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Microplastic (MP) Pollution in Aquatic Ecosystems and Environmental Impact on Aquatic Animals

Saiprasad Bhusare [a], Sagar Gorakh Satkar [b*], Ashish Sahu [b], Bhautik Savaliya [a], Tejaswini Karale [a] and Renuka Gautam [c]

[a] ICAR-Central Institute of Fisheries Education, Mumbai- 400 061, India.
[b] Faculty of Fisheries, Kerala University of Fisheries and Ocean Studies, Panangad, Kochi, Kerala- 682506, India.
[c] Central University of Gujarat, Gandhinagar, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Microplastics found in aquatic environments worldwide, often exceed the abundance of aquatic animals. The exponential growth in synthetic plastic production and inadequate waste management practices have resulted in a significant increase in plastic waste in our aquatic environments. Consequently, microplastics, defined as particles smaller than 5 millimetres, have become pervasive in both seawater and freshwater ecosystems, emerging as a concerning new type of contaminant. Sources of microplastics in aquatic systems are diverse, with wastewater treatment plants being a primary contributor. Microplastic abundance varies widely by location, ranging from

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**Corresponding author: Email: sagarsatkar1996@gmail.com;*

over 1 million pieces per cubic meter to less than one piece in 100 cubic meters. Microplastics pose various harmful effects on humans and other organisms, primarily through entanglement and ingestion. Moreover, they serve as carriers of toxins such as industrial additives and persistent contaminants, which can lead to significant health issues for humans. Studies on fish have demonstrated the bioaccumulation of microplastics and associated toxins, resulting in intestinal damage and metabolic profile alterations. Additionally, microplastics serve as vectors of toxic substances to a range of aquatic and avian species, including invertebrates, fishes, herpetofauna, and waterfowl. Despite growing awareness and concerted efforts to address plastic pollution, the persistence and complexity of the microplastic paradox demand innovative solutions and interdisciplinary approaches. By navigating this ecological conundrum with scientific rigor, societal engagement, and collective action, we can forge a path towards a more sustainable future, where water bodies thrive free from the scourge of plastic pollution.

Keywords: Microplastics; plastic pollution; aquatic ecosystems; ecotoxicology; bioaccumulation.

1. INTRODUCTION

Microplastics are tiny plastic particles comparable in size to planktonic organisms and have been detected in water columns and sediment across aquatic ecosystems worldwide [1,2] Microplastics (MPs) are increasingly recognized as a significant environmental concern due to their potential ecotoxicological effects on aquatic ecosystems [3,4], yet only a small portion of plastics are recycled. In 2018, the world produced 400.3 million tons of plastic, but only 9% successfully recycled. This major issue is expected to worsen as plastic production is forecasted to double over the next two decades [5,6]. Although plastic has revolutionized our lives, its inability to break down naturally and recycling challenges pose serious threats to the environment [7]. Even the world's most isolated regions are infested with microplastics, which are minute pieces of plastic smaller than 5 millimetres in size. The paradox is that these tiny contaminants, which are invisible to the naked eye, negatively impact on aquatic ecosystems. This essay explores the origins, spread, and significant environmental concerns associated with microplastic pollution in water bodies. By analyzing the complexities of this issue, we aim to underscore the importance of addressing microplastics within the broader context of plastic pollution. Microplastics originate from various sources, including the breakdown of larger plastic items, the abrasion of microbeads in personal care products, and the shedding of textile fibers. Their small size makes them easily ingested and absorbed by marine life, posing a serious threat to aquatic ecosystems [8]. The consequences of this ecological intrusion are far-reaching, affecting the entire food chain and potentially endangering human health. Microplastic contamination is pervasive, extending to freshwater systems, marine environments, and even remote regions like the Arctic and Antarctic [9,10,11]. Given their ability to travel long distances via ocean currents and air transmission, addressing microplastic pollution has become a pressing global issue. Tackling this challenge requires a multidisciplinary approach, from identifying and monitoring microplastics to implementing effective waste management strategies [12]. Despite the inherent challenges, there is room for innovative solutions and collaborative efforts. Scientists, policymakers, and environmentalists are working together to develop cutting-edge filtration systems and sustainable alternatives to plastic. By raising awareness, implementing sensible policies, and promoting behavioral changes, we can mitigate the ecological impact of microplastics and safeguard the health of our precious water bodies.

2. MICROPLASTIC, TYPE AND DIFFERENT SOURCES

Microplastics are microscopic particles with a diameter of less than 5 millimetres [13]. The larger plastic products undergo fragmentation through ultraviolet exposure, oxidation, mechanical degradation, wave action, and other processes, which lead to the formation of microplastic. In aquatic water bodies, microplastics exist in two groups such as primary microplastics and secondary microplastics [14]. Primary microplastics are manufactured in small quantities for specific purposes [15]. Primary plastics are raw plastics produced directly from petrochemical feedstocks such as natural gas or crude oil. They are the building blocks for various plastic products and materials used in everyday life, ranging from packaging and bottles to toys and electronics. The manufacturing process involves polymerization, shaping, and molding to create the desired plastic items, contributing to global plastic production and consumption. Microbeads are found in personal and skin care products such as facial cleansers, toothpaste, and body wash. They are intended to exfoliate or provide texture but are too tiny to pass through wastewater treatment plants. Pellets or nurdles are small, pre-production plastic resin pellets used as raw material in the manufacture of plastic products, Accidental spills or incorrect handling during manufacture and transportation might lead to their release into bodies of water [16]. Secondary plastics refer to recycled plastics obtained from the processing of post-consumer or post-industrial plastic waste. These plastics undergo a series of sorting, cleaning, shredding, melting, and reprocessing stages to be transformed into new plastic products. Recycling secondary plastics helps reduce the reliance on virgin plastic production, conserves resources, and mitigates environmental pollution by diverting plastic waste from landfills and oceans. Secondary microplastics are the outcome of bigger plastic items degrading and fragmenting. Plastic bottles, toothbrushes, bags, packing materials, and fishing nets degrade over time due to environmental influences such as sunshine, wave action, and mechanical stress (Auta et al., 2017). These materials decompose into tiny fragments, eventually creating microplastics. Microplastics can also be formed as a result of the shedding of synthetic fibres from fabrics after washing. Polymer types vary widely in their composition and sources. Common polymers like polyethylene (PE) and polypropylene (PP) originate from petrochemical feedstocks such as natural gas and crude oil, while others like polyvinyl chloride (PVC) and polystyrene (PS) are derived from specific monomers obtained through petrochemical processes. Polyethylene terephthalate (PET), used in bottles and packaging, stems from ethylene glycol and terephthalic acid, both sourced from petroleum. Additionally, biopolymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA) are derived from renewable biomass sources like corn starch or vegetable oils, offering more sustainable alternatives to traditional petrochemical-based polymers. We can classify microplastics, based on their size **(i)**. Large microplastics of size ranging between 5 mm to 1 mm, **(ii)**. Small microplastics of 1 mm to 1 μm size range, and **(iii)** Nanoplastics of <1μm size (Crawford and Quinn, 2017).

3. FACTORS AFFECTING THE ABUNDANCE AND PERSISTENCE OF MICROPLASTICS

The abundance and persistence of microplastics in water bodies are influenced by several factors, which contribute to the continuous presence and Microplastics build up in aquatic habitats [17]. Plastic lifespan and gradual degradation: Plastics are noted for their durability and resistance to natural breakdown [18,19]. Plastics can persist for hundreds of years before decomposing into microscopic particles. Microplastics disintegrate slowly, thus they can stay in water for a long time [20]. Microplastics are widely available due to poor waste management. Littering, illegal dumping, and poor recycling facilities unleash plastic debris into waterways [21,22]. Larger plastic particles disintegrate and shatter into microplastics in the water. Mechanical stress, wave action, and UV exposure can fracture plastic bottles, bags, packing materials, and fishing gear. These environmental factors break down larger plastic goods into microplastics [23].

Microplastic contamination can come from sewage and wastewater treatment plants. Despite their best efforts, some wastewater treatment methods may miss certain microplastics [24]. Therefore, treated wastewater may still include microplastics that are deposited into waterways, increasing their abundance. Manufacturing, using, and disposing of plastic items release microplastics into the environment. Processing, packing, and manufacturing can release microplastics into the environment. Through equipment damage or improper waste management, fishing and aquaculture can also release microplastics into aquatic bodies. Boating, fishing activities, and beach trips can release microplastics into the water [20]. Recreational use of microbead-containing personal care products releases microplastics into the aquatic environment. These variables all contribute to the prevalence and permanence of microplastics in water bodies, highlighting the importance of good waste management, sustainable manufacturing practices, and focused mitigation efforts to address this ecological concern.

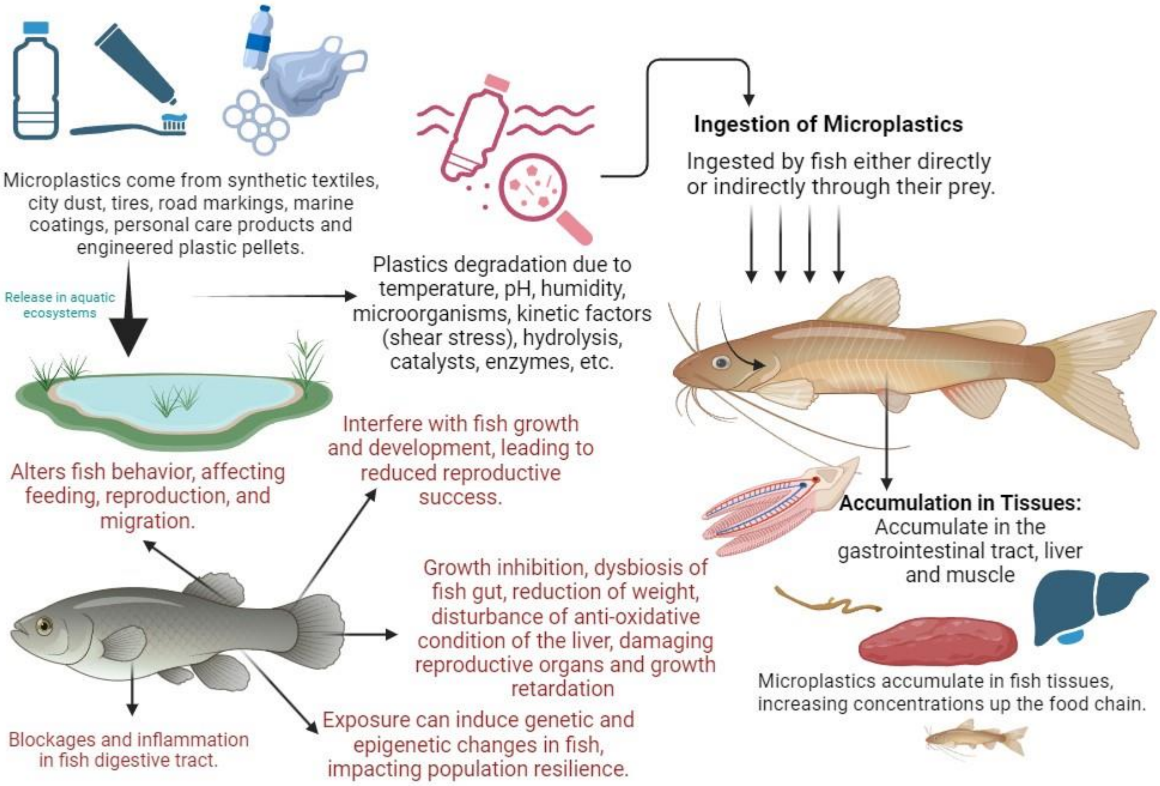

Fig. 1. Overview of microplastic and its impact on fish

Ecological Impacts of Microplastics: Microplastics have direct and indirect effects on aquatic organisms, impacting their physiology, behaviour, and overall ecological well-being. These effects can occur at various levels of the food chain and have cascading consequences throughout aquatic ecosystems [15,25,26]. Here are some key direct and indirect effects of microplastics on aquatic organisms:

Direct Effects:

i. **Ingestion:** Microplastics, also are erroneously eaten by zooplankton and bigger marine creatures [25]. These particles may seem like food or be eaten when filter-feeding. Physical obstruction from microplastics can limit feeding efficiency, malnutrition, and mortality.
ii. **Physical harm:** Microplastics can damage aquatic species' organs and tissues. Sharp or abrasive microplastic particles can induce digestive tract rips, ulcers, and inflammation, compromising organ function and health [25].
iii. **Chemical exposure:** Microplastics absorb and concentrate environmental chemicals. Ingesting microplastics may expose organisms to hazardous chemicals adsorbed on the plastic surface. Chemical exposure can cause food chain toxicity, bioaccumulation, and biomagnification (Arthur et al., 2009).

Indirect Effects:

1. **Altered behaviour:** Microplastic exposure can alter aquatic creature behaviour. Microplastics may influence fish eating, predator avoidance, and reproduction, according to certain research. Behavioural changes can alter ecological connections and cascade community dynamics [27].
2. **Biofouling and colonization:** Biofilms, algae, and other microorganisms can develop on microplastics. This biofouling effect can change microplastics' physical and chemical characteristics, influencing organism-environment interactions. It can also spread microplastics and bacteria up the food chain [28].
3. **Trophic transfer:** Transferring microplastics across the food web affects many trophic levels. Microplastics can accumulate in smaller creatures' tissues after ingestion [29]. Microplastics can

spread to higher trophic levels when predators eat these species, worsening their ecological effects.

4. **Impaired reproduction and development:** Microplastics can impair aquatic creature reproduction and growth. Microplastics affect reproductive hormones, induce embryonic defects, and impair reproductive success in fish, molluscs, and crustaceans, according to research. These factors may impact biodiversity and population dynamics [30,31].

4. PARADOXICAL RESPONSES: HARMFUL EFFECTS AND POTENTIAL BENEFITS?

When examining the ecological impacts of microplastics, paradoxical responses can arise, encompassing both harmful effects and potential benefits [32]. While the harmful effects of microplastic contamination on aquatic ecosystems have been well-documented, recent research has also highlighted certain potential benefits or unintended consequences associated with microplastics. It is important to note that the potential benefits should not overshadow the overall detrimental effects of microplastic pollution.

Harmful Effects:

i. Physical Damage: Microplastics can physically damage the organs, tissues, and digestive systems of aquatic organisms. Ingestion of microplastics can lead to internal injuries, blockages, and reduced nutrient absorption, ultimately affecting an organism's health and survival [20].
ii. Chemical Exposure: Microplastics can act as carriers of toxic substances. They can adsorb and concentrate harmful pollutants from the surrounding environment [33]. When organisms ingest microplastics, they may also be exposed to these toxic chemicals, leading to various adverse effects, including developmental abnormalities, reproductive impairments, and compromised immune systems.
iii. Disruption of Feeding and Behavior: Microplastics can disrupt the feeding behaviour and foraging efficiency of aquatic organisms. This can result in reduced food intake, altered energy allocation, and decreased overall fitness. The presence of microplastics in the environment can also alter the behaviour of organisms, affecting predator-prey interactions and ecosystem dynamics [20].
iv. Trophic Transfer and Biomagnification: As microplastics move through the food web, they can undergo biomagnification, resulting in higher concentrations in top predators. This amplifies the potentially harmful effects on these organisms and can have cascading impacts on the entire ecosystem [34].

Potential Benefits of Unintended Consequences

i. Substrate for Attachment and Colonization: Microplastics can provide additional surfaces for colonization by various microorganisms and biofilm formation [35]. This can potentially create new habitats or alter existing habitats, which may have both positive and negative effects on the composition and diversity of microbial communities.
ii. Floating Habitat and Transport: Microplastics that float on the water surface can serve as platforms for certain organisms, such as algae, bacteria, or small invertebrates [36]. They can provide a substrate for these organisms to attach and potentially disperse to new areas, although this can disrupt natural colonization patterns and introduce invasive species.
iii. Enhanced Buoyancy for Marine Organisms: In certain cases, microplastics with buoyant properties can facilitate the movement and dispersal of small organisms, such as some planktonic species [36]. This can potentially aid in their survival, reproductive success, and population dynamics, although the long-term implications are still not well understood [37].

5. ECOLOGICAL CONUNDRUM

Balancing microplastic exposure and other stressors in aquatic ecosystems

Balancing microplastic exposure with other stressors in aquatic ecosystems is a complex challenge that requires an integrated and multidisciplinary approach. Microplastics are just one of the many stressors that aquatic organisms and ecosystems face, including pollution from other sources, habitat degradation, climate change, and overfishing. Achieving a balance involves understanding the interactions and cumulative effects of these stressors and implementing strategies to minimize their combined impact [38]. Here are some considerations for achieving this balance:

i. Comprehensive Risk Assessment: Conducting comprehensive risk assessments is crucial to understanding the relative contributions and impacts of microplastics compared to other stressors in aquatic ecosystems [37]. This involves assessing the exposure levels, persistence, and toxicity of microplastics and integrating this information with data on other stressors. By prioritizing and quantifying the risks associated with different stressors, resource allocation and management strategies can be directed effectively.
ii. Pollution Control and Source Reduction: To achieve balance, efforts should focus on reducing the release of microplastics and other pollutants into aquatic environments. Implementing stringent regulations and waste management practices that target microplastic sources, such as plastic production, use, and disposal, can help minimize their input into water bodies. This requires collaboration between policymakers, industries, and consumers to promote sustainable plastic alternatives, recycling, and waste reduction.
iii. Ecosystem-Based Approaches: Implementing ecosystem-based management approaches can help address multiple stressors simultaneously. This involves considering the interactions between species, habitats, and ecosystem functions. By protecting and restoring key habitats, promoting biodiversity, and maintaining healthy ecological processes, ecosystems can be more resilient to the impacts of microplastics and other stressors [39].
iv. Integrated Monitoring Programs: Developing and implementing comprehensive monitoring programs that assess the status and trends of microplastic contamination, along with other stressors, is essential for effective management. These programs should incorporate standardized sampling methods, analytical techniques, and indicators of ecosystem health. Long-term monitoring allows for the detection of changes over time and the evaluation of the effectiveness of mitigation efforts [40].
v. Adaptive Management: Recognizing the dynamic nature of aquatic ecosystems and the uncertainties associated with managing multiple stressors, adaptive management approaches are crucial. This involves regularly reviewing and updating management strategies based on new scientific findings and monitoring data. Flexibility in adapting strategies ensures that management actions remain effective and responsive to changing conditions.
vi. Stakeholder Engagement and Collaboration: Achieving a balance requires the involvement of diverse stakeholders, including scientists, policymakers, industry representatives, local communities, and NGOs. Collaboration and knowledge-sharing among these stakeholders can lead to more informed decision-making, innovative solutions, and effective implementation of management measures [41].

Balancing microplastic exposure with other stressors in aquatic ecosystems is a complex task. It requires a holistic and integrated approach that considers the interactions and cumulative effects of multiple stressors [42]. By implementing targeted mitigation measures, promoting sustainable practices, and engaging stakeholders, it is possible to reduce the overall impacts on aquatic ecosystems and work towards a more balanced and sustainable future.

Challenges and Solutions:

Microplastic pollution in water bodies presents significant challenges, but several key strategies and solutions can help address this issue [43,44] these include:

i. **Monitoring and assessing microplastic contamination:** One of the primary challenges is accurately measuring and monitoring microplastic contamination in water bodies. This involves developing standardized sampling methods, employing advanced analytical techniques, and establishing comprehensive monitoring programs [41]. By consistently monitoring microplastic levels and distribution, scientists and policymakers can better understand the extent of the problem and track the effectiveness of mitigation efforts.

ii. **Developing effective mitigation strategies and policies**: Mitigating microplastic pollution requires the development and implementation of effective strategies and policies. This includes reducing the release of microplastics into the environment through regulations, promoting sustainable production and consumption practices, and encouraging innovation in plastic waste management [45]. Collaboration between governments, industries, and scientific communities is essential to establish comprehensive and enforceable measures.

iii. **Promoting sustainable plastic use and waste management practices:** Shifting towards sustainable plastic use and improving waste management practices are key solutions to mitigate microplastic pollution [46]. This involves reducing plastic consumption, promoting reusable alternatives, implementing effective recycling programs, and investing in innovative technologies for plastic waste treatment. By adopting a circular economy approach and minimizing plastic waste generation, the input of microplastics into water bodies can be significantly reduced [47-50].

iv. **The role of public awareness and citizen science in tackling the paradox:** Public awareness and engagement are vital in addressing the microplastic paradox. Education and outreach initiatives can raise awareness about the impacts of microplastics on the environment and human health, fostering behavioural changes at the individual level. Citizen science projects can also play a crucial role in data collection, monitoring, and research. Involving the public in scientific endeavours empowers communities and promotes a sense of responsibility and stewardship for the environment [51,52].

By combining these strategies, it is possible to tackle the challenges associated with microplastic pollution. Implementing effective monitoring, mitigation, and waste management practices, coupled with public engagement, can contribute to reducing microplastic contamination in water bodies. However, addressing the microplastic paradox requires a collective effort involving governments, industries, scientists, and individuals to foster sustainable practices and protect the health of aquatic ecosystems.

6. CONCLUSION

Navigating the Microplastic Paradox requires a comprehensive understanding of the ecological conundrum posed by microplastic pollution in water bodies. As we uncover the intricacies of this paradoxical phenomenon, it becomes evident that effective solutions require concerted efforts from scientists, policymakers, industries, and individuals. By embracing innovative approaches, raising awareness, and implementing sustainable practices, we can work towards mitigating the negative impacts of microplastics and safeguarding the health and integrity of our aquatic ecosystems.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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