate any organs. In addition, these nanocomponents may enter into placenta by passing through the blood barrier (Hollman et al., 2013). Moreover, the physicochemical properties, including roughness and hydrophobicity of MPs surface, greatly influence the absorption of various organic pollutants, including polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), hexachlorocyclohexane (HCHs), and dichlorodiphenyl trichloroethanes (DTTs). These pollutants could alter gut microbiota profile, which may consequently lead to intestinal inflammation or metabolic disorders (Lu et al., 2019). However, a few studies demonstrated cytotoxicity, genotoxicity, and metabolic disorders due to ingestion of MPs, shown in Fig. 3 (Yong et al., 2020).

On the other hand, MPs can also serve as microbiological toxicity vectors by carrying several biofilm-associated opportunistic bacterial pathogens and antibiotic resistance genes that could disrupt the gut microbial composition and colonization (Lu et al., 2019). On the other hand, MPs may accelerate the bioaccumulation of antibiotics in aquatic organisms by showing a higher affinity to interact with antibiotics, leading to residual antibiotic toxicity in these organisms (Wang et al., 2021). Referring to human health, consuming antibiotics-contaminated food can pose risks (Done and Halden, 2015). This antibiotic medication can be carcinogenic and, in certain instances, has caused antibiotic resistance in consumers (FDA, 2015).

Recent studies have reported another severe issue: MPs are detected in human blood, feces, and the placenta. For example, Leslie et al. (2022) detected MPs in human blood and measured the level of MPs in the blood (1.6 μg/ml). Again, Ragusa et al. (2021) identified twelve MPs (5–10 μm) in all placental membranes (maternal, fetal, and amniochorial membranes). Likewise, Braun et al. (2021) also detected microplastics (> 50 μm) in human placenta and fetal meconium. An in-vivo study reported that 10 μm of polystyrene−MPs exposure in C57BL/6-mated BALB/c mice caused maternal−fetal immune imbalance by reducing uterine arterioles, decidual natural killer cells percentage, increasing placental helper T cells, altering M1/M2 ratio, and proinflammatory cytokines (IL-2, IL-6, TNF-α, and IFN-γ) release (Hu et al., 2021). In addition, different types of microplastics were also identified in men's (Luqman et al., 2021) and pregnant women's stools (Ar et al., 2020). Zhang et al. (2021) also quantified MPs in adults' and infants' stools and concluded that infants are more vulnerable to MPs exposure than adults. This assumption is also supported by the study of Sripada et al. (2022), where they reported that the immature immunity of children is primarily responsible for comparatively higher susceptibility to MPs. The increasing evidence of MPs detection in humans indicates the alarming situation for the future of global public health. With the increasing concern among consumers about MPs, the question is raised globally: 'Should we stop fish consumption to avoid MPs ingestion?' (Rist et al., 2018; Simke, 2020; Smith et al., 2018). In addition, in Australia, it is suggested to pregnant or breastfeeding women to avoid the consumption of a few certain fish species, such as catfish, deep-sea perch, shark, swordfish, and marlin, to avoid the risk of mercury toxicity (NSW, 2017).

Since MPs are present in each phase from the beginning of fish farming to the end of the processing, it flows into the consumer market with effects lasting in the human body for extended periods (Zhou et al., 2021). Consequently, it is foreseeable that MPs will increase the prevalence of problems with all aquaculture products and reduce their market. However, no literature has been found on the negative impressions of consumers about MPs−contaminated aquaculture products or the adverse impacts on aquaculture fish market demand. Nevertheless, based on the incidence of products banned in many countries for adulteration or hazards (Khan and Lively, 2020), we are concerned that the MPs' presence in aquaculture fishes may raise negative impressions among consumers and decline the acceptability of aquaculture goods. However, additional research is necessary to determine the stability of microbial pollutants in the human body. In addition, it is worth considering MPs' potential role as carriers of additional pathogens, such as fungi and viruses. More in-depth studies should be taken to understand the risk patterns associated with MPs on consumer health. Therefore, more intensive research is needed to fully understand MPs' possible toxicity, fundamental processes, and long-term consequences in real-world settings (Vethaak and Legler, 2021).

6. Conclusion and future research needs

Microplastic abundance in nature is sharply increasing with the rising plastic pollution throughout the world. Accumulation of MPs in aquatic organisms is becoming a threat to productivity and global public health issues. Increasing plastic pollution in the marine environment leads to MPs accumulation in fishmeal−producing fish species through direct/indirect ingestion or trophic level transmission. MPs get access to entry into the aquaculture environment when MPs−contaminated fishmeal are incorporated in fish feed. Thereby, MPs can influence the productivity of the culture system through significant alterations to the aquatic ecosystem and physiological and behavioral attributes of fish. In addition, after ingesting MPs−contaminated farmed fish, the consumer may suffer from many severe physical complications due to MPs exposure, resulting in lower consumer acceptance and market demands for cultured fish and fish products. These impacts may arise challenges to aquaculture production and its sustainability. Therefore, detection and quantification of MPs and nanoplastics are crucial for understanding the fates of these plastic polymers. Many researchers applied various techniques such as density separation method, visual identification, FT-IR spectroscopy, ATR-FT-IR, Raman spectrometry, Pyrolysis-Gas Chromatography coupled with Mass Spectroscopy (Pyr-GC-MS), desorption combined with GC/MS, high-temperature gel-permeation chromatography (HT-GPC) with IR, EDS, and EDX (Table 1). These different methods show variable results in detecting and measuring MPs in samples. In addition, many of these analytical methods have significant limitations. Therefore, it is highly recommended to establish a standard analytical method to identify and quantify MPs and nanoplastics. Apart from these, more extensive research should be carried out to understand the interactions of MPs with aquatic flora and fauna and the impacts of MPs on cultured fishes and, in particular, these cultured fish consumers. It also needs to elucidate the consequences of MPs on host-parasite relationships for freshwater fishes. Apart from these, relevant stakeholders and authorities should be considered this issue sincerely and adopt cost−efficient environmental and health risk assessment approaches and monitoring systems. Most importantly, awareness about microplastic pollution and its consequences should be raised globally.

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