



## Impacts of Polystyrene Nanoplastics on Fisheries Biology and Prospective Remediation Approaches in Aquatic Ecosystems

Habiba Jamil<sup>1</sup>, Sidra Kamal<sup>2</sup>, Muhammad Saeed Lodhi<sup>3</sup>, Warda Wajee<sup>4</sup>, Hafiz Nidaullah<sup>5</sup>, Ayesha Kabir<sup>2</sup>, Farah Naseem<sup>6</sup>, Bushra Mushtaq<sup>7</sup>, Nimra Ashraf<sup>2</sup>

<sup>1</sup>Department of Biological Sciences, The Superior University, Lahore, Punjab, Pakistan.

<sup>2</sup>Department of Zoology, Wildlife and Fisheries, University of Agriculture, Faisalabad, Punjab, Pakistan.

<sup>3</sup>Department of Management Sciences, COMSATS University Islamabad, Abbottabad Campus, KP, Pakistan.

<sup>4</sup>Department of Zoology, Government College University, Lahore, Punjab, Pakistan.

<sup>5</sup>College of Veterinary Sciences, The University of Agriculture, Peshawar, Pakistan.

<sup>6</sup>Department of Biochemistry, The Women University Multan, Punjab, Pakistan.

<sup>7</sup>Department of Biology, Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi, Punjab, Pakistan.

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**Correspondence to:** Habiba Jamil, Department of Biological Sciences, The Superior University Lahore, Punjab, Pakistan.

**Email:** [hibaajamil99@gmail.com](mailto:hibaajamil99@gmail.com)

### Declaration

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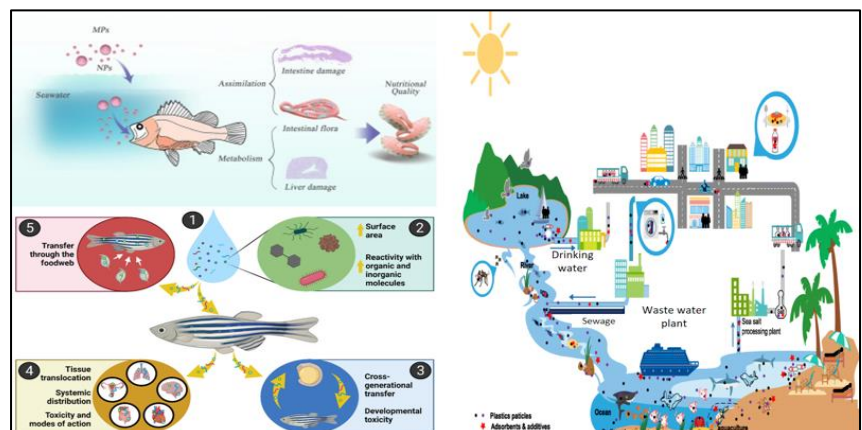
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### ABSTRACT

Concerns regarding the effects of the ubiquitous environmental contaminant polystyrene nanoplastics (PS-NPS) on aquatic environments, specifically in fisheries biology, have been raised. Because of PS-NPs special characteristics, such as their tiny size, large surface area, and hydrophobic nature, they are highly bioavailable and can enter the food chain by being consumed by aquatic creatures. With an emphasis on fish physiology, behavior, and reproductive health, this review paper thoroughly examines how PS-NPS impacts aquatic life. Fish species have altered development rates, behavioral abnormalities, and decreased reproductive success as a result of PS-NPs' toxicological effects, which include oxidative stress, inflammation, bioaccumulation, and disturbance of the endocrine and immunological systems, according to the review. The paper also addresses how PS-NPs interact with other environmental stresses, i.e., pesticides and heavy metals, which might increase their toxicity. The review also emphasizes the difficulties in determining PS-NPs' whole ecological effect because of the intricacy of their interactions in various aquatic habitats. Additionally included are potential remediation techniques to lessen PS-NPs' negative effects on aquatic ecosystems. These include novel techniques, including the use of nanomaterials for PS-NP sorption, bio-based remediation employing microbes and algae, and physical techniques like sedimentation and filtration. To address the rising danger presented by PS-NPs and safeguard fishery resources, the study highlights the necessity of multidisciplinary research, regulatory frameworks, and coordinated management techniques. The article's conclusion offers suggestions for further study targeted at creating long-term strategies to reduce PS-NP contamination in aquatic environments.

### Graphical Abstract



## INTRODUCTION

PS-NPs are found in both freshwater and marine settings worldwide and are sourced via industrial runoff, wastewater effluents, and the weathering of larger polystyrene products (Ijaz et al., 2024). The significance of fisheries biology, which is essential for tracking fish populations, evaluating ecological health, and comprehending trophic dynamics, is highlighted by the growing prevalence of PS-NPs in aquatic environments. Studying the relationships between PS-NPs and fish physiology, behavior, and reproduction is crucial for preserving aquatic biodiversity, ensuring food security, and ensuring the sustainability of communities that depend on fisheries (Abbas et al., 2024). Fish are also important indicators of environmental quality and essential parts of aquatic food webs. The advent of nanoplastics poses a more insidious threat due to their minute size, which allows them to infiltrate biological membranes, bypass cellular barriers, and accumulate in tissues of creatures, including humans (Joksimovic et al., 2022). Since nanoplastics cannot be seen with the human eye, they are more difficult to detect and control than macro- and microplastics. They may also absorb and transport harmful contaminants, including pesticides, heavy metals, and persistent organic pollutants, increasing their toxicity, thanks to their high surface area-to-volume ratio (Okoye et al., 2022). Concerns about nanoplastics' potential to upset ecosystems, bioaccumulate in food chains, and endanger human and wildlife health have grown as scientific knowledge of them has expanded. The difficulty is exacerbated by the absence of established techniques for identifying, quantifying, and evaluating the ecological impact of nanoplastics, underscoring the pressing need for more study, legislative changes, and environmentally friendly plastic substitutes (Allan et al., 2021).

A significant subgroup of nanoplastic contaminants, polystyrene nanoplastics (PS-NPs), has drawn more scientific interest because of their distinct physicochemical characteristics, extensive use, and enduring environmental presence (Wang et al., 2021). A lightweight, aromatic hydrocarbon polymer derived from the monomer styrene, polystyrene, makes up the structural makeup of PS-NPs, which are synthetic polymeric particles. Because of their high surface-area-to-volume ratio, heightened reactivity, and improved capacity to pass through biological membranes, these nanoplastics, which are usually smaller than 100 nanometers, have the potential to be hazardous to living things on a cellular and systemic level. PS-NPs can be spherical, irregular, or shattered particles, and they frequently have surface functional groups (such as amines and carboxyl) that affect how they interact with biological systems and environmental matrices (Libralato et al., 2017). The breakdown of bigger polystyrene-based items, such as food containers, packing materials, disposable utensils, and expanded polystyrene foam used in transportation and insulation, is one of the main sources of PS-NPs. Particularly in terrestrial and aquatic settings, these

materials deteriorate by processes such as mechanical fragmentation, thermal oxidation, and photodegradation. Furthermore, PS-NPs are common in freshwater, marine, and even atmospheric systems since they might come via runoffs, industrial operations, and urban wastewater discharge (Kumar et al., 2023). They build up in sediments, water columns, and biota because of their microscopic size, which enables them to evade traditional filtering systems. PS-NPs are widely distributed and may pose health hazards, as evidenced by studies that found them in human blood, fish, and invertebrates (Mousazadehgavan et al., 2024). The pervasiveness of PS-NPs in urban and natural ecosystems emphasizes the urgent need for enhanced waste management techniques, thorough monitoring, and regulatory measures to lessen their negative effects on the environment and biology (Awewomom et al., 2024).

The ecological and biological effects of pollutants are largely determined by environmental persistence, aggregation, and transport dynamics, especially when it comes to newly developing contaminants like heavy metals, nanomaterials, microplastics, and persistent organic pollutants (Wang et al., 2020). The capacity of a material to withstand deterioration by physical, chemical, or biological processes and hence endure in ecosystems for long periods is known as environmental persistence. Polychlorinated biphenyls (PCBs) and perfluorinated chemicals, for example, are well-known for their remarkable stability, which makes it easier for them to accumulate over time in soil, sediments, and water bodies (Nieder et al., 2018). The process by which individual particles group to create bigger agglomerates is known as agglomeration dynamics, and it frequently modifies the physicochemical characteristics, mobility, and bioavailability of these particles. Nanomaterials or microplastics may combine with other particles or organic matter in aquatic environments, changing their reactivity, sinking behavior, and interactions with biota (Al-Thawadi et al., 2020). The movement of these materials through the air, water, and soil is referred to as transport dynamics. It is influenced by a variety of elements, including biological vectors, hydrodynamics, and atmospheric circulation. Particle size, hydrophobicity, surface charge, and environmental factors, including temperature, ionic strength, and pH, all affect these dynamics (Liao et al., 2015). Compared to their dispersed counterparts, aggregated particles may travel differently, which frequently facilitates their transboundary migration and worldwide dissemination. When taken as a whole, these elements influence exposure routes, ecological hazards, and the efficacy of remediation techniques, all of which contribute to the complicated environmental behavior of pollutants. Predicting the destiny of contaminants, evaluating environmental risks, and creating strategies for sustainable pollution control all depend on an understanding of how persistence, aggregation, and transit interact (Dunnivant et al., 2006). Because it sheds light on fish population dynamics, reproductive patterns, and species interactions, fisheries biology is essential to

preserving the health of aquatic ecosystems. It aids in evaluating the effects on aquatic life of pollution, overfishing, and habitat destruction. Fisheries biology promotes ecological balance, biodiversity protection, and the long-term sustainability of aquatic resources by guiding sustainable management techniques (Marimuthu et al., 2020).

### Sources and Environmental Fate of Polystyrene Nanoplastics

The main sources of polystyrene nanoplastics (PS-NPs), a subset of nanoplastics produced by the decomposition of bigger plastic trash, are both industrial and consumer-based (Ali et al., 2022). PS-NPs are produced industrially during the production, processing, and disposal of products that include polystyrene, such as insulation, packaging materials, and single-use items like cups and silverware. Widespread use and inappropriate disposal of polystyrene items by consumers greatly contribute to environmental pollution; over time, photodegradation, mechanical abrasion, and normal wear and tear all aid in the creation of nanoplastic particles. Following their discharge, PS-NPs infiltrate aquatic ecosystems via several important routes, such as wastewater treatment plant effluents, urban stormwater runoff, landfill leachates, and the gradual disintegration of macro- and microplastics that are already in the environment. Because of their small size, a significant percentage of nanoplastics evade traditional barriers and eventually build up in freshwater and marine systems, even if some of them are filtered in treatment systems (Devi et al., 2022). PS-NPs have exceptional environmental durability in these conditions, fending against chemical and microbiological deterioration. Depending on variables including pH, ionic strength, and the presence of organic matter, they tend to aggregate and create complex colloidal structures that can either settle in sediments or stay floating in the water column. Additionally, they may enter distant aquatic environments and bioaccumulate in species of all trophic levels due to their tiny size and surface characteristics, which enable long-range transport via hydrodynamic processes. Because of these traits, PS-NPs are a persistent and widespread contaminant, which raises serious questions regarding their long-term effects on the environment and human health (Wang et al., 2021).

### Bioavailability and Uptake Mechanisms in Aquatic Organisms

Aquatic creatures' bioavailability and absorption processes are important factors in determining how pollutants, such as heavy metals and nanoparticles, affect physiological and ecological health (Kahlon et al., 2018). These processes start when chemicals contact biological membranes, which operate as specific obstacles to cellular entrance. Contaminants interact with lipid bilayers, protein channels, and transporters when they come into contact with the gills, skin, and digestive epithelia in aquatic settings. A substance's membrane permeability and transport efficiency are largely determined by its physicochemical characteristics, especially its size, surface

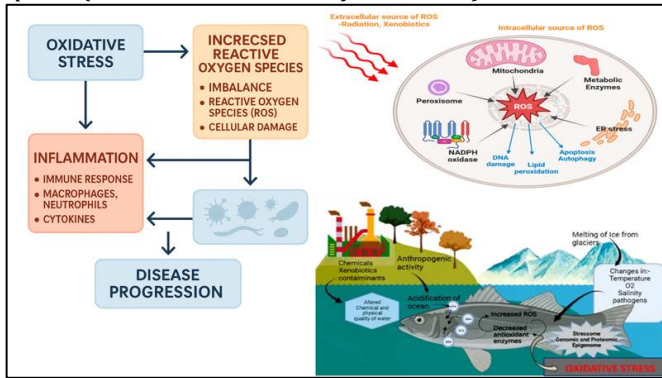
charge, and surface modifications. For example, surface charge affects the strength of electrostatic attraction or repulsion with negatively charged cell surfaces, but smaller particles can more easily pass through cellular membranes. By changing hydrophobicity or facilitating receptor-mediated recognition, surface changes like coating with biocompatible polymers or functional groups can either promote or prevent cellular absorption (Kunjiappan et al., 2021). Particularly in fish and aquatic invertebrates, endocytosis is a crucial absorption route that enables cells to absorb particles by receptor-mediated endocytosis, phagocytosis, or pinocytosis. Following internalization, these particles may move to other tissues and organs through intracellular trafficking. Because of their high surface area and direct exposure to the aquatic environment, gill epithelia are the principal sites of absorption in fish. Invertebrates may also absorb through specialized feeding appendages or integuments. Thus, a substance's bioavailability is influenced by a complex interaction of particle properties, membrane dynamics, and active cellular processes that govern its absorption, distribution, and ultimate biological impact rather than just its ambient concentration (Stielow et al., 2023).

### Physiological and Molecular Impacts on Fisheries Species

#### Oxidative Stress and Inflammation

Inflammation and oxidative stress are intricately linked biological processes that are essential to the etiology of many chronic illnesses, such as cancer, diabetes, neurological diseases, and cardiovascular problems (Sharifi-Rad et al., 2020). Damage to cells and molecules results from oxidative stress, which is caused by an imbalance between the body's antioxidant defense systems and the generation of reactive oxygen species (ROS). These ROS, which comprise free radicals like hydroxyl radical ( $\text{OH}\cdot$ ) and superoxide anion ( $\text{O}_2^-$ ), can harm proteins, lipids, and DNA, which will ultimately affect regular biological processes. The body's defense mechanism against damage or infection is inflammation, which is characterized by immune cell activation and the production of pro-inflammatory cytokines such as interleukin-6 (IL-6), tumor necrosis factor-alpha (TNF- $\alpha$ ), and interleukin-1 $\beta$  (Kany et al., 2019). Inflammation is strictly controlled under normal circumstances and goes away after the threat has been removed. Chronic inflammation, on the other hand, might prolong oxidative stress by inducing immune cells like neutrophils and macrophages to produce more ROS. By triggering redox-sensitive transcription factors like NF- $\kappa$ B and AP-1, which encourage the production of inflammatory genes, ROS, on the other hand, can intensify the inflammatory response. This results in a vicious cycle where inflammation and oxidative stress feed off one another, causing long-term tissue damage and the advancement of illness. Determining how oxidative stress and inflammation interact has become crucial to creating new treatment approaches that combine anti-inflammatory drugs, antioxidants, and lifestyle changes like exercise and nutrition to end this vicious cycle (Forman et al., 2021).

**Figure 1**  
*Physiological and Molecular Impacts on Fisheries Species(Oxidative Stress and Inflammation)*



**Disruption of Endocrine Functions**

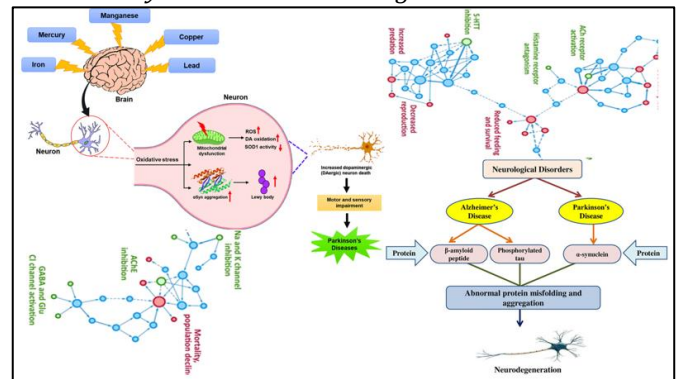
Endocrine disruption is the term used to describe the interference of artificial or natural substances with the regular operation of the hormone system, which controls development, metabolism, reproduction, and homeostasis in living things (Guarnotta et al., 2022). Bisphenol A (BPA), phthalates, dioxins, polychlorinated biphenyls (PCBs), pesticides like DDT, and heavy metals like lead and cadmium are examples of endocrine-disrupting chemicals (EDCs) that can imitate, obstruct, or change the body's natural hormone production, transport, binding, and elimination processes. Numerous physiological and developmental problems, including thyroid malfunction, metabolic syndromes, neurological deficiencies, reproductive diseases, and an elevated risk of hormone-related malignancies, can result from these changes. The mechanisms by which these chemicals exert their effects are complex and multifactorial, often involving interactions with estrogen, androgen, or thyroid hormone receptors, or through epigenetic modifications that alter gene expression (Amir et al., 2021). Furthermore, the widespread presence of EDCs in plastics, food packaging, personal care products, and the environment has raised significant public health concerns, prompting regulatory actions and ongoing research aimed at understanding their long-term impact on endocrine health and developing strategies for mitigation and safer alternatives. EDCs are especially harmful during critical windows of development, such as the fetal, neonatal, and pubertal stages, where even low-dose exposures can result in long-lasting or transgenerational effects (López-Rodríguez et al., 2021).

**Neurotoxicity and Behavioral Changes**

The term "neurotoxicity" describes harm to the nervous system brought on by exposure to natural or synthetic neurotoxicants, such as industrial chemicals, pesticides, heavy metals (such as lead and mercury), and some medications (Walker et al., 2000). Numerous behavioral and cognitive abnormalities can result from this injury, which can drastically modify the structure and function of the brain. Due to its extreme sensitivity and complexity, the central nervous system (CNS) is especially susceptible to these harmful shocks. Impaired memory, learning challenges, motor dysfunction, anxiety, sadness, and, in more severe situations, neurodegenerative illnesses like Parkinson's or Alzheimer's, are all signs of neurotoxicity.

Neurotoxic exposure has been connected to alterations in neurotransmitter levels, oxidative stress, inflammation, and neuronal death in both human and animal models (Bains et al., 1997). The length, timing, and intensity of exposure, such as throughout developmental stages, often determine behavioral changes. For example, exposure to neurotoxicants during pregnancy or the early years of life can interfere with important phases of brain development, resulting in long-lasting behavioral changes such as concentration problems, increased aggressiveness, and social disengagement. Furthermore, not all neurotoxicity symptoms appear right away, some consequences could take years to manifest after the initial exposure. Therefore, protecting mental health and cognitive function throughout life requires identifying and reducing the sources of neurotoxicants in the environment, the workplace, and medications (Cardenas-Iniguez et al., 2022).

**Figure 2**  
*Neurotoxicity and Behavioral Changes*



**Reproductive Impairments and Transgenerational Effects**

Chronic stress exposures, endocrine-disrupting substances, and environmental pollutants all have serious but sometimes overlooked impacts on reproduction and generational repercussions (Rattan et al., 2019). Reproductive health is compromised by these deficits, which show up as decreased fertility, changed hormone levels, aberrant sperm morphology, and irregular ovarian cycles. Gametogenesis, fertilization, implantation, and embryonic development can all be hampered in both males and females by exposure to toxic substances such as pesticides, plasticizers (like BPA and phthalates), heavy metals (like cadmium and lead), and persistent organic pollutants. Sadly, these negative consequences are not always limited to the person who was directly exposed, they can also affect subsequent generations due to epigenetic changes that change gene expression without altering the DNA sequence, such as DNA methylation, histone modification, and non-coding RNA expression (Bure et al., 2022). Reproductive issues, metabolic ailments, neurodevelopmental abnormalities, and even behavioral alterations in children can result from these molecular modifications, which are transmissible through germ cells in animals and increasingly in humans. For example, endocrine disruptor exposure during pregnancy has been associated with altered puberty onset and reproductive problems in females, as well as lower sperm counts and testicular dysgenesis in male offspring. Since

they suggest that present environmental and lifestyle variables may influence the reproductive and general health trajectories of several generations, these transgenerational impacts pose serious public health problems. To reduce long-term hazards to human and ecological health, preventative measures and well-informed regulatory policies must be developed, which requires a knowledge of the mechanisms behind reproductive deficits and transgenerational inheritance (Montano et al., 2020).

$$P_n = f((E \otimes G \otimes T) \otimes [(E_p \otimes M) + (S \otimes R)]) \rightarrow H_{n+1}$$

where:

- $P_n$  = Phenotypic manifestation in the n-th generation, such as fertility disorders, behavioral changes, or metabolic diseases.
- $E$  = Environmental exposure (e.g., toxicants, endocrine disruptors, stress).
- $G$  = Genetic predisposition or susceptibility of the exposed individual.
- $T$  = Time and dose-dependent factors influencing exposure.
- $E_p$  = Epigenetic alterations (DNA methylation, histone modification, non-coding RNA).
- $M$  = Maternal effects influencing fetal development.
- $S$  = Stress factors, including prenatal stress or psychological distress in the exposed individual.
- $R$  = Reproductive system disruption (e.g., hormone imbalances, gametogenesis impairment).
- $H_{n+1}$  = Heritable alterations transmitted to the (n+1)-th generation, resulting in changes in the offspring's phenotype.

This model illustrates how environmental (E) and genetic (G) factors, in conjunction with time (T) and transgenerational epigenetic mechanisms ( $E_p$ ), can interact with stress (S) and reproductive system disruptions (R) to yield a heritable change in phenotype across generations. These multivariable interactions suggest that an individual's exposure to harmful substances can not only impact their immediate health but also impose lasting effects on their descendants, with the potential for compounded effects through successive generations. This highlights the importance of considering both direct and indirect factors when studying transgenerational inheritance and reproductive health.

### Immune System Modulation and Disease Susceptibility

Modulation of the immune system is essential in defining a person's vulnerability to several illnesses, including autoimmune, infectious, and even malignant ailments (Brodin et al., 2017). By identifying and getting rid of dangerous infections and aberrant cells, the immune system, a dynamic and tightly controlled network of cells, tissues, and signaling molecules, maintains homeostasis. Its efficacy, however, depends on striking a careful balance between repression and activation. The body assaults its tissues when immune responses are overstimulated, as in autoimmune illnesses like lupus or rheumatoid arthritis. This results in organ damage and persistent inflammation. On the other hand, immunosuppression or immune dysregulation, which can be brought on by genetic

predispositions, environmental stressors, malnourishment, aging, or exposure to immunotoxic agents, can make it more difficult for the body to mount a strong defense, making immunocompromised people more susceptible to infections like influenza, TB, or opportunistic pathogens (Gambineri et al., 2012). Chronic low-grade inflammation also quietly changes immune function and increases vulnerability to illness. It is a characteristic of metabolic diseases and aging (inflammaging). Immunotherapies and vaccinations are examples of contemporary medical interventions that aim to optimize immune responses to maximize protective immunity and reduce unfavorable effects. To prevent unforeseen outcomes, these therapies must be customized to each patient's unique immunogenetic profile. Ultimately, knowing how the immune system is modulated through cytokine signaling, T-cell regulation, and microbiome-immune interactions offers important insights into how to prevent and treat disease as well as how to develop precision medicine strategies that take into account each person's particular immune profile (Juarez et al., 2022).

### Bioaccumulation and Trophic Transfer in Aquatic Food Webs

In aquatic food webs, bioaccumulation and trophic transfer pose serious ecological and health risks, especially for persistent pollutants such as heavy metals, polychlorinated biphenyls (PCBs), and other organic contaminants (Corsolini et al., 2017). Bioaccumulation, which frequently starts with primary producers or lower trophic creatures like phytoplankton and zooplankton, is the term used to describe the gradual accumulation of hazardous compounds in the tissues and organs of organisms over time in aquatic environments. Once absorbed or consumed, these pollutants are difficult to metabolize or eliminate, which causes them to build up in important organs, including the kidneys, liver, gills, and aquatic animals' muscular tissues. As these toxins move up the food chain through a process called biomagnification, the issue becomes increasingly alarming. Humans and other top-level consumers eventually ingest the contaminated plankton that is swallowed by tiny fish, which are then consumed by larger predatory fish (Thakur et al., 2025). For instance, consuming fish that have accumulated mercury or cadmium can seriously endanger human brain and renal health. The synergistic interactions between co-contaminants further exacerbate the intricacy of trophic transmission. When numerous contaminants such as heavy metals and PCBs coexist in the aquatic environment, they might interact in ways that enhance toxicity by changing metal-binding proteins, generating oxidative stress, or affecting endocrine function, thereby magnifying their individual deleterious effects. These interactions can raise the ecological load of pollution and cause aquatic creatures to exhibit erratic and exaggerated biological responses. Therefore, for efficient risk assessment and the creation of regulatory mechanisms to protect aquatic life and public health, it is crucial to comprehend both the accumulation in certain tissues and the trophic dynamics of these toxicants (Dey et al., 2024).

**Table 1**  
*Bioaccumulation and Trophic Transfer in Aquatic Food Webs*

Contaminant	Aquatic Organism & Trophic Level	Accumulation Sites	Trophic Transfer Pathway	Synergistic Co-Contaminants	Ecological & Human Implications
Methylmercury (MeHg)	Zooplankton (Primary Consumer)	Whole body; incorporated in lipid and protein fractions	Uptake from contaminated phytoplankton	Cadmium – increases oxidative stress	Bioavailability to small fish; poses neurodevelopmental risks if passed to higher consumers
Methylmercury	Tuna (Tertiary Consumer)	Muscle tissue; persistent and accumulates with age	From smaller contaminated fishlike sardines and mackerel	Polychlorinated biphenyls (PCBs) increase neurotoxicity	Elevated levels in seafood; associated with cognitive decline and fetal abnormalities
Cadmium (Cd)	Bivalves like mussels (Filter feeders)	Gills, digestive gland; binds to metallothioneins	Absorption from water and sediment	Lead – disrupts calcium metabolism	May exceed food safety limits; kidney and bone disorders in human consumers
Cadmium	Freshwater shrimp (Benthic Detritivore)	Hepatopancreas; critical in detox pathways	Accumulates from bottom sediments and organic debris	PCBs – inhibits detox enzymes	Chronic toxicity, biomagnified in bottom-feeding fish
PCBs	Zooplankton (Primary Consumer)	Lipid membranes; persists for long periods	Taken up through water and diet	Organochlorine pesticides – hormonal disruption	Starts accumulation in food chain; affects fish reproduction
PCBs	Salmon (Top Predator)	Adipose tissue and muscle; long-term storage	From consumption of smaller, contaminated fish	PAHs – synergistic hepatotoxicity	Found in human diets; increases cancer risk through fatty fish consumption
Microplastics	Filter feeders (e.g., oysters)	Gills and digestive tract; physically retained	Ingested directly from water	Heavy metals like zinc and lead – bind to particles	Act as carriers for toxicants; cause inflammation and gut damage
Microplastics	Sardines (Secondary Consumer)	GI tract; sometimes translocated to liver	Consumed along with plankton	PAHs – co-leach from plastics	Alters feeding behavior and digestive enzyme activity
Lead (Pb)	Snails and mollusks (Benthic Level)	Gills and nephridia (excretory organ)	Absorbed from sediments in polluted waters	Arsenic – increases cytotoxicity	Neurotoxicity; bioaccumulates in fish-eating birds and humans
Arsenic	Tilapia (Omnivore)	Skin, liver, muscle; inorganic forms highly toxic	Enters via sediment and detritus ingestion	Mercury – exacerbates genotoxic stress	Chronic intake linked to skin lesions and carcinogenesis
Selenium	Carp (Generalist Feeder)	Liver and reproductive tissues	Absorbed from sediment and dietary algae	Mercury – exhibits antagonistic/protective interactions	Beneficial at low levels; harmful in excess, especially during gestation
DDT	Top predators like seabirds	Fatty tissues, liver, eggs	Concentrates through long food chains	PCBs – co-accumulate and reduce reproductive success	Eggshell thinning; causes long-term reproductive harm in wildlife
Chromium (Cr)	Crustaceans (e.g., prawns)	Exoskeleton and gills; affects molting	Taken up from polluted sediment	Nickel – co-interference with molting and immune responses	Alters development and reduces viability of larvae
PAHs	Benthic worms (Deposit Feeders)	Soft tissues; accumulate with organic matter	From sediment ingestion	PCBs – increase DNA damage and liver anomalies	Entry point for fish; contributes to long-term bioaccumulation
Pharmaceuticals (SSRIs)	Perch (All consumer levels)	Brain, plasma; affect behavior	Direct absorption and prey ingestion	Synthetic hormones – endocrine system disruption	Alters predator avoidance and mating behavior in fish
PFAS	Amphibians and fish	Blood, liver, and developing eggs	Persistent compounds transferred maternally	PCBs – long-term body burden increase	Bioaccumulative even in humans; affects thyroid and immunity
Mercury (inorganic)	Aquatic insects (Intermediate Trophic Level)	Gut and cuticle; methylated by bacteria	Later consumed by fish and birds	Selenium – partial detox pathway	Increases through bird predation; linked to bird embryo mortality
Organochlorine pesticides	Pelagic fish (Migratory Predators)	Brain, liver, reproductive tissues	Bioaccumulates across long-distance food chains	PAHs – suppress detox enzymes	Found in high-fat fish species; potential carcinogenicity in consumers

**Implications for Fisheries Biology and Aquatic Biodiversity**

Environmental stressors have wide-ranging and significant effects on fisheries biology and aquatic biodiversity, especially when it comes to contaminants like heavy metals and chemical discharge (Samuel et al., 2023). The disturbance of fish development, survival, and recruitment rates is among the most direct effects, and it

has a direct impact on the long-term viability of fish populations. Toxin exposure and poor water quality can reduce the number of juveniles that reach maturity by stunting development, increasing mortality, and interfering with reproductive cycles. Aquatic species' ability to adapt to changes in their environment is weakened as a result of altered population dynamics, such as skewed sex ratios, decreased genetic diversity, and

changes in age structure (Stelkens et al., 2010). The equilibrium of aquatic ecosystems becomes more unstable when important species disappear or decline, which frequently leads to a loss of biodiversity and a reduction in ecosystem services. Additionally, aquaculture and fishery-based livelihoods are seriously threatened by these biological and ecological changes, especially in areas where populations primarily depend on fish as a source of economic revenue and protein. In addition to lowering fishery output, declining fish supplies, rising disease rates, and the bioaccumulation of toxins in edible species pose major health risks to the general public. Therefore, anthropogenically driven aquatic environment degradation poses a serious threat to conservation initiatives as well as the socioeconomic stability of people throughout the world who depend on fisheries (Han et al., 2024).

**Prospective Remediation and Mitigation Strategies  
Bioremediation Approaches**

A viable and sustainable strategy for reducing the environmental effects of polystyrene nanoplastics (PS-NPs) is bioremediation, which focuses on using bacteria, fungi, and microalgae to break them down (Tripathi et al., 2025). These microbes can interact with, change, and occasionally mineralize PS-NPs into less hazardous or inert byproducts because of their distinct metabolic pathways and enzymatic capabilities. Through processes including adsorption on cell surfaces, internalization, and enzymatic breakdown, microalgae like *Chlorella vulgaris* and *Scenedesmus obliquus* have demonstrated promise in PS-NP absorption and biodegradation. They support nutrient recycling and oxygenation in aquatic environments, in addition to helping to remove waste. Similar to this, fungus, especially species like *Aspergillus niger* and *Trametes versicolor*, release potent oxidative enzymes like laccases and peroxidases that may oxidize the backbone of polystyrene, starting the depolymerization process and allowing the fragments to be assimilated (Ramamurthy et al., 2024). These fungal entities' capacity to infiltrate PS-NP matrices and colonize solid surfaces makes them particularly potent. In the meantime, the PS-NP degradation potential of several bacterial strains, such as *Pseudomonas putida*, *Bacillus subtilis*, and *Rhodococcus ruber*, has been thoroughly investigated. These strains use enzymes like oxygenases and hydrolases to break down polymer chains and use the resulting compounds as carbon sources. Because some species may increase each other's enzymatic activity, the synergy among these microbial communities further

improves degradation efficiency. To enhance these bacteria's metabolic capacities and enable more thorough and quick PS-NP breakdown in terrestrial and aquatic environments, genetic engineering and bioaugmentation techniques are being investigated more and more. The rising problem of nanoplastic contamination may be solved in an environmentally responsible, economical, and scalable way by incorporating these bioremediation approaches into waste management frameworks (Zhou et al., 2022).

**Eco-friendly Filtration and Adsorption Technologies**

With rising worries about water shortages and environmental contamination, environmentally friendly filtration and adsorption technologies have become essential parts of sustainable water treatment techniques (Younas et al., 2021). The exceptional ability of biochar, zeolites, and nanocomposites to absorb pollutants while reducing their ecological effect makes them stand out among these green materials. The carbon-rich substance known as biochar, which is produced by pyrolyzing biomass, has a large surface area, porosity, and functional groups that allow it to efficiently adsorb pathogens, organic pollutants, and heavy metals from wastewater. In addition to lessening environmental impacts, its manufacture from agricultural waste provides a cheap and sustainable option for decentralized water filtration systems. Zeolites are crystalline aluminosilicates that may be manufactured synthetically or naturally. They have homogeneous pore diameters and a high cation-exchange capacity, which makes them perfect for eliminating radioactive materials, heavy metals, and ammonium ions from polluted water (Qasem et al., 2021). Their sustainability profile is further enhanced by their reusability and thermal stability. By combining nanoparticles like metal oxides or carbon-based materials with polymers or other substrates, nanocomposites provide customized surface chemistries and multifunctional qualities that improve the effectiveness of adsorption, antibacterial activity, and the catalytic breakdown of contaminants. These cutting-edge materials may be designed to specifically target pollutants, including newly discovered pollutants like endocrine disruptors and medicines. Utilizing waste-derived materials, cutting energy use, and minimizing secondary pollution, the synergistic application of biochar, zeolites, and nanocomposites represents a promising frontier in environmentally friendly water treatment (Hublikar et al., 2024). This approach is in line with the principles of sustainable development and green chemistry.

**Table 2**  
*Prospective Remediation and Mitigation Strategies for PS-NP Contamination*

Strategy Type	Remediation Agent/Material	Mechanism of Action	Application Area	Advantages	Limitations
Bioremediation	<i>Chlorella vulgaris</i> (microalgae)	Utilizes its negatively charged cell wall to adsorb PS-NPs. The microalgae also sequester particles via photosynthetic assimilation.	Commonly used in freshwater ponds and reservoirs, particularly in nutrient-rich waters.	Renewable and oxygen-producing; supports ecological balance in aquatic systems.	Sensitive to pH, temperature, and salinity changes; requires stable conditions.
Bioremediation	<i>Scenedesmus obliquus</i>	Removes PS-NPs via extracellular polymeric substances (EPS) and	Applied in open algal ponds and photobioreactors	Low-cost, easy to culture, and can simultaneously	Susceptible to contamination and

		intracellular uptake under light exposure.	treating municipal water.	reduce nutrient loads.	competition from other algal species.
Bioremediation	<i>Aspergillus niger</i>	Degrades polymer chains enzymatically through secreted ligninolytic enzymes such as peroxidases.	Effective in sediment-rich water bodies and contaminated estuaries.	Capable of degrading both PS-NPs and associated pollutants like PAHs.	Growth inhibition occurs under high pollutant concentrations or nutrient limitation.
Bioremediation	<i>Trametes versicolor</i>	White-rot fungus producing laccase and manganese peroxidase that oxidize microplastics.	Suitable for soil-aquatic boundary zones and forest runoff sites.	Broad-spectrum degradation; can degrade synthetic additives in PS.	Requires consistent moisture and carbon source; slower than bacterial systems.
Bioremediation	<i>Pseudomonas putida</i>	Produces biosurfactants that enhance PS-NP bioavailability and supports metabolic degradation.	Found in polluted river mouths, wastewater outflows, and treatment tanks.	Known for plastic-degrading versatility and robust adaptation.	Biofilm formation may reduce flow rates in treatment systems.
Bioremediation	<i>Bacillus subtilis</i>	Forms resilient biofilms on PS-NPs and breaks down surface polymers through hydrolase activity.	Integrated into constructed wetlands and lagoon systems.	Spore-forming, heat-resistant, and adaptable in various pH ranges.	Lower PS-NP degradation rate compared to mixed consortia.
Bioremediation	Microbial consortia	Synergistic interactions between multiple microbial species improve overall plastic degradation rates.	Ideal for natural ecosystems and complex wastewater mixtures.	Enhanced enzyme diversity and stability; more ecologically compatible.	Community shifts may reduce long-term stability and effectiveness.
Bioremediation	Genetically engineered bacteria	Inserted genes allow production of enhanced plastic-degrading enzymes like PETase and cutinase.	Experimental use in closed bioreactor systems with PS-NP contamination.	High specificity and degradation speed; potential for controlled biodegradation.	Raises concerns about ecological impact, containment, and biosafety.
Filtration/Adsorption	Biochar from agricultural waste	Removes PS-NPs via surface adsorption, van der Waals forces, and pore entrapment.	Used in rural drinking water systems and natural stream beds.	Low-cost, carbon-neutral, and often produced locally.	Adsorption capacity declines over time; regeneration is difficult.
Filtration/Adsorption	Iron oxide-coated activated carbon	Combines large surface area of activated carbon with magnetic recovery properties.	Employed in compact filtration units and water refill stations.	High affinity for nano-sized particles and easy post-use recovery.	Costlier production and less effective against high-volume pollution.
Filtration/Adsorption	Natural zeolites	Adsorbs contaminants by ion exchange, molecular sieving, and electrostatic interactions.	Common in groundwater filters and slow sand filtration systems.	Readily available and non-toxic; works across pH ranges.	May require modification to enhance affinity for polymers.
Filtration/Adsorption	Synthetic zeolites (e.g., ZSM-5)	Engineered pore structure allows precise trapping of nano-sized PS particles.	Applied in advanced industrial wastewater systems and research setups.	Highly efficient and chemically stable under harsh conditions.	Production costs are high; often reserved for high-tech applications.
Filtration/Adsorption	Graphene oxide nanocomposites	Provides high surface area and strong adsorption via $\pi$ - $\pi$ stacking and van der Waals forces.	Used in high-performance water purification membranes.	Rapid and selective removal of micro- and nano-plastics.	Expensive, and may lead to nanomaterial residues in treated water.
Filtration/Adsorption	Chitosan-coated membrane filters	Bioadhesive properties allow strong binding to PS-NPs while maintaining water flow.	Ideal for modular membrane bioreactors in remote areas.	Biodegradable, non-toxic, and selective for synthetic particles.	Short operational lifespan and low mechanical durability.
Filtration/Adsorption	Magnetic Fe <sub>3</sub> O <sub>4</sub> nanocomposites	Captures PS-NPs through adsorption followed by magnetic retrieval from water.	Portable kits for emergency clean-ups and industrial spills.	Reusable and easily removed from treated systems.	Susceptible to agglomeration and reduced surface activity over time.
Filtration/Adsorption	Cellulose sponge filters	Utilize modified cellulose fibers to trap PS-NPs by adhesion and filtration.	Applied in decentralized or temporary filtration systems.	Biocompatible, flexible, and affordable for rural use.	Limited reusability and prone to microbial degradation.
Filtration/Adsorption	TiO <sub>2</sub> -based photocatalysts	Use UV light to generate reactive species that degrade PS polymers and residues.	Deployed in UV-integrated treatment plants and solar-driven reactors.	Dual-action purification: degrades pollutants and disinfects pathogens.	Requires continuous UV exposure; ineffective in turbid waters.
Hybrid Approach	Bioreactor with immobilized microbes and adsorbents	Couples microbial plastic degradation with enhanced adsorption for complete remediation.	Used in municipal-scale water and wastewater treatment facilities.	High efficiency, modular scalability, and adaptable to pollutant type.	Complex operation and high maintenance cost over time.

### Green Chemistry and Biodegradable Alternatives

In the field of sustainable materials research, green chemistry and biodegradable substitutes have become revolutionary, especially in the fight to replace persistent polymers like polystyrene (Mülhaupt et al., 2013). Because it is lightweight and insulating, polystyrene is frequently used in packaging. However, because it is not biodegradable and contributes to microplastic contamination, it is a major environmental hazard. Sustainable polymer alternatives made from renewable feedstocks like starch, cellulose, polylactic acid (PLA), and polyhydroxyalkanoates (PHA) are being developed using the ethos of green chemistry, which promotes the design of chemical products and processes that minimize or eliminate hazardous substances. These biodegradable polymers reduce ecological impact by mimicking the functional properties of polystyrene while degrading more safely in the environment (Qin et al., 2021). Beyond biodegradability, sustainable polymer design takes into account lifetime factors including carbon footprint, manufacturing energy usage, and recyclability. Therefore, to improve mechanical qualities and reduce costs, researchers are also looking at the use of waste biomass and natural additives. Many packaging businesses are increasingly investing in green solutions in response to environmental restrictions and the increased demand from consumers for eco-conscious products. While companies are increasingly embracing corporate sustainability goals that give priority to circular economy models, governments and regulatory agencies have started providing financial incentives, tax exemptions, and research grants to encourage the production of eco-friendly products. The move away from polystyrene and toward more intelligent, environmentally friendly packaging options that balance industrial efficiency with environmental responsibility is being accelerated by the confluence of technological advancement and financial incentives (Patel et al., 2023).

### Emerging Research Tools and Methodologies

Our knowledge of the behavior, distribution, and effects of polystyrene nanoplastics (PS-NPs) in biological systems and the environment is being completely transformed by new research instruments and techniques (Kik et al., 2020). One of the most important developments is the creation of high-resolution imaging and tracking methods, like electron microscopy, Raman spectroscopy, and fluorescence microscopy, which enable accurate localization and real-time visualization of PS-NPs at the cellular and subcellular levels within tissues. Researchers can now more clearly identify PS-NPs' bioaccumulation patterns and their toxicological consequences thanks to these imaging methods. In addition to these instruments, omics techniques, which include proteomics, metabolomics, and genomics, provide a thorough understanding of the molecular reactions of creatures exposed to nanoplastics. While proteomics provides information on changed protein expression and exposure-disturbed pathways, genomics assists in identifying genes that are up- or down-regulated in response to PS-NPs. Conversely, metabolomics shows changes in metabolic patterns, which aid in linking molecular alterations to physiological effects (Wishart et al., 2019). When combined, these methods provide a comprehensive

knowledge of PS-NPs' biological impacts. Furthermore, in silico modeling has become an essential tool for forecasting the long-term ecological dangers connected to exposure to nanoplastics. The environmental fate, transport, and bioavailability of PS-NPs in diverse ecosystems are simulated using computational models that incorporate empirical data. Additionally, by predicting possible long-term effects on ecosystem function, biodiversity, and trophic interactions, these models help to influence mitigation measures and regulatory frameworks. When taken as a whole, these cutting-edge techniques represent a paradigm change in the study of nanoplastics, allowing researchers to more accurately and predictively decipher intricate biological relationships and ecological effects than previously possible (Nene et al., 2025).

### Knowledge Gaps and Future Research Directions

Significant information gaps still impede comprehensive environmental protection and policy creation, despite growing awareness of the possible threats that polystyrene nanoplastics (PS-NPs) represent to aquatic ecosystems (Gonzalez-Pleiter et al., 2019). The standardization of PS-NP detection methods across various environmental matrices, such as water, sediment, and biota, is one crucial issue that needs attention. Inconsistencies in data collection, reporting, and interpretation between research are caused by the current absence of well-recognized methods and analytical methodologies. Although sophisticated methods like electron microscopy, Fourier-transform infrared spectroscopy (FTIR), and Raman spectroscopy are often used, their sensitivity and repeatability differ, especially at the nanoscale. For precise PS-NP contamination measurement, characterization, and comparison on a worldwide scale, standardized procedures must be established. Long-term ecological research on fisheries recovery in areas poisoned by PS-NP is also desperately needed. Long-term studies examining the cumulative effects on fish populations, reproductive health, trophic transfer, and ecological resilience are still few, despite the abundance of short-term toxicological data (Qasim et al., 2024). By knowing how fisheries react to PS-NP exposure over time, sustainable management techniques may be informed by knowledge of ecological thresholds and the possibility of natural recovery. Additionally, including PS-NP risk into environmental impact assessments (EIAs) is a crucial area for future study. Despite its growing ecological danger, nanoplastic pollution is still infrequently taken into account as a criterion in EIAs. To forecast exposure scenarios and evaluate risks for different aquatic animals, multidisciplinary techniques integrating toxicology, materials science, and ecological modeling will be necessary to include PS-NP risk evaluations into regulatory frameworks. All things considered, closing these knowledge gaps through concerted worldwide research projects will be essential for efficient risk assessment, the creation of policies, and ecological preservation (Weichselgartner et al., 2010).

### CONCLUSION

The effects of cadmium on aquatic organisms, especially red tilapia, are summarized as a complex web of ecological, physiological, and toxicological disruptions that highlight the pressing need for all-encompassing mitigating

measures. In addition to having long-term consequences on growth, reproduction, and survival, cadmium bioaccumulation impairs essential biological processes, such as immunological response and osmoregulation. These effects jeopardize environmental balance and biodiversity by reverberating across aquatic food webs. Potential solutions for cleaning up polluted water include microbial consortia, aquatic plant-based bioremediation, and adsorption techniques based on nanotechnology. However, customized deployment tactics that take into account local environmental factors, species sensitivity, and long-term ecological sustainability are necessary for these solutions to be effective. An integrated, multidisciplinary strategy is necessary to safeguard

aquatic health since the problem of heavy metal contamination crosses disciplinary borders. To create predictive models, early-warning systems, and regulatory frameworks that can stop pollution and repair impacted ecosystems, ecotoxicologists, environmental chemists, microbiologists, aquaculture specialists, and legislators must work together. To guarantee a robust and knowledgeable response to environmental challenges, these initiatives also need to incorporate community involvement, public awareness, and educational outreach. Ultimately, the sustainability of essential freshwater resources and the protection of aquatic habitats can only be achieved by a collaborative strategy that unites research, technology, and policy.

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