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Effects of Microplastics in Aquatic Organisms and the Current Status of Microplastics Pollution in Indian Aquatic Bodies

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ABSTRACT:
The accumulation of microplastics and nanoplastics in aquatic bodies and its habitants become global-issue since last decade. Almost all the water bodies including polar regions become contaminated with plastic pollution by now. Therefore, the review mainly focused on the different effects of microplastics in fish. These particles interfere with aquatic ecology in many aspects. They disrupt the enzymatic functions among the microbes, reduce the food intake, growth and reproduction capacity among the zooplanktons. In fish, different polymers affect the behaviour, digestion, cause oxidative stress, suppress the immune genes etc. Most of the studies are on the conducted pelagic-fishes from wildcatches. In vitro studies on the effect of microplastics particles have been carried out in few selected fishes and showed the accumulations in different tissues including brain crossing the blood brain-barrier which may alter behaviour, cause various neurological problems. The review also focused on the status of microplastics pollution in Indian coastal regions, freshwaters (rivers, lakes) and freshwater indigenous fishes. The other riverine system remains untouched except River Ganga where the presence of microplastics were found in the sediment, water, and fishes. From all the reports, we found that there is a gap in the effects of microplastics in the gut associated microbes which is the primary site for accumulation. The reports on the circulatory or metabolism pathway of different polymers in fish bodies and long-term effect on the exposures are lacking. There are no reports on the colour development of ornamental fishes although reports on behavioural changes are there. Therefore, future studies may focus on gut microbes, metabolism, the effects of long-term exposure on neurological disorders and colour development as the particles get deposits in the skin of fishes.

Keywords:
Microplastics, Neurotoxic, Behavioural Disorders, Digestive and Immunological Disorders, Oxidative Stress

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INTRODUCTION

Plastic pollution has gained a lot of attention as it affects all the dimensions of ecosystems. Primary plastics are manufactured around millions of metric tons each year around the globe. The fragmentation of these primary plastics gave rise to the microplastics (1-5mm in size), a recent pollutant affecting entire living systems (Arthur et al, 2009; Gewert et al, 2015). These fragments can also be generated by mechanical weathering, biological action, and sunlight. The contaminations are mostly from food packaging, plastic fibres present in the laundry water of synthetic clothes microbeads from personal care products, fishing gear, and other human activities end up in lakes, rivers, and the ocean (Mattsson et al, 2015; Lin, 2016; Eriksen et al, 2013; Free et al, 2014). Microplastics (MPs) may be resulted from many synthetic polymers like high-density polyethylene (HDPE), low-density polyethylene (LDPE), polybutylene terephthalate (PBT), polyethylene terephthalate (PET), nylons, poly-propylene (PP), polyvinyl chloride (PVC), polystyrene (PS) and polyurethane (PUR) (Shimao, 2001; Barnes et al, 2009). Polystyrene-MPs (PS) are the most abundant plastic polymers in the environment (Hidalgo-Ruz et al, 2012), and aromatic monomers and styrene found in PS cause acute toxicity (Niaz et al, 2017). Plastics do associate many harmful additives like pesticides and other organic pollutants at high concentrations (Teuten et al, 2009; Barnes et al, 2009). These fragments may enhance the effect of heavy metals and the chemical additives which in turn affects adsorption capacity of organic contaminants (Ashton et al, 2010; Cole et al, 2011; Wagner et al, 2014; Brennecke et al, 2016; Bakir et al, 2014). The problem of plastic contamination is not limited to the surface area but also the high-density plastic hampers the ocean floor or depth of water bodies. The additional problem with accumulated plastic on the depth of water bodies is difficulty in degradation as the ocean floor remains absent of UV radiation. Microplastics represent a serious peril and possible gamble to the climate because of their movement, change, adsorption, and debasement properties. In marine environments, microplastics adversely affect the marine ecosystem. Numerous lab studies have examined the ingestion of microplastics by aquatic organisms (Cole et al, 2013; Lu et al, 2015). Polystyrene microbeads are the most often utilised microplastic in ecotoxicological research (Chae and An, 2017).

According to Cole et al (2011), there is great diversity of shapes, colours, sizes, and types of microplastics in the environment. These characteristics may have an impact on consumption (Ory et al, 2018). Among all the types, fibres are the most common synthetic particles found in most studies concerning MPs contamination in the marine environment, contributing to 35% of the world ocean's MPs burden (Hale et al, 2020). They are also the dominant MPs detected in the gastrointestinal tracts of marine fish worldwide (Wang et al, 2020). The notable changes include intestinal obstruction, gut microbiota, physical injury, and liver stress, among others (Browne et al, 2008; Wright et al, 2013; Guerrera et al, 2021; Huang et al, 2022). MPs also cause disturbances in microbial communities in *Symphysodon aequifasciatus*. Actinobacteriota was replaced as the skin-dominant phylum by Proteobacteria and Firmicutes. After being exposed, proteobacteria progressively took over in the gill ecosystem (Rizzatti et al, 2017). In humans, microplastics are reported to be contaminated in all parts like human lung, in maternal and foetal placental tissues, in human breast milk and in human blood too (Yang et al, 2023). Human health is in risk with the consumption of microplastics contaminated fish.

The relative abundances and composition of MPs in the Madeira Island (NE Atlantic) have shown seasonal variation in mesozooplankton (Sambolino et al, 2022). The accumulation of MPs in the environment is subjected to the environment conditions also as they are minute and can be transported and distributed by physical processes such as ocean currents and wind or precipitation (Lima et al, 2015; Cardoso and Caldeira, 2021; Brach et al, 2018). Therefore, the seasonal variations can be seen in the accumulation, or dispersion of microplastics. The accumulating rate of MPs in the organisms may also vary in different seasons as the rate of plankton bloom is not uniform in different seasons. MPs are not only dangerous during the transportation process but also found to show bioaccumulation processes within the food web, resulting in many environmental problems (Wang et al, 2020). The bioaccumulation was demonstrated on zebra fish by feeding MPs exposed *Poecilia reticulata*. The MPs particle were discovered from Zebrafish confirmed the transfer of MPs in higher trophic levels (da Costa Araújo et al, 2020).

EFFECTS OF MICROPLASTICS IN DIFFERENT BIOTA

Microbes and Planktons: Microplastics found to be ingested by a wide range of organisms in diverse habitats like benthic and pelagic ecosystems. These microplastics can be further broken down into nanoplastics which can interfere with the lower groups of algae, planktons, and bacteria, subsequently contaminating the primary producers of the food chain system. MPs have adverse impacts on aquatic-organisms at the physical and molecular levels. Microplastics could affect soil pH, respiration and enzymatic activities of microbes depending on the shape and nature of the polymer (Zhao et al, 2021). Microplastics can interfere with the functioning of the nutrient microbial cycle hampering the natural detoxification pathway. Likewise, MPs can inhibit the nitrogen cycle by interfering with nitrogen fixation, ammonification, nitrification, and denitrification processes by changing gene abundance, enzyme activity and microbial community composition (Wang et al, 2022). Polyvinylchloride (PVC) reported reduced ammonia oxidation at the rate 46.67% in which it was treated with 10, 000/L (Ji et al, 2023).

The planktons are the primary producers, the pollutants may enter the food chain level as this trophic level and transfer to the higher trophic levels. Finally, this can cause bioaccumulation and biomagnification. Due to their smaller size, microplastics are considered bioavailable to a huge range of marine organisms and ingestion of microplastics particles has been recorded in number of species, including marine zooplanktons (fishes, seabirds, decapod crustaceans, mussels and amphipods, lugworms, and barnacles (Browne et al, 2013; Cole et al, 2014). In both field and laboratory studies, the uptake of small microplastics particles by zooplankton species was frequently observed among the large cladocerans' despite of being filter feeders (Frias et al, 2014; Setälä et al, 2014; Rehse et al, 2016). The ingestion of microplastics may lead to adverse effects in cladocerans, such as nutrient deficiencies may block the alimentary canal (Ziajahromi et al, 2017; Fekete-Kertész et al, 2017). Some behavioural changes are also reported like swimming ability with the decreasing of grazing rate in cladocerans on algal cells (Zhang et al, 2017). The effect of microplastics and nanoplastics can be tremendous among the planktons. The reports suggest that the microplastics ingestion causes mechanical damage to the intestinal tracts of zooplankton, induces feeding disorders and malnutrition, reproductive ability, excretion, and increase in zooplankton mortality (Tang et al, 2019). MPs can influence gene regulation in *Daphnia* sp. MPs consumption also reduces the number of egg production in zooplanktons. Microplastics alter the copepods in the feeding behaviour, reproduction, and survival of the pelagic, small filter-feeding crustacean copepod *Calanus helgolandicus*. Some other effects on the microplastic-fed copepods are smaller egg size and reduced hatching success, although their egg-production rate was unaffected (Cole et al, 2013).

Fish: The bigger plastics are likely to increase the chances of feeding due to the similarity with zooplankton, fishes do involuntarily ingest the MPs particles from the environment. The consumption rate is affected by the habitat of fishes such as demersal and pelagic (Borges-Ramírez et al, 2020). So, MPs accumulation can be more severe in epipelagic fish because of the availability of synthetic particles accumulated at the sea surface, being made of low-density material and buoyant (Barnes et al, 2009; Cole et al, 2011). The ingested particles may accumulate in the gills, digestive-tract, and metabolic systems causing unfavourable cellular alterations (Karbalaei et al, 2018; Brennecke et al, 2015; Wright et al, 2013). The damages may be categorised into chemical and physical. Chemical disruptions are like oxidative damage, endocrine disruption, immunity response whereas the physical damages are blockage of the digestive system or absorbed from the digestive system into other body tissues or can be excreted (Brennecke et al, 2016; Galloway et al, 2017; Cunha et al, 2020; Tanaka and Takada, 2016). MPs also induced the changes in immune-related gene expression as well as antioxidant status in fish (Bhuyan, 2022). Other effects of MPs are affecting the physiological conditions like increase of mucous secretion rate by 30.0% and 62.9% of mucus cells and accumulating within the GI tract (Liang et al, 2023; Ma et al, 2020).

These particles can also alter the fish behaviour, growth rate, metabolism, and fecundity (Foley et al, 2018). These particles may also report to cross the blood-brain barrier of fish, intervening the behaviour, causing neurological problems among the fishes. In fish, MPs alone or in combination with other pollutants, caused neurotoxicity and behavioural abnormalities.

Behavioural changes and neurotoxic effects of microplastics in fish: Some of the notable changes in the behaviour due to microplastics and nanoparticles were locomotion, inhibiting AChE activity alterations in behavioural patterns, decreased brain mass and morphological changes in the cerebral gyri (Mattsson et al, 2017). When Adult Japanese rice fish (*Oryzias latipes*) were exposed to 1000 items/L of microplastic fibres for 2 h, the changes like the coughing behaviour was seen. The longer exposure leads to the decrease in predatory behaviours and reduction in daily food intake. The circulation of fluorescent polystyrene nanoplastics (40 nm, 10 mg/L) were traced in the above fish exposed for 7 days. The MPs were found primarily in the gills and intestine but also in testis, liver, and blood. These particles were also detected in the brain, indicating that nanoplastics have the innate capacity to cross the blood brain-barrier (Kashiwada et al, 2006). There are several reports on the neurotoxicity of polystyrene, polyethylene micro- and nanoplastics in fish. The deposition in the brain can interfere with behavioural changes. The accumulation of particle was also reported from *Oreochromis niloticus* where the presence of fluorescent polystyrene particles (0.1 µm, 1–100 µg/L) was observed using fluorescence spectrophotometry in lyophilized gut, gills, liver, and brain tissue after 1–14 days of exposure. The inhibition of AChE activity and induction of SOD in the presence of polystyrene microparticles were seen (Ding et al, 2018). In another exposure of amino-modified polystyrene micro- and nanoparticles (53 nm and 180 nm 100 mg/L), via trophic transfer in the aquatic food chain for 64 days in *Carassius carassius* showed the presence of particles in the brain where the amount of nanoplastics were higher than microparticles. The effect of MPs may depend on animal species, age of the organism, exposure duration, particle number and particle size. The neurological damage or alteration is not equally shown in all the fish as juvenile surgeonfish (*Acanthurus triostegus*) exposed to polystyrene microplastics (90 µm, 5 ×10^3 particles/L (~ 0.81 mg/L) for up to 8 days, did not show alterations in (foraging) behaviour, body weight or susceptibility to predation, although ingestion was there (Prüst et al 2020). A contrast report was seen in zebrafish (*Danio rerio*). Fish exposed to low-density polyethylene microplastics 10µm, 5–500 µg/L, for 10– 20 days. There was no particle detected in the brain except in the intestine. Gene expressions and growth were also seen least affected by the exposure (Karami et al, 2017). Similarly, adult zebrafish were exposed to high-density, fluorescent polyethylene microplastics (size range 10–22 µm up to 500–600 µm; 11–1100 particles/L and the particles were detected from gills and intestine. A notable change in the locomotory behaviour was recorded when exposed to ≥110 particles/L. Even the record of induced seizures was reported at 1100 particles/L in fish (Mac et al, 2019)

Effect of micro and nanoplastics in combination with other toxicants: Microplastics do have synergistic effects with other toxicants. These particles are affected differently when exposed separately or in combination. Exposure to the microplastics or nanoplastics in combination with other toxicants have been tried as in nature it may present with various other toxicants. Compounds like phthalates and bisphenols, heavy metals, polybrominated diphenyl ether (PBDE), polychlorinated biphenyls (PCBs) generally found together with plastics. Behavioural modulations are observed in zebrafish by PLA BioMPs like distinct social and anti-predatory behavioural reactions (as compared to the control group), and epidermal depigmentation (Chagas et al, 2021). Polystyrene nano- and microplastics (47 nm and 41 µm, 1 mg/L) with/without 17-αethynylestradiol (2 and 20 µg/L) were exposed to zebrafish larvae for 5 days. Fish co-exposed to a high concentration of 17-α-ethynylestradiol showed less particle presence (Chen et al, 2017a). Another compound which can be a carrier when exposed to polystyrene nanoplastics is Bisphenol A (BPA, 1µg/L). The concentration of BPA in the brain increases compared to BPA exposure alone. Some of the parameters like inhibition of AChE can only be induced with single exposure to BPA or nanoplastics alone while co -exposure leads to the inhibition of AChE (Chen et al, 2017b). In some cases, microplastics and nanoplastics behave differently as exposing to microplastics alone did not induce major effects but nanoplastics alone can induce in decreasing in body length, altering locomotion and AChE activity. Accumulation of plastic particles was observed in the brain, gills and muscle lyophilized tissues of adult zebrafish exposed to fluorescent polystyrene nanoplastics (50 nm, 1 mg/L) for 1–3 days. Another toxicant, pyrene (100nM) was exposed to juvenile barramundi fish and found to reduce the swimming movement, although this effect was minor compared to the effect of pyrene alone (Guven et al, 2018). Decreased AChE was reported from red tilapia was exposed to roxithromycin (ROX, 50µg/ L) showed attenuated the AChE activity while in combination with fluorescent polystyrene microplastics (0.1µm, 1–100 µg/L). Other activities, like inhibition of AChE activity in the brain, but not of AChE in muscle, an increase in LPO were seen in Sea bass fish exposed to microplastics (1–5 µm, 0.69 mg/L) alone while co-exposure with mercury (10 and 16 µg/L), lead to the increase of effects. Luiz et al (2015) reported the similar findings that the inhibition of AChE activity in juvenile common goby (*Pomatochistus microps*) exposure to fluorescent polyethylene microplastics (1–5 µm, 0.216 mg/L). When microplastics were co-exposed with 2µg/L17α-ethynylestradiol (EE2), the inhibitory effect of EE2 on locomotion was alleviated. This was likely because there was less EE2 that was readily dissolved (Chen et al, 2017a).

PHYSIOLOGICAL DISORDERS INDUCED BY MICROPLASTICS

Effect on the digestive system of fish: Aquatic-bodies of both freshwater and marine environments became sinks for microplastics and other toxicants. Microplastics have been found in the digestive systems of a variety of aquatic animals, including fish, zooplanktons, benthic macroinvertebrates, and even marine mammals (Li et al, 2018; Lusher et al, 2017). The activity of digesting enzymes in the stomach, such as pepsin, lipase, and α-amylase were decreased, indicating a relationship with the bacterial community, particularly Fibrobacterota. These findings imply that MPs have an impact on the microbial ecology and biomarkers in aquatic organisms that are tissue-specific (Huang et al, 2022). MPs aggregate in the digestive tract of fish which causes satiety leading to poor growth and eventually low survival rate (Lei et al, 2018; Wright et al, 2013). MPs have been found to compromise the normal enzymatic activities in the digestive tract (Wen et al, 2018a). Recent findings have highlighted the risk of particle exposure (including MPs) concerning gut microbiota dysbiosis and intestinal toxicity (Jin et al, 2018; Qiao et al, 2019). The adverse effect on the gut of juvenile guppy (*Poecilia reticulata*) was seen when exposed to 100 and 1000 µg/L concentrations of MPs (polystyrene; 32–40 µm diameters) for 28 days. Enlarged goblet cells, reduced enzymatic activity by digestive enzymes such as trypsin, chymotrypsin, amylase, lipase, and overexpression of immune cytokines (TNF-α, IFN-γ, TLR4 and IL-6) were also recorded which may be due to damage the digestive metabolism thereby stimulating immune response (Huang et al, 2020a). The presence of microplastics in the gut of 9 commercial species were seen in the commercial fishes of Pantai Indah Kapuk coast, Jakarta, Indonesia. *Girella laevifrons* was exposed to different concentrations of Poly (styrene-co-divinylbenzene) MPs mixed in their diet for 45 days, the histological evaluation showed damaged intestinal tissue, inflammation due to leukocyte infiltration, loss of Crypt cell and Villi cells. The lesion formation significantly increased with the increasing concentrations of MPs (Ahrendt et al, 2020). The similar effects were seen in survival rates, histological alterations like intestinal damage in

D. rerio, including villi cracking and enterocyte splitting, was produced by microplastic particles of PA, PE, PP, PS, and PVC (Lei et al, 2018).

Feeding habits of fish can have an impact on the amount of microplastics they consume. Herrera et al (2019) analysed the MPs fragments in pelagic planktivorous fish (*Scomber scomber*) nearby archipelago of Canary Islands showed a high rate of microplastic ingestion. The main particles found in the gastrointestinal tracts were fibres (74 %), followed by fragments (12 %), paint chips (12 %), lines (1 %) and films (1 %). The reports from six commercial fishes from Mexico revealed that the presence of different MPs present in the digestive tract of fish depending on different shapes, colours, size, chemical composition, and density. About 316 MPs were obtained from 240 individuals. Ingestion rate was affected by type, colour, shape of the polymers. A total of 169 of 174 fish had MPs with *Sardinella fimbriata* showing the highest and *Oreochromis mossambicus* lowest in MPs content. Fibres are the most common MPs followed by fragments and films. In case of colour, transparent particles were highest recorded, followed by blue, red, black, and green respectively. In terms of size fibre has the largest, followed by films and fragments being the least (Hastuti et al, 2019). In another study of the Colombian marine coastal region, digestive tract content of 22 fishes were analysed and found that the ingested MPs were 55% filaments, 23% fragments, 19% films, and 3% foam (Garcés-Ordóñez et al, 2020). Similarly, fishes of the Saudi Arabian coast of the Red Sea showed the presence of MPs in the digestive tract of 26 commercial and non-commercial fish species. MPs obtained were mainly films and fishing thread of polypropylene and polyethylene as major abundant polymers. The highest ingested MPs were reported in grouper (*Epinephelus* spp.) sampled at Jazan (Baalkhuyur et al, 2018).

Metabolism and Oxidative Stress: Toxicity triggered by microplastics stems from the production of free radicals, potentially causing genomic instability and alterations in pathology, physiology, and biochemistry (Alimba and Faggio, 2019). Microplastics exert substantial and noteworthy impacts on fish metabolism, including lipid metabolism, carbohydrate metabolism, oxidative stress and toxin excretion (Jacob et al, 2020). The heightened production of reactive oxygen species (ROS) has a detrimental impact on both cholesterol levels and enzyme activity linked to lipid metabolism in African catfish (*Clarias gariepinus*) exposed to virgin microplastics (Karami et al, 2016) and in larval Zebrafish exposed to polystyrene microplastics (Wan et al, 2019). Micro-sized PS particles caused more pronounced respiratory damage in tilapia fish, (*Oreochromis niloticus*) compared to their nano-sized counterparts (Zheng et al, 2024). The microplastic particles were readily trapped on the epithelial surface for a prolonged duration, resulting in significant inflammation and respiratory dysfunction. Long term exposure (90 days) to microplastics in gilthead seabream (*Sparus aurata* L.) triggered oxidative stress and elicited a pro-inflammatory response in the gut (Solomando et al, 2020). Like nanoparticle exposure, microplastics (MPs) have the potential to induce oxidative stress in marine fishes by being internalised into cells and distributed throughout various tissues (Torrealba et al, 2019).

Fish have evolved antioxidant enzyme mechanisms (Superoxide dismutase, Catalase and Glutathione-S-transferase etc.) to mitigate oxidative damage caused by the generation of reactive oxygen species (ROS), which can be induced by exposure to various toxic substances, including microplastics. According to Ding et al (2018), freshwater fish red tilapia (*Oreochromis niloticus*) exhibited elevated SOD activity after exposure to polystyrene microplastics, suggesting that the antioxidant system responded by generating reactive oxygen species (ROS), causing oxidative stress. Wen et al (2018a, 2018b) documented an elevation in both superoxide dismutase (SOD) and catalase (CAT) activity in the Amazonian cichlid fish, (*Symphysodon aequifasciatus*) following exposure to microplastics (PS). This elevated antioxidant response may be oxidative damage due to reactive oxygen species (ROS). Huang et al (2020b) proposed that exposure to microplastics (PS) amplifies the activity of SOD, CAT, and GST in juvenile guppy fish (*Poecilia reticulata*). A notable rise in GST activity observed in goldfish (*Carassius auratus*) upon exposure to virgin microplastics (PVC), potentially serving as a protective mechanism against cellular oxidative damage (Romano et al, 2020). Exposure of Nile Tilapia (*Oreochromis niloticus*) to microplastics results in a reduction of antioxidant enzymes, possibly due to the energy expended in combating oxidative stress (Hamed et al, 2020). Wang et al (2019) proposed that exposure to microplastics could inhibit the typical ROS-mediated oxidation process, noting a decline in CAT activity in marine medaka fish (*Oryzias melastigma*) after microplastic exposure. Xia et al (2020) documented a decrease in SOD levels following an initial rise in target organs (such as the intestine and gills) of common carp (*Cyprinus carpio*) exposed to microplastics (PVC). This decline was associated with the inhibition of antioxidant enzymes, as the ROS generated in tissues were not promptly eliminated. Espinosa et al (2019) documented a reduction in both SOD and CAT activities in European sea bass (*Dicentrarchus labrax*) exposed to microplastics (PE), which could potentially lead to oxidative stress.

Glutathione (GSH) plays a crucial role in maintaining the redox balance and preventing oxidative stress in fish when they are exposed to microplastics (Wen et al, 2018a, 2018b). GPx is an enzyme that aids in converting peroxides into less harmful hydroxyl compounds, thereby safeguarding cells from oxygen-induced damage. GSH and its associated enzymes are intricately linked to the antioxidant process aimed at eliminating free radicals produced due to microplastic exposure. Therefore, GSH could serve as an indicator to understand the antioxidant responses in fish after microplastic exposure. Chen et al (2017a, 2017b) documented a noteworthy reduction in GSH levels in Zebrafish (*Danio rerio*) larvae exposed to microplastics (PS). However, microplastic exposure did not affect GPx activity, suggesting that the redox buffer provided by GSH was depleted. Umamaheswari et al (2021) documented that exposure to microplastics (PS) led to a decrease in GPx activity in Zebrafish (*Danio rerio*). This decrease hindered the conversion of peroxide into a non-toxic hydroxyl substrate, resulting in the accumulation of ROS in tissues.

Specifically, malondialdehyde (MDA) serves as a biomarker for lipid peroxidation (LPO) since it represents the product resulting from oxidative damage to lipids (Alomar et al, 2017). Elevated levels of reactive oxygen species (ROS) in a marine teleost, the sheepshead minnow (*Cyprinodon variegatus*), induce oxidative stress, potentially resulting in inflammation and cellular apoptosis (Choi et al, 2018). Exposure to microplastics led to an excessive generation of ROS in goldfish (*Carassius auratus*) larvae (Yang et al, 2020). Increased lipid peroxidation (LPO) observed in European sea bass (*Dicentrarchus labrax*) exposed to microplastics (fluorescent red polymer microspheres) suggests the induction of oxidative stress and lipid damage (Barboza et al, 2018). MPs exposure disrupts the glutathione-dependent response cycles in fish, thus affecting antioxidant reactions. Consequently, exposure to various MPs disrupts the balance between ROS production and antioxidant capacity in fish, leading to oxidative damage.

Immunological Responses: In invertebrates, the primary mode of defence resides within the innate immune system, which combats pathogens, and similarly, in fish, it constitutes the fundamental defence mechanism (Magnadottir, 2006). The innate immune system comprises physical barriers, humoral components, monocyte-macrophages, natural killer cells, phagocytes, and granulocytes (Buchmann, 2014). Microplastics (MPs) have the potential to disrupt the fish immune system by triggering neutrophil activation, primary granule degranulation, and respiratory burst activity. MPs interacts with intestinal tissues, enters the circulatory system, consequently impairing the fish's immune responses (Hirt and Body-Malapel, 2020). Exposure to microplastics can result in intestinal inflammation and cytokine expression in zebrafish (Bhagat et al, 2020). Notably, dietary lead (Pb) exposure significantly stimulates the immune system of juvenile rockfish, *Sebastes schlegelii* (Kim and Kang, 2016). Espinosa et al (2017) investigate the ingestion of polyvinylchloride (PVC) microparticles may induce some notable effects on the immune activities of gilthead seabream (*Sparus aurata* L.). MPs exposure to gilthead seabream caused the peroxidase and immunoglobulin levels to increase and phagocytosis to decrease but showed no change in other organs (such as no changes in peroxidase level of serum and kidney). The innate immune response primarily targets positively charged microplastics, interacting with negatively charged cell membranes, thereby facilitating cell absorption. Hamed et al (2019) noted that the accumulation of microplastics in the tissues of early juvenile Nile Tilapia (*Oreochromis niloticus*) has the potential to affect the immune system by decreasing neutrophil levels, hindering nutrient absorption, and reducing energy allocation. In fathead minnow (*Pimephales promelas*), the presence of polycarbonate and polystyrene aggregates significantly increases the levels of neutrophils and peroxidase, acting as stressors and eliciting innate immune responses (Greven et al, 2016). The lysozyme and immunoglobulin levels were significantly reduced in common carp (*Cyprinus carpio*) following exposure of MPs particles (Banaee et al, 2019). The reduction in immunoglobulin levels might be linked to the suppression of cholinesterase level following exposure of MPs in common carp. Espinosa et al (2019) reported that the dietary inclusion of PVC and PE microplastics may impact innate immunity, leading to increased levels of immunoglobulins in European sea bass (*Dicentrarchus labrax* L.). Ahmadifar et al (2021) found that lysozyme and neutrophil levels significantly increased in Nile tilapia (*Oreochromis niloticus*) following exposure to waterborne polystyrene microparticles. In adult zebrafish, high-density polyethylene (PE) and polystyrene (PS) microplastics induce immune responses, evidenced by elevated levels of lysozyme and neutrophils (Limonta et al, 2019). Microplastics are recognized as foreign particles capable of either stimulating or suppressing immune functions in fish through various mechanisms. The *in-vitro* effects of polyvinylchloride (PVC) and polyethylene (PE) microplastics on head-kidney leucocytes of gilthead seabream (*Sparus aurata*) and European sea bass (*Dicentrarchus labrax*) suggest that continue exposure of fish to these MPs could damage the fish immune responses (Espinosa et al, 2018). This damage is probably due to oxidative stress generated in fish leucocytes. According to Choi et al (2023), juvenile crucian carp (*Carassius carassius*) exhibited a reduced level of lysozyme and immunoglobulin M (IgM) following exposure to polyamide (PA) microplastics.

Based on these studies, it can be concluded that microplastics have adverse impacts on fish immune systems. However, comprehensive research investigating fish immune responses to microplastic exposure is still pending.

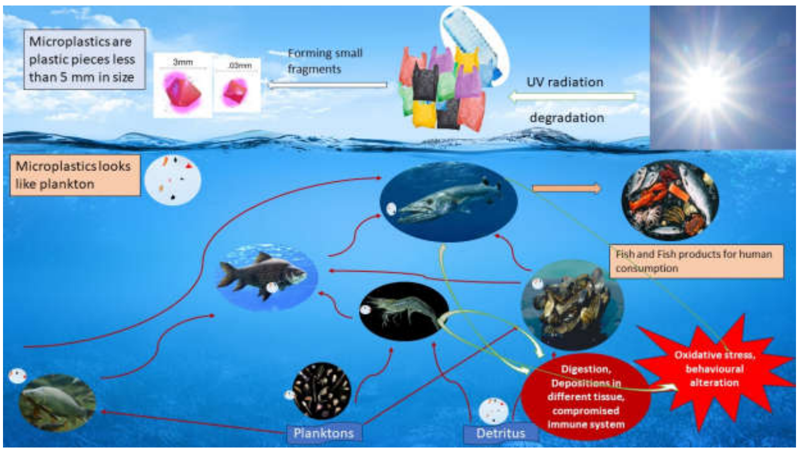

Figure 1: Microplastics pollution in food-web and effects on human health

MICROPLASTICS POLLUTION IN THE INDIA

India is huge consumer of plastics generating around 5.6 million tons of plastic waste annually (http://swachhbharaturban.gov.in/writereaddata/SBM%20). This plastic-waste makes land infertile, choking the drains, littering in the ecosystem, and ingested by the organisms (CPCB, 2017). The major input pathways are land-based sources, recreational fishing, domestic activities, coastal populations, and beach visitors (Kumar et al 2016; Dowarah and Devipriya, 2019). The presence of MPs is reported from various ecosystem such as sediments, aquatic bodies like rivers, lake and coastal areas of India.

Microplastics accumulations in Indian marine ecosystem: Most of the studies are conducted in southeast coast Indian. These coastal gives emmesns reasons to study as India has got long coastal line about 7500 supporting various activities like tourism, recreational, religional, commercial activities. Gathering of pilgrims increases anthropogenic derived MPs in the region such as Rameshwaram (Vidyasakar et al, 2018), Velankanni (Karuppasamy et al, 2020), and Thiruchendur (Jeyasanta et al, 2020). MPs are quite abundant in Indian marine sediments, beaches, and seawater (Raha et al, 2021, Manickavasagam et al, 2020, Vidyasakar et al, 2020, Jeyasanta et al, 2020, Patterson et al, 2019, Suman et al, 2020, Patchaiyappan et al, 2020, Selvam et al, 2020). One of the reports from the Gujarat coast showed that detection of small plastic debris (81 mg/kg) such as polyurethane, nylon, polystyrene, polyester particles had been reported by Reddy et al (2006). Like other places of the world, the accumulation of MPs varies by season in India too. The rate of distribution is also affected by monsoon type, tide condition and other physical factors. There was higher MPs in the monsoon season in eastern Arabian Sea, India showing the possible wash off from the terrestrial surface (Gurjar et al, 2023).

As marine become sink for plastic waste, MPs were detected in many marine biota in different parts of India (James et al, 2020; Daniel et al, 2020; Dowarah et al, 2020; Sathish et al, 2020a; Devi et al, 2020; Karuppasamy et al, 2020; Naidu, 2019; Patterson et al, 2019; Kumar et al, 2018; Naidu et al, 2018). Pavithran et al (2021) studied the MPs accumulation in 5 selected sites of the northern coast of Kerela and found out that polypropylene (PP) was the dominant (31–52% of the randomly selected subset (10%) of total fibre particles) among the five polymer types collected followed by Poly (ethylene-*co*-vinyl acetate) or PEVA, polyamide (PA), polybutadiene (BR) and polyethylene (PE) . Sathish et al (2020b) reported different types of MPs such as Polyethylene (73.2%), polypropylene (13.8%), nylon (8.2%), polystyrene (2.8%) and polyester (2%) from different coast of Tamil Nadu.

A survey had been conducted on the 270 pelagic fishes analysed (n = 30 per species) in Kerela, India. Microplastics were found in both edible and inedible tissues like muscle and skin and muscle and skin respectively. Out of that 41.1% of the fishes were detected with microplastics in their inedible tissues while only 7% of fishes had microplastics in their edible tissues. There was a total of 163 particles consisting mainly of fragments (58%). The deposition rate was different in filter feeders and visual predatory fishes as the concentration of particles was higher in inedible tissue of filter feeders than in visual predators. The average concentration of microplastics in edible tissues was 0.07 ± 0.26 items/fish and 0.53 ± 0.77 items/fish in inedible tissues (Daniel et al, 2020). In another study conducted in Tuticorin, southeast coast of India, and the polyethylene was most abundant followed by polyester and polyamide in the samples of *Harpodon nehereus*, *Chirocentrus dorab*, *Sardinella albella*, *Rastrelliger kanagurta*, *Katsuwonus pelamis* and *Istiophorus platypterus*. The scenario might be due to the deposition of MPs by domestic sewage and intensive fisheries in the area (Sathish et al, 2020a). Another study from Nattika coast Kerela, India in 2017 and 2018 revealed that microplastic amounts were 70.15 items kg/ of sand and 120.85 items kg/ sand in both the years, respectively (Ashwani and Verghese, 2019). Microplastics pollution was analysed in water, sediment and fish samples from selected stations along the Cochin estuary and nearby coastal areas in Kochi. The estuarine water and sediment samples recorded a larger number of microplastics than in beach samples with a mean abundance of 751.7 ± 452.21 particles/m3 and 1340 ± 575.22 particles/kg, respectively (Suresh et al, 2020). Similar study was conducted on Girgaon Mumbai (Arabian Sea coast), Tuticorin, and Dhanushkodi (Bay of Bengal coast) by Tiwari et al (2019). The results indicated that the plastic type were polyethylene (43%) followed by polyethylene terephthalate (17.3%) ≈ polystyrene (17%), polypropylene (12.3%), Others (11%) and polyvinylchloride (1.33%).

Motivarash et al (2024), investigated 400 fishes of 40 species from the Coast of Gujarat, India. The selected fishes were commonly edible and of good market value in domestic international markets. The fishes belonged to different feeding habits such as primary consumers (4 out of 40), and the remaining were either carnivorous or omnivorous. During this study, they recorded 100% MPs occurrence in the inedible tissues and 68% was found in edible tissues of the fish. Highest abundance of MPs in edible tissue was recorded in *Acetes indicus* and lowest abundance was recorded from *Parastromateus niger*, while in inedible tissue, the highest and lowest abundance was found in *Rastrelliger kanagurta* and *Otolithes cuvieri* respectively. Prusty et al (2023) assessed the microplastic contamination in *Harpadon nehereus* collected from India's northwest coast from four different sampling sites Gujarat and Mumbai, Maharashtra. The specimens were found to be contaminated with MPs of 3409 particles. The highest MPs were found at Jaffrabad, followed by Jakhau, Mumbai, and Okha. The types of polymers were polyethylene, polystyrene, and polyurethane.

Microplastics accumulation in Indian freshwater ecosystem: India possesses a variety of aquatic environments. There are 12 major riverine systems with so many tributaries. In addition to rivers, the freshwater ecosystems of India are enriched by lakes, ponds, canals, estuaries etc. India has many large reservoirs also. There are about 62 major lakes including diverse forms like glacial, freshwater, saline and brackish water lakes are found in India. But there is only a little information regarding plastic pollution compared to the marine ecosystem. The MPs pollution, source, transport, and fate of the Indian Rivers remains largely unexplored. One of the reasons for increasing microplastics is the gathering of pilgrims which is a major source of microfibers in the Netravathi river of Karnataka (Amrutha and Warrier, 2020**).** Neelavannan and Sen (2023) reviewed and analysed 18 papers relevant to the freshwater ecosystems of India concluded that common polymer types accumulated in the freshwater ecosystems were fragments of polypropylene (PP), polyethylene terephthalate (PET), and polyethylene (PE). A study in River Ganga, specially the lower or middle course, was conducted to analyse the occurrence and distribution of MPs in the river environment and common fishes (*Tor tor*, *Schizothorax richardsonii*, *Labeo dero* and *Gara gotyla gotyla*). The results showed that the river was contaminated MPs with the contamination of water (118.5 ± 49.65 particles/1000 L), sediment (131.5 ± 53.60 particles/kg dry weight). MPs were also recorded in fishes such as found in river like Tor *tor* (53.13 ± 63.77) was highest accumulated by MPs followed by *Schizothorax richardsonii* (36.33 ± 22.34), *Labeo dero* (15.42 ± 9.33) and *Gara gotyla gotyla* (12.63 ± 5.93) particles/individual respectively. The types of abundant polymers were polyethylene (PE) predominant in water, polypropylene (PP) dominant in sediment, and polyethylene terephthalate (PET) and polystyrene (PS) most abundant in fish samples (Badola et al, 2023).

Another study on river Ganga from Rishikesh (Uttarakhand) to Farakka (West Bengal) was carried out by Rajan et al (2023). 22 sampling sites selected and reported that MPs accumulated in the river were classified into different categories like fragments, pellets, filaments, films, foams. During this study, the highest concentration of MPs was collected from nine sampling stations.

Table 1: Microplastics pollution in Indian rivers

SI. No.	Name of water rivers	Types of polymers found	Authors
1.	Netravathi river, Karnataka	Microfibre	Amrutha and Warrier (2020)
2.	River Ganga (Middle and lower region)	Polyethylene (PE) predominant in water, polypropylene (PP) dominant in sediment, and polyethylene terephthalate (PET) and polystyrene (PS)	Badola et al. (2023)
3.	River Ganga from Rishikesh (Uttarakhand) to Farakka (West Bengal)	Fragments, pellets, filaments, films, foams	Rajan et al. (2023)
4.	Ulhas River	Polyethylene, LDPE, HDPE, polypropylene, polyester, polystyrene, and nylon	Verma et al. (2022)
5.	Kosasthalaiyar River Adyar River Muthirappuzhayar	Fibres, Fragments and Pellets of PE PP and PS	Lechthaler at. el. (2021)
6.	Alaknanda river	Fragments, films, foam, fibre and pellets	Chauhan et al. (2021)

Kanpur, followed by Patna, Allahabad, and Varanasi respectively, while the lowest MP concentration was recorded at Rishikesh. The average MPs in surface waters of the river Ganga were 92.85± 50.69 (SD) particles m/cube. Verma et al (2022) quantified MPs pollution in the Ulhas River which runs through Inda's most populous metropolis city Mumbai and contributes significantly to MPs entering the Arabian Sea. The results indicated that every sediment sample was contaminated with MPs and primary polymers present in sediment samples were polyethylene, LDPE, HDPE, polypropylene, polyester, polystyrene, and nylon. Results of this study concluded that agricultural land use–dominating basins and forest-dominating basins have lower risk of MPs pollution compared to urban and industrial clusters dominating basins. Therefore, they declared urban and industrial clusters dominating basins as MPs hotspots in the Ulhas River.

Lechthaler et al (2021) compared the MPs concentrations in urban rivers (the Kosasthalaiyar River and the Adyar River, in the megacity Chennai) and rural River (Muthirappuzhayar River). The average microplastics concentration of urban rivers was recorded 0.4 microplastic particles/L, while rural rivers had an average concentration of 0.2 microplastic particles/L. A total number of 447 MP particles were evaluated in which dominates by the fibres (64.1%), followed by films (21.7%), fragments (12.0%) and pellets (2.2%). Three different types of polymers were identified by PE (46.7%) followed by PP (46.7%) and PS (6.7%). Study conducted on Alaknanda River of Uttarakhand by Chauhan et al (2021), from five water and 4 sediment samples and recorded five types of polymers (fragments, films, foam, fibre, and pellets). The number of MPs were 955 particles, in which 566 were found in water and 389 were found in the sediment samples. The highest number of MPs were threads/fibres (766) as compared to fragments (79), pellets (28) and films (73) and the foam (9). Studies were conducted on some of the commercially important bottom-feeding fishes and shellfish (*Arius maculatus*, *Etroplus suratensis*, *E. maculatus* and *Villorita* sp.) from brackish water lake Vembanad Lake India. The most abundant type of MPs found is fibre in organisms as well as water columns. The average sizes ranged between 0.04 and 4.73 mm (4 ± 3 mm), with most particles being <4 mm (Nikki et al, 2021). The types of polymers were chlorinated polyvinyl chloride, polyethylene, polypropylene, and polyester. The concentrations were compared in the water column and organism. The water columns found higher MPs than organisms as the average abundance of MPs were (872±573 nos./m^3) than in finfishes (15±13 particles per fish) and shellfish (23±20 nos./ind.).

Table 2: Microplastics accumulated in Indian Fishes

SI. No.	Name of the fish	Amount and types of polymers found	Authors
1	*Channa punctatus*, *Labeo rohita, Labeo bata and the* indigenous fishes like *bacaila* and *Puntius amphibius, Salmostoma bacaila*	**Amount**: The highest MPs particle was 7.86 ± 2.0 items/individual in *Channa punctatus* followed by *Labeo rohita* (4.17 ± 0.6 items/individual) and *Labeo bata* (3.03 ± 0.4 items/individual). **Type:** The type of MPs was Fibre type besides fragments and pellets	Pandey et al .(2023)
2	*Arius maculatus, Etroplus suratensis, E. maculatus* and *Villorita* sp.	**Amount**: The most abundant type of MPs is fibre .04 and 4.73 mm (4 ± 3 mm), with most particles being <4 mm **Type:** chlorinated polyvinyl chloride, polyethylene, polypropylene, and polyester i	Nikki et al. (2021)
3	*Tor tor*, *Schizothorax richardsonii*, *Labeo dero* and *Gara gotyla gotyla*	**Amount**: *Tor tor* (53.13 ± 63.77) was found to be the highest followed by *Schizophora richardsonii* (36.33 ± 22.34), *Labeo dero* (15.42 ± 9.33)and *Gara gotyla gotyla* (12.63 ± 5.93) particles/individual respectively **Type: P**olyethylene (PE) predominant in water, polypropylene (PP) dominant in sediment, and polyethylene terephthalate (PET) and polystyrene (PS) most abundant in fish samples	Badola et al. (2023)

There are few reports from indigenous fishes. One of the studies was conducted in freshwater fishes like *Channa punctatus*, *Labeo rohita, Labeo bata, Salmostoma bacaila* and *Puntius amphibius.* MPs particles were detected in *a*ll the fishes (n = 35/species). The highest MPs particle was found in *Channa punctatus* (7.86 ± 2.0 items/individual) followed by *Labeo rohita* (4.17 ± 0.6 items/individual) and *Labeo bata* (3.03 ± 0.4 items/individual). MPs were not limited to the bigger size fishes but also MPs were found in the smaller fishes such as *Salmostoma bacaila* and *Puntius amphibius*. The type of MPs was Fibre type besides fragments and pellets as other habitats also found to be dominated by fibres (Pandey et al, 2023).

Risk of MPs in ornamental fish industry: Ornamental industry is one the fastest growing industries. India has huge potential for the diversity of fishes as we have two very important hotspots. Ornamental values of the fishes are determined by the colour and behaviour. Microplastics are found to interfere with many aspects of these ornamental fishes just like other edible fishes. And also, ornamental fishes are more vulnerable to the plastics as the fishes exposed certain types of plastic components in the culture system including pellet feeds, decorative items and filters etc. Prüst et al (2020) Effect on skin colour development is seen in Discus (*Symphysodon aequifasciatus),* which was given exposure for up to 30 days to fluorescent polyethylene microplastics (70–88μm, 200μg/L). Studies from other fishes like Goldfish (*Carassius auratus*) and Zebrafish *Danio rerio* were carried out to evaluate the effect of MPs and showed the different concentration of microplastics in different parts of the fishes (Jabeen et al, 2018; Abarghouei et al, 2021). Some of the microplastics have been shown to cross the blood-brain barrier. The effects in the colour development and behaviour will hamper the aquarium-industry.

CONCLUSION

The effects of microplastics have been very prominently seen in all the trophic levels, right from microbes to humans. The most notable effects in fish are alteration of behaviour like swimming, coughing and food intake etc. These effects may be due to internal depositions and affecting various cellular pathways in the organism's body. The rate of metabolism is also affected in certain ways. Induction of oxidative stress is another fish health problem caused by MPs. The results of the studies emphasised the mismanaged or improper waste disposal were the major contributors of MPs.

The Indian ecosystem is not affected less compared to the other international water bodies. There are many studies from coastal regions both from east and west reporting accumulation of microplastics to the environment, such as soils, water columns and fishes. Freshwater ecosystems are limitedly explored. So, the review compiles the available data from important rivers and fishes. In vitro studies were carried out in some of the selected fishes with selected polymers to study the exact effects. The data derived from such studies confirmed the accumulation in both edible and non-edible tissues of fishes, and affecting various systems like digestive system, immune-system, endocrine system and neurological problems etc. Although research on MPs pollution in India has gained momentum over the past decade, we still have a long way to go with such few reports from Indian freshwater ecosystems.

Future scope:
In vitro studies of consumable fishes with all the types of polymers at various concentrations is required. As most of the studies are only confined to the detection in tissue, the acute and chronic effects of long-term exposure need to be studied. Long term effects of microplastics have not been studied yet in different trophic levels although accumulation has been reported. There is no report on the effect of gut microbes of fish. These gut microbes are responsible for many vital systems of the fish body and the gut is also the primary site for microplastics accumulations, there must be correlation between the particles and microbial community. Metabolic disturbances have not been studied well; therefore, a circulatory pathway is needed to be established in the fish. Associated microbiota are very important aspects when we discuss the digestion and immunology of the organism. Therefore, this area has a huge gap to be filled with the effects of MPs in Fishes.

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