

Ecotoxicity of Microplastics

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1. Introduction

Microplastics, typically defined as plastic particles smaller than 5 mm in diameter, have emerged as a pervasive environmental contaminant of global concern [1]. Generated through the fragmentation of larger plastic debris or released directly as primary microplastics from industrial and consumer products, these particles have been detected in virtually all environmental compartments, including marine, freshwater, terrestrial, and atmospheric systems [2–5]. The widespread distribution and persistence of microplastics have raised significant concerns regarding their potential ecological impacts and implications for environmental sustainability.

The ecotoxicity of microplastics has become an increasingly important area of research due to their ability to interact with a wide range of organisms across different trophic levels [6]. Numerous studies have demonstrated that microplastic exposure can adversely affect aquatic and terrestrial organisms through physical, chemical, and biological mechanisms [7,8]. The toxicological effects of microplastics depend greatly on their physicochemical properties, including particle size, shape, polymer composition, surface characteristics, and degree of environmental weathering [9]. Emerging evidence suggests that different classes of plastic particles exhibit distinct toxicity profiles. For example, microplastics and nanoplastics may differ in their environmental behavior, biological interactions, and toxicological outcomes, while aged or weathered microplastics often display altered surface properties and contaminant-binding capacities compared with pristine particles [10–13]. Similarly, biodegradable plastics, which are increasingly promoted as sustainable alternatives to conventional petroleum-based plastics, may exhibit different degradation pathways and ecotoxicological effects in environmental systems [14,15]. These variations highlight the complexity of assessing microplastic ecotoxicity and underscore the need to consider particle-specific characteristics when evaluating ecological risks.

Beyond their direct toxicity, microplastics can act as vectors for environmental contaminants such as heavy metals, pesticides, polycyclic aromatic hydrocarbons, and pharmaceutical compounds [16]. The adsorption of these pollutants onto microplastic surfaces may enhance their environmental persistence, bioavailability, and trophic transfer, resulting in complex mixture effects that often exceed the toxicity of individual contaminants [17]. Recent studies have also highlighted the potential for microplastics to alter microbial communities, disrupt nutrient cycling, and affect ecosystem functioning [18,19].

Despite substantial progress in understanding microplastic ecotoxicity, significant knowledge gaps remain regarding long-term chronic exposure, environmentally realistic concentrations, and the combined effects of microplastics with other emerging contaminants. Addressing these uncertainties is essential for improving ecological risk assessments and developing effective management strategies to mitigate the environmental impacts of plastic pollution in both aquatic and terrestrial ecosystems.



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2. Microplastics Versus Nanoplastics

Although both microplastics and nanoplastics can adversely affect animal health, current evidence indicates that nanoplastics generally exhibit greater toxicity due to their enhanced bioavailability, cellular uptake, and molecular reactivity [20,21]. Unlike microplastics, which predominantly cause physical damage through ingestion, obstruction, tissue irritation, and mechanical stress, nanoplastics can readily penetrate biological membranes, enter cells, and interact directly with intracellular organelles and molecular pathways [22,23]. Consequently, nanoplastics often induce toxic effects at lower exposure concentrations and affect a wider range of biological systems [21].

One of the most significant differences lies in tissue distribution. Yang et al. [20] demonstrated that 100 nm polystyrene nanoplastics rapidly accumulated in blood, adipose tissues, brain regions, and reproductive organs following oral exposure in mice, whereas 3 μm particles exhibited limited distribution and 10 μm particles showed minimal tissue penetration. This enhanced biodistribution allows nanoplastics to cross biological barriers such as the blood–brain barrier, leading to neurotoxicity characterized by oxidative stress, microglial activation, mitochondrial dysfunction, synaptic disruption, cognitive impairment, and Parkinson’s disease-like neurodegeneration [24–26].

At the cellular level, nanoplastics and microplastics also differ markedly in their toxicological mechanisms. Cheng et al. [21] reported that 100 nm polystyrene nanoplastics entered intestinal epithelial cells via endocytosis and induced oxidative stress and ferroptosis by activating the Fosl1–p53–GPX4 signaling axis, resulting in iron accumulation, glutathione depletion, and lipid peroxidation. In contrast, 10 μm microplastics primarily caused mechanical injury, cytoskeletal remodeling, metabolic shifts toward anaerobic glycolysis, and inflammatory responses mediated by the YAP pathway. These findings suggest that nanoplastics exert toxicity mainly through molecular and subcellular disruptions, whereas microplastics predominantly affect tissue integrity and cellular architecture.

Comparative studies further demonstrate that nanoplastics often induce more severe organ toxicity than microplastics. In mice, polyethersulfone nanoplastics (50 nm) caused greater liver and lung damage than corresponding 5 μm microplastics following both dietary and inhalation exposure [27]. Similarly, kidney toxicity studies revealed that smaller plastic particles elicited stronger oxidative stress, inflammation, and tissue damage than larger particles [28]. Overall, the available evidence supports a size-dependent toxicity gradient in which decreasing particle size enhances biological uptake, tissue penetration, and toxicity. Therefore, while both microplastics and nanoplastics pose ecological risks, nanoplastics are generally considered a greater toxicological concern because they act at cellular and molecular levels, whereas microplastics primarily exert physical and mechanical effects.

3. Conventional Versus Biodegradable Microplastics

Biodegradable microplastics are increasingly promoted as environmentally friendly alternatives to conventional microplastics; however, growing evidence suggests that their ecotoxicological impacts are not consistently lower than those of conventional plastics. The most important distinction between the two lies in their interactions with biological communities and degradation processes. Unlike conventional microplastics such as polyethylene, polystyrene, and polyethylene terephthalate (PET), biodegradable microplastics such as polylactic acid (PLA), polybutylene succinate (PBS), and polybutylene adipate terephthalate (PBAT) can serve as carbon sources for microorganisms, resulting in distinct microbial community structures and metabolic functions [29,30]. For example, PLA and PBS promoted soil microbial multifunctionality and altered bacterial community compo-

sition, whereas polyethylene and polystyrene produced comparatively minor changes in microbial function [30].

Despite these potential ecological benefits, biodegradable microplastics are not necessarily less toxic than conventional microplastics. Several studies have reported comparable toxicities of conventional and biodegradable plastics to soil organisms. In earthworms (*Eisenia fetida*), PLA exhibited toxicity similar to polyethylene and was considered no more environmentally benign than polyethylene or polypropylene copolymers [31–33]. In plants, biodegradable microplastics sometimes produced stronger adverse effects than conventional ones. PBAT caused greater oxidative damage, photosynthesis inhibition, soil aggregation, and alterations in soil ammonium levels than polyethylene in lettuce cultivation [34], while PLA and polyhydroxybutyrate (PHB) inhibited root growth more strongly than polypropylene [35].

The differences become more pronounced in aquatic environments. In freshwater systems, PLA frequently demonstrated greater toxicity than PET and polyethylene. Exposure of *Daphnia magna* to PLA resulted in higher mortality, reduced reproduction, embryo deformities, and greater oxidative stress than PET [36]. Similarly, Luangrath et al. [37] found that PLA exhibited higher bioaccumulation and induced greater oxidative stress than PE, particularly after environmental aging. Furthermore, biodegradable microplastics may facilitate the dissemination of antibiotic resistance genes more effectively than conventional microplastics, as PBAT biofilms contained higher levels of resistance genes than polyvinyl chloride biofilms [38]. Collectively, these findings indicate that while biodegradable microplastics may enhance biodegradation and modify microbial processes, they are not inherently less toxic than conventional microplastics and can, under certain conditions, pose equal or greater ecological risks.

4. Aged Versus Pristine Microplastics

Microplastics undergo continuous physical, chemical, and biological weathering after entering the environment, resulting in substantial changes to their physicochemical characteristics. The most important distinction between pristine and aged microplastics is that aging generally exacerbates their ecotoxicity. Aged microplastics may produce significantly stronger adverse effects on aquatic organisms than pristine particles across multiple biological endpoints, suggesting that the ecological risks associated with microplastics may increase over time following environmental release [39–41].

The increased toxicity of aged microplastics is primarily attributed to two mechanisms. First, aging promotes the release of plastic additives and degradation products, which are often more toxic than the original polymer matrix [42–44]. Second, aging alters particle size, shape, surface area, surface chemistry, and adsorption capacity, thereby increasing the likelihood of contact, ingestion, accumulation, and interaction with organisms [45,46]. These modifications frequently enhance the bioavailability of microplastics and facilitate their uptake by aquatic biota. Indeed, several studies have linked the greater toxicity of aged microplastics to increased accumulation within organisms, including zebrafish, *Epinephelus moara*, and *Artemia salina* [47–49].

Compared with pristine microplastics, aged particles exert stronger effects on growth and development, behavior, sensory and neuromuscular functions, metabolism, digestive and excretory systems, and antioxidant defenses. Metabolic processes appear particularly sensitive, with ATPase activity, lipid metabolism, and protein metabolism showing pronounced responses to exposure to aged microplastics [50–52]. Furthermore, the extent of toxicity enhancement depends on factors such as aging method, polymer type, particle shape, and particle size. Light-induced aging generally produces a stronger increase in

toxicity than biological aging, while aged polyethylene, polystyrene, and polyvinyl chloride particles exhibit greater toxicity than their pristine counterparts [53–55].

5. Overview of Published Articles

The articles published in this Special Issue (see the List of Contributions for details) provide new insights into the occurrence, environmental distribution, biological uptake, physiological responses, and toxicological mechanisms associated with exposure to plastic particles. Collectively, these studies highlight the complexity of microplastic pollution and demonstrate that ecological risks extend beyond simple particle ingestion to encompass biochemical, physiological, behavioral, and ecosystem-level effects.

Several contributions focus on the occurrence and environmental distribution of microplastics in natural ecosystems. Wu et al. (article 1 in the List of Contributions) demonstrated widespread ingestion of microplastics by aquatic insects inhabiting a remote, high-altitude stream in Taiwan using automated focal-plane array micro-Fourier transform infrared spectroscopy (FPA- μ FTIR). Their findings revealed that even relatively pristine environments are not exempt from microplastic contamination, emphasizing the global reach of plastic pollution. Similarly, Cáceres-González et al. (article 4) documented microplastic contamination in estuarine sediments from south-central Chile, showing clear relationships between microplastic abundance and anthropogenic activities, while identifying distinct polymer compositions among contrasting estuarine environments.

A second theme of this Special Issue concerns organismal responses to microplastic exposure. Sureda et al. (article 2) reported that microplastic ingestion by the peacock wrasse (*Symphodus tinca*) was associated with elevated antioxidant, detoxification, and inflammatory enzyme activities, which suggests that microplastic burden can trigger physiological stress responses even in wild fish populations. Comparable findings were reported by Fortuna et al. (article 3), who demonstrated that poly(methyl methacrylate) microplastics impaired growth, reproduction, lifespan, intestinal integrity, and oxidative stress responses in the nematode *Caenorhabditis elegans*. Together, these studies provide evidence that oxidative stress and associated defense mechanisms represent common responses to microplastic exposure across taxa.

The Special Issue also highlights the importance of evaluating specific organ- and system-level effects. Pablos et al. (article 5) investigated dietary exposure to polystyrene microplastics in *Xenopus laevis* tadpoles and observed developmental and mild histological alterations, while emphasizing the need for standardized methodologies in ecotoxicological assessments. Quigley et al. (article 6) further demonstrated that photoaged polyethylene microplastics can exert different effects on soil mesofauna than virgin particles, indicating that environmental weathering modifies toxicity and should be considered in ecological risk assessments.

Recognizing the growing concern surrounding smaller plastic particles, Neves et al. (article 7) evaluated the effects of poly(methyl methacrylate) nanoplastics on the shore crab *Carcinus maenas*. Their results showed behavioral alterations, neurotoxicity, oxidative stress, and tissue damage, illustrating the heightened biological activity of nanoscale plastics. Expanding on this theme, Tang (article 8) provided a comprehensive review comparing the toxicity of nanoplastics and microplastics across animal taxa. The review concluded that nanoplastics generally exert stronger and more systemic toxic effects due to their enhanced bioavailability, cellular uptake, and molecular interactions.

The studies in this Special Issue demonstrate that the ecotoxicity of microplastics and nanoplastics is highly dependent on particle characteristics, environmental transformations, exposure pathways, and species-specific sensitivities.

6. Conclusions

Microplastics have emerged as complex and multifaceted environmental contaminants capable of affecting organisms across diverse ecosystems and trophic levels. The existing evidence demonstrates that microplastic ecotoxicity is strongly influenced by particle characteristics, including size, polymer type, degradability, and environmental weathering. This Special Issue brings together original research and review articles that advance current knowledge of the occurrence, biological uptake, toxicological mechanisms, and ecological consequences of microplastics and nanoplastics. The contributions span diverse ecosystems and taxa, from aquatic insects in remote mountain streams and estuarine sediments to fish, amphibians, soil invertebrates, nematodes, and marine crustaceans. The studies document widespread microplastic contamination even in relatively pristine environments and demonstrate that plastic particle exposure can induce oxidative stress, inflammation, developmental impairment, reproductive dysfunction, neurotoxicity, behavioral alterations, and tissue damage. Several articles highlight the importance of environmental transformations, showing that photoaged microplastics can exert effects distinct from those of virgin particles, while others reveal physiological and biochemical responses that may serve as early-warning indicators of ecological stress. The Special Issue also expands current understanding of nanoplastic toxicity, providing evidence that nanoscale particles often produce more severe and systemic effects than larger microplastics. By integrating field observations, laboratory experiments, and comparative reviews, this Special Issue addresses critical knowledge gaps concerning environmentally realistic exposure scenarios, aging effects, and nanoplastic hazards. The findings provide valuable insights into ecological risk assessment, environmental monitoring, and the development of effective strategies to mitigate plastic pollution.

Despite substantial advances in understanding microplastic ecotoxicity, several important knowledge gaps remain. Most existing studies have been conducted under controlled laboratory conditions using relatively high concentrations of pristine particles that may not accurately reflect environmental exposure scenarios. Long-term and multigenerational studies are still limited, hindering our understanding of chronic ecological consequences and potential transgenerational effects. Furthermore, the majority of studies focus on single-species responses, whereas ecosystem-level impacts involving trophic interactions, food-web transfer, biodiversity changes, and ecosystem functioning remain poorly understood. Future research should prioritize environmentally realistic exposure conditions, including the use of aged, weathered, and environmentally sourced microplastics. Greater attention should also be given to nanoplastics, which remain understudied despite growing evidence of their heightened toxicity. Comparative studies that examine conventional, biodegradable, pristine, and aged plastics within standardized experimental frameworks are needed to improve cross-study comparability and support robust risk assessments. In addition, interactions between microplastics and co-occurring contaminants, such as heavy metals, pesticides, pharmaceuticals, and antibiotic resistance genes, warrant further investigation, as mixture effects may substantially alter toxicity outcomes.

Advances in omics technologies, imaging techniques, and mechanistic toxicology offer valuable opportunities to elucidate the molecular pathways underlying microplastic-induced effects. Ultimately, integrating laboratory, field, and modeling approaches across multiple levels of biological organization will be essential for developing more accurate ecological risk assessments and informing effective policies and mitigation strategies to address the growing challenge of plastic pollution in aquatic and terrestrial environments.

Conflicts of Interest: The author declares no conflicts of interest.

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