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## Microplastic Ingestion by Zooplankton and Its Ecological Implications for Aquatic Trophic Dynamics

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Microplastics (<5 mm) have become ubiquitous contaminants in aquatic ecosystems, with significant consequences for zooplankton communities and broader trophic networks. This technical paper examines the mechanisms by which zooplankton ingest microplastic particles, the physiological and ecological consequences of such ingestion, and the downstream effects on aquatic food webs. Evidence from laboratory and field studies indicates that microplastic ingestion impairs feeding, reproduction, and energy transfer in zooplankton, consequently disrupting trophic efficiency from primary producers to higher-order consumers. Understanding these dynamics is critical for evaluating ecosystem-level risks of plastic pollution and informing mitigation strategies. Zooplankton, as essential intermediates linking primary producers to higher trophic levels, play a crucial role in nutrient cycling and energy transfer within aquatic ecosystems. Due to their non-selective feeding behaviour and widespread distribution, zooplankton are highly vulnerable to microplastic exposure. Ingestion of microplastics can result in reduced feeding efficiency, altered metabolism, oxidative stress, impaired growth, decreased fecundity, and increased mortality. These physiological disturbances may subsequently influence population dynamics and community structure, leading to changes in ecosystem functioning. The accumulation and trophic transfer of microplastics through aquatic food webs have raised concerns regarding bioaccumulation and biomagnification in higher consumers, including commercially important fish species and humans. Furthermore, microplastics can act as vectors for toxic pollutants, pathogens, and additives, intensifying ecological risks. Environmental factors such as particle size, shape, polymer composition, concentration, and exposure duration significantly influence the extent of microplastic impacts on zooplankton ecology. This paper synthesizes current findings on microplastic–zooplankton interactions, evaluates their implications for trophic dynamics and ecosystem health, and highlights emerging analytical techniques for detection and characterization of microplastics in aquatic environments. It also identifies existing knowledge gaps and proposes future research directions aimed at improving ecological risk assessment and developing effective management strategies to reduce plastic pollution in aquatic systems.

**Keywords:** Microplastics; Zooplankton ecology; Trophic dynamics; Aquatic ecosystems; Ecotoxicology; Trophic transfer.

### Introduction

The proliferation of plastic debris in aquatic environments represents one of the most pressing environmental challenges of the 21st century. Plastics fragment through physical, chemical, and biological weathering into microplastics, defined as particles below 5 mm in diameter (Thompson et al., 2009). Global estimates suggest that over 8 million metric tonnes of plastic enter the oceans annually, with microplastics now detected in virtually every

aquatic habitat from coastal estuaries to deep-sea sediments and polar ice sheets. Zooplankton, comprising heterogeneous assemblages of copepods, cladocerans, amphipods, and meroplankton, occupy a pivotal trophic position as primary consumers transferring energy from phytoplankton to higher trophic levels. Their size range (0.2–20 mm) and non-selective suspension feeding behaviour render them particularly susceptible to microplastic ingestion. The ecological implications extend beyond individual organism physiology to encompass entire trophic cascades, carbon flux dynamics, and the bioaccumulation of persistent organic pollutants (POPs) adsorbed onto plastic surfaces. This paper reviews current knowledge on zooplankton–microplastic interactions, synthesising evidence on ingestion mechanisms, sub-lethal effects, trophic transfer, and ecosystem-level consequences, while identifying key knowledge gaps warranting further investigation.

## Microplastics in Aquatic Ecosystems

### Sources, Distribution, and Size Fractions

Microplastics originate from two principal pathways: primary microplastics, manufactured at micro-scale for industrial or cosmetic applications (e.g., microbeads, resin pellets), and secondary microplastics, resulting from the fragmentation of larger plastic items. Polymer types commonly identified in aquatic systems include polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET). Environmental concentrations vary by region and habitat, ranging from  $<1$  particle  $m^{-3}$  in open ocean surface waters to  $>10,000$  particles  $m^{-3}$  in coastal and estuarine zones (Eriksen et al., 2014).

### Physicochemical Properties Relevant to Zooplankton

Particle size, shape, density, surface chemistry, and the degree of weathering collectively influence the bioavailability of microplastics to zooplankton. Spherical particles in the 1–10  $\mu m$  range most closely mimic phytoplankton cells in terms of hydrodynamic properties and are therefore most readily captured by copepod mouthparts. Weathered plastics exhibit altered surface hydrophobicity and charge, facilitating the adsorption of heavy metals and POPs that confer additional toxicological risks upon ingestion.

## Mechanisms of Microplastic Ingestion by Zooplankton

### Passive vs. Active Ingestion

Zooplankton encounter microplastics through two broad mechanisms. Passive ingestion occurs in filter-feeding taxa (e.g., *Daphnia* spp., salps, appendicularians) that non-selectively retain particles within a specific size range using mucus filters or setose appendages. Active ingestion is characteristic of raptorial and ambush predators such as calanoid copepods, which may exhibit partial discrimination based on particle characteristics; however, discrimination becomes impaired at environmentally realistic concentrations. Cole et al. (2013) demonstrated that thirteen zooplankton taxa, spanning six phyla, ingested polystyrene microspheres under laboratory conditions, underscoring the taxonomic breadth of this phenomenon.

### Retention, Egestion, and Gut Translocation

Once ingested, microplastics may be egested intact within faecal pellets, retained within digestive tissues, or particularly for nanoplastics translocated across gut epithelial membranes into haemolymph and reproductive organs. Gut retention times vary across taxa and particle sizes, with smaller particles exhibiting longer retention. Translocation of nanoplastics has been documented in amphipods and bivalves, raising concerns about systemic accumulation and transfer to predators (Sussarellu et al., 2016).

## Physiological Effects on Zooplankton

### Feeding Impairment and Pseudo-satiation

Microplastic ingestion induces pseudo-satiation, a condition whereby gut volume is physically occupied by indigestible particles, reducing the capacity for nutritious food intake. Experimental studies on *Calanus helgolandicus* demonstrated significant reductions in

phytoplankton ingestion rates at polystyrene concentrations of 75 particles mL<sup>-1</sup>, accompanied by decreased faecal pellet production and altered defecation rates (Cole et al., 2013). This reduced energy assimilation compromises metabolic maintenance, growth, and reproduction.

### **Reproductive and Developmental Impacts**

Sub-lethal chronic exposure to microplastics impairs fecundity, egg viability, and larval development across multiple zooplankton taxa. In *Daphnia magna*, nano-polystyrene exposure at 0.5 mg L<sup>-1</sup> significantly reduced brood size and neonate survivorship. Bivalve larvae exposed to microplastics exhibited arrested veliger development and increased malformation rates (Sussarellu et al., 2016). Such reproductive impairments can rapidly propagate through population dynamics, reducing zooplankton biomass and community diversity.

### **Biochemical and Oxidative Stress Responses**

Microplastic ingestion triggers oxidative stress pathways characterised by elevated reactive oxygen species (ROS), lipid peroxidation, and induction of antioxidant enzyme activity (superoxide dismutase, catalase). Concurrent exposure to POPs adsorbed onto plastic surfaces compounds these effects through endocrine disruption and genotoxicity. Such biochemical perturbations at the individual level can translate into reduced competitive fitness and altered foraging behaviour at the population level.

## **Trophic Dynamics and Ecological Implications**

### **Trophic Transfer and Biomagnification**

Zooplankton occupying intermediate trophic positions mediate the transfer of microplastics from primary producers to fish, marine mammals, and seabirds. Trophic transfer occurs when predators consume microplastic-laden zooplankton, accumulating particles in digestive tissues. Studies on Atlantic mackerel and herring have documented microplastics in gut contents, with zooplankton identified as the primary vector (Lusher et al., 2013). The associated chemical contaminants may exhibit trophic magnification, increasing in concentration at successive trophic levels, though the precise contribution of plastic-vectored POPs relative to direct dietary exposure remains debated.

### **Disruption of the Biological Carbon Pump**

Zooplankton play a central role in the biological carbon pump through the production of rapidly sinking faecal pellets that transport particulate organic carbon (POC) to the deep ocean. Microplastic ingestion alters faecal pellet density, sinking velocity, and composition, thereby reducing carbon export efficiency. Turner (2015) documented that microplastic-contaminated faecal pellets exhibited significantly reduced sinking rates in laboratory columns, potentially retaining carbon in surface waters and diminishing oceanic carbon sequestration capacity with implications for global climate regulation.

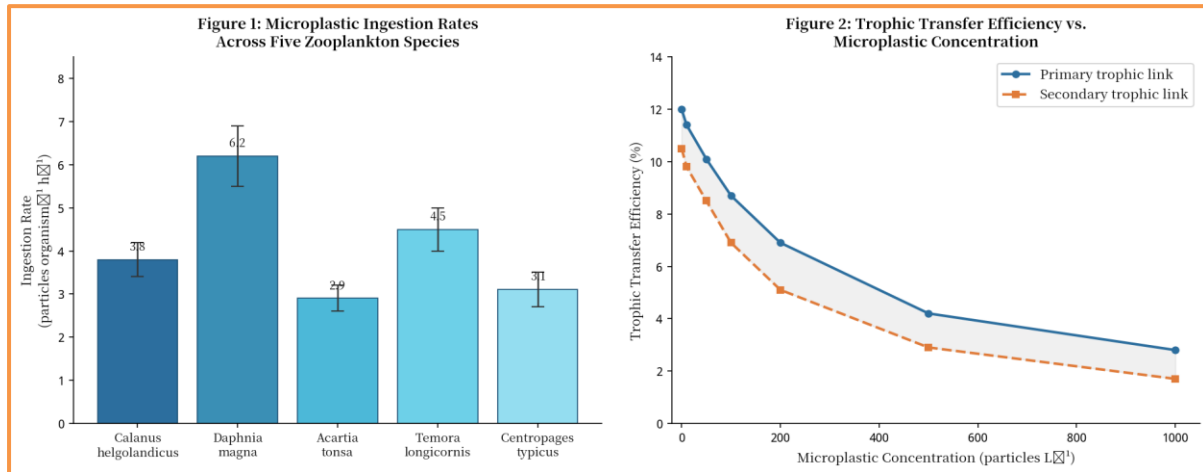
### **Community-Level Cascading Effects**

Population-level declines in zooplankton biomass precipitate cascading trophic consequences. Reduced zooplankton standing stocks diminish grazing pressure on phytoplankton, potentially promoting harmful algal blooms and altering phytoplankton community composition. Concurrently, decreased zooplankton availability constrains energy transfer to planktivorous fish, with ramifications for fisheries productivity and marine mammal nutrition. These cascading effects highlight the systemic nature of microplastic contamination and the disproportionate ecological leverage exerted through disruption of zooplankton community function.

## **Knowledge Gaps and Future Research Directions**

Despite considerable advances, critical knowledge gaps remain. First, environmentally realistic exposure concentrations and particle heterogeneity (size, shape, polymer type, surface fouling) are seldom replicated in laboratory experiments, limiting ecological extrapolation. Second, nanoplastics (<1 µm) represent a growing fraction of environmental microplastics but remain analytically challenging; their bioavailability and toxicity to

zooplankton are poorly characterised. Third, the synergistic toxicity of microplastics combined with adsorbed chemical contaminants under field conditions warrants systematic investigation. Fourth, long-term multi-generational exposure studies are required to assess evolutionary adaptation and epigenetic effects. Finally, integration of zooplankton–microplastic dynamics into coupled biogeochemical and ocean circulation models is essential for projecting ecosystem-scale impacts under future plastic pollution scenarios.



**Figure 1 & 2: (Left) Mean microplastic ingestion rates across five common zooplankton species; (Right) Trophic transfer efficiency as a function of microplastic concentration across primary and secondary trophic links.**

## Conclusion

Microplastic ingestion by zooplankton represents a multifaceted ecological threat operating across individual, population, community, and ecosystem scales. The convergence of pseudo-satiation, reproductive impairment, trophic transfer, and disruption of biogeochemical cycling underscores the systemic nature of microplastic pollution. Zooplankton, by virtue of their trophic centrality and ecological multifunctionality, serve as both sensitive indicators of microplastic contamination and critical conduits through which plastic-associated effects propagate through aquatic food webs. Effective mitigation requires stringent source reduction, improved wastewater treatment, and standardised international monitoring frameworks, underpinned by continued mechanistic and ecosystem-level research.

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