

# Microplastics as emerging pollutants: ecological insights from aquatic systems and impacts on human health – A review

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## Abstract

Micro plastics (MPs) have emerged as a significant environmental concern due to their minute size and their ability to act as vectors for toxic pollutants, including synthetic dyes, heavy metals, and organic contaminants. Their pervasive presence in aquatic systems has positioned them as a critical hazard to both aquatic ecosystems and human health. MPs exhibit diverse physical and chemical properties, with polypropylene, polyethylene, polystyrene, polyvinyl chloride, and polyethylene terephthalate being the most frequently identified polymer types in aquatic environments. This review is organized into three core sections to comprehensively address the issue of MP pollution. The first section categorizes and describes the types of MPs found in aquatic systems, their interactions with aquatic organisms, and their subsequent accumulation in the human body. The second section elucidates the deleterious effects of MPs on aquatic organisms, detailing their modes of entry, bioaccumulation, and bio-magnification within the food web. The third section focuses on remediation strategies and proposes evidence-based recommendations for mitigating MP pollution and its ecological and health impacts. By synthesizing findings from studies on MP types and their adverse effects on aquatic and human health, this review highlights the devastating effects of MPs on aquatic species, how they contaminate our food, and their dangerous influence on human health. It also integrates insights from research on interaction of MPs with human cell lines and tissues, along with advances in remediation techniques. This review underscores the urgent need for effective interventions to address microplastic pollution and its far-reaching ecological and public health implications.

**Keywords:** *Microplastics, Aquatic ecosystems, Bioaccumulation, Remediation strategies.*

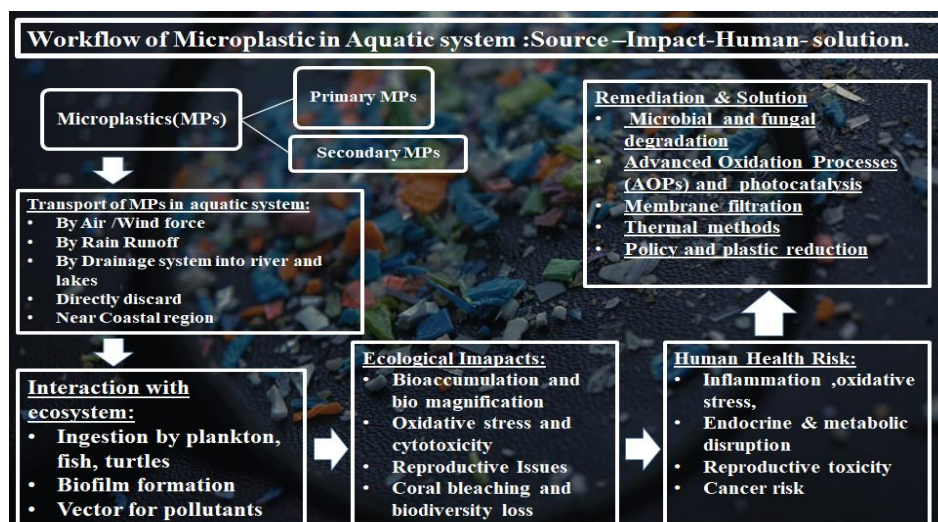


Figure 1  
Graphical abstract

## **Introduction**

The global reliance on plastics has escalated with industrial advancements, leading to pervasive environmental pollution. Among these pollutants, microplastics (MPs) have emerged as a ubiquitous contaminant in aquatic ecosystems, primarily driven by human activities and inadequate waste management (Debnath et al., 2024). MPs enter water systems through untreated waste discharge, industrial effluents, and insufficient wastewater treatment, with wastewater treatment plants retaining 68–910 MPs per liter but still discharging significant quantities (Rakib et al., 2023; Soo et al., 2021). Additionally, terrestrial sources, such as soil erosion and runoff, contribute to MP pollution, intensifying contamination in aquatic environments. MPs are classified into two categories viz. primary or secondary depending on their mode of formation. Primary MPs are intentionally manufactured at a microscopic scale, such as microbeads in cosmetics or industrial abrasives. In contrast, secondary MPs result from the breakdown of larger plastics due to UV exposure, mechanical abrasion, or environmental degradation. These particles, smaller than 5 mm, are predominantly composed of synthetic polymers, including polyethylene, polypropylene, and polystyrene (Ashrafy et al., 2023). The physical and chemical properties of MPs influence their mobility and interactions with aquatic organisms, affecting their fate in ecosystems. Aquatic organisms, including zooplankton, ingest MPs due to their bioavailability, leading to bioaccumulation and physiological damage. Retained MPs reduce energy reserves and cause inflammation, with approximately 700 aquatic species, such as sea turtles and crustaceans, documented as being affected globally (Sridharan et al., 2021; Issac & Kandasubramaniam, 2021). Microplastics have been widely recognized as an emerging threat to aquatic ecosystems and human health (Habumugisha, et al., 2024). MPs also act as vectors for pollutants like heavy metals and dyes, which adhere to their surfaces and enter aquatic food webs, amplifying toxicity through trophic transfer. This process ultimately affects humans who consume contaminated seafood or water (Debnath et al., 2024; Zhu et al., 2024). Human exposure to MPs extends beyond dietary sources, including inhalation, skin contact, and consumption of contaminated products like water, salt, and soft drinks (Kutralam-Muniasamy et al., 2023). Studies reveal MPs as small as 150  $\mu\text{m}$  can penetrate cell membranes, accumulate in organs, and cause oxidative stress, inflammation, and metabolic disruptions in animals and humans. Additionally, MPs alter cellular morphology

and disrupt gut microbiota, further highlighting their potential health risks (Zhu et al., 2024). Despite growing evidence of MPs' detrimental impacts, knowledge gaps persist regarding their long-term effects and behavior under realistic environmental conditions. Microplastic contamination in aquatic systems has been steadily rising, mirroring the increased global reliance on plastic products (Debnath et al., 2024). Addressing these challenges requires improved waste management, enhanced wastewater treatment technologies, and comprehensive research into MPs' ecological and health implications.

## **How microplastics are deteriorating aquatic health!**

Plastic particles smaller than 5 mm are known as microplastics, have emerged as a pervasive environmental pollutant with far-reaching implications for aquatic ecosystems. These contaminants come from a number of sources, including as inappropriate waste management, industrial discharge, urban runoff, and the breakdown of bigger plastics. Industrial discharge (30%) and urban runoff (25%) are among the most significant contributors to MP pollution. These sources introduce plastic fragments into freshwater and marine ecosystems, facilitating bioaccumulation in aquatic species (Soo et al., 2021). Once introduced into aquatic environments, microplastics persist due to their non-biodegradable nature and ubiquitous distribution. Their accumulation in marine and freshwater systems has detrimental consequences for aquatic organisms, ecosystems, and human livelihoods (Debnath et al., 2024). A 2016 UN study found that over 800 species suffer from plastic pollution, with ingestion and entanglement being common mechanisms (Bist and Negi, 2020; Ma et al., 2020; Hitchcock, 2020). For example, microplastics were found in 18.5% of top predators and 36.5% of pelagic and demersal fish, including tuna and swordfish, in the central Mediterranean Sea (Tursi et al., 2022). MPs accumulate in fish guts, leading to malnutrition, starvation, and death. Marine litter, primarily plastic, threatens over 4,000 marine species, with fish, seabirds, and crustaceans being the most affected. Litter impacts include ingestion (40.4%), colonization (34.3%), and entanglement (17.4%). One of the critical pathways through which microplastics harm aquatic systems is ingestion. Their small size and resemblance to natural food items often result in their consumption by a wide range of aquatic organisms, from plankton to fish and larger vertebrates. This ingestion causes physical and chemical stress, leading to

negative impacts on growth, reproduction, and survival. Additionally, microplastics act as carriers for environmental pollutants like heavy metals and persistent organic pollutants, amplifying their toxicity as they move through food chains (Gundogdu et al., 2024). The effects of microplastics are not isolated; they follow a cascading pattern through ecosystems. Once ingested by lower trophic organisms such as plankton, microplastics bio accumulate in tissues and are transferred to predators. Over time, as organisms at higher trophic levels consume prey contaminated with microplastics, these particles bio magnify, leading to higher concentrations in apex predators. Ultimately, these pollutants infiltrate human diets through seafood consumption, posing risks to human health. The widespread presence of microplastics in aquatic environments highlights an urgent need to understand their ecological consequences. By examining their effects on different organisms and the mechanisms by which they interact with ecosystems, can develop mitigation strategies to address this pressing environmental issue.

#### **Harmful effects on aquatic organisms**

Microplastics affect marine species across trophic levels, including plankton, fish, and benthic invertebrates. (Table 1) For example, *Phalacrocorax bougainvillii*, *Spheniscus humboldti*, and *Larus dominicanus* exhibit altered eating patterns and reproductive outcomes due to MP ingestion. MPs mimic prey items, leading to their ingestion by fish such as amber stripe scads and flathead grey mullet (Ma et al., 2020). The severity of microplastic impact across aquatic organisms could be understood from the fact that fish exhibit the highest vulnerability (90/100), experiencing gut blockage and metabolic stress, while mussels (85/100) and zooplankton (70/100) also show significant bioaccumulation effects. MPs impair crucial processes like development, reproduction, and immunity in marine species. Furthermore, MPs transport contaminants, facilitating bioaccumulation and energy transfer across trophic levels. In aquatic environments, MPs serve as vectors for microorganisms and pollutants, further endangering biological populations. Microplastic ingestion also leads to oxidative stress and metabolic disturbances across a range of aquatic species, compounding ecological impacts.

**Effects on invertebrates in aquatic ecosystems.** Microplastics severely threaten marine ecosystems by impacting primary producers like algae, which form the foundation of aquatic food webs. MPs reduce photosynthetic efficiency, inhibit cell growth, and cause

oxidative stress in algae (Paul et al., 2024). By adhering to algae such as *Chlorella sp.* and *Scenedesmus*, for instance, when these algae are exposed to high concentrations of microplastics, their chlorophyll content declines, impairing their ability to convert sunlight into energy. This not only disrupts algal populations but also affects the organisms that depend on them as a primary food source. Benthic invertebrates, such as mussels, clams, and crabs, are also at risk. When filter feeders like mussels ingest microplastics, the particles accumulate in their tissues, leading to inflammatory responses and physiological stress (Debnath et al., 2024). Mussels exposed to microplastics exhibit reduced energy reserves, which compromises their reproductive capabilities. In crabs and shrimp, microplastics have been linked to impaired mobility and feeding behavior, further jeopardizing their survival. Coral reefs, which are biodiversity hotspots, are also under threat. Microplastic accumulation on coral surfaces has been linked to increased rates of coral bleaching and structural damage. These impacts weaken coral resilience, making them more vulnerable to climate change and other stressors (Pantos, 2022). Given that coral reefs support over 25% of marine species, the cascading effects of microplastic pollution on these ecosystems are profound. Invertebrates like rotifers exposed to MPs show reduced fertilization and population growth rates, along with oxidative stress. Freshwater crustaceans such as *Daphnia galeata* exhibit decreased survival and reproduction when exposed to MPs. MPs damage tissues, disrupt immune responses, and alter behavior in species like *Artemia salina* and *Litopenaeus vannamei* (Contino et al., 2023; Hsieh et al., 2023). Economically significant bivalves like *Mytilus edulis* and *Crassostrea gigas* ingest MPs, leading to oxidative stress and digestive issues. MPs remain in the digestive tract of corals for extended periods, affecting pollutant toxicity and energy transfer (Debnath et al., 2024). Such disruptions at the base of the food web have long-term consequences for ecosystem stability and biodiversity.

**Effects on vertebrates in aquatic ecosystems.** Bioaccumulation of MPs occurs across taxa, including fish, reptiles, birds, and marine mammals. MPs are commonly ingested by marine creatures like turtles, which suffer from digestive system damage, reduced stomach capacity, and even death (Hawke et al., 2024; Ali et al., 2024). Fish exposed to MPs show oxidative stress, lipid peroxidation, and disruptions in metabolism and immunity (Benedetti et al., 2022). For instance, zebrafish accumulate MPs in their liver, intestines, and gills, lea-

ding to oxidative DNA damage and disrupted energy metabolism (Debnath et al., 2024). Sea turtles, known for their reliance on jellyfish as a food source, often mistake floating plastic bags and other debris for prey. This misidentification leads to the ingestion of microplastics, which obstructs their digestive systems and reduces their ability to absorb nutrients. Similarly, seabirds are at high risk, as microplastics are often found in the stomachs of species like albatrosses and puffins. The ingestion of these particles reduces stomach capacity, leading to starvation and decreased reproductive success (Ali et al., 2024). The biomagnification of MPs through aquatic food webs creates significant risks for human health. Marine mammals, such as dolphins and whales, are also impacted. For instance, stranded whales often show significant amounts of microplastics in their stomachs during necropsies. These findings highlight the pervasive nature of microplastic pollution and its effects on apex predators in marine ecosystems (Tursi et al., 2022). Freshwater fish like roach exhibit behavioral changes, intestinal inflammation, and altered gene expression after ingesting MPs. Studies on fish from Turkish waters revealed widespread MP contamination, with polymers like polypropylene and polyethylene being most common (Alak et al., 2022). MPs also affect bees, which transport them along with other pollutants, further amplifying ecological risks (Kadac-Czapska et al., 2024). The organism list is summarized in Table 1.

**Microplastics as vectors for pollutants in aquatic environment.** As carriers for other environmental pollutants, microplastics worsen ecological devastation in addition to their direct effects. Because of their hydrophobic properties and high surface area-to-volume ratio, microplastics can easily absorb harmful substances from nearby water, including heavy metals and persistent organic pollutants (POPs) (Torres et al., 2021). These pollutants, which might otherwise degrade or disperse, remain bound to microplastics and are transported through aquatic systems. The ingestion of microplastics loaded with pollutants has severe consequences for aquatic organisms. For instance, heavy metals such as mercury and cadmium are often found attached to microplastics. These toxic elements accumulate in the tissues of aquatic species, causing oxidative stress, immune suppression, and developmental abnormalities. In freshwater ecosystems, bivalves like *Corbicula fluminea* have been shown to accumulate both microplastics and associated heavy metals, highlighting the dual threat posed by these pol-

lutants. The implications of microplastic-mediated pollutant transfer extend beyond individual organisms. When contaminated species are consumed by predators, the associated toxins biomagnified through the food web, impacting higher trophic levels, including humans. For example, studies in Turkish coastal waters have found high levels of microplastics in commercially important fish species such as anchovies and mackerel (Alak et al., 2022). Recent studies indicate significant morphological and physiological alterations in marine species due to microplastics exposure (Paul et al., 2025). This contamination raises concerns about seafood safety and underscores the need for stricter regulations on plastic waste management. Updated findings highlight microplastic accumulation and associated toxicity in a range of aquatic animals (Khanjani et al., 2025).

#### **Broader ecological and economic implications**

The ecological consequences of microplastic pollution are deeply intertwined with economic and social concerns. Fisheries, aquaculture, and tourism industries rely heavily on the health of aquatic ecosystems. The degradation of coral reefs, loss of biodiversity, and contamination of seafood directly threaten these sectors. According to estimates by the United Nations, the global cost of marine plastic pollution, including microplastics, exceeds \$13 billion annually (Bist & Negi, 2020). Additionally, the impacts of microplastics are not limited to marine environments. Freshwater systems, including rivers and lakes, act as conduits for microplastics to enter oceans. In these systems, microplastics disrupt ecosystem services such as water purification and nutrient cycling. This highlights the need for integrated approaches to tackle microplastic pollution across terrestrial, freshwater, and marine environments.

#### **How microplastics affect human health**

Microplastics are becoming an alarming environmental issue, infiltrating ecosystems and human lives alike. They are pervasive in daily-use items such as drinking water, bottled water, seafood, salt, sugar and milk. These particles are inadvertently consumed in significant quantities; Europeans, for instance, ingest approximately 11,000 microplastic particles annually through shellfish consumption alone. More broadly, it is estimated that the average person consumes between 39,000 - 52,000 plastic particles per year, depending on their dietary habits Figure 3 (Li et al., 2023; Mao et al., 2022). Shellfish and other marine organisms are parti-

**Table 1.** Impact of different types of MPs on Aquatic Organism (PE – Polyethylene; PS – Polystyrene; PET – Polyethylene Terephthalate; PP – Polypropylene; PVC – Polyvinyl Chloride; PA – Polyamide)

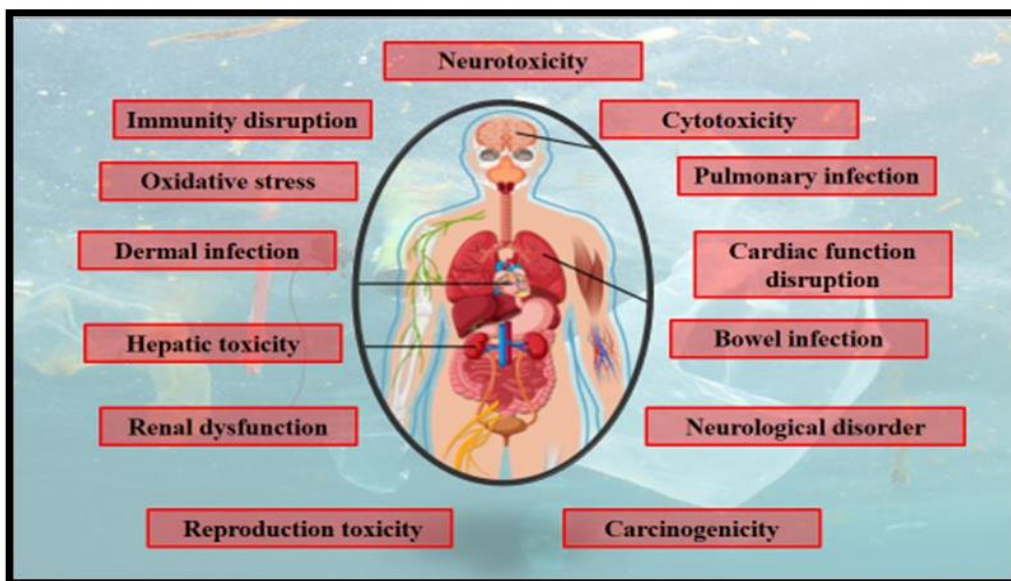
S. No.	Microorganism name	Type of MPs	Family and Classification	Impact on Organism	References
<b>A. Marine Species</b>					
1.	Artemia parthenogenetica	PS	Artemiidae (Crustacean)	Growth and Survival rate decreased	Arat, 2024
2.	Isochrysis galbana		Isochrysidaceae (Algae)	Increase mortality	
3.	Goniopora columna	PE	Poritidae (Coral)	Reduced polyp length	
4.	Lepidochelys olivacea	PP	Cheloniidae (Turtle)	Digestion problem	
5.	Skeletonema costatum		Thalassiosiraceae (Algae)	Decrease in photosynthesis ability	
6.	Artemia franciscana	PS	Artemiidae (Crustacean)	Increased acetylcholinesterase and propionyl-cholinesterase enzyme activity	Benedetti et al., 2022
7.	Ostrea edulis	PP, PE	Ostreidae (Bivalve)	Obstruct the filtering mechanisms	Bhuyan et al., 2022
8.	Artemia salina	PS	Artemiidae (Crustacean)	Lethal effect	Contino et al., 2023
9.	Amphibalanus amphitrite	PET	Balanidae (Barnacle)	Blockage of digestive tract	Debnath et al., 2024
10.	Mytilus		Mytilidae (Bivalve)	Increased ROS	
11.	Brachionus koreanus	PS	Brachionidae (Rotifer)	Inhibition of multiple resistance to p-glycoproteins	
12.	Forsterygion capito	PE	Tripterygiidae (Fish)	Increased stress and ROS	
13.	Tigriopus koreanus	PS	Harpacticidae (Copepod)	Increased energy loss	Huang et al., 2021
14.	Chaetoceros neogracile		Chaetocerotaceae (Algae)	Reduced secretion extracellular polysaccharides	
15.	Cyprinodon variegatus	PS	Cyprinodontidae (Fish)	Oxidative stress	Khan et al., 2023
16.	Heterostegina depressa	PS	Nummulitidae (Foraminifera)		Li et al., 2023
17.	Dicentrarchus labrax	PP, PS, PE	Moronidae (Fish)	Hepatic accumulation and oxidative stress	Li et al., 2024
18.	Mugilogobius abei	PE, PS	Gobiidae (Fish)	Decreased cell growth rate	Mao et al., 2022
19.	Balaenoptera physalus	PS, PE, PP	Balaenopteridae (Mammal)	Disrupt the filtering mechanisms	Paul et al., 2024
20.	Chlamys farreri	PS	Pectinidae (Bivalve)	Disturbed gills function	Raju et al., 2022
21.	Sargassum ilicifolium	PP, PS	Sargassaceae (Algae)	Decreased Phosynthesis	
22.	Brachionus plicatilis	PS,	Brachionidae (Rotifer)	Obstruct reproductive mechanisms	Seong et al., 2024
<b>B. Freshwater Species</b>					
1.	Xiphias gladius, Thunnus thynnus and Thunnus alalunga	PE, PS, PET	Scombridae (Fish)	Digestion tract problem	Alak et al., 2022
2.	Danio rerio	PE, PP, PVC, PA	Cyprinidae (Fish)	Intestinal damage	Aranda et al., 2024
3.	Gambusia holbrooki	PE	Poeciliidae (Fish)	Increased antioxidant enzymes	
4.	Oryzias latipes		Adrianichthyidae (Fish)	Liver stress	
5.	Pimephales promelas	PS	Cyprinidae (Fish)	Increased ROS	
6.	Chlorella vulgaris	PVC	Chlorellaceae (Algae)	Inhibit growth	Arat, 2024
7.	Daphnia magna	PET	Daphniidae (Crustacean)	Increased mortality	Debnath et al., 2024
8.	Rutilus rutilus	PE, PS	Cyprinidae (Fish)	Alterations in immunity, reproduction	
9.	Corbicula fluminea		Cyrenidae (Bivalve)	Inhibition of cholinesterase enzyme activity	
10.	Danio rerio	PE	Cyprinidae (Fish)	Oxidative Stress	
11.	Daphnia galeata		Daphniidae (Crustacean)	Decreased survival rate	
12.	Chlorella sp.	PS	Chlorellaceae (Algae)	Reduced photosynthesis efficiency	

cularly problematic for human health because they accumulate microplastics. Once ingested, these particles can penetrate human tissues and cells due to their small size, potentially causing significant health risks. While many microplastics are expelled from the body through feces, some have been detected in critical organs such as the lungs, placenta, and bloodstream, raising concerns about long-term health impacts (Zhang et al., 2024). Microplastic transfer through the aquatic food chain follows a stepwise accumulation pattern. Starting from primary consumers like plankton (5 units), MPs progressively concentrate in higher trophic levels, reaching alarming levels in humans (80 units), and increasing potential health risks (Zhu et al., 2024).

**Microplastics as carriers of toxic pollutants**

Microplastics not only pose direct physical risks but also act as carriers for other harmful pollutants, such as heavy metals, pesticides, and persistent organic pollutants. These pollutants, absorbed into microplastics

from the environment, have been linked to many human health issues, including obesity, diabetes, cancer, hormonal imbalances, cardiovascular diseases, and reproductive disorders (Senathirajah et al., 2020; Tang et al., 2021). Ecotoxicological studies suggest that microplastics impair feeding, growth, and reproduction in aquatic organisms across trophic levels. Importantly, they also act as vectors for persistent organic pollutants and heavy metals, increasing bioaccumulation and biomagnification risks (Laforsch & Imhof, et al., 2016). Consuming these harmful particles can cause oxidative stress, inflammation, disturbance of the gut microbiota, and even damage to DNA. Concerns regarding the possible hazards to human health are raised by the environmental microplastics' pervasiveness. However, the exact concentrations of MPs in seafood remain unclear, and the health impact of consuming contaminated seafood is uncertain. MPs can affect human health directly by causing physical stress or indirectly by carrying harmful environmental pollutants. The harmful impact of MPs illustrated in Figure 2.



**Figure 2**  
Effect of microplastic pollution on human body

**Effects on human cells: insights from *In Vitro* studies**

Extensive laboratory studies have shed light on the detrimental effects of microplastics on human cell lines. For example, research on human intestinal cells (HRT-18) and murine epithelial cells (CMT-93) has revealed that exposure to polystyrene microplastics induces inflammation and oxidative stress (Mattioda et al., 2023). Similarly, kidney and liver cells exposed to polystyrene microplastics showed elevated levels of reactive oxygen species (ROS) and reduced activity of an-

tioxidant enzymes, impairing the body's ability to combat oxidative stress (Goodman et al., 2022). Prolonged exposure further exacerbates these effects, causing mitochondrial dysfunction and long-term cellular damage. The gastrointestinal system appears to be particularly vulnerable. Studies on human colorectal cells (Caco-2 and HT-29) have shown decreased cell vitality and increased oxidative stress when exposed to polyethylene microplastics (Herrala et al., 2023). Similarly, skin squamous carcinoma cells exposed to polyethylene microplastics exhibited enhanced cancer cell

growth, while the growth of normal skin cells was inhibited (Wang et al., 2023). Other studies have demonstrated that microplastics alter cell signaling pathways, potentially leading to chronic inflammation and tissue damage. One alarming finding is the potential link between microplastics and cancer. Research suggests that microplastics may act as covert promoters of tumor growth by enhancing cell migration and encouraging metastasis, particularly in colorectal cancer cells. Furthermore, exposure to polypropylene microplastics has been associated with increased pro-inflammatory cytokine production, indicating heightened immune system activation.

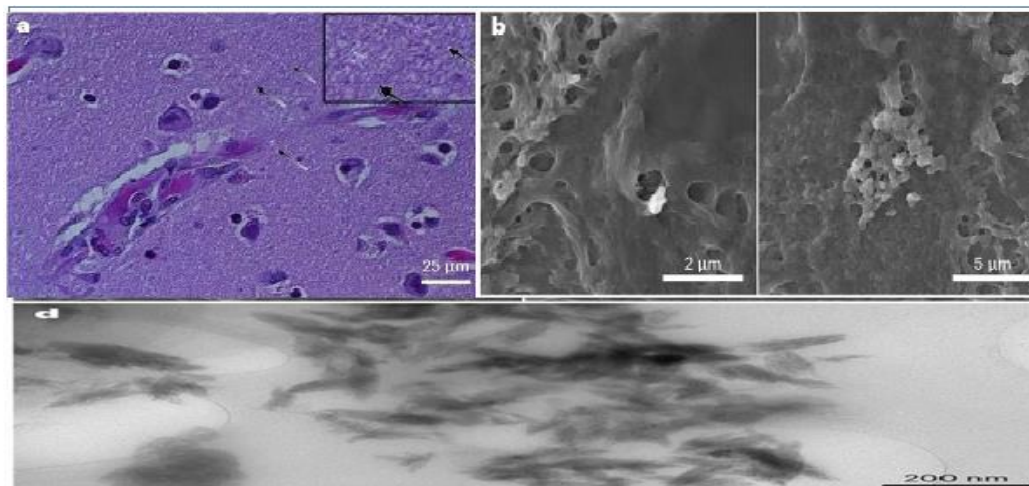
### ***In Vivo* studies: real-world implications**

Microplastics are not just theoretical hazards; they have been detected in human bodily fluids such as blood, urine, and even the placenta. Studies have identified microplastics in fecal samples, with concentrations ranging from 3.33 to 13.99 micrograms per gram of feces in individuals from coastal and highland regions (Wibowo et al., 2021). Microplastics in urine samples have also been documented, with polyethylene vinyl acetate, polypropylene, and polyvinyl chloride being the most common types. This widespread contamination suggests that microplastics are entering the human body through multiple routes, including food, water, and air. Alarmingly, microplastics have been found in 50% of analyzed blood samples, with the most common types being polyethylene terephthalate (PET), polystyrene (PS), and polyethylene (PE) (Kadaczapska et al., 2024). These particles can travel through the bloodstream, potentially accumulating in organs such as the liver and kidneys. For example, oral exposure to microplastics has been shown to cause bioaccumulation in the kidneys of mice, leading to renal impairment (Yang et al., 2022).

***Impact on the endocrine system.*** Microplastics often contain endocrine-disrupting chemicals (EDCs), such as bisphenol A (BPA), which can mimic hormones and disrupt normal bodily functions. High levels of BPA in human urine have been linked to reduced ovarian response, impaired blastocyst formation, and low birth weight in offspring. Additionally, chronic exposure to obesogens - substances that promote fat accumulation - has been implicated in the global obesity epidemic. These substances, including microplastics, affect energy balance and lipid metabolism, increasing the risk of metabolic disorders (Kannan and Vimalkumar, 2021).

### ***Neurotoxicity of microplastics*** (Nihart et al., 2025).

Recent research published in *Nature Medicine*, has highlighted the presence of microplastics and nanoplastics (MNPs) in human brain tissues (Fig. 2), raising concerns about their potential neurotoxic effects. Studies show that MNPs can cross the blood-brain barrier and accumulate in neural tissues, where they may contribute to oxidative stress, neuroinflammation, and cellular damage. These effects are particularly concerning given their potential links to neurodegenerative conditions such as dementia. The plastic fragments were detected in cerebrovascular walls and immune cells, indicating a potential role in neuro-inflammatory processes. Given the increasing environmental prevalence of microplastics, their presence in human tissues is a growing public health concern. As MNP exposure continues to rise, addressing its neurotoxic potential through further research, stricter regulations, and improved waste management practices is crucial. Understanding the pathways of MNP entry into the brain will help develop strategies to mitigate their impact, complementing broader discussions on respiratory and reproductive health risks associated with microplastic exposure.



**Figure 3**  
*Different microscopy techniques (Polarization wave microscopy (PWM), SEM and EM) were used to study the presence of MPs in human brain. Image adapted from Nihart et al., 2025.*

**Respiratory and reproductive health risks.** Microplastics also pose risks to respiratory health. Studies have detected microplastics in lung tissues and sputum samples, suggesting inhalation as a major exposure route. Workers in industries such as textiles and plastic manufacturing are particularly vulnerable, with higher rates of interstitial lung diseases and airway disorders reported. Chronic inhalation of microplastics can lead to oxidative stress, gene mutations, and inflammatory responses, which may exacerbate pre-existing respiratory conditions (Huang et al., 2022). Reproductive health is another area of concern. Microplastics have been found in the placentas of pregnant women, with potential implications for fetal development. Studies on mice have shown that microplastic ingestion reduces sperm count and alters testicular function. Additionally, exposure to microplastics during pregnancy has been linked to low birth weights and hormonal imbalances in offspring.

#### Emerging evidence and future research

While existing research highlights the alarming health risks posed by microplastics, many questions remain unanswered. The exact mechanisms by which microplastics cause cellular and tissue damage are not fully understood, nor are the long-term effects of chronic exposure. More research is needed to clarify these mechanisms and develop strategies to mitigate microplastic pollution. One promising area of investigation is the role of the gut microbiome in microplastic degradation. Recent studies have identified genes encoding plastic-degrading enzymes in gut bacteria, suggesting an adaptive response to microplastic contamination (Nugraha et al., 2022). However, the health implications of these adaptations remain unclear.

#### Remediation techniques

##### Microbial degradation of microplastics

Microbial degradation offers a sustainable and cost-effective way to tackle microplastic (MP) pollution. Microorganisms like bacteria and fungi utilize plastics as sources of carbon and nitrogen for growth. However, degradation rates are generally slow, with weight loss ranging from 1–10% over 30 days to a year (Roager and Sonnenschein, 2019). One noteworthy exception is *Ideonella sakaiensis* 201-F6, which nearly entirely broke down PET at 30°C in just six weeks (Hu et al., 2021). Various bacteria, such as *Psychrobacter*, *Shewanella*, *Moritella*, and *Pseudomonas*, have demonstrated the ability to degrade MPs (Gola et al., 2021). Similarly, fungi release enzymes capable of breaking down petro-

leum-based plastics like LDPE, HDPE, PP, and PVC (Zoppas et al., 2023). Fungi's adaptability and enzymatic capabilities make them valuable for MP degradation. As shown in Figure 2D, filtration techniques offer the highest removal efficiency (90%), followed by advanced oxidation (85%). In contrast, microbial degradation, while sustainable, remains slower and less effective (65%) in large-scale applications (Hu et al., 2021).

##### Advanced Oxidation Processes (AOPs)

AOPs, particularly photo-catalytic degradation, are energy-efficient methods for breaking down MPs in water. Semiconductor photo-catalysts like TiO<sub>2</sub> and ZnO generate reactive oxygen species (ROS) under light, leading to polymer chain rupture and mineralization into CO<sub>2</sub> and water (Zhang et al., 2024). For instance, PS and phenol formaldehyde resins degrade more readily than PE due to the presence of benzene rings (Sacco et al., 2023). Solid-phase photo-catalysis employs materials like TiO<sub>2</sub> nanoparticles, palladium, and carbon nanotubes to enhance degradation efficiency. Palladium nanoparticles improve visible light absorption, while carbon nanotubes and manganese oxide facilitate PE degradation (Hu et al., 2021; Sacco et al., 2024). Despite advancements, studies on MP degradation in water remain limited. Fenton and Fenton-like processes use peroxides to generate ROS, which effectively oxidize MPs. For instance, hydrothermal-coupled Fenton systems achieved a 95.9% weight loss of polyethylene within 16 hours (Hu et al., 2021). However, optimizing reaction temperatures and reducing energy consumption remain key challenges.

##### Thermal processes

Thermal methods like pyrolysis, gasification, and catalytic cracking are widely used to process plastic waste into valuable products. Pyrolysis, for example, produces up to 80% liquid oil at 500°C, alongside other byproducts like gas and char (Hu et al., 2021). Adjusting parameters like temperature and catalyst type allows for flexible output customization. Additionally, thermal treatment enables the conversion of plastic waste into advanced materials like carbon nanotubes, which have diverse applications due to their exceptional properties. However, industrial-scale implementation faces challenges, including energy demands and the effects of contaminants. These limitations have spurred interest in bioremediation as a more sustainable alternative.

##### Other methods

Membrane separation technology is an effective and

sustainable method for removing MPs from wastewater. Processes like reverse osmosis, nanofiltration, ultrafiltration, and microfiltration ensure high selectivity, enabling the removal of organic pollutants and disinfection byproducts (Shen et al., 2020). These technologies are commonly employed in secondary or tertiary stages of wastewater treatment or combined with biological processes. Studies show that membrane technology effectively eliminates MPs, offering a reliable solution for water purification (Reddy and Nair et al., 2022; Hu et al., 2021).

### **Future prospects and recommendations**

Most current research on microplastics (MPs) has centered on their impact on fish and aquatic organisms, but there is an urgent need to expand this scope to include other species, particularly invertebrates. Additionally, further studies are essential to understand how the unique properties of plastics influence feeding behaviors and ecological dynamics across different populations.

***Simplified degradation processes.*** Degradation of MPs often requires extreme conditions, such as high temperatures or strong alkaline solutions, which demand significant energy input and pose risks to reactor systems. To address this, research should focus on milder and more practical methods, including advanced oxidation processes (AOPs) like ozonation, sonication, and integrated techniques involving thermal, photocatalysis, and peroxide-based systems. For instance, some Fenton and Fenton-like systems have shown promise in decomposing MPs efficiently and sustainably.

***Reutilization of plastics.*** Future research must evaluate the efficiency of converting plastics into valuable products such as carbon nanotubes, methane (CH<sub>4</sub>), and hydrogen (H<sub>2</sub>). Understanding the hydrogen/carbon reutilization potential of plastics will shed light on the economic feasibility, technological applications, and carbon emission reductions of these processes.

***Reducing plastic dependency.*** A global shift toward reducing plastic reliance and improving the management of plastic and microplastic waste is crucial. Stringent measures must be implemented to minimize the plastic waste that ends up polluting aquatic environments.

***Enforcing regulations.*** Comprehensive and immediate policies are needed to address microplastic contamination. Current wastewater treatment processes lack

global mandates for microplastic elimination. This policy gap may stem from limited awareness about the dangers posed by MPs. Clear guidelines and regulations are necessary to ensure uniform action, particularly at the consumer level, where microplastic production begins.

***Innovative solutions.*** Efforts should focus on developing new technologies to prevent microplastic generation. For example, converting plastics into value-added products like adipic acid - a precursor for bioplastics - has shown promise in recent studies. Valenzuela-Ortega et al. (2023) demonstrated the use of *E. coli* to convert polyethylene terephthalate into adipic acid, offering an eco-friendly alternative for addressing plastic waste.

***Advanced removal techniques.*** To address existing and future microplastic contamination in aquatic systems, nanomaterial-based electrocoagulation methods need further exploration and optimization.

***Bioremediation efforts.*** Harnessing naturally occurring microorganisms or algae in the environment could pave the way for sustainable, eco-friendly bioremediation technologies to combat microplastic pollution.

### **Conclusions**

Microplastics (MPs) are an emerging contaminant found in water and aquatic ecosystems, posing both scientific and societal challenges. Due to their physico-chemical properties, plastics degrade slowly, leading to their accumulation in aquatic environments and the subsequent generation of MPs. This raises significant concerns about their toxicity and ecological impacts. MPs absorb pollutants from water, further amplifying their harmful effects on aquatic ecosystems. Their origins, toxicity, and impact on marine and freshwater life have been extensively studied, along with potential management and remediation strategies. However, only humans are responsible for introducing MPs into waterways. Urban rivers, marine environments, deep-sea sediments, and even Polar Regions are now contaminated with MPs, highlighting the global scale of this issue. When ingested by aquatic organisms, MPs can cause toxicity and physical harm. As these pollutants move up the food chain through marine food consumption, they also pose risks to human health, with links to cancer, oxidative stress, and immune dysfunction being increasingly evident. The rapid growth in plastic production and the resulting increase in plastic and MP waste exacerbate this global environmental crisis. MPs are particularly concerning due to their small size, high abundance, and potential to be consumed by organisms

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across the food chain, from plankton to humans. When ingested, plastic particles and the chemical additives they carry can lead to physical and nutritional imbalances in these organisms. This review underscores the critical need to address microplastic pollution. From its impact on aquatic life to its eventual transfer to humans, MPs represent a pressing environmental and public health issue that demands urgent attention through innovation, regulation, and global collaboration.

### Author contribution

M.K. Bhardwaj: Data curation, Writing- Original draft preparation, Writing- Reviewing and Editing – H. Kumar: Conceptualization, Methodology - N.A. Khan: Visualization, Investigation, Supervision - S.K. Goyal: Formal analysis. M.K. Bhardwaj and H. Kumar has equal contribution.

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