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(Research Article)

Ecotoxicological impacts of Microplastic (MP) Pollution in Fish

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Abstract

Microplastic (MP) pollution has become a major environmental concern, mainly in aquatic ecosystems. The present study aims to evaluate the bioaccumulation, physiological impacts, and ecological risks of microplastic exposure in fish by synthesizing recent scientific findings. The objectives include assessing the effects of microplastics on fish health, identifying tissue distribution patterns, and examining immune, reproductive, and behavioral disruptions.

This study synthesizes secondary data to outline effective strategies for mitigating microplastic (MP) pollution in aquatic ecosystems, highlighting source reduction, advanced wastewater treatment, and sustainable aquaculture. It highlights the harmful impacts of MPs on fish, including oxidative stress, tissue damage, and reproductive impairments, particularly in females, alongside their role in spreading antibiotic resistance genes and chemical contaminants. The study advocates for public awareness, stringent policies, standardized toxicity assessments, and bioremediation research. The study also highlights the frightening consequences of microplastic exposure, including transgenerational effects, metabolic disruptions, and behavioral alterations in fish.

The findings highlight the need for strong mitigation strategies, such as improved wastewater treatment, biodegradable plastic alternatives, and stricter regulatory policies. Future research should focus on long-term ecological impacts, species-specific vulnerabilities, and the development of standardized testing protocols. Enhancing public awareness and promoting sustainable plastic management practices are vital to limit microplastic contamination and protect aquatic biodiversity.

Keywords: Microplastics; Bioaccumulation; Oxidative Stress; Immune Response; Genotoxicity; Reproductive Disruption; Aquatic Pollution; Fish Health; Antibiotic Resistance

1. Introduction

Microplastic pollution has arisen as a critical ecological topic, with increasing concerns about its long-term effects on aquatic ecosystems. Microplastics, defined as plastic particles less than 5 mm in size, originate from various sources, including plastic debris degradation, synthetic textiles, and industrial processes (Jovanović, 2017). These particles persevere in the atmosphere due to their chemical stability, low degradation rates, and extensive distribution in marine and freshwater ecosystems (Banaee et al., 2024). Among aquatic organisms, fish are mainly susceptible to microplastic pollution through direct ingestion and trophic transfer, raising concerns about ecological imbalances and human health risks through seafood consumption (Fred-Ahmadu et al., 2024).

The accumulation of microplastics in fish poses significant threats to their physiological functions, including metabolism, immunity, and reproduction. Given their ability to adsorb harmful pollutants and microbial pathogens,

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microplastics act as carriers of contaminants, further exacerbating their toxicological impact (Li et al., 2024). This study aims to analyze the bioaccumulation, toxic effects, and physiological disruptions caused by microplastics in fish by synthesizing findings from recent studies. Understanding these impacts is essential for developing mitigation strategies and regulatory frameworks to reduce plastic pollution in aquatic environments. Previous research has widely documented the harmful effects of microplastics on fish health. Jovanović (2017) emphasized that microplastic ingestion in fish leads to gastrointestinal blockages, reduced energy intake, and decreased growth rates. Similarly, Ding et al. (2018) confirmed that polystyrene microplastics accumulate in the liver of red tilapia (Oreochromis niloticus), leading to oxidative stress, inflammatory responses, and histopathological damage. Jo et al. (2025) further confirmed that microplastic exposure disrupts hematological parameters, reducing red blood cell counts and hemoglobin levels, which impairs oxygen transport and metabolic function.

Besides this physiological stress, microplastics can also induce significant immune and reproductive alterations. Wang et al. (2019) found that polystyrene microplastics caused sex-specific reproductive disruptions in Oryzias melastigma, with females experiencing reduced fecundity and altered hormone levels. Similarly, Wu et al. (2025) reported that female zebrafish were more affected than males under microplastic exposure, exhibiting increased mortality and reproductive decline. In terms of immune responses, Li et al. (2024) noted that microplastic exposure suppresses immune gene expression, making fish more susceptible to infections and increasing disease transmission risks in aquaculture settings. Microplastics also contribute to genetic toxicity and metabolic dysfunction in fish. Sampsonidis et al. (2024) demonstrated that both virgin and UV-aged polyethylene microplastics cause DNA strand breaks, mitochondrial damage, and metabolic disturbances in Perca fluviatilis. Banaee et al. (2024) further emphasized that microplastics not only induce genotoxic effects but also disrupt lipid metabolism and liver function, leading to long-term physiological consequences. Additionally, Fred-Ahmadu et al. (2024) warned that microplastics serve as vectors for environmental pollutants, such as pesticides and heavy metals, increasing the risk of chemical bioaccumulation in fish.

The presence of antibiotic resistance genes (ARGs) in microplastic-contaminated environments presents another major concern. Li et al. (2024) found that polyvinyl chloride (PVC) microplastics facilitate the spread of ARGs in fish gut microbiota, exacerbating the global challenge of antimicrobial resistance. This issue raises serious implications for food safety, as microplastics can transfer ARGs through the food chain, affecting both aquatic organisms and human consumers. Despite the growing body of research on microplastic toxicity in fish, significant knowledge gaps remain in understanding their long-term ecological and evolutionary consequences. Most studies focus on laboratory-controlled experiments, often failing to capture the complex interactions occurring in natural aquatic ecosystems (Banaee et al., 2024). There is also limited research on species-specific vulnerabilities, transgenerational effects, and the combined impact of microplastics with other environmental stressors, such as climate change and heavy metal pollution. Furthermore, existing mitigation strategies for microplastic pollution remain inadequate. While wastewater treatment plants can filter large plastic debris, they are ineffective in removing micro- and nanoplastics, allowing these particles to persist in water bodies (Fred-Ahmadu et al., 2024). Developing innovative solutions, such as biodegradable plastic alternatives and stricter regulatory policies, is crucial for minimizing microplastic contamination and its associated risks.

This study, therefore, aims to consolidate recent research findings on the toxicological effects of microplastics in fish, with a focus on bioaccumulation, immune suppression, reproductive impairments, and metabolic disruptions. By synthesizing secondary data from multiple sources, this research will provide a comprehensive understanding of microplastic-induced toxicity in fish, highlighting the need for policy interventions and sustainable plastic management strategies.

By addressing these research gaps, this study seeks to contribute to the ongoing discourse on microplastic pollution and its broader implications for aquatic biodiversity, fisheries sustainability, and public health.

2. Methodology

The present study primarily utilizes secondary data from peer-reviewed scientific journals and online databases, including ScienceDirect (https://www.sciencedirect.com), PubMed (https://pubmed.ncbi.nlm.nih.gov), SpringerLink (https://link.springer.com), and Google Scholar (https://scholar.google.com), along with institutional repositories. It also draws on data from various government and institutional reports, such as those published by the United Nations Environment Programme (UNEP) and the Food and Agriculture Organization (FAO), which address microplastic contamination in fisheries and aquaculture. Additionally, open-access platforms like ResearchGate and MDPI were used to access articles on microplastic bioaccumulation and its health impacts. Besides, the study integrates offline resources, including textbooks, reference materials, print journals, and conference proceedings. These offline materials provide historical data and foundational insights into microplastic pollution and its effects on aquatic ecosystems.

Results and Discussion: The secondary data from the above studies together validate that microplastic exposure poses complicated risks to fish health, including bioaccumulation, immune dysregulation, genotoxicity, and behavioral alterations. The cumulative effects of MPs can potentially impact fish populations, aquatic biodiversity, and food safety.

2.1. Bioaccumulation and Tissue Distribution

Recent studies stress the widespread bioaccumulation of microplastics (MPs) in fish tissues, posing risks to aquatic health and human consumers. Li et al. (2022) found MPs in the gastrointestinal tracts and muscle tissues of estuary-caught fish, causing oxidative stress and inflammation. Jia et al. (2022) reported that MPs enhance triclosan bioaccumulation in tilapia, disrupting lipid metabolism and energy production. Nath et al. (2024) detected MPs in edible fish tissues from urban lakes in Bangladesh, raising food safety concerns. Supporting studies by Ding et al. (2018) and Jovanović (2017) revealed that MPs trigger oxidative stress, tissue damage, and reduced fish growth. Sampsonidis et al. (2024) further showed that UV-aged MPs intensify genotoxicity and metabolic disruptions in Perca fluviatilis. Collectively, these findings highlight MPs' capacity to accumulate fish tissues, impair physiological functions, and increase toxicity risks, emphasizing the need for stricter pollution controls and seafood safety measures.

2.2. Hematological and Oxidative Stress Responses

Contemporary studies reveal that microplastic (MP) exposure significantly disrupts fish hematological parameters and induces oxidative stress, compromising immune function and overall health. Jo et al. (2025) reported that polyethylene MPs increased reactive oxygen species (ROS) production, lipid peroxidation, and antioxidant enzyme activity alterations in Korean bullhead (Pseudobagrus fulvidraco), indicating oxidative stress and immune impairment. Similarly, Wang et al. (2022) found that polystyrene MPs triggered oxidative stress and histological damage in loach juveniles (Paramisgurnus dabryanus) via the Keap1-Nrf2 signaling pathway, highlighting the cellular-level toxicity of MPs. Supporting these findings, Kim et al. (2021) conducted a thorough review, confirming that MP bioaccumulation leads to hematological disturbances, oxidative stress, and immune dysregulation in various fish species. Lee et al. (2023) specifically demonstrated that polyethylene MPs alter hematological parameters and antioxidant responses in Korean bullhead, further linking MP exposure to systemic stress and inflammation. Nair and Perumal (2024) observed similar effects in Nile tilapia (Oreochromis niloticus) exposed to polypropylene MPs, reporting reduced hemoglobin, increased ROS levels, and impaired growth performance, indicating metabolic stress and reduced physiological resilience.

Collectively, these studies highlight the extensive threat of MPs to fish health, demonstrating that MP exposure not only induces cellular-level oxidative stress and tissue damage but also compromises immune function and growth. The consistent observation of hematological disruptions and antioxidant response alterations underscores MPs' potential to weaken fish defenses, reduce survival rates, and ultimately threaten aquatic biodiversity and ecosystem stability.

2.3. Immunotoxicity and Inflammatory Response

Microplastic (MP) exposure induces immunotoxicity and chronic inflammation in fish, weakening their defenses and increasing infection susceptibility. Li et al. (2024) observed elevated pro-inflammatory cytokines and reduced antioxidant defenses, indicating immune dysregulation. Pei et al. (2025) found that polystyrene MPs activate the ROS-driven NF-κB pathway in zebrafish (Danio rerio), promoting inflammation and tissue damage. Del Piano et al. (2023) demonstrated region-specific immune responses in gilthead seabream (Sparus aurata), with MPs causing localized gut inflammation. Yang et al. (2024) showed that MPs damage kidneys and suppress innate immunity in zebrafish larvae. Zhi et al. (2024) highlighted MPs as pathogen carriers, further enhancing their immunotoxic effects. These findings reveal MPs' potential to impair fish immunity, disrupt population health, and destabilize aquatic ecosystems.

2.4. Behavioral and Neurological Impacts

Several studies report that MPs alter fish behavior and neurophysiology. Limonta et al. (2019) demonstrated that MPs cause transcriptional changes, immune suppression, and behavioral alterations in adult zebrafish. Fish exposed to MPs exhibited reduced swimming activity and increased anxiety-like behavior, indicating neurotoxicity. Wu et al. (2025) further revealed sex-specific neurotoxicity, with female zebrafish being more affected by MP exposure than males. These behavioral changes suggest potential neurological impairments, which could influence predator avoidance, foraging efficiency, and reproductive success.

2.5. Reproductive and Transgenerational Effects

Microplastic (MP) exposure significantly disrupts fish reproduction and induces transgenerational effects. Wang et al. (2025) revealed that polystyrene MPs, combined with acetochlor exposure, increase reproductive toxicity and cause transgenerational defects in zebrafish (Danio rerio), with reduced fertility and developmental abnormalities in offspring. Similarly, Sun et al. (2022) found that MPs impair male reproductive health in freshwater prawns, reducing sperm quality and causing transgenerational fertility decline. Xia et al. (2023) exhibited that polyethylene MPs reduce egg production and increase offspring mortality in loach (Paramisgurnus dabryanus), indicating cross-generational reproductive damage. However, Qiang et al. (2020) noted negligible transgenerational effects of polystyrene MPs at low concentrations in zebrafish, suggesting that MP toxicity may be dose dependent. Bhat et al. (2024) highlighted that both MPs and nanoplastics (NPs) disrupt fish fertility by inducing hormonal imbalances and reducing reproductive fitness. He and Yin (2024) further emphasized MPs' potential to compromise mammalian fertility, highlighting their broader ecological risks. These findings demonstrate that MP exposure not only impairs current fish reproductive success but also threatens future generations, potentially reducing population stability and biodiversity.

2.6. Antibiotic Resistance and Microbiome Disruption

Microplastic (MP) exposure notably promotes the distribution of antibiotic resistance genes (ARGs) in fish, posing ecological and human health risks. Li et al. (2024) demonstrated that polyvinyl chloride (PVC) MPs in aquatic environments act as carriers of pathogenic bacteria and ARGs, modifying fish gut microbiota and promoting antimicrobial resistance. Similarly, Zhang et al. (2024) found that oxytetracycline-bound MPs enable trophic transfer of ARGs in fish, triggering immune suppression and gut microbiome dysbiosis. In a metagenomic study, Zhang et al. (2022) revealed that aged MPs combined with roxithromycin exposure significantly alter gut microbiota composition in Carassius auratus, promoting ARG enrichment and reducing microbial diversity. Xie et al. (2024) highlighted the collaborative interaction between MPs, antibiotics, and ARGs in aquaculture, highlighting their shared role in rushing resistance spread. These findings underscore the ecological risks of MP pollution, as they not only accumulate contaminants but also act as vectors for antibiotic resistance, threatening both aquatic and human health.

2.7. Combined Effects with Other Pollutants

MPs interact with chemical contaminants, enhancing their toxicity. Zhang et al. (2019) demonstrated that polystyrene MPs combined with roxithromycin (an antibiotic) increased bioaccumulation and oxidative stress in red tilapia, amplifying biochemical toxicity. This synergistic effect raises concerns about the compounded risks of MPs and chemical pollutants in aquatic environments.

Microplastics (MPs) pose a significant threat to fish health and aquatic ecosystems through multiple pathways. They bioaccumulate in various tissues, causing oxidative stress, genotoxicity, and metabolic disruptions, while also inducing immune dysregulation and chronic inflammation, weakening fish defenses. MPs further impact neurological functions, altering fish behavior and triggering neurotoxicity, which reduces survival and reproductive fitness. Their reproductive effects extend across generations, impairing fertility and causing transgenerational developmental defects. Additionally, MPs facilitate the spread of antibiotic resistance genes, heightening risks to both aquatic life and human health. Their presence also amplifies the toxicity of chemical pollutants, worsening ecological damage. Collectively, these findings highlight the pervasive and multifaceted threat of MP pollution, underscoring the urgent need for monitoring, regulation, and effective mitigation strategies. These findings collectively underscore the pervasive threat of MP pollution to fish health and aquatic ecosystems, emphasizing the urgent need for monitoring, regulation, and mitigation strategies.

2.8. Mitigation Strategies

Addressing the pervasive threat of microplastic (MP) pollution in aquatic ecosystems necessitates a multi-pronged approach combining preventive, regulatory, and remedial measures. Source reduction and improved waste management are critical strategies for limiting the entry of MPs into water bodies. Regulatory policies aimed at curbing plastic production, promoting biodegradable alternatives, and reducing single-use plastics are essential (Mallik et al., 2021). Strengthening plastic recycling programs and implementing efficient waste segregation systems can significantly reduce plastic leakage into aquatic environments (Fred-Ahmadu et al., 2024).

Enhancing wastewater treatment plant (WWTP) efficiency is another vital measure. Studies have shown that existing WWTPs are major pathways for MPs entering aquatic systems, as they lack the capacity to filter out smaller plastic particles (Wu et al., 2025). Upgrading WWTPs with advanced filtration systems, such as membrane bioreactors, sand filtration, and nanotechnology-based filters, can effectively capture MPs before they are discharged into water bodies (Sampsonidis et al., 2024). In aquaculture settings, adopting sustainable practices, such as using biodegradable nets and plastic-free feed packaging, can reduce MP contamination. Regular monitoring of fish farms for MP presence is also necessary to prevent bioaccumulation in aquaculture products (Fred-Ahmadu et al., 2024). Furthermore, bioremediation technologies offer a promising solution. Recent studies highlight the potential of plastic-degrading microbial consortia and enzyme-based remediation techniques to mitigate MP pollution (Pei et al., 2025).

Raising public awareness and implementing policy interventions are equally important. Educational campaigns on the environmental impacts of MPs can encourage consumers to reduce plastic usage. Additionally, stricter enforcement of international regulations, such as the ban on microbeads in personal care products, can significantly limit MP discharge into water bodies (Hamed et al., 2021). Combining these strategies with continuous monitoring and adaptive management practices is essential to curbing MP pollution.

3. Conclusion

The reviewed studies collectively demonstrate that MP pollution poses a significant and multifaceted threat to fish health and aquatic ecosystems. MPs accumulate in various fish tissues, causing oxidative stress, genotoxicity, and metabolic disruptions (Jo et al., 2025). The immunotoxic effects of MPs weaken fish defenses, making them more susceptible to pathogens and environmental stressors (Li et al., 2024). Furthermore, MPs trigger neurological and behavioral changes, reducing fish survival and reproductive fitness (Limonta et al., 2019). The reproductive toxicity and transgenerational impacts of MPs, including developmental defects in offspring, underscore their far-reaching ecological consequences (Wang et al., 2019).

Moreover, MPs facilitate the spread of antibiotic resistance genes (ARGs), posing a dual threat to aquatic and human health (Li et al., 2024). The synergistic toxicity of MPs with chemical pollutants further amplifies their harmful effects, worsening ecological degradation (Sun et al., 2024). These findings highlight the urgent need for comprehensive MP monitoring programs, stricter pollution regulations, and the development of effective mitigation strategies.

Future Recommendations

To effectively combat MP pollution, future research and policy efforts should prioritize several key areas. Firstly, long-term ecotoxicological studies are necessary to assess the chronic impacts of MPs on fish populations, including transgenerational effects and potential evolutionary adaptations (Mallik et al., 2021). Large-scale field experiments are essential to understand the cumulative effects of MPs on aquatic food chains and ecosystem health (Hamed et al., 2021). Secondly, developing standardized protocols for MP quantification and toxicity assessment is crucial. Current studies often use varying methodologies, making cross-study comparisons difficult. Establishing standardized guidelines will enable more accurate assessments of MP contamination and its ecological impacts (Fred-Ahmadu et al., 2024). Thirdly, bioremediation and eco-friendly cleanup technologies should be further explored. Research into plastic-degrading microbial consortia and enzymes shows promise for sustainable MP removal (Pei et al., 2025). Field trials and pilot-scale applications of these technologies can help validate their effectiveness. Additionally, promoting microplastic-free aquaculture practices is essential. Developing MP-free fish feeds, adopting eco-friendly packaging, and regularly monitoring aquaculture farms for MP contamination can minimize risks to seafood safety (Fred-Ahmadu et al., 2024).

Finally, given the potential human health risks of consuming MP-contaminated fish, future studies should focus on human health risk assessments. Research on the transfer of MPs and ARGs through the food chain is necessary to understand their potential impact on human health (Li et al., 2024). By implementing these future strategies, supported by continuous monitoring and stringent regulations, the global community can mitigate the ecological and health threats posed by MP pollution in aquatic ecosystems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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