

Microplastics in Aquatic Environments: A Growing Concern

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Abstract

The increasing occurrence of microplastics in aquatic environments is an overwhelming global concern. Microplastics are tiny plastic particles that endanger both live of flora and fauna and human health. In general, microplastics originate from the disintegration of plastic waste, industrial processes, residential items or wastewater treatment plants. Once they enter waterways, these chemicals are frequently eaten by marine animals, which can absorb them and potentially cause ill health effects higher up the food chain. Technical restrictions still exist in assessing the ecological toxicity risk of microplastics. To clog these layers, this paper examines microplastic sources in detail to aquatic environments, their transport, pollution in the environment and health, relevant international policy interventions, and methods for reducing plastic loads from non-point sources in the freshwater ecosystem.

1. Introduction

Microplastics (MPs) are small size (<5 mm) plastic particle and has considered as one of the major environmental problems due to their long existence in the environment, and wide spread distribution in aquatic systems on a global scale. The US National Oceanic and Atmospheric Administration (NOAA) first found these particles in ocean water in the 1970s. Microplastics - small plastic fragments less than 5 mm in size. The problems stem primarily from the improper management of plastic materials during the processes of their manufacture and disposal. Their occurrence in water ecosystems from the surface water to bottom sediments is ecologically disruptive and poses significant health risks to humans (Mithun et al., 2024). In recent times, the lower costs of their consumption have caused increased manufacturing and consumption. Consequently, vast amounts of synthetic plastic polymers are carelessly and irreversibly littered without recycling in land and water ecosystems. The World Economic Forum reported in 2016 that more than 150 million tons of plastic waste is accumulating in these ecosystems and brought to the world's attention the alarming level of plastic pollution in water ecosystems (Witczak et al., 2024). Tackling the issue of plastic pollution in water ecosystems is challenging because plastic waste is cheap to produce and very durable, leading to a devastating plastic waste problem. Plastic objects are estimated to constitute over 75% of contaminants found in marine environments, an alarming categorization given their sustainability and resistance to decay (S.Ali et al., 2024). The Lancet Planetary Health (2017) cites a 2015 study which determined 6300 tons of plastic waste were produced, of which 9% was recycled, 12% incinerated, and 79% either landfilled or left in the environment (Vivekanand et al., 2021). While plastics appear crucial to human

development, the Mediterranean Sea has, unfortunately, become one of the plastic and microplastic pollution hotspots. Advanced projections indicate the number could grow to 11 billion tons of plastic waste pollution in land and water ecosystems by 2025. Moreover, microplastics can act as a sponge for other pollutants making considerable damage to ecosystems on land and in water (S.Ali et al., 2024). Microplastics pollutants are accessible anywhere in the world, increasingly infiltrating different environments as the result of different forms of plastics products. Due to the manufacturing of items, humans are faced on endless encounters of products that are low costing and too durable. At the moment, microplastics are reckoned as one of the most fiercely persistent pollutants that poses a great danger on many forms of life. These synthetic contaminants are arising the fear of specialists and environment protectors with their enormous spread. They are encountered in great numbers in the oceans too, as well as on all forms of fresh water, land, and the even the most far separated regions of the world (S.Ali et al., 2024). Primary Microplastics (MPs) are generated from personal care products and cosmetology, while secondary MPs are created through the breakdown of larger plastics via UV, heat, physical, or biological processes. The lightness and resilient characteristic of MPs allows them to spread wide. For instance, rivers are estimated to 70-80% of the plastic waste released in the ocean. MPs in different forms and densities are consumed by most organisms from plankton to large mammals and become part of the different resource levels in the aquatic ecosystem. Many species are unable to distinguish MPs from food which leads to stunted growth, reproductive problems, and neurotoxicity which is very harmful. The harmful impacts are more severe when MPs are further degraded into nanoplastics. Microplastics, is one of the forms of plastic that is detrimental to the ecosystem (Vanapalli et al., 2021).

2. Microplastics

Plastics are synthetic polymers appreciated for their versatility and ability to be molded into different forms. They include long chains of molecules comprising carbon, hydrogen, oxygen, silicon, and chlorine, which are usually obtained from fossil fuels, natural gas, petroleum, and coal. The synthetic plastics PE, PP, PS, PET, PVC, LDPE, and HDPE are the most produced and constitute almost 90% of the plastics produced worldwide.

Because of their lightweight nature, durability, corrosion resistance, cost-effectiveness, and electrical and thermal insulating properties, plastics are utilized in a variety of industries and sectors. The production of plastics in 1950 was around 1.5 million tons, while in 2015 it surged to approximately 322 million tons.

However, the disposal of plastics continues to be a large environmental issue. With the aid of environmental factors, a significant amount of waste plastic becomes tiny fragments between meters and micrometers in size. These microplastics, defined as particles of plastic smaller than 5 mm, are extremely persistent. Microplastics can be classified into different categories based on their size, shape, and chemical composition (Chatterjee and Sharma, 2019).

3. Types of microplastics

Microplastics can be categorized into two types based on their origin: primary and secondary microplastics.

Primary microplastics are manufactured intentionally as small particles of synthetic polymers for use in sandblasting, maintaining plastic products, chemical formulations, and in the making of synthetic fabrics. Microbeads are a form of primary microplastics, being made of PE, PP, or PS based microplastics, and are less than 2 mm in size. Microbeads are commonly used in personal care and cosmetic products.

Secondary microplastics, on the contrary, are the result of smaller plastic debris (macro or mesoplastics) due to environmental processes of biodegradation, photodegradation, thermal degradation, thermo oxidative degradation, and hydrolysis.

Furthermore, even more diminutive particles, nanoplastics, less than 1 micrometer in diameter, are likely a result of further degradation. For both microplastics and nanoplastics, their great surface area to volume ratio makes them prone to act as a carrier to contaminants and hazardous substances, thus posing a serious threat to bioaccumulation and biomagnification in the living organisms. (Chatterjee and Sharma, 2019).

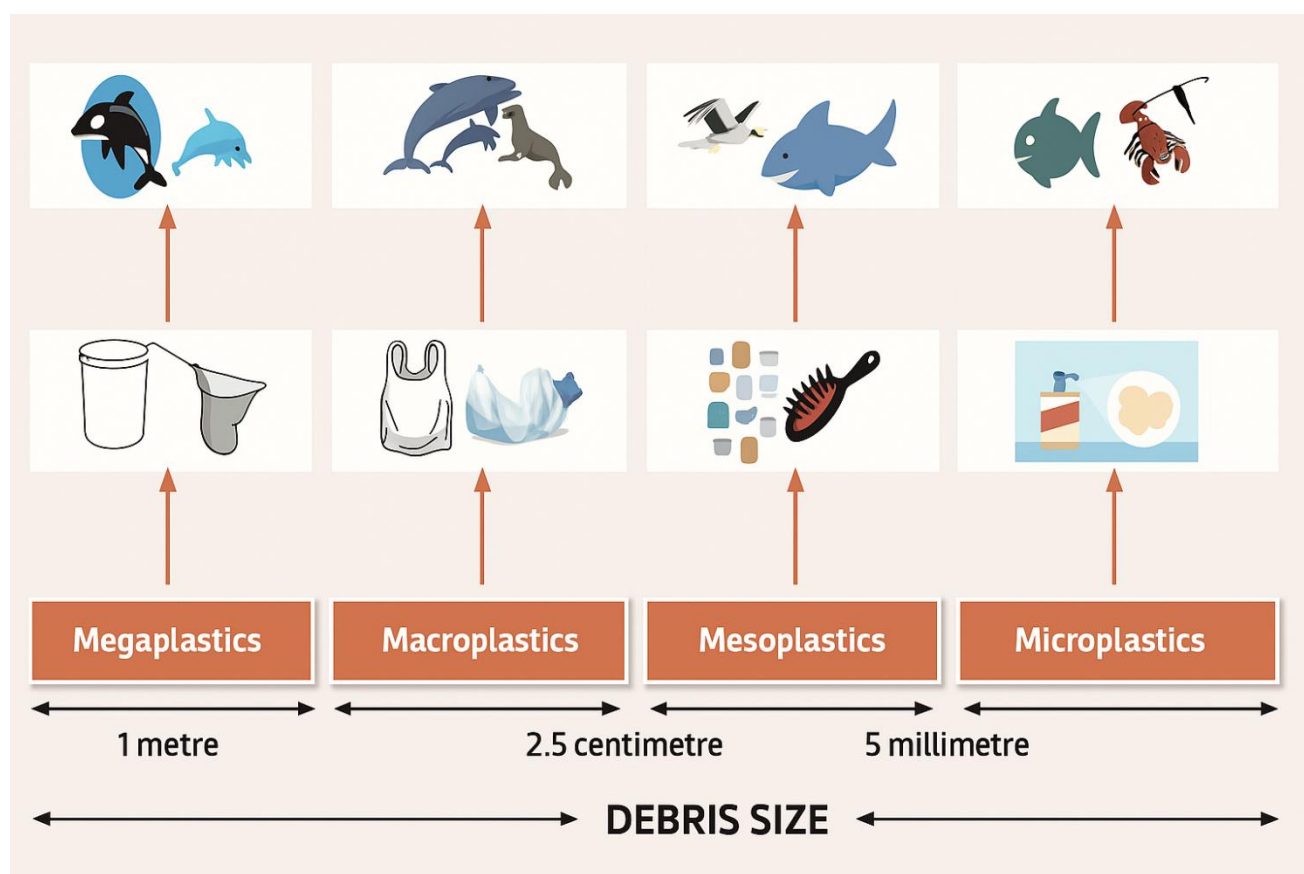


Figure1. Diagrammatic representation of different types of plastics and their effect on marine organisms.

4. Microplastic pollution in aquatic environments

4.1 Sources and transport of microplastic pollution

Identifying the sources of microplastics (MPs) is critical for managing their pollution. These sources are generally classified as either land-derived or ocean-derived based on their entry point into aquatic systems. Certain types of microplastics are discharged directly into water bodies. In contrast, larger plastic debris coming from land will either transmute into microplastics over time before reaching water bodies or while being transported (Vanapalli et al., 2021). The presence of dangerous plastic pieces in land and water bodies is mainly due to human activities such as domestic, industrial, and coastal activities. In relation to water bodies, microplastics are largely carried into the ocean through domestic runoff, which includes disposed microbeads as well as fragments of microplastics from personal care and consumer products (Chatterjee and Sharma, 2019).

As noted by the Scientific Advice Mechanism of the European Commission, by 2019 microplastics had become pervasive, manifesting in every region of our planet. Domestic disposals serve as the primary contributors to microplastics and include the synthetic polymers that make up as constituents of personal hygiene and cleansing products and their manufacturing processes. Furthermore, the use of plastic powder and plastic pellets in air blasting techniques in industrial sectors contribute greatly, with emissions between 5,000 and 80,000 tonnes. Secondary microplastics, in contrast, result from the breakup of larger plastic items (between 1.1 and 41.8 mm in size) due to mechanical forces and ultraviolet radiation over time (Vivekanand et al., 2021). It is quite interesting that, during the course of their treatment, the wastewater undergoes additional treatment processes from which the concentration of secondary microplastics is increasing. Compared to primary microplastics, secondary microplastics dominate wastewater effluent, which is the opposite of what is assumed. This is likely because secondary microplastics are smaller and their physical properties help them evade capture by filtration systems (Katare et al., 2021). A significant fraction of land-based microplastics infiltrating water bodies originates from wastewater treatment and industrial facilities. Smaller and more buoyant poly fragment microplastics are often found suspended on the surface of water bodies, while larger and denser fragments, with a median size of 3.6 mm, tend to settle into sediments. The microplastics that get suspended in the water column have a higher likelihood of being consumed by aquatic animals while bottom-deposited microplastics get trapped in sediments. Current and wind patterns act like a conveyor belt, moving plastic micro fragments to the designated zone, which then accumulate in specific areas. Such concentrated deposits increase the ecological danger posed to marine and adjoining coastal ecosystems. In polar regions, microplastics are transported by sea ice in a different manner. During the formation of sea ice, these microplastics get locked within the ice, often having a vertical distribution based on polymer type. But, with the increase of climate change, the faster-apart sea ice becomes, the more microplastics are released back into the water, and further increasing the pollution level. Due to the manner in which microplastics are manufactured, they are found within

anthropogenic and natural water cycles. In these systems, they are found in the municipal sewage alongside the influent and effluent wastewater treatment plants (Vivekanand et al., 2021).

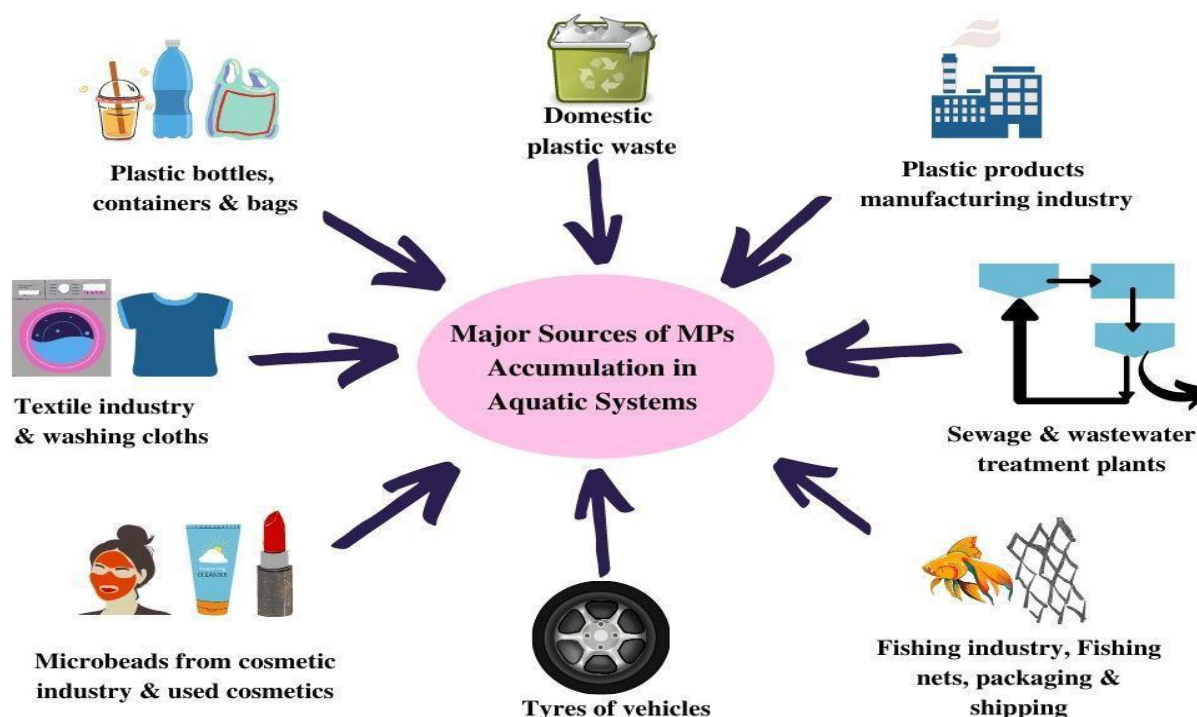


Figure 2. Major sources of microplastics in aquatic systems

4.2 Abundance and distribution of microplastics in the aquatic environment

The accumulation of microplastics within the sediments, the waters, and the living organisms is influenced by a number of geographical, ecological, and man-made elements. The presence and distribution of microplastics is influenced by the particular winds and currents, seasons, the location of the beach, and the local coastal geomorphology. Additionally, cumulative impacts of waves and longshore drift, the mixing and stratification of salt and freshwater, and the morphodynamic condition of beaches can also be significantly spatially and temporally impact the distribution of microplastics (Vanapalli et al., 2021).

Microplastics in sediments, seawater, and freshwater

Research on microplastics has demonstrated their widespread occurrence in water bodies and microplastics are an environmental issue. For instance, Nava et al. [32] studied 38 lakes in different parts of the world and reported that more than 93% of them had plastic pollution, particularly in the form of microplastics. Out of these lakes, 55% (21 lakes) had low concentration of less than one particle per cubic meter, 37% (14 lakes) had one to five particles and 8% (3 lakes) had more than five particles (Witczak et al., 2024). Ocean waves are responsible for the transportation of a majority of litter found in the ocean onto the shores, however, a combination of factors such as the wind, ocean currents, the shape of the coastline, and the quantity of microplastics determines how microplastics are transported and redistributed across distant coastal regions. For instance, Veerasingam et al. reported that in the

month of June, there was a concentration of microplastics on beaches located in South Goa which was not seen in the month of January. This was attributed to the seasonal reversal of net longshore drift to a south direction during June and July.

The coastal climate of India is twinned with the southern and northeastern monsoon seasons, which occur in June to September and October to November, respectively. These seasons are characterized by intense monsoonal winds which also enhance the transport and deposition of microplastic (MP) pollution along the coast. Further, the flushing of MPs through riverine systems and the heavy monsoonal flow from estuarine systems play important roles in determining the distribution of MPs. Such distribution patterns have been documented along and offshore in the west coast in states like Goa, Mumbai, and Karnataka, extending to the east coast of Pondicherry and Tamil Nadu. Conversely, during the northeast monsoon, the Goa coastline exhibited reduced levels of newly deposited MPs, likely due to oceanic currents and wind patterns counteracting the onshore transport of microplastics.

In contrast, during the Northeast monsoon, the Goa coast reduced the level of newly deposited MPs, which is likely to combat the coastal transport of microplastics due to ocean streams and air patterns. Several studies focused on source-to-sink characterization have demanded to establish a relationship between microplastic (MPS) contamination in depression, water bodies and marine organisms. The relationship between these compartments is affected by factors such as plastic, bounce of environmental transport mechanisms and particle sizes, and rapidly buried by MPs due to sedimentary deposition processes (Vanapalli et al., 2021).

4.3 Characteristics, chemical composition and deterioration of MPs in the aquatic environment

Microplastics (MP's) found in water bodies are defined in reference to their size, shape, colour, and polymer composition. Often, microplastics are initially separated and classified according to their size using sieving and filtration. To assess their shape and colour, visual and microscopic examination is usually sufficient. For polymer identification, FT-IR (Fourier Transform Infrared Spectroscopy) is the most common technique used owing to its ability to identify specific polymer functional groups. Different studies have performed size fraction analysis and reported microplastics to be heterogeneously sized throughout the aquatic environment. Some studies found younger sediments and water samples to be dominated by larger sized microplastics, whereas, other studies found the smaller size fractions to be more dominant.

From the environmental samples, different types of microplastics (fragments, fibers, films, foams, and pellets) were all collected. The high population of fragments is mainly due to the decomposition of larger plastic pieces from diverse point and non-point sources, probably because of erosion and weathering as they are transported over long distances. On the contrary, microfibers are mostly associated with commercial fishing nets and synthetic fibers released through laundry and domestic wastewater.

The microplastics (MPs) detected in bodies of water are primarily made up of polymers like Polyethylene (PE), Polyethylene terephthalate (PET), Polystyrene (PS), Polypropylene (PP), Polyvinyl chloride (PVC), nylon, and polyester. Of all the polymers, PE and PP have been identified as the most abundant polymers in several research studies. This is likely because their density is low enough to keep them suspended in water. Interestingly, significant concentrations of these low-density polymers have been found in the sediments of lakes and rivers. This is likely due to physicochemical and biological processes such as biofouling, aggregation, or adsorption of particles that increase effective density and enable these polymers to sink. Also, Reddy et al. [29] described the occurrence of PU, nylon, PS, and polyester in marine sediments collected from the Alang-Sosiya ship-breaking yard. These polymers are used in the construction of ships and in industrial insulation, textile, and packaging, which further indicates the impact that localized industrial activities have on the composition of MPs in sediments. As with many materials, color is another characteristic of microplastics (MPs) which is often assessed because it may indicate their identity, some additives, the degree of degradation, and their origin. To illustrate, the presence of white or transparent MPs is often correlated with some certain types of MPs, source materials, weathering of the environment over time, and some additives reacting to certain conditions such as heat or sunlight. The yellowing in beach sediments of white and transparent MPs is generally linked to the photo-oxidative degradation, which is dependent on the time of UV exposure and the type and concentration of additives that were initially in the plastic (Vanapalli et al., 2021).

4.4 Ingestion of MPs by aquatic biota

The consumption of microplastics (MPs) by aquatic organisms poses great concern not just for the welfare of these organisms, but also for the human populations that depend on them for food. The level of bioaccumulated MPs in different aquatic species is determined by such factors as the size, color, and the species of MP, as well as the organisms habitat, lifecycle, metabolic behavior, and the MPs contamination level in their surroundings. MPs have been reported in species that reside in the epipelagic, mesopelagic, demersal, reef, and benthic zones, but Sathish et al. [27] examined fishes from shallow water and observed them with more MPs, likely due to their proximity to human activities. The consumption of MPs by benthic organisms may pose more severe ecological concerns due to the potential of contaminant transfer throughout the aquatic food web.

The smallest microplastics (MPs) pose an increased ecological threat as they can be ingested by the simplest forms of aquatic life. The addition of heavy metals like lead (Pb), cadmium (Cd), mercury (Hg), and chromium (Cr) to plastic products increases the toxicity of MPs within water ecosystems. These metals can leach at toxic levels and adversely affect aquatic life. Moreover, MPs are capable of losing toxic materials to a greater degree than larger plastic fragments because of the weathered surfaces of MPs and the greater ratio of surface to volume. MPs are also known to readily combine with other environmental contaminants, such as persistent organic pollutants (POPs), polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs). This can increase the ability of such pollutants

to be transported across environmental media and aid in the biomagnification of toxins via the food web, thus threatening tertiary consumers and other organisms at higher levels of the food chain.

While microplastic (MPs) particles have been detected in the gastrointestinal systems of fish, the chances of human consumption in fish that are gilled and gutted is minimal. This does not apply to dried fish, a delicacy in many parts of India, where fish are consumed in the entirety with no prior gilling or gutting. In such cases, the consumption of microplastics trapped in the gastrointestinal tract poses serious risks to health. Consuming dried shrimp, white shrimp in particular, which are not deveined adds another layer of potential microplastics exposure. Along with these species, other marine organisms such as green mussels, great clams, and Indian edible oysters also raise similar concerns. Oysters, due to a sessile lifestyle, are suggested to be effective species to monitor microplastic contamination in aquatic habitats. (Vanapalli et al., 2021). Horton et al. [65] evaluated fish samples from the Thames and Stour rivers for microplastics in the digestive tracts of European flounder (*Platichthys flesus*), whiting (*Merlangius merlangus*), and Atlantic herring (*Clupea harengus*). According to the study, they discovered that 41.5% of fish tested positive for at least one microplastic particle, with species-specific rates of 37.5% for European flounder (*Platichthys flesus*), 52.2% for whiting (*Merlangius merlangus*) and 28.6% for Atlantic herring (*Clupea harengus*). Hamed et al. conducted an independent trial in which full-text revision was similarly reliable (86 %). Yet, the muscles and livers of market fish were free from microplastics however particles were evident in stomachs and intestines (Vitzak et al., 2024). Many aquatic organisms are visual hunters, so the color is predominant for ingestion with MPs in fish and other aquatic organisms as it cannot differentiate them from their prey. Daniel et al. [16], Reported increased intake of red/blue particles in fiber and benthic fish because of the preference for shrimp for particles with specific morphology and color, which has a resemblance to prey (Vanapali et al., 2021).

Most of the aquatic organisms are visual predators and therefore, the colour of MPs can be a predominant factor for their ingestion by fishes
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5. Behavior and transformation of plastics into MPs/NPs in aquatic ecosystem

Plastics have high resistance to natural deterioration, and their persistence in the environment leads to gradual changes into small particles such as MPs and NPs. These changes occur due to various abiotic and biotic mechanisms specific to the hydraulic environment, including photodegradation, thermal and chemical, mechanical fracture and biological processes. Each mechanism varies polymer type and environmental conditions (Pal et al., 2025).

6. Adsorption of contaminants by microplastics

Microplastic has a large surface area, making it an attractive magnet for pollutants. These microplastics act as reservoirs for various environmental contaminants. Environmental conditions, physicochemical properties of pollutants, type of polymer and concentration of pollutants influence the

adsorption of contaminants on microplastics. The concentration of chemical contaminants on microplastic surfaces can be up to six times higher than that in water. Li et al. [115] Investigated the adsorption behavior of five antibiotics sulfadiazine (SDZ), amoxicillin (AMX), tetracycline (TC), ciprofloxacin (CIP) and trimethoprim (TMP) on five microplastic polymers: polyethylene (PE), polystyrene (PS), polypropylene (PP), polyamide (PA) and polyvinyl chloride (PVC). They found that polyamide demonstrated a strong relationship for AMX, TC and CIP in freshwater, mainly due to hydrogen bond formation. The remaining plastic absorbing ability followed the trend: CIP> AMX> TMP> SDZ> TC. When they are displayed by several experimental studies on animal models, the toxicity of microplastics increases significantly (Witczak et al, 2024).

7. Adverse effects of microplastics

The pervasive existence and biological repercussions of microplastics (MPs) impose grave risks on the entire biosphere, including human beings. Their existence and potential toxicity can disrupt ecological balance. There is a growing body of evidence confirming the detrimental effects of microplastics on aquatic life. Specifically, microplastics exposure is known to cause reproductive dysfunctions in some aquatic and mammalian species, and, in some cases, is lethal when concentrated to a certain level. Reduced egg hatching and larval growth, as well as increased developmental toxicity, have also been exhibited with microplastics exposure. Gastrointestinal blockage due to microplastics can result in travel-time feats of animal instinct and behavioral quirkiness.

Research on marine fauna has revealed that ingestion of microplastics causes oxidative stress, cytotoxic damage, gastrointestinal damage, growth inhibition, increased exogenous infection susceptibility, and altered physiological and genomic domains. In adult zebrafish, microplastics disrupt intestinal homeostasis through gut dysbiosis and damage enterocytes, vilification, and disrupt normal angiogenesis. Long-term exposure (approximately 21 days) has also been associated with dysbiosis and the loss of essential metabolic functions.

Numerous studies have explored marine organisms' toxicological impacts concerning microplastics (MPs). Additionally, study reports have documented microplastics' (MPs) bioaccumulation in human samples such as meconium, stool, colectomy specimens, and even placental tissue, suggesting human exposure and possible internalization of microplastics (MPs). Aquatic mammals are known to consume a wide variety of synthetic polymers, including polyethylene (PE), polypropylene (PP), polyester, and nylon. These synthetic polymers (MPs) exert toxic effects through many exposure routes including dermal contact, subcutaneous injection, intraperitoneal, oral ingestion, and even intravenous injection. Based on the description provided, these exposures may be classified as either direct or indirect. While direct exposure usually results in acute toxicity, often short-lived in nature, physical contact between the exposed organism and the initiator of toxins is necessary. Indirect exposure occurs when toxins are incorporated into the food web through bioaccumulation; this leads to long-term organ toxicity that is chronic in nature. Following exposure to MPs, marine organisms such

as fishes, invertebrates, and corals experience acute and chronic physiological and biochemical disturbances (Ali et al., 2024).

8. Ecotoxicity of microplastics (MPs)

Over the last several decades, pollution from plastic waste has been consistently rising. Microplastics (MPs), which are particles of plastic that are less than 5 millimeters in size, are found in both sediments and water, which creates a considerable ecological danger. Microplastics can accumulate and transport harmful toxins which can damage marine life and ecosystems. Secondary microplastics result from the breakdown of larger plastic items through physical, chemical and biological processes, rather than fermentation, and their release into the environment increases pollution. The range of microplastics includes fragments, fibers, foams, and films. From the perspective of health and environment, the issue of prevalence of microplastics is increasing. MPs can be ingested by marine life, and then through the processes of bioaccumulation and biomagnification, transfer into the food supply of larger organisms. In fish and humans, some of the biological and toxicological changes which might occur include inflammation, oxidative stress, and disruption of the endocrine system and more (Katare et al., 2021).

8.1. Toxicity due to chemical and physical properties of microplastics

Microplastics (MPs) physicochemical properties fundamentally determine their impact biologically and environmentally. In water bodies, their bioaccumulation and toxicity hinges largely on their inert and persistent nature.

The interactions MPs have with living organisms is influenced by these properties at the same time while also affecting the possibility of harm through ingestion, dermal exposure, or even breathing. MPs have been associated with abnormal changes in genes and possible concerns linked to the safety of drinking water, which raises red flags as to why their short and long-term impacts on the ecosystem and humanity needs to be studied thoroughly. Hence, such properties of MPs contribute towards their bio accumulative, persistent nature while the concentration of different species reflects their probable bio accumulative impact towards humans and the ecosystem. In addition, the consequences of microplastics are determined by the nature of the waste and the feeding habits of the organisms. For example, microplastics are more likely to be consumed by carnivorous predators who rely on limited and primary sensory cues to identify food if the microplastics resemble their natural prey.

The morphology and behavior of microplastics in aquatic environments are affected by their physical properties, such as shape, size, and density. These properties also impact their bioavailability and water sorption distribution, leading often to natural material-like mimicry.

The chemical nature of microplastic is decided by the plastic composition and synthesis strategies, and it is expressed as whole different functional groups, upon their stability and innovation source may vary completely changing the detection of the plastics contaminants in terms of possibility to release particles or to capture environmental pollutants on a surface. Chemicals may have different the persistence in the environment that is more likely to be related to their physical properties (ingestion,

estion, or any other physical injury) while polymeric particles might exert this kind of persistent contaminant toxicity due to their characteristic morphological and bio-chemical properties. Because the presence of microplastics changes how additives are enhanced or released, chemical characteristics were utilized to analyze the behavior of microplastic (Katare et al., 2021).

8.2 Potential impact on aquatic life

Microplastics can carry a lot of toxins from industrial production, including additives that are not disintegrated by natural conditions and can be transported with water. These particles have been found all over the world in fresh water lakes, oceans and seas, dispersed in the liquid column and water sediments in deep holes. The physical effects of microplastic on the aquatic life are mainly associated with chewing and chewing studies conducted on microplastic in sea water. More than 200 marine species have been affected by research on physical interaction with synthetic debris, such as entanglement and internal blockage due to chewing. These physical interactions can cause injuries, mobility problems, disorder of food and even severe cases. Death Research indicates that Entanglement in plastic debris, especially ghost nets, causes severe damage to hydrophytic species. Vulnerable populations of sea -turtle through Ghost net are particularly endangered; They get stuck when they kill or starve. Their survival requires both appearance of predators and access to basic needs. Microplastics come into the food chain with direct and indirect ingestion. It leads to remarkable bioaccumulation, especially in organisms at high trophic levels such as sea birds, seals and sea lions. Fish usually eat microplastic by consuming contaminated prey, leading to secondary intervention. Reports indicate that microplastic concentration can increase 160 times in water bodies for predators such as seals. Large marine organisms are often affected by the physical blocks of microplastus. However, microplastic contamination has been detected in almost all trophics, affecting many marine species such as zooplankton, marine polychaete worms, mussels, oysters, fish, sea turtle, dolphin, whale and seabird. The scope of microplastic toxicity is influenced by both biological and chemical factors. Once ingested can cause many toxic effects not only in marine organisms but also in humans through trophic transfer. Various polymers used in plastic production contain harmful chemicals such as copper ions and other toxic additives that can cause leaching in organisms and disrupt biological systems (Katare et al., 2021).

9. Interaction of Microplastics (MPs) with Aquatic Biota

Aquatic Biota	Interaction with Microplastics (MPs)	Effects/Consequences	References
Microalgae	Higher interaction potential due to size similarity (µm–mm). MPs affect at cellular to population level.	- Inhibition of growth rate - Disruption of photosynthesis - ROS & RNS production → oxidative stress in algal cells	Pal et al., 2025

Molluscs (Bivalves)	Filter-feeding traps MPs fibers; uptake through passive (adhesion to feeding structures) and active (selective ingestion, cilia/siri movement, muscle contractions) ways.	- MPs accumulate in molluscan tissues - Affects trophic network - Human health risk due to seafood consumption	Pall et al., 2025
Fish	MPs resemble natural food → ingestion common; accumulate in GIT, migrate to liver, gills, and muscles.	- Bioaccumulation & systemic distribution - Long-term adverse health effects on humans via consumption	Pal et al., 2025
Coral Reef	Corals actively ingest MPs (~50 µg plastic cm ⁻² h ⁻¹). MPs found in mesenterial tissues and gut cavity.	- Coral damage - MPs act as carriers of harmful microorganisms	Chatterjee & Sharma, 2019

10. Human Health Risk

The persistent nature, bioavailability, and unfamiliar nature of microplastics (MPs) raises critical health concerns due to the widespread exposure. While eating, breathing, or even touching, individuals are exposed to microplastics. The aforementioned activities filter the body's systems such as the gastrointestinal, respiratory, reproductive, and even the brain which mandates looking into the risks brought by microplastics as well as developing them into necessary and protective laws (Pal et al. 2025).

11. Knowledge gaps and future research priorities

Compared to the research done on marine microplastics, the freshwater microplastics research comes with significant gaps (Wagner et al., 2014). From what we know, the study of microplastics in the river systems of India has been quite limited. Thorough research, however, the study of the spatiotemporal distribution of microplastics in Indian river systems has the potential to significantly improve our understanding of their concentration and the sources of microplastics in these water bodies. Considering the wide availability of freshwater fish, especially in the southern parts of the country, studying the concentration of microplastics in riverine ecosystems is essential in order to determine the potential health risks and hazards posed to the populations due to the consumption of these fish.

Studying river systems is critical in understanding the transport of microplastics into marine ecosystems. Profiling microplastic pollution in these ecosystems from river sources to the coastal areas near river mouths, however, would greatly enhance models describing the transport of plastic particles and contribute to devising effective plastic waste removal and management methods. In addition, due

to microplastic pollution being more acute in stagnant water bodies like lakes compared to moving waters and coastal parts, these areas should be the focus of further research.

Although many studies have looked at microplastic (MPs) accumulation in epipelagic fish, the specific ways in which different species accumulate or expel microplastics remain poorly understood. Furthermore, seasonal fluctuations in microplastic concentration in relation to different life stages, dietary habits, and species preferences present additional avenues for research (Vanapalli et al., 2021).

12. Global policy framework

The dangerous consequences of microplastics (MPs), particularly concerning the contamination of water bodies and the potential harm to human health, have led to markable global discussions and public policies. International organizations, including the United Nations (UN), G20, G7, and Asia Pacific Economic Cooperation (APEC), have recognized microplastics as a problem of transnational environmental concern. Moreover, the World Economic Forum (WEF) estimates that by the year 2050, the amount of microplastics present in the oceans will be greater than the biomass of marine life.

As highlighted by Pabortsava and Lampitt (2020), the microplastics problem is more concerning as recent studies have shown that three different forms of microplastics discovered in different layers of the Atlantic Ocean are present in much greater numbers than previously estimated, often by a factor of ten. The findings of this and other similar studies have led to the establishment of more rigorous international, national, and local policies to combat the problem of plastic waste as well as microplastic pollution in water.

Frameworks for policies related to the management and monitoring of microplastics in water bodies. To promote global sustainability for the marine environment, the United Nations proclaimed the Decade of Ocean Science for Sustainable Development (2021-2030) (UN, 2020) with the goal of enhancing science-policy interfaces to foster informed governance of oceans and coasts. Almost all the policies discussed at any given level have one common framework.

- Prevention: 3R policy of reduction, reuse and recycle is applicable.
- Removal: surveillance and proactive measures to mitigate the accumulation of the plastic debris are required.
- Mitigation: framework for robust regulations pertaining to litter and discharge is needed.
- Education: comprehensive campaign and drastic approaches towards behavioural modification is required (Vivekanand et al., 2021).

13. Recent strategies for microplastic remediation

Bioremediation aims to remove contaminants from an environment using living organisms, and in this case, it can be done physiochemically for microplastic removal. There is increasing focus on the removal of microplastics using advanced methods like membrane bioreactors (MBR), synthetic biology, organosilane methods, biofilm mediated microplastic remediation, and methods utilizing nanomaterials (Ali et al., 2024).

13.1. Biofilm-Mediated Microplastic (MP) Remediation

Microplastics (MPs) enter aquatic environments where the surfaces are colonized rapidly by microorganisms forming stable complex biofilms. Among the many bacteria which reside in biofilms, some can biodegrade hydrocarbons and may help to adsorb pollutants to microplastic surfaces. Most notably, the associations of biofilms with microplastics can lead to changes in the chemistry and some physical aspects of the plastic polymers which make them more amenable to biological degradation. Thus, this represents a productive route for microplastic remediation through microbial transformation and degradation (Ali et al., 2024).

13.2. Synthetic Biology and Organosilane-Based Approaches

There is an increase in the utilization of synthetic biology to study microbe-environment interplay, specifically focusing on the biodegradation of synthetic polymers. Often, advanced “omics” technologies like, genomics, transcriptomics and proteomics, are employed to elucidate the biological principles at work. In this area, one of the goals is to modify specific metabolic pathways to increase the rate at which microbes break down the waste of petroleum fossil fuels. At the same, organosilane techniques are being studied for their plastic degradation enhancement through the surface modification and catalytic transformation of polymeric substances (Ali et al., 2024).

13.3 Membrane Bioreactor (MBR) Technology

The use of membrane bioreactor (MBR) systems in microplastics (MPs) removal from wastewater is unparalleled, as they are able to extract more than 90% of MPs waste in comparison to the more primitive methods advanced in standard wastewater treatment (WWT) facilities (Ali et al., 2024).

13.4 Nanomaterial-Enabled Strategies for Microplastic Remediation

The field of nanomaterials has opened new pathways for the more efficient microplastic remediation during waste water treatment (WWT), both methodologically and in terms of energy consumption. Remediation using nanomaterials is efficient owing to their greater surface area, tunable properties, and superior catalytic activity. Most recently, novel photocatalytic nanostructures have been developed to boost light absorption, limit charge carrier recombination, and augment the density of light-responsive sites. To obtain these enhancements, photocatalysts are usually engineered at the nanoscale, or primary photocatalysts are doped with a variety of functional nanomaterials to optimize their photocatalytic efficiency (Ali et al., 2024).

14. Conclusion

Plastics, especially microplastics, are a major environmental threat due to their persistence and ecological toxicity. They infiltrate both freshwater and marine ecosystems, harming aquatic life and adsorbing other pollutants, yet research on their freshwater impact remains limited. Since eliminating plastics entirely is not feasible, strong laws and regulations are needed to reduce their use and establish safety limits, such as Maximum Residue Limits (MRLs) in fishery products, to protect human health and manage plastic pollution in the food supply.

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