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The Dual Role of Environment and Particle Characteristics in Shaping Nanoplastics Toxicity and Fate

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Abstract

Nanoplastics (NPs) enter aquatic environments through direct discharge, wastewater, and atmospheric deposition, posing significant risks to ecosystem health. This review article examines the environmental fate, physicochemical properties, and toxic effects of NPs. Scientific sources were identified through a comprehensive search of peer-reviewed literature, with a focus on studies investigating the behavior of NPs in aquatic and terrestrial systems and their interactions with natural organic matter. The findings indicate that NPs disrupt food chains in aquatic ecosystems and can enhance toxicity when combined with other pollutants. The formation of an eco-corona also alters the bioavailability and toxicity of NPs, thereby intensifying their harmful effects on aquatic organisms. These findings highlight the need for targeted management and regulatory measures, as well as for future research on computational toxicology and the combined effects of pollutants.

Keywords: Aquatic Environment; Bioaccumulation; Eco-Corona; Fate; Nanoplastics; Toxicology

نقش دوگانه‌ی محیط و ویژگی‌های ذرات در تعیین سمیت و سرنوشت محیط‌زیستی نانوپلاستیک‌ها

نویدالله امین

دیپارتمنت زولوژی، پوهنځی بیولوژی، پوهنتون کابل، کابل، افغانستان

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چکیده

نانوپلاستیک‌ها از طریق تخلیه‌ی مستقیم، فاضلاب و رسوب جوی وارد محیط‌های آبی می‌شوند و خطرات قابل‌توجهی را برای صحت ایکوسیستم‌ها به‌وجود می‌آورند. این مقاله‌ی مروری به بررسی سرنوشت محیط‌زیستی، ویژگی‌های فزیکی-کیمیاوی و تأثیرات سمی نانوپلاستیک‌ها می‌پردازد. منابع علمی از طریق جست‌وجوی جامع در مقالات مرورشده شناسایی شدند، با تمرکز بر تحقیقات که رفتار نانوپلاستیک‌ها را در سیستم‌های آبی، خاکی و همچنان تعامل آن‌ها را با مواد عضوی طبیعی بررسی کرده‌اند. یافته‌ها نشان می‌دهد که نانوپلاستیک‌ها زنجیره‌های غذایی را در ایکوسیستم‌های آبی مختل می‌سازند و هنگامی که با سایر آلوده‌کننده‌ها ترکیب می‌شوند، می‌توانند سمیت را افزایش دهند. تشکیل اکو-کرونا نیز در دسترسی زیستی و سمیت نانوپلاستیک‌ها تغییر ایجاد کرده و تأثیرات زیان‌بار آن‌ها بر موجودات آبی را تشدید می‌نماید. این یافته‌ها بر ضرورت مدیریت و مقررات هدفمند و توسعه‌ی تحقیقات آینده با تمرکز بر سم‌شناسی محاسباتی و تأثیرات ترکیبی آلوده‌کننده‌ها تأکید می‌کند.

واژه‌های کلیدی: اکو-کرونا؛ تجمع زیستی؛ سرنوشت؛ سم‌شناسی؛ محیط‌های آبی؛ نانوپلاستیک‌ها

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Introduction

Nanoplastics are defined as plastic particles with dimensions less than 1 μm (1000 nm) and represent a significant environmental contaminant with potential risks to both ecosystems and human health (Antunes et al., 2024). These particles can originate from the degradation of larger plastic waste, synthetic textiles, and various industrial processes (Adhikari & Thapar, 2025). Due to their small size, NPs can translocate across biological barriers, accumulate in vital organs, and potentially trigger inflammatory responses, oxidative stress, and genotoxicity. Furthermore, NPs can adsorb harmful pollutants, such as persistent organic pollutants (POPs), which may exacerbate their toxic effects (Antunes et al., 2024). The widespread presence of NPs in aquatic environments, with concentrations reaching alarming levels, underscores the urgent need for comprehensive research and regulatory measures to address their impact on health and the environment.

Nanoplastics exhibit distinct fates and behaviors across freshwater, marine, and soil environments, significantly impacting ecosystems. In freshwater systems, NPs can disrupt food webs by adversely affecting key organisms, such as daphnia and phytoplankton, while having minimal effects on less efficient grazers, such as copepods (Ekvall et al., 2024). In marine environments, NPs are subject to complex transport dynamics influenced by factors like water flow and particle morphology, leading to variable concentrations and potential bioaccumulation in aquatic organisms (Arif et al., 2018; Chanda et al., 2024). Soil environments also face threats from these particles, which can be introduced through biosolids applications and runoff, affecting soil biota and plant health (Arif et al., 2018). Furthermore, the behavior of NPs differs significantly, with unique adsorption and interaction patterns with natural colloids, complicating their environmental impact assessments (Wang et al., 2024).

The formation of an ecological corona (Eco-corona) on NPs significantly influences their environmental behavior, bioavailability, and toxicity. Natural organic matter (NOM) plays a crucial role in this process, as it can stabilize pristine NPs through hydrophobic interactions while destabilizing photochemically weathered NPs through hydrogen bonding, thereby promoting aggregation via polymer bridging (Xu et al., 2025). The interaction of NPs with biomolecules, such as proteins, leads to the formation of a protein corona that alters their biological fate, enhancing translocation and exacerbating toxic effects in organisms like zebrafish and marine medaka (Liu et al., 2024; Wang et al., 2023). Additionally, the physicochemical properties of NPs, including surface area and chemical additives, affect protein adsorption, which is critical for understanding their ecological impacts (Dawson et al., 2024).

Therefore, this study aims to integrate knowledge from previous studies to highlight the interplay between environmental factors and physicochemical properties of NPs.

Research Methodology

A narrative literature review approach was used to collect relevant information on the fate, behavior, and toxicity of NPs. Scientific databases, including Web of Science, Scopus, and PubMed, were searched using general keywords such as *nanoplastics*, *fate*, *toxicity*, *behavior*, and *aquatic environment*. No time restriction was applied, and studies published up to January 2025 were considered. Since this was not a systematic review, no PRISMA protocol or quantitative screening process was followed; instead, studies were selected based on their relevance to NPs in aquatic, marine, and soil environments, their interaction with natural organic matter, and their toxicological impacts on living organisms. Articles focusing solely on microplastics or macroplastics, without specific reference to nanoplastics, were not emphasized. The selected literature was then critically reviewed and synthesized to identify major research trends, key findings, and gaps in current knowledge.

Results and Discussion

Physicochemical Properties of Nanoplastics

The physicochemical properties of NPs are critical for understanding their environmental impact and behavior. These properties include size, shape, surface area, and chemical composition, which influence their interactions with biological systems and ecosystems (Figure 1). Nanoplastics exhibit diverse physicochemical properties that significantly influence their behavior in various environments. For instance, studies reveal that the size, shape, and surface properties of NPs can vary widely, with concentrations during mechanical recycling processes reaching up to 1,300,000 particles/cm³ for particles between 10 and 420 nm (Swinnerton et al., 2024). Additionally, NP aging alters their structural arrangement and chemical properties, thereby affecting their mobility and stability in aquatic systems (Şengül et al., 2024). Techniques such as AI-assisted nano-DIHM provide real-time characterization of these particles, enabling the identification of their optical phase and surface roughness, which are crucial for understanding their environmental impact (Wang et al., 2024). Overall, the physicochemical properties of NPs are critical for assessing their ecological risks and necessitate further investigation to inform environmental management strategies.

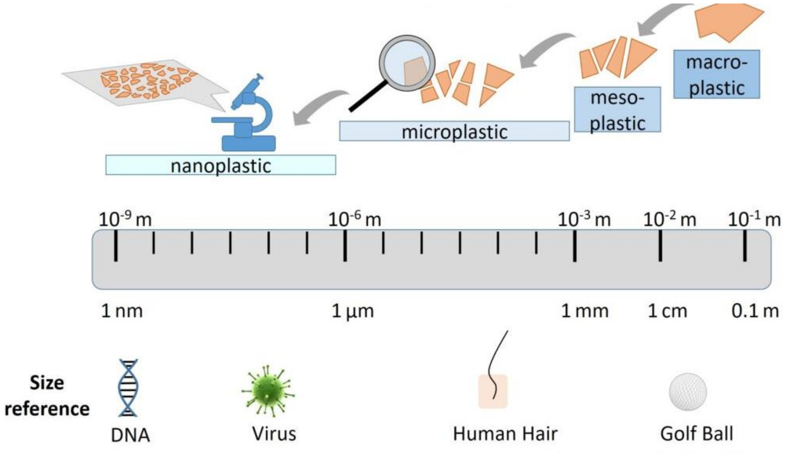

Figure 1. *Size classification of plastic particles (Cirino, 2022)*

Environmental Factors Affecting Nanoplastics Fate

The stability and dispersion of NPs in water are significantly influenced by pH and ionic strength, as these factors affect electrostatic interactions and particle aggregation. Higher pH levels tend to increase the transport of NPs by enhancing deprotonation, thereby increasing electrostatic repulsion and reducing aggregation, thereby promoting dispersion (Liu et al., 2022). Conversely, lower pH levels can lead to increased aggregation due to reduced electrostatic repulsion (Ruan et al., 2024). Ionic strength plays a crucial role, with divalent cations like Ca^{2+} having a more pronounced effect on NPs aggregation compared to monovalent cations like Na^+. This is due to the stronger charge-screening effect of divalent cations, which reduces electrostatic repulsion between particles, leading to faster aggregation (Singh et al., 2019). At ionic strengths below 80 mmol/L, Na^+ facilitates sedimentation, while higher concentrations promote aggregation and suspension (Tang et al., 2024). Natural organic matter can stabilize NPs through steric hindrance and electrostatic repulsion, with humic acid and sodium alginate particularly effective at enhancing stability at high ionic strengths (Pradel et al., 2021). The presence of NOM can also retard heteroaggregation of oppositely charged NPs, with humic acid being more effective than sodium alginate in NaCl solutions (Ruan et al., 2024). These findings underscore the complex interplay between pH, ionic strength, and organic matter in determining the environmental fate of NPs in aquatic systems.

Interactions between NPs and NOM can significantly influence their fate and transport in aquatic and soil environments. Natural organic material can stabilize pristine NPs through hydrophobic interactions, while photochemical weathering alters this dynamic, leading to destabilization via polymer bridging in weathered NPs (Xu et al., 2025). Additionally, NPs can enhance the aggregation of dissolved effluent organic matter, particularly under high salinity, which may affect microbial communities and settling velocities of aggregates (Vazquez et al., 2024). In soil, different types of dissolved organic matter (DOM) promote NPs transport, with humic acid showing the most significant effect due to electrostatic repulsion and steric hindrance (Tan et al., 2024). However, studies indicate that NPs do not significantly enhance contaminant transport, as their desorption rates are too rapid for effective mobility under typical conditions (Hofmann et al., 2024). Furthermore, low-molecular-weight organic acids can facilitate NPs migration through electrostatic forces, highlighting the complex interplay between NPs and organic matter in environmental contexts (Chen et al., 2024).

Salinity significantly influences the fate and transport of NPs in aquatic environments, particularly in coastal and polar regions. High salinity levels can restrict NPs' mobility due to increased aggregation with other nanoparticles, such as nano zinc oxide, forming heteroaggregates that inhibit NPs' transport in seawater (35 PSU). Conversely, in brackish water (3.5 PSU), NPs enhance the transport of nano zinc oxide, indicating a complex interaction that depends on salinity levels (Hou et al., 2025). Additionally, salinity alters the chemical properties of pore water and soil structures, affecting NPs migration in coastal wetlands, where increased salinity can reduce NPs mobility by over 20% (X. Zhang et al., 2024). In polar environments, NPs are expelled from forming sea ice, highlighting their distinct behaviors under varying salinity conditions (Pradel et al., 2021). Marine plastic pollution follows a complex pathway from industrial and consumer sources into aquatic environments, where it degrades into smaller particles and accumulates in food webs (Figure 2).

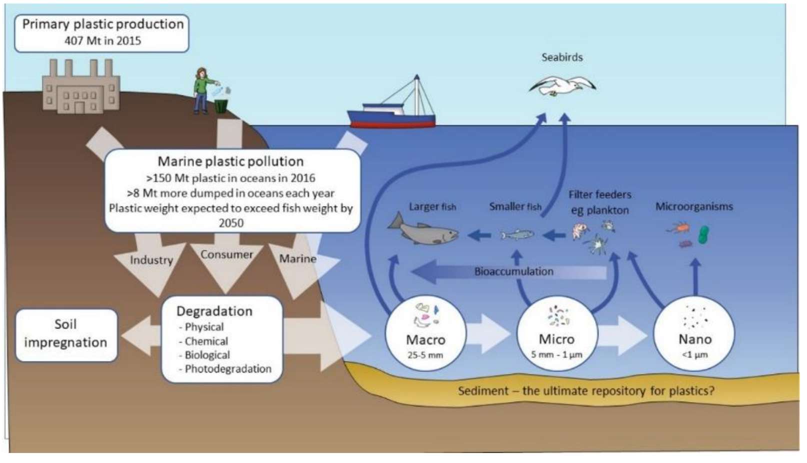

Figure 2. Pathways of marine plastic pollution, degradation, and bioaccumulation in aquatic food webs (Gangadoo et al., 2020).

Nanoplastic-Environment Interactions

The interplay among NPs' characteristics and environmental conditions significantly influences their behavior and ecological impacts. Nanoplastics, particularly those derived from photoaged plastics, exhibit altered properties that enhance their interactions with environmental factors, such as pH, temperature, and the presence of co-contaminants, including heavy metals and organic pollutants (Gao et al., 2024; Müller et al., 2025; Junaid et al., 2024). For instance, photoaged NPs demonstrate increased sorption capacities for pollutants, which can exacerbate their toxic effects on aquatic organisms, leading to altered growth and survival rates (Junaid et al., 2024). Additionally, the structural integrity of biological membranes is compromised by NPs, with varying resilience observed across different membrane types (Qian et al., 2024). The complex interactions between NPs and environmental conditions can also modulate the transfer of antibiotic resistance genes, highlighting the multifaceted risks posed by these emerging contaminants (Chen et al., 2024).

The formation of eco-corona on NPs significantly influences their bioavailability and toxicity, as evidenced by various studies. Eco-corona, formed by the adsorption of biomolecules and organic matter onto NPs, alters their interaction with aquatic organisms, enhancing bioaccumulation and toxicity. For instance, Liu et al. (2024) demonstrated that different eco-coronas on NPs led to varied toxicological effects in zebrafish embryos, with bovine serum albumin-corona (BSA-corona) showing lower toxicity compared to humic-acid-corona. Zhao et al. (2024) found that the presence of NPs reduced the bioavailability and cytotoxicity of perfluoroalkyl substances, indicating that eco-corona can modulate chemical interactions and cellular uptake. Additionally, eco-corona can facilitate the translocation of NPs in marine organisms, exacerbating their toxic effects on immunity and metabolism (Liu et al., 2024). Additionally, the interaction between NPs and natural organic matter, including humic acid and bovine serum albumin, can exacerbate toxicological effects, as evidenced by increased reactive oxygen species generation and apoptosis in zebrafish embryos (Liu et al., 2024) (Figure 3). In terrestrial ecosystems, eco-corona formation can mitigate the phytotoxicity of NPs, aiding their absorption by plants and influencing their ecological fate (Giri et al., 2024; Schefer et al., 2023).

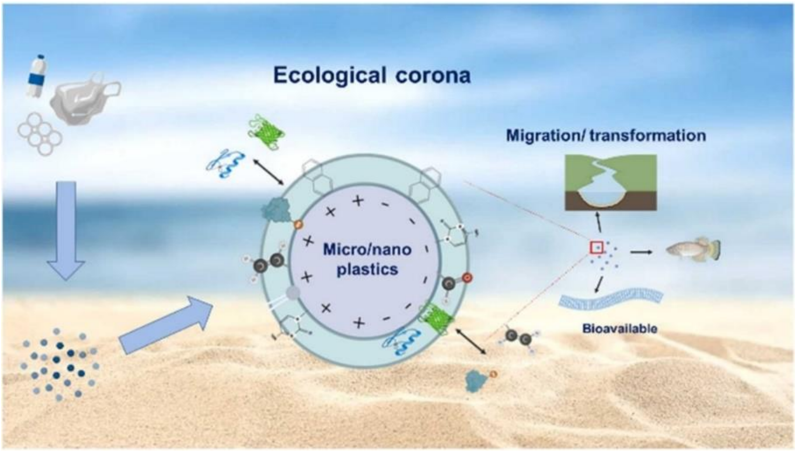

Figure 3: Schematic representation of the ecological corona formation on micro/nanoplastics and its role in environmental interactions (Zhang et al., 2022).

The eco-corona plays a significant role in modulating the toxicity of NPs in aquatic species by altering their bioavailability, translocation, and toxicological effects. Eco-corona, formed by the adsorption of biomolecules onto NPs, enhances their interaction with biological systems, as evidenced by studies showing that polystyrene NPs (NPs50) can penetrate embryos more readily than larger microplastics (MP5) due to eco-corona effects. Furthermore, the presence of eco-corona can exacerbate the toxic effects of co-occurring pollutants, such as chlorinated compounds, thereby increasing bioaccumulation and oxidative stress in zebrafish embryos (Liu et al., 2024). Additionally, eco-corona influences the toxicological behavior of NPs by altering their physicochemical properties, potentially leading to greater ecological risks than pristine particles (Ali et al., 2024).

Toxicological Impacts of Nanoplastics

Nanoplastics are emerging environmental contaminants that pose significant risks to living organisms through mechanisms such as oxidative stress, inflammation, and genotoxicity. Exposure to these particles can lead to the production of reactive oxygen species (ROS), which are implicated in cellular damage and inflammatory responses across various biological models, including cell lines and animal systems (Antunes et al., 2024; Mahmud et al., 2024). The oxidative stress induced by NPs can result in DNA damage, chromosomal abnormalities, and altered gene expression, contributing to reproductive health issues and potential carcinogenesis (Shukla et al., 2025). Furthermore, NPs can translocate across biological barriers, accumulate in vital organs, and exacerbate health risks, including neurodegenerative and cardiovascular diseases (Antunes et al., 2024; Shukla et al., 2025). The activation of inflammatory pathways, such as MAPK and NF-κB, further underscores the complex interplay between NPs exposure and cellular responses, necessitating further research to fully elucidate the long-term consequences of chronic exposure to these pollutants (Wang et al., 2024).

The uptake and biomagnification of NPs in aquatic food webs present significant ecological concerns, as evidenced by various studies. Research indicates that NPs, particularly polystyrene nanoparticles, are readily absorbed by freshwater organisms such as *Daphnia magna*, with larger particles showing higher accumulation rates. However, the transfer of these particles to higher trophic levels, such as mysids, is limited, suggesting minimal biomagnification within this specific food chain (Yu et al., 2024). In contrast, studies on marine species such as Coryphaena hippurus demonstrate that although NPs can be transferred through the food web, significant retention occurs in the gut, with potential for translocation to vital organs (Dey et al., 2024). Furthermore, the presence of NPs disrupts key ecological functions, particularly affecting primary producers and grazers, thereby altering food web dynamics (Ekvall et al., 2024; Habumugisha et al., 2024). Overall, while NPs are absorbed and can move through food webs, their potential for biomagnification appears limited, underscoring the need for further research to understand their ecological impacts fully.

Nanoplastics, such as polystyrene, can enhance the toxicity of heavy metals, such as copper, to organisms, indicating that their presence exacerbates the harmful effects of these metals in soil ecosystems (Zhu et al., 2024). Additionally, interactions between micro- and nanoplastics and airborne organic pollutants have been shown to increase cytotoxicity in human neurodevelopmental cells, suggesting that these combinations can lead to heightened oxidative stress and cellular damage. In aquatic environments, synergistic effects between micro/nanoplastics and emerging contaminants are frequently observed, while terrestrial studies indicate similar trends, although less explored (Bastante-Rabadán & Boltes, 2024). Furthermore, the mechanisms of interaction, including adsorption and complexation, reveal that NPs can act as vectors for heavy metals, altering their mobility and toxicity in soil systems (Ceylan et al., 2024; Maity et al., 2021). This complex interplay underscores the need for comprehensive risk assessments of these pollutant mixtures in various ecosystems.

Knowledge Gaps and Future Research Directions

Current challenges in understanding NPs' toxicity and environmental fate include their pervasive presence in ecosystems, difficulties in quantification, and the complexity of their interactions with biological systems. Nanoplastics, defined as particles smaller than 100 nm, can translocate across biological barriers, leading to adverse health effects such as oxidative stress, inflammation, and genotoxicity in various organisms (Antunes et al., 2024). Despite the alarming increase in plastic production, with 390.7 million tons produced in 2021, research has primarily focused on laboratory settings, necessitating broader real-world studies to assess long-term impacts (Shukla et al., 2025). Future research directions should emphasize integrating computational toxicology to better understand toxicity mechanisms better better, exploring the combined effects of NPs with other environmental contaminants, and developing innovative biodegradation strategies to mitigate their ecological impact. Enhanced detection methods and interdisciplinary approaches are essential for effectively addressing these challenges.

Conclusion

Nanoplastics are emerging environmental pollutants with unique physicochemical properties that dictate their fate, transport, and toxicity across aquatic and terrestrial ecosystems. The formation of an eco-corona, driven by interactions with natural organic matter and biomolecules, plays a crucial role in modulating their bioavailability and toxicity. Key environmental parameters, including pH, ionic strength, and salinity, significantly influence NPs aggregation, mobility, and interactions with co-contaminants, leading to variable ecological impacts. Additionally, the interplay between NPs size, surface chemistry, and environmental conditions affects their role as vectors for heavy metals and organic pollutants, potentially amplifying their toxicological effects. Experimental studies provide strong evidence of NPs-induced oxidative stress, inflammation, and genotoxicity in aquatic organisms, along with disruptions to microbial communities and plant physiology in terrestrial environments. A comprehensive understanding of these complex interactions is essential for assessing the long-term ecological risks posed by NPs and developing effective regulatory strategies for environmental management.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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