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Biomagnification and Its Ecological Consequences in Aquatic Ecosystems

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Abstract

The process by which the concentration of harmful contaminants rises at successive trophic levels in an aquatic food chain is known as biomagnification. Through agricultural runoff, industrial discharge, urban wastewater, atmospheric deposition and persistent pollutants such heavy metals, pesticides, herbicides, microplastics, oil hydrocarbons and industrial effluents infiltrate aquatic environments. These contaminants build up in aquatic species and grow more concentrated in higher trophic levels, especially in predatory fish, aquatic birds and mammals, since they are resistant to degradation. Numerous ecological effects of biomagnification include neurotoxicity, immunological suppression, developmental anomalies, reproductive impairment and increased mortality. Additionally, it reduces biodiversity, modifies community structure, disturbs food-web dynamics and lowers ecological productivity. Additionally, microplastics facilitate the spread of contaminants across food chains by acting as transporters of hazardous substances. Consuming seafood puts human health at serious risk due to the buildup of contaminants in commercially relevant fish species. To reduce biomagnification and preserve the sustainability of aquatic ecosystems, efficient pollution control and environmental monitoring are crucial.

Keywords: Biomagnification, Aquatic pollution, Food web, Heavy metals, Microplastics, Human health risk

1. Introduction

Emerging pollutants are mostly novel compounds that have been discharged into water bodies in significant amounts due to social and economic changes over the past few decades, posing a risk to aquatic ecosystems. (Zenker et al., 2014). Particularly when it comes to the management of dredged materials, the possible ecological implications of pollutants connected with sediment are concerning (Suedel et al., 1994). Understanding and measuring the fate, bioaccumulation, exposure and potential for negative impacts of chemicals discharged into the environment is of interest to both scientists and regulators. In comparison to concentrations at lower trophic levels, trophic biomagnification across a food chain or food web can significantly raise chemical concentrations at higher trophic levels, hence increasing exposure and possible risk (Mackay et al., 2016).

Some authors define biomagnification as the increase in concentration between trophic levels; if the biomagnification factor (concentration in predator/concentration in prey) >1, the compound is biomagnified. The standard definition of biomagnification is the transfer of a xenobiotic chemical from food to an organism, resulting in a generally higher concentration within the organism than source (Gray, 2002). Rapid development over the past few decades has increased atmospheric emissions, especially from non-ferrous metal smelters and geothermal plants (Zhang et al., 2020).

Water (waterborne uptake) and food particles (foodborne uptake) are the many sources of uptake for aquatic species. However, bioaccumulation and bioavailability are considered together in ecotoxicological research. Studying bioaccumulation without taking bioavailability into account would be impossible and vice versa. Therefore, both are taken into consideration here together with the application of bioaccumulation in biomonitoring. In particular, the pathways of exposure and internalization in the cell and organism determine the rate of uptake of designed nanomaterials and their negative effects (Gupta et al. 2017). Based on the exposure route, there are three primary types of uptakes, as seen in Fig. 1: bioconcentration, bioaccumulation and biomagnification. Biomagnification poses the greatest threat to human health and the environment out of the three (Uddin et al., 2020).

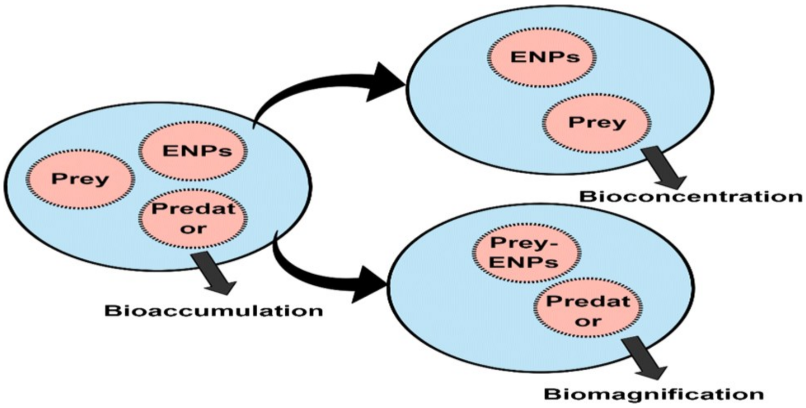

Fig. 1 Conceptual illustration of bioaccumulation, bioconcentration, and trophic biomagnification of engineered nanoparticles (ENPs) in aquatic ecosystems (Uddin et al., 2020)

2. Historical Background

This article traces the history of persistent, bioaccumulative and toxic chemicals (PBTs) from Faraday's 1825 synthesis of technical benzene hexachloride (BHC) to the ongoing global initiatives to phase out 12 persistent, organic pollutants (POPs) under the United Nations Environmental Program (UNEP). The search for new applications for chlorine in the 1930s resulted in the development of several chlorinated insecticidal compounds, such as DDT, which won Müller the Nobel Prize in Medicine for its remarkable effectiveness in controlling typhus, malaria, typhoid fever and cholera both during and after the War.

DDT and other PBTs/POPs raised environmental concerns in the 1960s because they bioaccumulate and biomagnify in food chains, harming wildlife reproduction. Their high lipid solubility causes them to accumulate in organisms, leading to global efforts to control their use and disposal.

Multimedia emissions and volatility also cause long-distance environmental movement through water and the atmosphere, which contaminates humans and biota at locations far from their use. The United Nations Environmental Program (XJNEP) Governing Council organized an international working group in May 1995 to create evaluations for 12 POPs. Aldrin, chlordane, dieldrin, DDT, endrin, heptachlor, hexachlorobenzene, mirex, toxaphene, PCBs, polychlorinated dibenzofurans (PCDFs) and polychlorinated dibenzo-p-dioxins (PCDDs) are the twelve POPs (Lipnick & Muir, 2000).

3. Sources of Toxic Pollutants in Aquatic Ecosystems

3.1 Agricultural Sources

Pesticide

Pesticides and agrochemicals in general have grown in importance in the world's agricultural systems, allowing for notable gains in crop yields and food supply. Fish species and other aquatic organisms that are a part of the tropical food web have been shown to be severely poisoned by pesticides. Invasive and harmful pests are controlled with pesticides in forestry, agriculture and landscaping. They can travel great distances and could potentially enter the hydrological cycle at any time (Ray & Shaju, 2023).

Herbicides

Runoff and drainage from agricultural fields are the primary ways that herbicides can find their way into surface waters. Wastewater treatment facilities, storm sewers, or a combination of sewer overflows and runoff from metropolitan areas are urban sources of herbicide pollution to surface water (Vonk & Kraak, 2020).

3.2 Industrial Sources

Heavy Metals (Mercury, Cadmium, Lead and Arsenic)

Surface water systems may contain heavy metals from both natural and man-made sources. Volcanic eruptions, weathering of rocks containing metals, sea salt sprays, forest fires and natural weathering processes are examples of geological and ecological sources that can start the release of metals from their native skies to various environmental areas. Heavy metals can be found in various forms, including hydroxides, oxides, sulphides, sulphates, phosphates, silicates and organic molecules (Sonone et al., 2020).

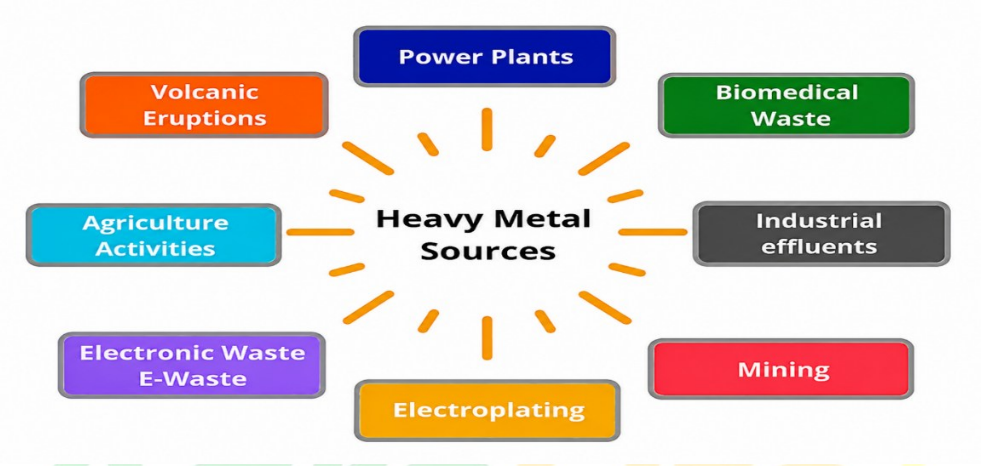

Fig 2. Different sources of contamination heavy metal in water

Industrial effluents

Some of the main sources of pollution include household sewage, municipal garbage and industrial waste that is directly released into the natural water system. Water contamination results from untreated waste discharge. The discharge of untreated manufacturing effluents into water bodies is the main cause of contamination of surface and groundwater (Sonone et al., 2020).

3.3 Urban Sources

Pharmaceutical Residues

Wastewater from a range of industrial, agricultural and residential sources is constantly released, which can contaminate freshwater habitats with pharmaceuticals. Animal and human excrement are the main sources of this pollution. Only a portion of the active substances in medications are metabolized; the remainder are eliminated in the urine or faces. These drug residues enter the wastewater system mostly through toilets and drains. Wastewater and other aqueous systems are contaminated by veterinary medications (Aib et al., 2025).

Microplastics

Plastic pollution in aquatic ecosystems is largely caused by wastewater discharge. Untreated and inadequately treated wastewater can directly dump microplastics into aquatic environments. Basin waters are one of the primary sources of MPs in water bodies, as are the microplastics transported by household effluent from washing machines, outlets and showers. Microfibers from synthetic fabrics like polyester are released in large quantities from laundry wastewater in particular. Up to 1900 fibres can be released in a single wash. Additionally, this pollutant burden is increased by personal care items that contain synthetic microplastics and microbeads. If these MPs are not processed, they end up in sewage and eventually accumulate in water bodies (Aib et al., 2025).

4. Mechanism of Biomagnification

The concept of biomagnification, in which a chemical is moved up the food chain to higher trophic levels and its concentration in predators exceeds what is anticipated when an organism and its surroundings are in equilibrium, is shown in Fig. 3. The measurement of an organism's bioconcentration, trophic transfer, and biomagnification in an ecosystem can be better understood by using several terminologies that lead to different processes (Saidon et al., 2024).

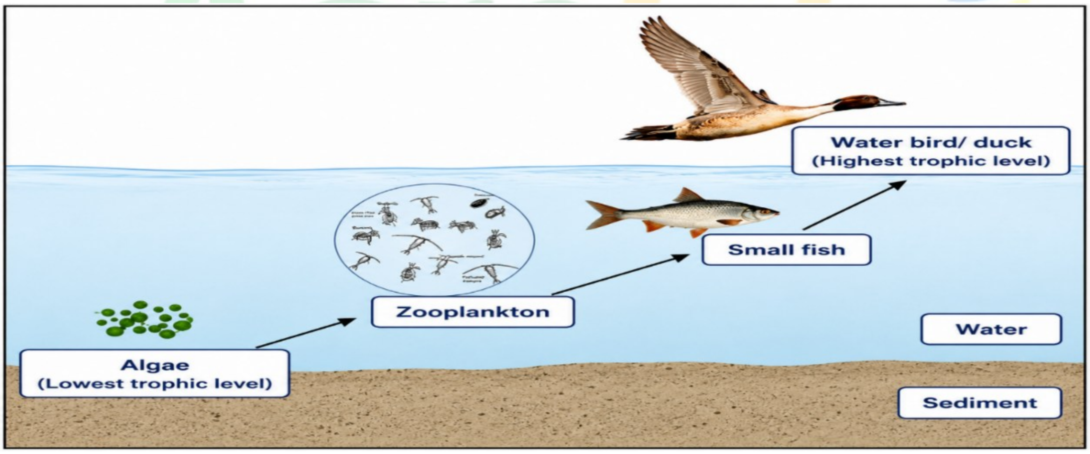

Fig. 3 The trophic transfer from organism at lowest trophic level to highest trophic in an aquatic ecosystem (Saidon et al., 2024)

5. Ecological consequences in aquatic ecosystems

5.1 Heavy Metals

Among the most hazardous contaminants in aquatic environments are heavy metals like mercury (Hg), cadmium (Cd), lead (Pb), and arsenic (As). They remain in water and sediments for decades since they are not biodegradable. Following phytoplankton absorption, these metals ascend the food chain and accumulate more in fish, birds, and aquatic mammals. Neurotoxicity, reproductive dysfunction, developmental problems, immunological suppression, decreased growth, behavioural disorders, and mortality are all consequences of this biomagnification. The highest quantities are accumulated by top predators, who frequently experience significant physiological stress and population decreases.

Table 1 Ecological consequences of heavy metal biomagnification

Ecological Consequence	Description	Example
Neurotoxicity	Damage to nervous system	Mercury poisoning in tuna
Reproductive impairment	Reduced fertility and hatchability	Cadmium in fish
Growth reduction	Stunted growth and poor development	Lead exposure in fish
Immune suppression	Increased disease susceptibility	Arsenic contamination
Biodiversity loss	Decline of sensitive species	Mining-affected rivers

5.2 Pesticides

After entering water bodies through agricultural runoff, persistent pesticides including DDT, Endosulfan, Aldrin, and Dieldrin build up in aquatic food chains. These substances affect hormone production, interfere with endocrine systems, and hinder reproductive processes. Predatory fish and fish-eating birds are particularly vulnerable to the biomagnification of pesticides. Eggshell thinning, decreased hatchability, aberrant development, and population decreases are all consequences of prolonged exposure.

Table 2 Ecological consequences of pesticide biomagnification

Ecological Consequence	Description	Example
Eggshell thinning	Weak eggs break during incubation	DDT in pelicans
Endocrine disruption	Hormonal imbalance	Endosulfan exposure
Embryonic defects	Abnormal development	DDT-contaminated fish
Reduced fertility	Fewer offspring produced	Fish populations
Population decline	Long-term reduction in abundance	Aquatic birds

5.3 Herbicides

The main way that herbicides like Atrazine, Glyphosate, Paraquat, and Simazine impact aquatic ecosystems is by decreasing the productivity of aquatic plants and phytoplankton. Higher trophic levels are indirectly impacted by herbicide contamination because these creatures are the base of aquatic food webs. Lower oxygen generation, less food availability, and changed community organization are the outcomes of reduced photosynthesis.

5.4 Microplastics

Plankton, molluscs, crabs, and fish consume microplastics, which physically harm their digestive systems. Toxic substances including heavy metals and persistent organic pollutants are also transported by them. Microplastics cause physiological stress, inflammation, decreased feeding efficiency, poor reproduction, and the spread of harmful compounds across food webs through biomagnification.

Table 3 ecological consequences of herbicide contamination

Ecological Consequence	Description	Example
Reduced photosynthesis	Inhibition of plant growth	Atrazine
Lower oxygen levels	Reduced dissolved oxygen	Glyphosate
Food-web disruption	Less food for consumers	Aquatic ecosystems
Habitat degradation	Loss of aquatic vegetation	Paraquat
Reduced productivity	Lower biomass production	Simazine

Table 4 Ecological consequences of microplastic biomagnification

Ecological Consequence	Description	Example
Digestive blockage	Reduced nutrient uptake	Fish and shellfish
Reduced feeding	Lower food consumption	Zooplankton
Tissue inflammation	Internal injuries	Marine fish
Reproductive impairment	Lower fertility	Mussels
Toxic chemical transfer	Adsorbed pollutants transferred	Marine food webs

5.5 Oil hydrocarbons

Oil spills and industrial discharges produce oil hydrocarbons, particularly polycyclic aromatic hydrocarbons (PAHs). When these substances build up in aquatic species, they can result in cellular damage, genetic changes, aberrant growth, decreased reproductive success, and even death. Additionally, eating, migratory, and predator-prey relationships are all hampered by oil pollution.

Table 5 Ecological consequences of oil hydrocarbon biomagnification

Ecological Consequence	Description	Example
Genetic damage	DNA alterations	PAH exposure
Developmental defects	Abnormal growth	Fish larvae
Reduced reproduction	Lower spawning success	Marine fish
Behavioural changes	Altered feeding and movement	Crustaceans
Mortality	Death of aquatic organisms	Oil spill events

5.6 Industrial effluents

Heavy metals, dyes, medications, hydrocarbons, detergents, and hazardous organic compounds are all mixed together in industrial effluents. Chronic pollution and biomagnification result from ongoing discharge into aquatic habitats. These contaminants disrupt physiological systems, decrease biodiversity, change species composition, and upset ecological processes.

Table 6 Ecological consequences of industrial effluent biomagnification

Ecological Consequence	Description	Example
Biodiversity loss	Decline of sensitive species	Polluted rivers
Community alteration	Dominance of tolerant species	Industrial lakes
Physiological stress	Organ damage	Fish populations
Food-web disruption	Altered trophic interactions	River ecosystems
Ecosystem degradation	Reduced ecosystem health	Industrial zones

6. Human Health Implications

Bioaccumulated and biomagnified chemicals can cause serious health problems in humans. According to studies, neurological and developmental issues can be brought on by heavy metals like lead and mercury that are biomagnified through aquatic food webs. highlights how methylmercury buildup in fish has a major impact on human brain function, especially in young children and pregnant women.

There are also serious dangers associated with persistent organic pollutants like dioxins and polychlorinated biphenyls (PCBs). Numerous negative effects, such as immune system suppression and an elevated risk of cancer, have been connected to PCB exposure. Factors including age, sex and underlying medical issues frequently make the effects of these substances worse (Awafung et al., 2025).

7. Conclusion

In aquatic food webs, biomagnification is a crucial environmental mechanism that raises the concentration of persistent harmful contaminants at successive trophic levels. Aquatic ecosystems are contaminated by heavy metals, pesticides, herbicides, microplastics, oil hydrocarbons, industrial effluents, agricultural runoff, industrial discharge, urban wastewater, and other human activities. These pollutants build up in aquatic species and become more concentrated at higher trophic levels because of their persistence and resistance to degradation. Therefore, biomagnification has a variety of negative ecological effects, such as neurotoxicity, impaired reproduction, aberrant development, immunological suppression, loss of biodiversity, disturbance of the food chain, and deterioration of ecosystems. Because they acquire the largest quantities of contaminants, top predators such as humans, marine mammals, and fish-eating birds are especially at risk. Aquatic biodiversity, environmental stability, and human health are all seriously threatened by these contaminants' rising prevalence. Therefore, to lower pollutant inputs and lessen the negative effects of biomagnification, effective pollution control methods, sustainable waste management practices, ongoing environmental monitoring, and stringent regulatory laws are crucial. Long-term environmental sustainability, biodiversity conservation, and ecological balance all depend on the preservation of aquatic ecosystems.

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