

## INVISIBLE CONTAMINANTS: THE IMPACT OF MICROPLASTICS ON FRESHWATER BIODIVERSITY

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### Abstract

Microplastic have been a persistent and pervasive pollutant in freshwater systems in the past decade and are a major ecological and environmental concern. Pollutant is referred as plastic particulate matter whose size is under 5 mm in diameter, including primary pollutants such as industrial products and items in people's care and secondary pollutants that are created because massive plastic particles break down. Freshwater is another important route and sink for micro plastic; they can be dispersed more extensively through environment via rivers, lakes and streams. This paper summarizes the sources, types, routes, and environmental impacts of micro plastics in fresh water. It highlights its spatial diversification, sedimentation and role in generation of special microbial communities. The interaction with new water organisms is also considered and includes fresh water organism ingestion, trophic transfer, physiological stress, and possibly toxicity. Moreover, Microplastics act as carriers of poisonous substances and microorganisms, which only contributes to increasing its environmental contribution. The paper also reviews the current detection, quantification and removal technologies for Microplastic, including the latest analytical technologies and wastewater treatment technologies. However, all this has not yet been achieved without significant headwinds, due to the variability in approach and measurement capability it lacks for the smaller particles such as nanoplastics. Lastly, the review covers the control strategies and identifies key gaps in the research, especially in the ecological impact of the control interventions in the long term and the standardized research methods. Overall, the findings emphasize the need for an integrated approach that incorporates technological advancements, policy measures, and public education to minimize Microplastic pollution and protect freshwater ecosystems.

### Introduction

Over the last ten years, Microplastics have originated as one of the key environmental factors in the freshwater ecosystems because of their permanency and pervasive nature. Such particles are generally describe as below 5 mm in size and

are now commonly found in rivers, lakes and streams around the globe (Wagner and Lambert 2018). The fact that they are small means that they can go unnoticed as they continuously build up in water bodies (Eerkes-Medrano, Thompson et al. 2015).

The vulnerability of freshwater systems is especially high since they serve as sinks and pathways of Microplastics with a terrestrial origin (Dris, Imhof et al. 2015). Rapid urbanization, population increase, and the increasing use of plastics have greatly accelerated the discharge of Microplastics into these ecosystems (Andrady 2017). Contrary to large plastic debris, Microplastics cannot be easily cleared, and may therefore linger longer in the water and sediments (Cole 2016)..

Recent research has demonstrated that Microplastics are easily taken up by freshwater organisms, such as zooplankton, insects, and fish (Scherer, Weber et al. 2017). This consumption may result in physical obstructions, decreased feeding performance, and energy loss in aquatic organisms (Windsor, Durance et al. 2019).. Also, Microplastics are not only able to uptake harmful pollutants, including heavy metal ions and organic contaminants, but additionally function as vectors that carry these substances in the food chain network (Rochman, Brookson et al. 2019). The growing body of evidence about ecological risks related to Microplastics underscores the need to comprehend their properties, sources, and distribution in freshwater systems. This knowledge is crucial in coming up with measures to reduce their effects on aquatic life and their health to the ecosystems (Li, Song et al. 2020).

Microplastic can be generally categorized into primary and secondary types as per their way of origin which helps in determining their environmental behaviour and sources (Andrady 2017).. Industrially manufactured Microplastics are deliberately generated in a small size and are highly utilized in industrial and commercial products (Boucher and Friot 2017).. These consist of microbeads that are contained in cosmetics, cleaning agents (Fendall and Sewell 2009).

Due to their minor size, primary micro plastics can easily pass through wastewater treatment plants and enter freshwater systems. (Sun, Zhu et al. 2021). Another crucial source is industrial plastic pellets that are mostly wasted during the manufacturing and transportation processes (Boucher and Friot 2017).

Secondary Microplastics occur when bigger plastic materials like plastic containers, packaging and fishing gear decompose into secondary Microplastics. This process of fragmentation is accelerated by environmental factors like ultraviolet radioactive energy, surface erosion, and temperature fluctuations (Zhang, Zhang et al. 2020). Consequently, the secondary Microplastics are more usual in freshwater ecosystems due to the ongoing breakdown of plastic wastes (Kumar, Sharma et al. 2021).

Microplastics can be also classified according to their physical form which includes fibers, fragments, films, and beads (Eerkes-Medrano, Thompson et al. 2015). One of the most dominant forms is the fibers, primarily derived out of synthetic textiles that are released during washing (Dris, Gasperi et al. 2016). Regarding polymer composition, usual plastics are polyethylene (PE), and polystyrene (PS) with different densities and environmental characteristics (Guo and Wang 2019).

The difference in size, shape, and composition affect how Microplastics interrelate with organisms and their environments. Smaller particles have higher chances of being ingested and even penetrate biological tissues, making them potentially more toxic (Silva, Bastos et al. 2018).

#### Origins of Microplastics

Microplastics enter freshwater systems via numerous different sources, which are broadly divided into point and non-point sources (Blettler, Abrial et al. 2018). The water treatment plants for freshwater are considered as included in the largest resources of the point. Regardless of the treatment processes, a substantial amount of particles is released into rivers due to effluent discharge (Lares, Ncibi et al. 2018).

Domestic actions like washing synthetic clothes are also contributing to the pollution of Microplastics as they release microfibers into the wastewater systems (Napper and Thompson 2016). Such fibers are usually too minute to be fully removed during the treatment procedures. Pellets and fragments also enter the nearby water bodies as a direct result of industrial activities,

especially in the production of plastic (Boucher and Friot 2017).

Urban runoff, agricultural activities, as well as atmospheric deposition qualify as non-point sources. Rainfall may cause plastic waste to enter rivers. The discharge of Microplastics into the surrounding water bodies is contributed in irrigation systems in farming areas (Kumar, Sharma et al. 2021).

The atmospheric movement has also been cited as a considerable route, in which lightweight Microplastics are carried by wind and accumulated into the freshwater systems (Allen, Allen et al. 2019). When in the water body, Microplastics may either be suspended or settled in the sediment, depending on their density and size (Wagner and Lambert 2018).

The Rivers plays major roles in the transportation of Microplastics in land sources to larger bodies of water as major conduits of the global plastic cycle (Lebreton, Van Der Zwet et al. 2017). The fact that Microplastics continuously move and accumulate stresses the complexity of their distribution and the lack of control over their distribution process (Kumar, Sharma et al. 2021).

#### **Dispersion and occurrence of Microplastic in freshwater**

The original study research focused on the ocean topic but recent findings indicate that freshwater systems are now the major sources of transport and accumulation of Microplastics in the surroundings (Zhu et al., 2023).

The spatial circulation of Microplastics is also very heterogeneous, and this is due to the nature of the studied area, including the presence/absence of urbanization, industrialization, agricultural runoff, and the presence of wastewater treatment plant effluents (Bayo et al., 2023). A broad spectrum of study results has been published regarding the levels of Microplastics in freshwater ecosystems, which vary significantly based on hydrological factors and human activities (Li et al., 2024).

Global research has shown that the existence of micro plastics varies between inland water ecosystems. Fiber- and fragment-dominated Microplastics in surface water in rivers are found

in excess of 500 particles/L in the Danube, Ganges, and Yangtze (Zhu et al., 2023). The levels of particles per kg of dry sediment in Lake Sediments from Lake Geneva and Lake Taihu range from  $10^2$  to  $10^4$  particles/kg, this reflects long-term accumulation processes (Cera et al., 2022). Generally higher concentrations are found near industrialized and more populated areas and the comparatively low but detectable concentrations found in remote alpine lakes is due to atmospheric deposition (Li et al., 2024).

Freshwater sediments are important sinks, with the recent results from sediment core analyses showing that roughly 90% of the Microplastics eventually end up in benthic sediments (Rummel et al., 2024). High-density polymers like polyvinyl chloride (PVC) and polyethylene terephthalate (PET) tend to settle quickly because of their density, while low-density polymers like polyethylene (PE) and polypropylene (PP) are prone to biofouling that raises the density of particles and aids in settling (Gong et al., 2024).

Microplastics are reported to build up in aquatic sediments over long periods, and are directly affected by sediment-dwelling organisms through long-term exposure (Li et al., 2024). The relationship between sediment particles and Microplastics also affects the transport and bioavailability in benthic environments. Long-term sediment monitoring has illustrated that Microplastics are present in freshwater ecosystems and that they have impacts on these systems (Rummel et al., 2024).

Microplastics also provide a unique ecological niche that facilitates the growth of specialized microbial communities and the formation of biofilms on plastic surfaces creating a plastisphere (Wu et al., 2025). Biofilms alter the physical characteristics and environmental responses of micro-plastic in freshwater ecosystems. Besides, pathogenic microorganisms and antibiotic resistance genes (ARGs) can be present in plastisphere communities, potentially raising environmental and public health concerns (Kukkola et al., 2023).

The plastisphere also promotes microbial interactions and the exchange of genetic information between microorganisms, which may

impact microbial dynamics in freshwater systems (Wu et al., 2025). The complex interaction of synthetic materials and natural biotic processes can have a significant impact on the functioning of the ecosystem and on the transport of pollutants to aquatic systems (Bayo et al., 2023).

#### Identification and Evaluation of Microplastics

Identification and quantifying micro-plastics are essential to know the occurrence and effects of micro-plastics in the ecosystem. Traditional visual sorting techniques are also known to have high error rates of up to 70% highlighting the need for the advanced analytical approaches (Prata et al., 2023). Advanced methods offer increased sensitivity and precision in the detection of Microplastics with different sizes and polymer types (Luo et al., 2023).

InfraRed (IR) Spectroscopy, specifically FTIR spectroscopy is a popular practice for polymer assessment and recognition of Microplastics by analysis of infrared absorption spectra (Luo et al., 2023). Raman microspectroscopy is capable of providing spatial resolution that is higher than what FTIR can provide, and it is especially useful for the detection of nanoplastics and smaller particles (Xu et al., 2024).

Another important method is pyrolysis-GC-MS for measuring the overall plastic mass in environmental and biological samples (Dierkes et al., 2022).

In the environmental sample analysis and bottled water research areas, Nile Red staining has been identified as a high throughput screening method for Microplastics (Bowden et al., 2024). It is a fluorescent dye which selectively stains polymer plastics and allows for efficient visualization and detection of Microplastics. The fusion of Nile Red staining with FTIR has been effective in the identification of polymers like PS, PE, PA, etc. (Prata et al., 2023).

Although there has been significant technological progress, there are still significant challenges in the accurate quantification of Microplastics: sampling methods and reporting units are not uniform (Horton et al., 2024). Variations among studies are due to differences between surface-only and

depth-integrated sampling methods, as well as enzymatic and oxidative digestion methods (Li et al., 2024).

The nanoplastics frontier is even more difficult due to the need for specialized methods of analysis for particles under 1  $\mu\text{m}$  (Horton et al., 2024). Single Particle Inductively Coupled Plasma Mass Spectrometry (SP-ICP-MS) has been found to be a potential monitoring tool of metal doped nanoplastics and solving the “missing plastic” problem of traditional counting methods. A harmonised and robust analytical protocol for all environmental matrices thus needs to be established to achieve a comprehensive understanding of microplastic pollution (Xu et al., 2024).

#### Consumption by Freshwater Organism

Mechanical interference, chemical toxicity and biological vectoring are the types of interactions between Microplastics and freshwater organisms (Sarfraz et al., 2023). *Daphnia magna* and benthic shredders like *Gammarus pulex* are two main sources of entry of micro-plastics into aquatic food webs (O'Connor et al., 2024). Trophic magnification was confirmed by fluorescent tracking studies, which found that concentrations rise up the trophic levels to the Northern Pike *Esox lucius* (Trestrail et al., 2023).

Ingestion of Microplastics can cause digestive blockage, decrease feeding efficiency, growth suppression, and reproductive toxicity in organisms, including zooplankton and larger species of fish (Sarfraz et al., 2023). Polyethylene microplastic toxicity has been demonstrated in freshwater leeches (*Eryopdella johanssoni*) and an increase in temperature increases toxicity to *Daphnia magna* (Gong et al., 2024). These particles can reduce the amount of food consumed by organisms, requiring them to use more energy to a lower intake of nutrients (Kukkola et al., 2023).

Micro-plastics can be transferred from the lower level to the higher level of the food chain by direct ingestion or by ingesting prey that has been contaminated (O'Connor et al., 2024). This is a concern about biomagnification and possible

exposure through consumption of polluted aquatic organisms by humans (Yuan et al., 2025). In various fish species, including *Danio rerio*, the buildup of Microplastics inside the gut can lead to neuro-sensory feedback mechanisms that cause them to feel full and result in decreased appetite, growth and reproductive attainment (Trestrail et al., 2023). All such physiological impacts can have a profound influence on aquatic behavior and in resilience of ecosystem (Sarfraz et al., 2023).

In addition to physical damage, Microplastic exposure causes oxidative stress and inflammation, and effects on gene expression pattern (Trestrail et al., 2023). In freshwater benthic invertebrates, the effects of polyethylene Microplastics have been recorded to change metabolomic response, which showed potential for multigenerational impacts (Gong et al., 2024). Chronic microplastic exposure in fish (such as zebrafish). has been found to cause neurotoxicity and hepatic toxicity (Zhang et al., 2024).

#### **Chemical leaching using the Trojan Horse method**

Microplastics also operate as carriers for hydrophobic organic pollutants (HOPs), heavy metals and industrial additives (Yuan et al., 2025). Once ingested, acidic gut conditions allow for the desorption of contaminants, like Bisphenol-A, lead (Pb) and cadmium (Cd) that lead towards oxidative stress as well as on and endocrine disruption. The toxicity can be more than from Microplastics or pollutants individually (Gong et al., 2024).

Microplastics in sediments could also disrupt nutrient cycles and facilitate the creation of composite particles in aquatic environments, which may carry contaminants (Li et al., 2024).

However, recent histological findings indicates that Microplastics may enter the blood-brain barrier and suppress the activity of acetylcholinesterase (AChE), causing behavioral changes such as an inability to avoid predators and erratic swimming (Zhang et al., 2024).

#### **Physiological and Biological Impacts of Microplastics**

Microplastics enter living organisms through contaminated food, drinking water and air. These particles move the body and accumulate in tissues and organs, causes abnormal physiological activities. (Du et al., 2021). Micro plastics induce oxidative stress, inflammation, cellular toxicity, and disrupt metabolic functions in aquatic and terrestrial organisms. Smaller particles have more toxicity because they are easily able to cross biological membranes. (Amobonye et al., 2021).

Living organisms consume Microplastics through contaminated food, drinking water, and air. These particles enter the body and accumulate in tissues and organs, causing physiological activities to damage. (Vázquez & Rahman, 2021). Exposure to Microplastics can cause fish and shellfish to grow less, act strangely, have reproductive problems, and have lower immune systems. These impacts result in reduced survival in aquatic systems over time. (Yang et al., 2021).

Microplastics can also disrupt digestion by blocking the pathway to feeding and the absorption of nutrients. Consequently, organisms eat less and they use less energy to grow normally. (Vázquez & Rahman, 2021). Long contact with Microplastics results in respiratory irritation, disruption of gut flora, endocrine disruption, and inflammatory responses in humans, according to recent studies. (Amobonye et al., 2021).

#### **Microplastics as Vectors of Other Pollutants**

Microplastics are known to be carriers of toxic pollutants due to the ability of the surface to readily absorb harmful chemicals from their surrounding environments. Such chemicals are pesticides, hydrocarbons etc. (Amelia et al., 2021). Microplastics can be transported on currents and rivers far from their place of origin, polluting remote marine environments. This mobility increases the difficulties to control environmental contamination. (Guerrini et al., 2021).

Microplastics have been found to also act as surfaces for settlement of microbes, harmful bacteria and pathogens have been reported. As such, they are also biological vectors as well as chemical vectors. (Yang et al., 2021). The synergistic effects of exposure to Microplastics and toxic pollutants are often more harmful than

exposure to each pollutant separately. These interactions exacerbate oxidative stress and tissue injury. (Vázquez & Rahman, 2021).

As the plastic becomes more degraded in the environment, it absorbs more pollutants since the surface area and chemical reactivity of the plastic increases due to degradation.(Chaukura et al., 2021).

### Impacts on Ecosystem Function

Microplastics affect ecosystem function as they alter nutrient cycling, microbial diversity and energy flow through food webs. The widespread persistence of Microplastics could have detrimental impacts on ecosystem function globally. (Amobonye et al., 2021). Feeding efficiency and survival of various plankton species are reduced in the presence of Microplastics. Since plankton era plays a major role as major producers in the aquatic ecosystems any disturbance to them may also affect organisms at higher trophic levels.(Liu et al., 2021).

The presence of micro plastics in soil can modify soil composition, decrease its ability to retain moisture and interfere with normal Microbial functions. As a result, both plant development and overall soil productivity may be negatively influenced. (Chaukura et al., 2021).

Researchers further reported that the long term buildup of micro plastics contributes to environmental instability and reduces habitat diversity in contaminated areas. Delicate organisms, including fish and other small aquatic species, are particularly vulnerable to highly polluted surroundings.(Vázquez & Rahman, 2021).

Microplastics can further influence climate associated processes by disrupting the efficiency of the oceanic biological carbon cycle and limiting the storage of carbon in marine environments.(Yang et al., 2021). Due to their extremely slow breakdown process, plastic particles persist in natural environments for many year's leading to their gradual buildup in aquatic systems, sediments and biological organisms.(Amobonye et al., 2021).

The fact that Microplastics are small, comprise of various materials, and have a wide distribution has

made their removal in freshwater systems a significant challenge. Over the past few years, various physical, chemical, and biological approaches have been examined to overcome this problem (Iyare, Ouki et al. 2020).

The enhancement of wastewater treatment technologies can be regarded as one of the most widely used methods. The proportion of Microplastics that can be removed using conventional treatment plants is large, and they include such processes as sedimentation, filtration, and biological treatment (Murphy, Ewins et al. 2016).. These systems however are not entirely efficient particularly when it comes to smaller particles. Higher removal efficiencies have been demonstrated with improved treatment techniques such as membrane infiltration, swift sand filtration and dissolved air flotation in controlled conditions often exceeding 90% under controlled conditions. (Talvitie, Mikola et al. 2017).

Adsorption methods have also been identified as one of the effective ways of removing microplastic. Activated carbon, biochar, and nanomaterials are some of the materials capable of binding Microplastics and allow them to be separated with water. Such techniques have found application especially in removing small particles, which are very hard to eliminate using traditional filtration. (Sen Gupta, Mukherjee et al. 2022).

Biological approaches are a new promising field of research in recent years. In laboratory settings, some microorganisms such as bacteria and fungi have been demonstrated to be able to degrade certain types of plastics. Though still in its initial stages, this approach provides a sustainable and environmentally friendly alternative to microplastic management in the long term. (Yoshida, Hiraga et al. 2016).

The application of coagulation and flocculation processes is another innovative approach whereby the chemical is added to aggregate microplastic particles into larger clusters that can be easily removed. In the same manner, electrocoagulation methods have demonstrated the possibility to improve the efficiency of the removal process, using the electric currents to separate the particles and the water (Qin, Gong et al. 2022).

### Prevention Strategies and Control Measures

Although removal methods are significant, prevention of entry of Microplastics into freshwater systems is regarded as an efficient and sustainable way to handle the problem. The control measures are aimed at minimizing the use of plastics, enhancing waste management, and raising environmental awareness (Kumari and Kumar 2021).

Among the strategies is cutting on the manufacturing and use of single-use plastics. The policies that have been implemented to limit plastic waste include bans on plastic bags, microbe ads in cosmetics, and other disposable products (Xanthos and Walker 2017).

Enhanced waste management systems are also necessary in the prevention of plastic leaks to freshwater systems. The adequate collection, recycling, and disposal of plastic waste can greatly decrease the rate of material that ultimately breaks down to Microplastics. In new areas, it is especially crucial to fortify waste infrastructure in order to curb the problem. (Lebreton and Andrady 2019). Harnessing public awareness and behavioural change are equally important elements of prevention strategies. One way to tackle this environmental issue is to educate communities on the consequences of plastic contamination on the environment. Small steps, such as reducing plastic use, reusing, and supporting eco-friendly products, can make a big difference. (Rochman and Hoellein 2020).

Another factor in prevention is technological innovations. Indicatively, by developing washing machine filters, it will be possible to reduce the emission of microfibers by synthetic textiles. Likewise, the development of biodegradable and other materials can help reduce the use of conventional plastics (Henry, Laitala et al. 2019).

### Research Gap and Future Prospects

Although the research on Microplastics is growing, there are still several gaps in the knowledge regarding Microplastics, especially when it comes to freshwater bodies. These gaps should be addressed to build effective mitigation strategies and comprehend long-term ecological effects (Wagner and Lambert 2018).

One of the greatest limitations is that there are no standardized protocols of sampling, identification, and quantification of Microplastics. Various researchers tend to employ different methods, and it is hard to compare the findings and make the same conclusions. It is important to develop standard protocols to enhance the reliability of the data and worldwide evaluations. (Hidalgo-Ruz, Gutow et al. 2012).

Another important research gap is the data deficiency on the long-term results of Microplastics on freshwater organisms and ecosystems. While laboratory research has demonstrated negative effects, the real-world ecological effects are still not fully understood. These effects require further assessment through long-term, field-based studies. (Windsor, Durance et al. 2019). Also the aspect of Microplastics as a carrier of pollutants and pathogens should be explored further. The extent of their impact on food webs and human health is still uncertain, although scientific research has shown that microplastics can adsorb harmful chemicals and microorganisms. (Rochman, et al. 2019).

There is also very little research on the smaller particles such as nanoplastics which may be more dangerous as they can penetrate biological tissues. In fresh water systems these particles require sophisticated analytical techniques for identification and study. (Gigault, Ter Halle et al. 2018).

Further studies should also aim at developing cost effective and scalable removal technologies. Most of these approaches have shown promise in the laboratory, but their real life application is underutilized. It will be important to incorporate interdisciplinary approaches such as environmental science, engineering and policy making. Closing these research gaps overall will not only advance our knowledge of microplastic contamination but also help in the creation of effective solutions to combat the problem. (Iyare, Ouki et al. 2020).

### Conclusion

Micro plastic pollution is a major environmental concern which is rapidly changing freshwater ecosystems at different levels. As this review points out, Microplastics are not only pervasive in rivers, lakes and sediments, but are also persistent because of their resistance to degradation. They are present in freshwater due to several factors, including urbanisation, industrial discharge and poor waste management, which all contribute to their constant input into freshwater. Results reveal complex interactions of Microplastics with aquatic life. These particles are very dangerous to freshwater biodiversity, through ingestion and trophic transfer, as well as physiological and biochemical effects. Their capability to serve as carriers of toxic chemicals and pathogenic micro-organisms increases their ecological impact. Furthermore, the formation of plastisphere communities offers additional levels of interaction for microorganisms, which could change the function of ecosystems and nutrient cycles. Although several removal methods such as advanced wastewater treatment, adsorption and biological degradation have shown promising results, their extensive use has not been realized. The measures to prevent it such as limiting the use of plastics, improving the systems for collection and disposal of waste and training people on the subject seem to be more sustainable and effective in the long run.

While research in this area is growing, there remain important gaps in the literature, especially with respect to standardized detection methods, long-term ecological effects, and nanoplastics behaviour. These gaps require interdisciplinary research work and development of affordable and scalable solutions. In conclusion, the problem of micro plastic pollution in freshwater ecosystems needs an integrated approach which includes scientific studies, technological advances and policy reforms. Without immediate and coordinated countermeasures, the further build-up of Microplastics is likely to cause irreversible damage to aquatic organisms and possibly pose a risk to human health.

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