CHAPTER 15

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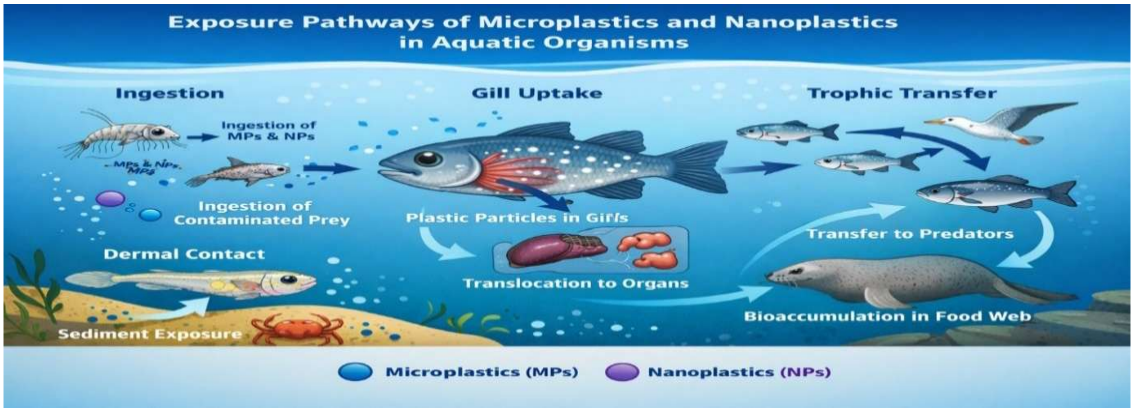
Ecotoxicological Impacts Of Microplastics And Nanoplastics On Aquatic Organisms

The rapid increase in global plastic production over the past few decades has resulted in a troubling buildup of plastic waste in our water bodies, which poses significant ecological and health risks. Among the various pollutants stemming from plastics, microplastics (MPs; less than 5 mm) and nanoplastics (NPs; less than 1 µm) have become particularly concerning due to their tiny size, durability, and widespread presence in freshwater, estuarine, and marine environments (Cole *et al.*, 2011; Galloway *et al.*, 2017). These tiny particles can either be primary plastics, which are intentionally made at such small sizes (like cosmetic microbeads and industrial abrasives), or secondary plastics, which form when larger plastic items break down and weather due to physical, chemical, and biological processes (Andrady, 2011). Microplastics and nanoplastics are now everywhere in our water systems, found in surface waters, sediments, and the organisms that live there. Their small size and unique characteristics, like a high surface-area-to-volume ratio and a tendency to repel water, allow them to easily bond with organic matter, microorganisms, and harmful chemicals, which helps them stick around in the environment and be absorbed by living things (Koelmans *et al.*, 2016). As a result, all kinds of aquatic creatures—from tiny plankton and bottom-dwelling invertebrates to fish and larger predators—are regularly exposed to these particles through eating, breathing, and skin contact (Wright *et al.*, 2013). The ecotoxicological importance of microplastics (MPs) and nanoplastics (NPs) goes beyond just their physical presence; it also includes their ability to cause a variety of harmful effects, both sublethal and lethal. On a physical level, they can lead to issues like gastrointestinal blockages, tissue damage, decreased feeding efficiency, and changes in energy distribution, all of which can negatively affect growth, reproduction, and survival (Avio *et al.*, 2017). When we look at the cellular and molecular aspects, exposure to MPs, and particularly NPs, has been linked to oxidative stress, inflammation, genotoxicity, and disruptions in metabolic and signaling pathways (Bhattacharya *et al.*, 2010; Revel *et al.*, 2018). NPs are especially worrisome because their tiny size allows them to pass through biological membranes, build up in tissues, and interact directly with subcellular components. Not only are microplastics and nanoplastics toxic on their own, but they can also carry along other harmful substances, including heavy metals, persistent organic pollutants, pharmaceuticals, and even pathogens. These harmful materials can stick to the surfaces of plastics and enter organisms when they are consumed, potentially changing how toxic and available these contaminants are (Rochman *et al.*, 2013). Moreover, the additives used in plastics, such as plasticizers, stabilizers, and flame retardants, can leach into surrounding tissues. Many of these substances are known to disrupt hormonal functions and immune responses (Lithner *et al.*, 2011). Microplastics and nanoplastics are a real challenge for our aquatic ecosystems due to their persistence, bioavailability, and complex ways of affecting the environment. Even though there's been a surge in research, we still have a lot to learn about the long-term effects of exposure, the specific toxicity of nanoplastics, and how they interact with other environmental stressors like climate change and low oxygen levels. This chapter aims to give a thorough overview of how microplastics and nanoplastics impact aquatic life, focusing on how organisms are exposed, the mechanisms behind their effects, and the broader ecological implications that are crucial for assessing and managing environmental risks.

Sources and Environmental Behavior - Microplastics (MPs) and nanoplastics (NPs) find their way into our water systems through various human activities and natural processes. Primary microplastics are specifically created at tiny sizes for use in things like personal care products, industrial abrasives, resin pellets, and even biomedical applications. On the other hand, secondary microplastics and nanoplastics come from breaking down larger plastic items, such as packaging, fishing gear, textiles, and particles from tire wear, all thanks to factors like UV radiation, mechanical wear, and microbial

action (Andrady, 2011; Cole *et al.*, 2011). The main routes these plastics take into aquatic environments include effluents from wastewater treatment plants, runoff from urban and agricultural areas, industrial discharges, leachates from landfills, and even deposition from the atmosphere. This really emphasizes how widespread and ongoing plastic pollution is (Dris *et al.*, 2016). When microplastics (MPs) and nanoplastics (NPs) enter aquatic environments, their behavior is shaped by their physical and chemical properties. This includes things like the type of polymer, size, shape, density, and surface charge, as well as environmental factors such as salinity, temperature, turbulence, and the presence of organic matter (Koelmans *et al.*, 2015). For example, lighter polymers like polyethylene and polypropylene tend to stay afloat and accumulate in the upper layers of water, while denser materials like polyvinyl chloride and polyethylene terephthalate are more likely to sink and settle into sediments. Moreover, the growth of microorganisms and algae on these particles can change their density, which can lead to their movement and redistribution in the water column (Rummel *et al.*, 2017). Microplastics and nanoplastics experience aging and weathering that change their surface traits, making them rougher and increasing the number of functional groups. These modifications enhance their ability to absorb dissolved organic matter, heavy metals, and hydrophobic organic contaminants, which affects their movement and ecological interactions (Hüffer and Hofmann, 2016). Nanoplastics, in particular, behave like colloids, allowing them to stay suspended for longer and travel over greater distances. Together, these processes shape how long microplastics and nanoplastics last, how available they are to living organisms, and their ecological importance in aquatic ecosystems.

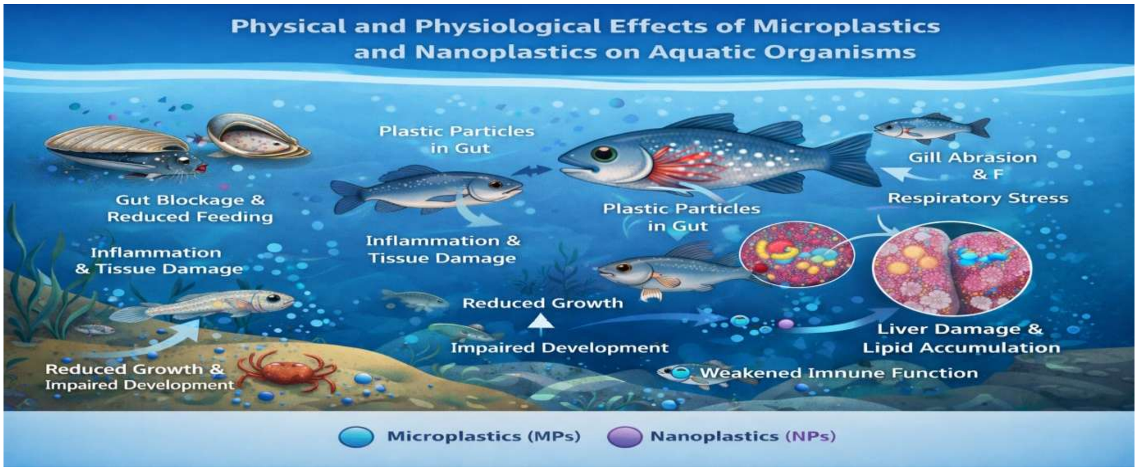
Exposure Pathways in Aquatic Organisms- Aquatic organisms face exposure to microplastics (MPs) and nanoplastics (NPs) through a variety of overlapping pathways, largely due to the pervasive nature of these particles in water, sediments, and aquatic food webs. The primary route of exposure is ingestion, which can occur directly from the environment or indirectly through contaminated prey.



Plankton, zooplankton, and filter-feeding creatures like bivalves tend to ingest MPs and NPs easily, as their feeding mechanisms are non-selective, and the size of plastic particles often matches that of their natural food sources (Cole *et al.*, 2013; Wright *et al.*, 2013). Fish may also consume plastic particles, either by accident or on purpose, mistaking them for food. Respiratory exposure through gills is a significant concern, especially for fish and crustaceans. During the breathing process, suspended microplastics (MPs) and nanoplastics (NPs) can get trapped in the mucus lining their gills. Nanoplastics, being so tiny, can actually penetrate the gill membranes and make their way into the bloodstream, potentially reaching critical organs like the liver, brain, and gonads (Lu *et al.*, 2016). This pathway becomes even more alarming in cases of chronic exposure and in waters that are heavily contaminated. Dermal and epithelial contact significantly contributes to exposure, especially in the early life stages of embryos and larvae, which have thin and permeable skin. Benthic organisms are also exposed through their close interaction with contaminated sediments, where deposit feeding enhances both ingestion and skin absorption (Revel *et al.*, 2018). After being absorbed, MPs and NPs can shift within organisms and be transferred to predators, which means they can travel through food webs. This additional exposure pathway increases ecological risks and brings up concerns about biomagnification and the possibility of human exposure through seafood consumption (Galloway *et al.*, 2017).

Physical and Physiological Effects

Microplastics (MPs) and nanoplastics (NPs) have a variety of physical and physiological effects on aquatic life, and these effects are largely influenced by factors like particle size, concentration, the type of polymer, and how long the organisms are exposed.



One of the most immediate physical consequences is the buildup of plastic particles in the gastrointestinal tract after ingestion. This can cause gut abrasion, blockage, inflammation, and even a misleading feeling of fullness, which can lead to reduced food intake, poor digestion, and lower energy absorption (Wright *et al.*, 2013). These impacts are especially severe in smaller organisms, such as zooplankton and benthic invertebrates, where their limited gut capacity makes them more vulnerable to physical stress. When it comes to our bodies, long-term exposure to microplastics (MPs) and nanoparticles (NPs) can really throw a wrench in our metabolic processes and how we allocate energy. Research has shown that fish and invertebrates experience slower growth rates, lower condition factors, and reduced reproductive success, all of which point to the higher energy costs that come with dealing with stress and detoxifying (Cole *et al.*, 2015). In fish, eating MPs has also been linked to damage in the intestinal lining and shifts in gut microbiota, which could mess with nutrient absorption and immune health. Nanoplastics raise significant concerns since they can cross biological barriers and directly affect tissues and organs. Studies have shown that these nanoparticles can migrate from the gut or gills to organs like the liver, causing histopathological changes, fat accumulation, and reduced liver function (Lu *et al.*, 2016). Additionally, when plastic particles build up on gill surfaces, they can lead to respiratory stress by disrupting gas exchange and osmoregulation. When you put all these physical and physiological disruptions together, they can really take a toll on an organism's fitness and survival, which could have ripple effects on both population and ecosystem levels. While a lot of the effects we've seen happen in controlled lab settings, there's growing evidence that even low levels of microplastics (MPs) and nanoplastics (NPs) in the environment can cause sublethal yet ecologically important physiological stress in aquatic life.

Cellular and Molecular Toxicity

Microplastics (MPs) and nanoplastics (NPs) can be quite harmful to aquatic life, causing cellular and molecular toxicity mainly through oxidative stress, disrupting membranes, and messing with gene expression. Because they're so tiny and reactive—especially NPs—these plastic particles can easily interact with cellular membranes. This interaction can change how permeable the membranes are and compromise the integrity of the cells (Bhattacharya *et al.*, 2010). Once inside, these particles can settle in the cytoplasm and organelles. A key factor in molecular toxicity is the overproduction of reactive oxygen species (ROS). When ROS levels rise too high, they can overwhelm the body's antioxidant defenses, leading to issues like lipid peroxidation, protein oxidation, and DNA damage (Jeong *et al.*, 2016). In both fish and invertebrates, exposure to microplastics (MPs) and nanoparticles (NPs) has been linked to changes in the activity of important antioxidant enzymes, including superoxide dismutase, catalase, and glutathione peroxidase. This suggests that there's an oxidative imbalance happening at the cellular level. If oxidative stress continues, it can activate pathways that lead to apoptosis, resulting in cell death and tissue dysfunction. At the molecular level, exposure to plastic particles can actually alter the expression of genes that play a role in stress response, inflammation, detoxification, and metabolism. Transcriptomic research has shown that there's an increase in heat shock proteins and pro-inflammatory cytokines, along with disruptions in the pathways that govern energy metabolism and immune regulation (Zhang *et al.*, 2021). Furthermore, microplastics (MPs) and nanoplastics (NPs) can act as carriers for toxic chemicals and metals, which can heighten molecular toxicity through their combined or synergistic effects.

Immunotoxic and Endocrine Effects

Microplastics (MPs) and nanoplastics (NPs) have been increasingly recognized as **immunotoxic and endocrine-disrupting agents** in aquatic organisms. Exposure to these particles can impair both innate and adaptive immune responses by inducing oxidative stress and inflammation. In fish and invertebrates, MPs have been shown to alter the activity of immune-related enzymes and reduce phagocytic efficiency of hemocytes and macrophages, weakening pathogen defense mechanisms (Espinosa *et al.*, 2019). Chronic exposure often results in immunosuppression, increasing susceptibility to infections and disease outbreaks in natural populations. At the endocrine level, microplastics (MPs) and nanoplastics (NPs) can mess with our hormonal balance by acting as carriers for harmful endocrine-disrupting chemicals like bisphenol A, phthalates, and persistent organic pollutants that cling to their surfaces. These substances can throw off hormone production, release, and receptor signaling, which can lead to a disruption in our endocrine system's homeostasis (Rochman *et al.*, 2014). Research on fish has shown shifts in levels of thyroid and sex hormones, as well as changes in the expression of genes that play a role in steroid production and hormone metabolism (Sussarellu *et al.*, 2016). When organisms are exposed to plastic particles, it can disrupt their endocrine systems, which can have serious consequences for their growth, reproduction, and overall development. This disruption may result in delayed maturation, decreased reproductive success, and unusual larval development. The dual impact of microplastics (MPs) and nanoplastics (NPs) on both immune and endocrine functions is a major ecological issue, as it can weaken the fitness and resilience of species, ultimately threatening population stability and the health of aquatic ecosystems.

Trophic Transfer and Food Web Implications

Microplastics (MPs) and nanoplastics (NPs) are easily transferred across different levels of aquatic food webs, which raises concerns about the stability of ecosystems and the potential for biomagnification. Primary producers, such as phytoplankton and benthic algae, can absorb or ingest these plastic particles. These are then consumed by zooplankton and invertebrates, allowing MPs and NPs to move up the food chain to predatory fish, seabirds, and eventually humans through seafood consumption. Plastics may not biomagnify like some persistent organic pollutants do, but they can still build up in food chains due to ongoing exposure and their slow breakdown (Au *et al.*, 2017). It's important to recognize that microplastics (MPs) and nanoplastics (NPs) serve as carriers for hydrophobic contaminants, metals, and pathogens, which can enhance the transfer of these toxic substances through food webs. As a result, predators that consume contaminated prey might experience increased toxic effects. Plastic particles in food webs can really mess with feeding habits, energy flow, and nutrient cycling. When animals consume plastic, it can degrade the quality of their prey and affect how well they digest food, which may lead to less efficient energy transfer between different levels of the food chain. This could have a negative impact on the growth and reproductive success of larger predators (Farrell and Nelson, 2013). Over time, these disruptions might cause changes in species composition, alter predator-prey dynamics, and reduce the resilience of ecosystems. That's why it's so important to understand how trophic transfer works when evaluating the long-term ecological risks that microplastics and nanoplastics bring to aquatic environments.

Future Research Directions

Future research on microplastics and nanoplastics in our water systems should really focus on figuring out their long-term and chronic effects at levels we actually see in the environment. We need to pay more attention to nanoplastics because their tiny size, high reactivity, and ability to slip through biological barriers are still not well understood. It's crucial to have standardized methods for sampling, characterizing, and testing toxicity to make sure studies can be compared effectively. Research should also dive into how multiple stressors interact, like climate change, low oxygen levels, and chemical contaminants, to better mimic real-world conditions. Plus, we're missing studies that connect subcellular and physiological responses to outcomes at the population and ecosystem levels. Gaining a better understanding of how these materials transfer through food webs, their bioavailability, and how they're eliminated will really enhance our ecological risk assessments. Lastly, we need interdisciplinary approaches that bring together ecotoxicology, environmental chemistry, modeling, and policy studies to guide mitigation strategies, regulatory frameworks, and sustainable plastic management, all aimed at cutting down long-term risks to our aquatic ecosystems**.**

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