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Drenched in microplastic environment: Physiological and metabolic disruptions in fish

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Abstract

Microplastic pollution is an escalating environmental concern, particularly in aquatic ecosystems. Fish, as key organisms in these systems, are highly susceptible to the impacts of microplastics, which lead to physiological and metabolic disruptions. The study employed a comprehensive literature search to identify peer-reviewed articles focusing on fish models and organ-specific studies. The findings reveal that microplastic exposure can lead to various adverse effects on fish organs, including the gastrointestinal tract, liver, kidney, gills, intestines, brain, and reproductive organs. These effects encompass inflammation, oxidative stress, tissue damage, metabolic and endocrine disruptions. Species-specific variability exists, with some fish showing higher susceptibility. This review summarizes existing research on the effects of microplastics on fish with a focus on organ-specific damage, metabolic changes, and species-specific responses.

Keywords: Microplastics, Effects of Microplastics, physiological alterations, metabolic disruptions, inflammation, oxidative stress, tissue damage, organ-specific damage

1. Introduction

Micro-plastics (MPs) are plastic particles sized between 1 μm and 5000 μm , while smaller particles are termed nano-plastics (NPs). MPs can be categorized into primary and secondary types. Primary MPs are intentionally manufactured small particles found in products like cosmetics and personal care items (Benson, N. U., *et al.*, 2022) [3] while Secondary MPs arise from the degradation of larger plastic items, such as bags and bottles, due to environmental factors like sunlight, UV radiation, and abrasion. Bacteria also contribute to the breakdown of plastics into smaller particles (Ioni, Y. V., *et al.*, 2025) [16]. The rate of MP formation is influenced by various factors, including the type of polymer, environmental conditions etc. (Ge, J., *et al.* 2023) [11]. Understanding the sources and impacts of MPs is essential for developing strategies to mitigate their environmental effects.

Fish serve as excellent model organisms for studying microplastic impacts as it shares more common features with humans as compared to other invertebrates. Their physiological responses provide insights into the overall effects of microplastics on aquatic life (Prokić, M. D., *et al.*, 2021; Foley, C. J., *et al.*, 2018) [30, 9]. Research has revealed that different fish species exhibit diverse responses (Hossain, M. A., & Olden, J. D. (2022) [15]; At the cellular level, exposure results in inflammation, oxidative stress, and cell death, with damage severity depending on particle concentration and size (da Silva Brito, W. A., *et al.*, 2023) [5]. Moreover, the potential entry of microplastics into the human food chain via food and other sources emphasizes the importance of assessing risks and establishing proper guidelines. This review aims to consolidate current knowledge about the specific physiological and metabolic disruptions in different fish species. It documents the most commonly affected organs, their histopathological changes, and variations in microplastic concentrations across diverse aquatic environments.

2. Methods

A comprehensive literature search was performed using databases such as PubMed, Web of Science, Scopus, ScienceDirect, and Google Scholar. The inclusion criteria focused on peer-reviewed articles published between 2010 and 2025, centered on fish models and organ-

specific studies. Studies not peer-reviewed or lacking organ/tissue-level assessments were excluded. Keywords employed in the search included "microplastics," "fish," "organ damage," "metabolic disruption," "histopathology," "polymer type," "exposure duration," and "species-specific responses." This strategy captured a broad array of studies on the physiological and metabolic impacts of microplastics on fish, ranging from microplastic types to their specific effects on various fish species.

3. Effects of Microplastic Exposure on Freshwater Fish Survival Rates

Exposure to MPs can decrease the survival rate of fish by causing blockage or toxicity in their gastrointestinal tract. By inducing malnutrition or changing eating habits, it may also have an impact on the particular growth rate of fish. Studies have demonstrated that prolonged exposure to MPs might result in decreased overall health and reproductive effectiveness in fish communities (Diana, Permatasari., *et al.*, 2023; Numair, Masud., *et al.*, 2023; and Mostafa, A. R., *et al.*, 2022) [6, 29, 28]. A Study conducted by Md., Moshir, Rahman., *et al.*, 2022 [24] revealed that males exposed to MPs had a considerably elevated death rate in comparison to the other groups. The impact of MP exposure on fish survival and growth rates might differ based on the specific characteristics of the MPs, such as their kind, size, and concentration in the surrounding environment (Mostafa, A. R., *et al.*, 2022) [28].

4. Effects of MP Exposure on various Organs of Fish.

4.1 Liver

MPs have been discovered to accumulate in the liver, resulting in possible harm and disturbance of regular liver function. MPs in the liver can impair its capacity to efficiently eliminate noxious compounds from the body. MPs have been associated with hepatic injury, such as inflammation and fibrosis. Exposure to MPs can also cause hemorrhage, degeneration, necrosis, and apoptosis (Jeyaraj, Jeyavani., *et al.*, 2023; Mohamed, Hamed., *et al.*, 2021; and Alaa, El-Din, H., *et al.*, 2022) [17, 27, 1].

4.2 Kidney

Kidneys are affected by MPs as they can accumulate in the renal system and may contribute to kidney damage or dysfunction. Exposure to MPs can induce oxidative stress in the kidneys, leading to inflammation and potential impairment of kidney function or other renal disorders. The presence of MPs in the kidneys can trigger renal toxicity, which can affect the normal filtration and excretion

functions of the kidneys. (Mohamed, Hamed., *et al.*, 2021; Alaa, El-Din, H., 2022) [27, 1].

4.3 Gills

MPs can cause damage to gill tissues, reducing the surface area for oxygen exchange affecting the fish's ability to extract oxygen from water, leading to inflammation, impaired respiratory function and feeding issues (Cao, J., *et al.*, 2023; Mohamed, Hamed., *et al.*, 2021; Fritz-Peter, Hager., 2022) [4, 27, 10].

4.4 Intestines

MPs can cause blockages and damage to the intestinal lining in fishes, leading to reduced nutrient absorption and overall health (Ricardo Almeida, 2023) [37]. It can also accumulate in the intestines, potentially leading to inflammation and other adverse effects on digestive health. Disruption/ Alterations in gut microbiota due to MPs can include changes in the diversity and composition of microbial communities within the gut. (Mehdi, Banaei., *et al.*, 2022; John, J., *et al.*, 2022; Miao, Teng., *et al.*, 2022; Jiamin, Hu., *et al.*, 2022) [25, 19, 26, 18].

4.5 Brain

Exposure to MPs have been found to impact the brain, potentially leading to neurotoxicity, degeneration, necrosis, alteration of neurotransmitter metabolites, impaired cognitive function and neurobehavioral changes. Disruption of blood-brain barrier integrity, Inflammation and oxidative stress, Impaired neurotransmission, synaptic plasticity, induces neuroinflammation, and impairs learning and memory are also observed (Köktürk, M., *et al.*, 2023; Giacomo, Limonta., *et al.*, 2021; Fritz-Peter, Hager., 2022; Miao, Teng., *et al.*, 2022; Hamed, M., *et al.*, 2022; Shan, S., *et al.*, 2022; Ding, P., *et al.*, 2023; Xiong, F., *et al.*, 2023; Lee, C. W., *et al.*, 2022) [21, 12, 10, 26, 13, 32, 8, 36, 22].

4.6 Reproductive organs and endocrine disruption

Exposure to MPs can lead to Reduced fertility in fishes, Abnormal development of reproductive organs in fishes, Decreased hatching success of offspring, and Developmental problems (Tarasco, M., *et al.*, 2022; Wang, J., *et al.*, 2021; Hodkovicova, N., *et al.*, 2022) [34, 35, 14]. Endocrine disruption caused by MP exposure may include interference with hormone regulation, potentially leading to reproductive, developmental or other detrimental impacts (Lin, W., *et al.*, 2023, Solleiro-Villavicencio, H., *et al.*, 2020) [23, 33].

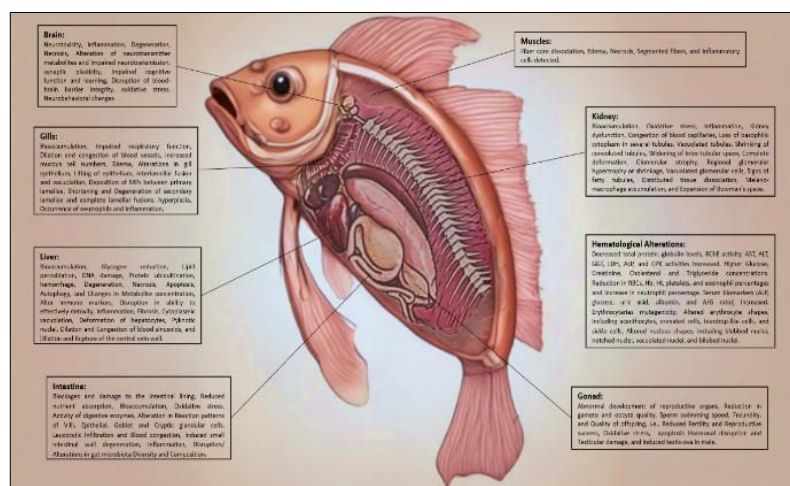


Fig 1: Effects of MP Exposure on various Organs of Fish**Table 1:** Study outlining the species studied, MPs polymer utilized, damaged organs, study parameters, and observed changes, with references.

Sr. no.	Species Studied	Type of microplastic Polymer used	Organs affected	Parameters Accessed	Alterations Seen	References
1.	<i>Oreochromis mossambicus</i>	PP-MPs	Liver, brain.	Fluctuations in homeostasis, an upsurge in ROS levels, an alteration in antioxidant parameters, including SOD, CAT, GST, and GPx; a promotion in the oxidation of lipid molecules; and a denaturation in the neurotransmitter enzyme acetylcholinesterase (AChE)	Necrosis of hepatocytes and Infiltration of sinusoids with leukocytes and dilation of sinusoids	Jeyaraj, Jeyavani., <i>et al.</i> , 2023 ^[17]
2.	<i>Danio rerio</i> and <i>Perca fluviatilis</i>	PP-MPs	Liver, gills	Assessment of cellular function and biomarkers in fish tissues	Lipid peroxidation, DNA damage, protein ubiquitination, apoptosis, autophagy, and changes in metabolite concentration	Dimitra, Bobori., <i>et al.</i> , 2022 ^[7]
3.	<i>Carassius carassius</i>	PE-MPs	Liver, Gut	Growth, Liver Damage, and Gut Microbiome Composition	medium and high PE-MPs groups had decreased Weight, liver damage, Proteobacteria, <i>Fusobacteria</i> , <i>Firmicutes</i> , and <i>Bacteroides</i> were the dominant species in the gut. Pathogens <i>Staphylococcus</i> and <i>Ralstonia</i> were present.	Jiamin, Hu., <i>et al.</i> , 2022 ^[18]
4.	<i>Cyprinus carpio</i>	PE-MPs	Liver, intestine and Blood	Biochemical parameters, oxidative biomarkers, and gene expression assays performed.	Mt1, Ces2, and P450 mRNA expression were enhanced. Mt2 gene expression decreased. Higher MDA and carbonyl protein levels. Antioxidant capacity and glycogen contents declined. Inhibited GR, G6PDH, and CAT activities. SOD and GPx activities increased. Decreased total protein, globulin levels, BChE activity in blood. AST, ALT, GGT, LDH, ALP, and CPK activities increased. Higher Glucose, creatinine, cholesterol and triglyceride concentrations.	Mehdi, Banaei., <i>et al.</i> , 2022) ^[25]
5.	<i>Scophthalmus maximus</i>	PE-MPs and PP-MPs most dominant type	brain, liver, gill, and muscle tissues	Evaluation of oxidative damage biomarkers	SOD, CAT, GPx, PON, AR, MPO, and MDA biomarkers were evaluated	Köktürk, M., <i>et al.</i> , 2023 ^[21]
6.	<i>Oreochromis niloticus</i>	-	Kidney, liver, Pancreas, muscle, Gills, spinal cord and notochord	Histological analysis	In Kidneys, congestion of blood capillaries, inflammatory cells, loss of basophilic cytoplasm in several tubules, vacuolated tubules, shrinking of convoluted tubules, widening of inter-tubular space, complete deformation, glomerular atrophy, vacuolated glomerular cells, and signs of fatty tubules. The liver tissue exhibited vacuoles, hydropic degeneration, necrotic area, severe deformation of hepatocytes, pyknotic nuclei, and dilation and congestion of blood sinusoids. Pancreatic tissue revealed shrunken and degenerated acini with pyknotic nuclei, hemorrhage, necrotic area, inflammatory cells, fatty cells, and congested blood capillaries. In the muscle tissue, fiber core dissociation, edema, necrosis, segmented fibers, and inflammatory cells were detected. Gill tissue demonstrated dilation and congestion of blood vessels, complete	Mohamed, Hamed., <i>et al.</i> , 2021 ^[27]

					lamellar fusions, lifting of epithelium, shortening and degeneration of secondary lamellae, hyperplasia, and deposition of MPs between primary lamellae. In spinal cord and notochord, the effects were degeneration and protrusion of meninges, deformation and deviation of notochord from its central axis, edema, degeneration of notochord (disappearance of vacuolar cells), deviation of spinal cord from the central axis, and loss of vacuolar cells in notochord. The intestinal tissue exhibited degeneration of basement membrane, inflammatory cells, goblet cells, atrophy of submucosa, pyknotic nuclei, hemorrhage, and vacuolization of mucosal cells.	
7.	<i>Clarias gariepinus</i>	-	Kidney, Liver and Intestine	Histological and histochemical examinations	Kidney revealed distributed tissue dissociation, regional glomerular hypertrophy or shrinkage, melano-macrophage accumulation, and expansion of Bowman's space, while liver tissue exhibited dilation and rupture of the central vein wall, hemorrhage, cytoplasmic vacuolation, and cellular necrosis or apoptosis. Connective tissue fiber accumulation around renal blood vessels, renal tubules, the central hepatic vein, hepatic blood sinusoids and serosal muscle, and submucosal layers of the intestine.	Alaa, El-Din, H., <i>et al.</i> , 2022 ^[1]
8.	<i>Danio rerio</i>	mix of PS-MPs and high-density PE-MPs	Head and kidney	enzymatic biomarkers, acetylcholinesterase and lactate dehydrogenase were investigated	Up-regulated genes involved in xenobiotics catabolic processes (cyp2p8), and adaptive immunity (tcra). Acetylcholinesterase activity was inhibited	Giacomo, Limonta., <i>et al.</i> , 2021 ^[12]
9.	<i>Poecilia reticulata</i> (Fish) and <i>Gyrodactylus turnbulli</i> (Parasite)	PP-MPs	-	host susceptibility to disease and mortality was assessed	higher pathogen burdens, increased mortality events and reduced disease resistance	Numair, Masud., <i>et al.</i> , 2023 ^[29]
10.	<i>Clupea harengus</i> , <i>Gadus morhua</i> , <i>Platichthys flesus</i> , <i>Taurulus baublis</i> , <i>Cyclopterus lumpus</i>	Cellophane, polyamide, PE-MPs, PP-MPs, PET, polyvinyl propionate, Polyacrylonitrile, and polyester	gills, digestive tract, liver	Presence of MPs in fish organs Abundance and characteristics of MPs in fish organs (size, color, polymer composition)	-	Paulina, Piskula., <i>et al.</i> , 2023
11.	<i>Oreochromis niloticus</i>	-	-	Antioxidant biomarkers (SOD, CAT, TAC) DNA damage (fragmentation) Muscle protein profile (electrophoretic pattern)	The activities of superoxide dismutase, catalase, total peroxides, and oxidative stress index (OSI), as well as lipid peroxidation and DNA fragmentation, increased. Activity of total antioxidant capacity decreased. Electrophoretic pattern of muscle proteins revealed alteration in the proteinogram	Mohamed, Hamed., <i>et al.</i> (2020) ^[13] .
12.	<i>Cyprinus carpio</i>	mixture exposure of the PE-MPs and 4-nonylphenol (4-NP)	Gills, brain, Liver,	histopathological and histochemical biomarkers	Alterations included severe edema, lifting of the outer epithelium, interlamellar fusion and vacuolation, secondary lamellar shortening and complete fusion, increased mucous cell numbers in the gill tissue, enlargement of inner layer stratum periventricular, cell degeneration with pyknotic nuclei, increased blood capillaries, spongiosis in the brain tissue (optic tectum), central vein hemorrhage, shrunken and fatty degeneration of hepatocytes, rosette shapes around small	Fritz-Peter, Hager., (2022) ^[10]

					congested blood sinusoids, vacuoles, necrosis, and severe glycogen reduction in the liver tissue.	
13.	<i>Coregonus peled Gmelin</i>	Fluorescent PS-MPs	Intestine	Activity of digestive enzymes (α -Amylase, non-specific esterases, pancreatic trypsin, bile salt-activated lipase, aminopeptidase N) Activity of antioxidant enzymes (catalase, glutathione S-transferase, glutathione reductase, glutathione peroxidase)	positive effect on the activity of pancreatic trypsin and bile salt-activated lipase. Intestinal membrane enzyme aminopeptidase stimulated. Increase in the specific activity of catalase.	Yulia, A., <i>et al.</i> , 2023 ^[38]
14.	<i>Zebrafish</i>	PS-MPs	Intestine, brain	Growth inhibition and adverse effects on inflammatory responses and intestinal permeability Alteration of neurotransmitter metabolites and changes in microbial groups	inhibited growth and affected inflammatory responses and intestinal permeability. Transgenerational deficits and disrupted the regulation of the brain-intestine-microbiota axis.	Miao, Teng., <i>et al.</i> , 2022 ^[26]
15.	<i>Cyprinus carpio</i>	PE-MPs	Brain, tectum and retina	Activity of acetylcholinesterase (AChE), monoamine oxidase (MAO), and nitric oxide (NO) Necrosis, fibrosis, changes in blood capillaries, tissue detachment, edema, degenerated connective tissues, and necrosis in large cerebellar neurons and ganglion cells in the carp tectum. Necrosis, degeneration, vacuolation, and curvature in the inner layer of the carp retina	Exposure to plastic particles reduced activity of biochemical biomarkers in carp brain. Plastic particles caused necrosis, fibrosis, and degeneration in carp tectum and retina.	Hamed, M., <i>et al.</i> , 2022 ^[13]
16.	<i>Oreochromis urolepis</i>	PE-MPs	Small intestine. (Goblet and cryptic glandular cells)	Villi height, width, and epithelial cell height. Indices of damage to the small intestine.	Villi height and width and epithelial cell height were affected. Indices of damage to the small intestine organ and reaction patterns of villi, epithelial, goblet and cryptic glandular cells, leucocytic infiltration and blood congestion revealed alteration. Induced small intestinal wall degeneration	John, J., <i>et al.</i> , 2022 ^[19]
17.	<i>Chanos chanos, Chanda nama, Chelon macrolepis, Carangoides malabaricus and Gerrus filamentosus</i>	-	-	MPs in the gastrointestinal (GI) tracts of five fish species Size, shape, color, and abundance of MPs in the fish GI tracts	-	K., Anandhan., <i>et al.</i> , 2022 ^[20]
18.	<i>Dicentrarchus labrax</i>	Fluorescent red polymer microspheres	Gills, Liver	Oxidative stress and lipid oxidative damage in gills and liver Bioconcentration and bioaccumulation of mercury in gills and liver	MPs increased mercury concentration in gills and liver	Barboza, L. G. A., <i>et al.</i> , 2018 ^[2]
19.	<i>Oreochromis niloticus</i>	-	Testicular tissue Gonads	Number of erythrocytes RBCs, Hb, Ht, platelets, and eosinophil percentages. Biomarkers included: aspartate aminotransferase (AST), alanine aminotransferase (ALT) and alkaline phosphatase (ALP) activities, glucose (GL), cholesterol, total protein (TP), albumin (AL), globulin (GLO), creatinine (CR), and uric acid (UA). Superoxide dismutase (SOD), Catalase (CAT) and Total antioxidant capacity (TAC) was determined. e follicle stimulating hormone (FSH), luteinizing hormone (LH), and testosterone (T) were measured. Testicular histological degenerative changes and testis-ova.	A remarkable reduction in RBCs, Hb, Ht, platelets, and eosinophil percentages after exposure to MPs. neutrophil percentage significantly increased. Serum biomarkers (ALP, glucose, uric acid, albumin, and A/G ratio) increased. SOD and CAT levels were elevated. The blood smears from all treated groups had altered erythrocyte shapes, including acanthocytes, crenated cells, teardrop-like cells, and sickle cells. Altered nucleus shapes were found, including blebbed nuclei, notched nuclei, vacuolated nuclei, and bilobed nuclei. High number of altered erythrocytes in blood smears. Overall, MPs prompted oxidative stress, hormonal disruption and testicular damage, and induced testis-ova in male	Rania, F., <i>et al.</i> (2021). ^[31]

5. Conclusion

Microplastics present a significant threat to fish health by inducing oxidative stress, inflammation, and metabolic disruptions across various organ systems. The adverse effects, varying among different species, necessitate the implementation of effective mitigation strategies to safeguard aquatic ecosystems.

Public awareness initiatives, alongside rigorous regulatory measures that include bans on single-use plastics and microbeads, have shown measurable reductions in microplastic contamination. One more Promising approach includes advanced wastewater treatment technologies and future research should prioritize these areas to inform robust and adaptive management strategies for aquatic ecosystems.

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