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Nanoplastics in Aquatic Environments: Detection, Distribution and Ecological Risks

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Abstract **Review Article**

Nanoplastics, originating from the degradation of larger plastics, represent a critical concern for aquatic ecosystems worldwide. Their extensive distribution is confirmed across diverse habitats, including oceans, the Arctic, and freshwater systems, with evidence of ingestion by various organisms, indicating potential bioaccumulation. However, accurately quantifying their prevalence poses challenges due to analytical limitations, resulting in an underestimation of their true levels and unclear geographic distribution patterns. The review advocates for the adoption of cutting-edge technologies in nanoplastic research. Techniques such as spectroscopy, microscopy, and high-throughput methods are poised to enhance the detection and detailed study of nanoplastics. It calls for a multidisciplinary approach, integrating knowledge from polymer science, environmental chemistry, biology, and ecotoxicology, to fully comprehend the complexities of nanoplastic behavior and effects in aquatic environments. Emphasizing the necessity for advanced analytical tools, long-term studies, and exploration of interactions between nanoplastics and living organisms, the review suggests that a deeper understanding of environmental variables such as seasonal changes, climate effects, and microbial processes is essential to elucidate the long-term fate of nanoplastics. This comprehensive review lays the groundwork for current nanoplastic research, identifies major obstacles, and proposes directions for future work to fill knowledge gaps and guide effective environmental policy.

Keywords: Nanoplastics, Aquatic environment, Environmental fate, Detection techniques, Ecotoxicology.

INTRODUCTION

A pressing concern is the proliferation of secondary microplastics (<5mm) and nanoplastics (<100nm) – incredibly small plastic particles created from the breakdown of larger plastic products through mechanical, photolytic, thermal, or microbial processes occurring over months to decades in environmental contexts (Boyle and Örmeci, 2020; Dube and Okuthe, 2023). Up to 23 million tons of microplastics contaminate aquatic systems, with levels anticipated to rise in proportion to the plastic waste generation trend (Walker and Fequet, 2023a). Among sea surface samples collected globally, up to 57,000 microplastic particles per km^2 have been recorded, indicating ubiquity (Boyle and Örmeci, 2020; Zhao *et al.,* 2025). Nanoplastics likely constitute an even greater proportion of the synthetic particle burden based on release rates from plastic weathering, yet severe analytical limitations have prevented corroborating field measurements (Gigault, J., ter Halle, A., Baudrimont, M., Pascal, P. Y., Gauffre, F., Phi, T. L., ... & Reynaud, 2018). With their greater surface area to volume ratio enhancing sorption of hydrophobic persistent organic pollutants (POPs) by orders of magnitude compared to microplastics and pristine plastic (Fu *et al.,* 2021; L. C. Wang *et al.,* 2024) ,nanoplastics may serve as global vectors introducing POP contamination to remote polar regions and deep oceans ecosystems where plastics have already accumulated (Farale *et al.,* 2025; Henkel *et al.,* 2025). Furthermore, the nanoscale matches sizes capable of penetrating epithelial membranes, traversing cellular barriers, and passing into organs, implying risks of particle toxicity and associated adsorbed chemical bioaccumulation not linked to microplastics (Shukla *et al.,* 2024; Yang *et al.,* 2023). Accordingly, nanoplastics necessitate urgent, dedicated research attention.

Addressing these critical gaps requires a concerted effort from the scientific community to

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develop new analytical tools, conduct comprehensive environmental monitoring, and perform ecosystem-based impact studies. By advancing our methodological capabilities and deepening our understanding of nanoplastics' environmental behavior and impacts, we can better inform policy decisions, mitigate potential risks, and protect aquatic environments. This endeavour represents an opportunity to fill existing knowledge gaps and foster interdisciplinary collaborations that will drive the field of environmental science. In this study, we address the pressing challenge of nanoplastic pollution in aquatic environments by introducing cutting-edge analytical techniques and conceptual frameworks. Our novel contributions include the development of a highly sensitive and specific analytical toolkit that leverages advanced spectroscopy and microfluidics technologies, integrated with machine learning for enhanced data analysis. By proposing a comprehensive environmental fate model for nanoplastics, we pave the way for a deeper understanding of their ecological impacts. Our interdisciplinary approach sets a new benchmark for nanoplastic research and underscores the importance of collaborative efforts in environmental science.

Our comprehensive review identified several critical gaps in the current literature surrounding nanoplastic pollution in aquatic environments. Firstly, there is a significant shortfall in developing and validating analytical techniques capable of detecting and quantifying nanoplastics at environmentally relevant concentrations. While methods such as Fourier Transform Infrared (FTIR) Spectroscopy and Raman Spectroscopy have been established for microplastics, their sensitivity is limited for nanoparticles below 20 µm, and they cannot adequately visualize nanoscale particle morphology (Berkel and Özbek, 2024; Othman *et al.,* 2023).Advanced techniques like Asymmetrical Flow Field Fractionation (AF4) coupled with Multiangle Light Scattering (MALS) exist but lack harmonized methods tailored for diverse environmental matrices (Ventouri *et al.,* 2022). This gap hinders our understanding of nanoplastics' distribution patterns, environmental fate, and ecological impacts, emphasizing the urgent need for standardized, sensitive, and accessible detection methodologies (Nene *et al.,* 2025a; Wang, 2025). Furthermore, the environmental dynamics of nanoplastics, including their interactions with biota and potential for bioaccumulation and biomagnification, remain poorly understood due to these analytical challenges (Thakur *et al.,* 2025; Trevisan *et al.,* 2022). Despite known risks associated with their small size and large surface area, which may enhance the sorption of harmful pollutants, comprehensive studies elucidating the long-term ecological impacts of nanoplastics are scarce (Permana *et al.,* 2025). This knowledge gap underscores the necessity for long-term ecological studies and toxicological assessments to fully comprehend the risks nanoplastics pose to aquatic ecosystems and human health.

Plastic pollution poses one of the most critical global environmental threats of the 21st century (Nayanathara Thathsarani Pilapitiya and Ratnayake, 2024a; Stoett, 2022). While plastics only rose to mass production in the early 20th century, annual global output increased exponentially from 2 million metric tons in 1950 to over 400 million metric tons today (Dokl *et al.,* 2024; Kibria *et al.,* 2023a; Kumar *et al.,* 2021a). Projections suggest a doubling to 800 million MT by 2040 under business-as-usual conditions. Up to 12 million metric tons of mismanaged post-consumer plastic waste escapes from land-based sources into aquatic ecosystems annually (Nayanathara Thathsarani Pilapitiya and Ratnayake, 2024b; Saleem *et al.,* 2025). Without intervention, models predict this annual plastic outflow will double from 2016 to 2030 Plastic debris infiltrates diverse environments, from Arctic sea ice to the deep ocean. trenches, with estimates of 75-199 million tons found on coastlines and benthic sediments alone.

Detection Methods of Nanoplastics

Nanoplastics, the particles resulting from the degradation of larger plastic debris into fragments smaller than 100 nm, present a unique and emerging environmental threat to aquatic ecosystems (Farale *et al.,* 2025; Zhi *et al.,* 2025). Their small size, high surface area to volume ratio, and persistence in the environment make them particularly challenging to detect and monitor. As these particles degrade further, they become more widely distributed, ultimately accumulating in water bodies, sediments, and marine organisms (Ramsperger *et al.,* 2023; Yang *et al.,* 2023). While microplastics < 5 mm have gained significant attention in scientific and policy discussions, nanoplastics are receiving increasing focus due to their potential for far-reaching ecological impacts, such as bioaccumulation and biomagnification across aquatic food webs (Pothiraj *et al.,* 2023).

The challenge of detecting nanoplastics lies in their diminutive size, which places them at the limits of current detection technologies. Their physical properties differ significantly from larger plastic debris, making it difficult to visualize and quantify them using traditional methods (Ivleva, 2021; Jakubowicz *et al.,* 2021). Furthermore, nanoplastics' small size allows them to easily pass through cellular membranes, introducing potential toxic effects that are not yet fully understood. As such, there is a growing need for accurate, reliable, and sensitive analytical techniques capable of detecting nanoplastics in the complex and often contaminated aquatic environments (Akhbarizadeh *et al.,* 2019; Ramsperger *et al.,* 2023; Yang *et al.,* 2023).

Effective detection and quantification of nanoplastics are crucial for assessing their environmental and ecological risks. Quantifying their concentrations across various aquatic environments, such as oceans, lakes, rivers, and estuaries is necessary to understand their distribution patterns, persistence, and potential long-term effects on aquatic organisms (Habumugisha *et al.,* 2024; Shukla *et al.,* 2025). However, existing methods for detecting nanoplastics are hindered by issues such as low sensitivity, interference from natural particles, and the complexity of environmental matrices. These challenges make it difficult to fully comprehend the extent of nanoplastic pollution and its ecological consequences (Catarino *et al.,* 2023).

Detection Techniques

Quantifying the concentrations and mass flows of nanoplastics in freshwater and marine ecosystems is an urgent research priority due to projections of increasing environmental releases and limited toxicity data (Horton, A.A.; Walton, A.; Spurgeon, D.J.; Lahive, E.; Svendsen, 2021a). Robust quantification serves as a crucial precursor for elucidating nanoplastics' fate, transport mechanisms, and exposure pathways across trophic levels (Dennis *et al.,* 2025) .However, detection and measurement techniques tailored for environmentally relevant nanoplastics are still under development, creating barriers to understanding their occurrence patterns, risks, and impacts (Koelmans, A.A.; Besseling, E.; Shim, 2020). (Horton, A.A.; Walton, A.; Spurgeon, D.J.; Lahive, E.; Svendsen, 2021b). Synthesized aquatic toxicology evidence for nanoplastics while highlighting uncertainty about current environmental levels, emphasizing challenges in conducting ecological risk assessments. Accordingly, this review critically examines recent advances in analytical methods for detecting, isolating, and quantifying nanoplastics <100 nm to support ongoing aquatic research and monitoring. In **Table 1**, a comparative overview of the various analytical methods used for nanoplastic detection and quantification is presented. We assess the strengths and limitations of current approaches to identify future technical developments and harmonization needed to address key knowledge gaps surrounding nanoplastic proliferation as an emerging environmental issue.

Ultra-high-resolution microscopic techniques like TEM enable direct Nano-visualization and elemental composition confirmation but require extensive preparatory steps, increasing risks of artefacts and secondary nanoplastic generation, as well as providing only semi-quantitative estimates reliant on statistical extrapolation (Catarino, A.I.; Macchia, V.; Sanderson, W.G.; Thompson, R.C.; Henry, 2021). Spectroscopy techniques utilize quick, reagentless identification of polymer functional groups, although they remain partially confounded by interferences from non-plastic fractions requiring extensive quality control (Käppler, A.; Fischer, D.; Oberbeckmann, S.; Schernewski, G.; Labrenz, M.; Eichhorn, 2022). Among benefits, AF4- and SEM-based approaches facilitate simultaneous size classification and quantification, albeit throughput bottlenecks constrain extensive sampling (He, Y.; Zhang, Y.; Liu, F.; Lan, 2022).

Table 1: Overview of current Analytical Techniques for Nanoplastic Detection in Aquatic Environment

Method	**Principle**	**Applications**	**Advantages**	**Limitations/ Challenges**	**References**
Current Techniques					
FTIR Spectroscopy	Measures infrared light absorption to identify chemical bonds	Identifies polymer types in water, sediment, biota.	Non-destructive, provides chemical composition	Limited sensitivity for <20 µm particles, natural material interference	(Choi *et al.,* 2024; Nene *et al.,* 2025b)
Raman Spectroscopy	Measures inelastic light scattering for molecular bonds	Characterizes polymers in complex matrices.	High molecular specificity, non-destructive.	Low concentration detection issues, water/organic interference.	(Chakraborty *et al.,* 2023; Dąbrowska, 2021)
AF4 with MALS	Separates particles by size, measures light scattering.	Quantifies nanoplastics in water, sediment.	Precise size determination, handles mixtures	Low throughput, specialized equipment, sensitivity limits	(Drexel *et al.,* 2020; Giorgi *et al.,* 2021; Huang and Xu, 2025; Luo *et al.,* 2021)
TEM	Uses electron beams for high-resolution imaging.	Visualizes nanoplastics in samples.	High resolution, detailed structure.	Extensive preparation, not for large-scale monitoring.	(Fang *et al.,* 2023; Papke *et al.,* 2024)
NTA	Tracks Brownian motion for size distribution.	Measures particle size/concentration in liquids.	Real-time, wide size range (50–1000 nm).	High concentration needed, no chemical data, matrix effects.	(Peters *et al.,* 2022; Zhang *et al.,* 2023)
Py-GC-MS	Analyzes volatile products from polymer pyrolysis	Detects/quantifies nanoplastics by polymer type	Highly sensitive, accurate for	Requires pyrolysis, expensive, matrix effects	(“Pyrolysis-GC-MS | Pyrolysis Gas Chromatography |

			complex samples.		EAG Laboratories," n.d.; Seeley and Lynch, 2023)
Emerging Technologies					
Hyperspectral Imaging	Captures a wide range of wavelengths across the electromagnetic spectrum, offering detailed spectral data.	Used for detecting and mapping nanoplastics in aquatic environments, providing real-time analysis in complex samples.	- Non-destructive- Can detect specific chemical signatures - Real-time, in situ monitoring	- Large dataset size requires significant computational power - Water absorption interference in aquatic systems	(Faltynkova *et al.,* 2021; Rajabi *et al.,* 2023)
Infrared Photoacoustic Spectroscopy (PAS)	Measures the acoustic signal generated by the absorption of infrared light by a material.	Detects nanoplastics in water, sediments, and biota at low concentrations, with potential for real-time monitoring.	- High sensitivity for low concentrations- Real-time detection- Non-destructive	- Limited by interference from organic material- Requires advanced equipment and processing	(Dumitras *et al.,* 2020; Workman, 2024)
Microfluidic Devices	Uses microscale channels to manipulate small fluid volumes, integrated with sensors for particle detection	Portable, on-site detection of nanoplastics in liquid samples, particularly for field-based monitoring	- Portable- Low cost- Low sample volume required	- Early development phase for nanoplastic detection- Limited throughput and scalability	(Xiao *et al.,* 2024; Zhou *et al.,* 2024)
Electrochemical Sensors	Uses the electrochemical properties of nanoplastics to detect their presence through electrochemical reactions.	Detection of nanoplastics in water samples using electrochemical sensors, with potential for real-time monitoring	- Real-time, low-cost detection - Portable sensors for field-based use	- Limited sensitivity for very low concentrations - Potential interference from other particles	(Xiao *et al.,* 2024; Zhou *et al.,* 2024)
Laser-Induced Breakdown Spectroscopy (LIBS)	Uses laser pulses to ablate the sample and ionize the material, generating a plasma for spectral analysis	Detection of nanoplastics in complex environmental matrices, including water and sediments.	- High sensitivity- Non-destructive- Fast, real-time analysis	- Requires complex instrumentation- Matrix effects from the sample can interfere with results	(Hiltunen *et al.,* 2024; Sommer *et al.,* 2021)
Single-Particle ICP-MS (Inductively Coupled Plasma Mass Spectrometry)	Measures the mass-to-charge ratio of ions generated from single particles to quantify them.	Used for high-precision quantification of nanoplastics in environmental samples, especially for metals embedded in plastics.	Extremely sensitive- Can analyze individual particles with high precision	Requires expensive equipment- Sample preparation can be time-consuming	(Caldwell *et al.,* 2022; Jiménez-Lamana *et al.,* 2020)

Global Distribution

Recent investigations have revealed that complex factors shape nanoplastics' propagation across aquatic ecosystems. As shown in **Table 2**, the distribution and concentration of nanoplastics across different aquatic environments vary significantly. Spatial evaluations of Chinese and Brazilian rivers determined contamination aligned with wastewater effluents and heavily populated watersheds (Jolaosho *et al.,* 2025; Trevisan *et al.,* 2022). Marine assessments also found that ocean currents and gyres concentrated buoyant nanofragments in floating patches or depositional zones like trenches and poles (Hidalgo-Ruz *et al.,* 2012). Coastal enclosed seas and estuaries likewise accumulated higher nanoplastics near aquaculture, harbours, and shipping lanes, indicative of human activities(N V Lakshmi Kavya *et al.,* 2020; Tuuri and Leterme, 2023) .

Sedimentation additionally plays a key role as higher density nanoparticles deposit into benthic strata. Benthic feeders consequently ingested more nanofragments than surface organisms in Arctic food webs, showing vertical skew (Arif *et al.,* 2024; Courtene-Jones *et al.,* 2017).Larger-scale global modelling determined emissions near developing cities and stormwater overflows increase terrestrial runoff inputs that spatially disperse plastics across hydrologically connected environments (Müller *et al.,* 2020; Palmer *et al.,* 2025a). Applying geospatial distribution predictions and monitoring contamination flows aids directing mitigation efforts to highly exposed ecosystems. Further analysis of fate mechanisms and transport behaviors will support models enhancing environmental forensics and remediation prioritization for this emerging contaminant class.

Table 2: Global Distribution Patterns of Nanoplastics in Aquatic Environments

Aquatic Environment	**Key Distribution Mechanisms**	**Notable Findings/Case Studies**	**Reference**
Marine Environments	- Ocean currents transport nanoplastics over vast distances. - Nanoplastics accumulate in gyres and coastal regions. - Deep ocean currents can transport nanoplastics to remote areas.	- North Pacific Gyre: High concentrations of nanoplastics found in surface waters, primarily due to shipping lanes. - Arctic Ocean: Nanoplastics detected in surface waters and sea ice.	(Farale *et al.,* 2025; ten Hietbrink *et al.,* 2025)
Rivers and Estuaries	- Rivers serve as conduits for transporting nanoplastics from land to ocean. - Estuaries act as transitional zones, accumulating nanoplastics due to slower water flow.	- Yangtze River: Significant concentrations of nanoplastics near urban and industrial zones, with high transport to the East China Sea. - Pearl River Delta: Estuarine hotspots for nanoplastic accumulation.	(Chau *et al.,* 2023; S. Wang *et al.,* 2024)
Freshwater Systems (Lakes & Ponds)	- Nanoplastics enter through wastewater discharges and runoff. - Tend to accumulate in sediments due to low water flow in lakes and ponds.	- Great Lakes (USA/Canada): Nanoplastics found in both water and sediment samples, especially in areas affected by industrial activities. - Lake Victoria: Significant concentrations found in surface waters.	(Egessa *et al.,* 2020; Fuschi *et al.,* 2022)
Wetlands & Mangroves	- Wetlands filter water, accumulating nanoplastics in sediments. - Mangroves trap nanoplastics from river discharge or direct ocean deposition.	- Mangroves in Thailand: High concentrations of nanoplastics found in sediment and water columns. - California Wetlands: Nanoplastics accumulate in sediment layers, impacting local biodiversity.	(Chaisanguansuk *et al.,* 2023; Ouyang *et al.,* 2022)
Polar Regions (Arctic/Antarctic Oceans)	- Nanoplastics transported via ocean currents. - Airborne nanoplastics can settle into polar waters.	- Arctic Ocean: Nanoplastics detected in surface waters, raising concerns about contamination in remote regions. - Antarctic Waters: Microplastics and nanoplastics found in sea ice and deep water.	(Collard *et al.,* 2025; Huang *et al.,* 2023)

Sources and pathways

A diversity of point and nonpoint sources drives environmental nanoplastics contamination spanning industrial emissions, plastic waste breakdown, and multi-pathway hydrologic dispersal across terrestrial and aquatic compartments (Palmer *et al.,* 2025b; Richard *et al.,* 2024). As shown in **Figure 1**, Primary industrial discharges of both unintentionally produced nano-sized polymer particles as well as engineered plastic nanomaterials are key direct contributors identified (Ali *et al.,* 2025; Mandal *et al.,* 2024). Textiles manufacturing constitutes a predominant origin category, where up to 40% of synthetic fabric coatings and rinses applied contain nano-polyester and acrylic emulsions measuring 50-300nm upon garment washing (Hernandez, L.M.; Yousefi, N.; Tufenkji, 2022). Modelling estimates 0.3-0.5 million MT of microfibers enter waste streams annually from global apparel laundering alone (Lau, W.W.Y.; Shiran, Y.; Bailey, R.M.; Cook, E.; Stuchtey, M.R.; Koskella, J.; Velis, C.A.; Godfrey, L.; Boucher, J.; Murphy, n.d.). Additionally, nano-additives, including silver nanoparticles, incorporated into textiles get emitted. Plastics manufacturers have commonly utilized nano-sized polymer emulsions, allowing desired physical properties in production, subsequently released through wastewaters (Ali *et al.,* 2024; Jalali *et al.,* 2024; Shah *et al.,* 2022).Cosmetic microbeads introduced both for abrasive cleaning applications as well as carriers for lipophilic pigments and polyaromatic UV-absorbers also contribute; although partially phased-out, aquatic detections still occur as reservoirs get flushed (Not *et al.,* 2025).

Moreover, larger plastic litter acts as a secondary nanoplastics source. Photodegradation from solar radiation, thermo-oxidative erosion, and microbial biodegradation abrade macroplastics into micro and nano-fragments, as shown across polyethylene, polypropylene, and polystyrene global sampling (Li *et al.,* 2025). Among the fastest formation rates known is expanded polystyrene foam buoyant in seawater, converted into nanoparticles within months (Wu *et al.,* 2025). Plastics accumulate on urban and agricultural soils, serving as upstream nanoplastic sources reaching lakes and oceans during stormwater runoff events (Sarkar *et al.,* 2021).

Atmospheric fallout enabling surface transport is increasingly documented as urban dust and road deposition samples reveal high nanopolymers fractions up to 46%, suggesting precipitation scavenging of volatile plastic additives during use (Cai, M.; Zeng, Z.; Bai, J.; Li, J.; Zhang, J.; Chen, 2022). Hydrophobic nanoplastics easily migrate into groundwater aquifers underlying contaminated soils (Wang, L.; Lu, J.; Ogunyemi, S.O.; Li, X.; Cai, J.; Li, 2022). Across aquatic systems, biofouling of microplastics enabling increased density for downward export coupled with aggregation onto organic flocs that vertically sediment, drive benthic accumulation documented in deep sediments (Cantillo, A.Y.; Scherer, C.; Mittelstaedt, H.; Rezanezhad, 2021; Doyle, R.D.; Hart, K.M.; Jackson, 2022). Such combination of diffuse pathways now far outpaces the localized direct discharge route of municipal wastewater effluent polyethylene and polypropylene particles verified decades earlier (Ziajahromi, S.; Kumar, A.; Neale, P.A.; Leusch, 2022). Still, wastewater treatment facilities remain nanoplastic sources where 1000 to 4600 tons annually discharge into receiving waters in a major U.S. urban region alone (Mason, S.A.; Welch, V.L.; Goldberg, E.M.; Cai, 2022).

Recent elucidation of indirect pathways, including multi-media environmental cycling and in-situ degradation of plastic 'secondary micro- and nanoplastics', now dominate burden explanations over discrete emissions (Hartmann, N.B.; Lusher, A.L.; Thompson, R.C.; Ziajahromi, S.; Galloway, 2022). Improved circular economics, reducing fugitive losses during production and end-of-life, while stimulating biodegradable alternatives, can enhance control of these diffuse nanoplastic contamination routes (Wang, W., Ndungu, A. W., Li, Z., & Wang, 2021).

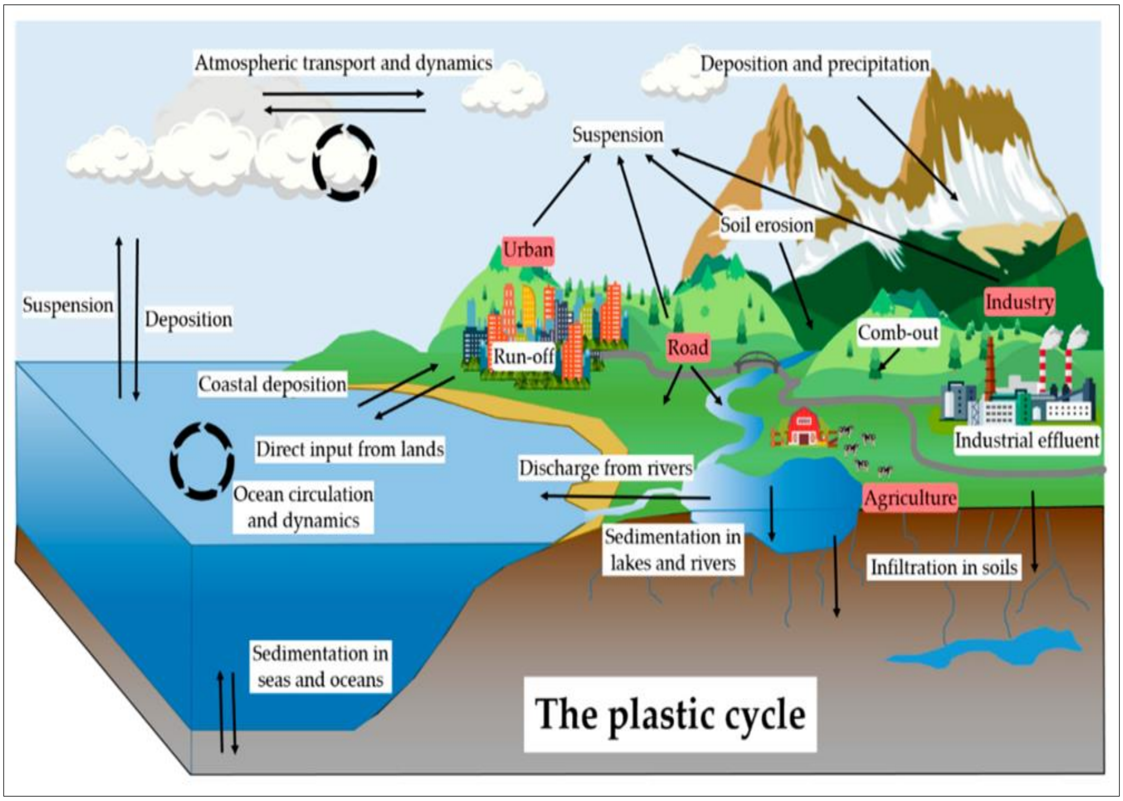

Figure 1: Conceptual model of the biogeochemical cycle of plastic. Red boxes indicate primary sources, while white boxes represent transport mechanisms and influencing factors. Arrows depict the pathways of plastic transport (Bianco and Passananti, 2020)

Ecological Risks of Nanoplastics

Tropical transfer and Bioaccumulation

The ecological dynamics encompassing trophic transfer and bioaccumulation of nanoplastics in aquatic ecosystems are intricate and substantiated by an expanding body of empirical evidence derived from both controlled laboratory assays and extensive environmental sampling efforts (Farale *et al.,* 2025). **Figure 2** illustrates the fate and impacts of nanoplastics on aquatic species, demonstrating the complex interactions within these ecosystems. Diverse aquatic organisms spanning phytoplankton, microbial communities, invertebrates, teleosts, and marine mammals have been conclusively demonstrated to internalize nanoscale plastic particles, as elucidated in seminal works by (McCormick, A.R.; Hoellein, T.J.; Mason, S.A.; Schluep, J.; Kelly, 2022; Wang, Z.; Shi, H.; Yuan, X.; Zhang, Z.; Jiang, L.; Zhao, Y.; Yu, G.; Liu, 2019). Employing sophisticated electron and fluorescent microscopy methodologies, exemplified by the research endeavors of (Caruso, G.; Avella, M.A.; d'Amore, E.; Ferrando, S.; Gallus, L.; Gambardella, C.; Guida, M.; Rotini, A.; Bernardi, G.; Aprea, 2021; Jin, Y.; Lu, L.; Tu, W.; Luo, T.; Fu, 2018), researchers have visually ascertained the ubiquitous presence of nanoplastics intricately sequestered within the gastrointestinal tracts and tissues of various organisms, encompassing taxa from wild zooplankton to economically significant seafood species (Hutton *et al.,* 2024; Thakur *et al.,* 2025).

Controlled dosing experiments, a cornerstone in elucidating trophic transfer dynamics, have been instrumental, particularly in studies conducted by (Chen, Q.; Gundlach, M.; Yang, S.; Jiang, J.; Velki, M.; Yin, 2017). These investigations reveal the discernible accumulation of polystyrene nanoparticles across successive trophic levels, accentuating the phenomenon of biomagnification within aquatic food webs. Field collections, as underscored by (Koven, 2022), substantiate and extend these findings, elucidating augmented microplastic burdens that correlate with elevated trophic levels. Despite the wealth of empirical insights, the accurate quantification of nanoplastics in natural aquatic settings remains impeded by pervasive detection limitations, constituting a persistent challenge in comprehensively deciphering the nuanced dynamics governing trophic transfer and bioaccumulation in aquatic ecosystems (Fu *et al.,* 2020; Kokilathasan and Dittrich, 2022).

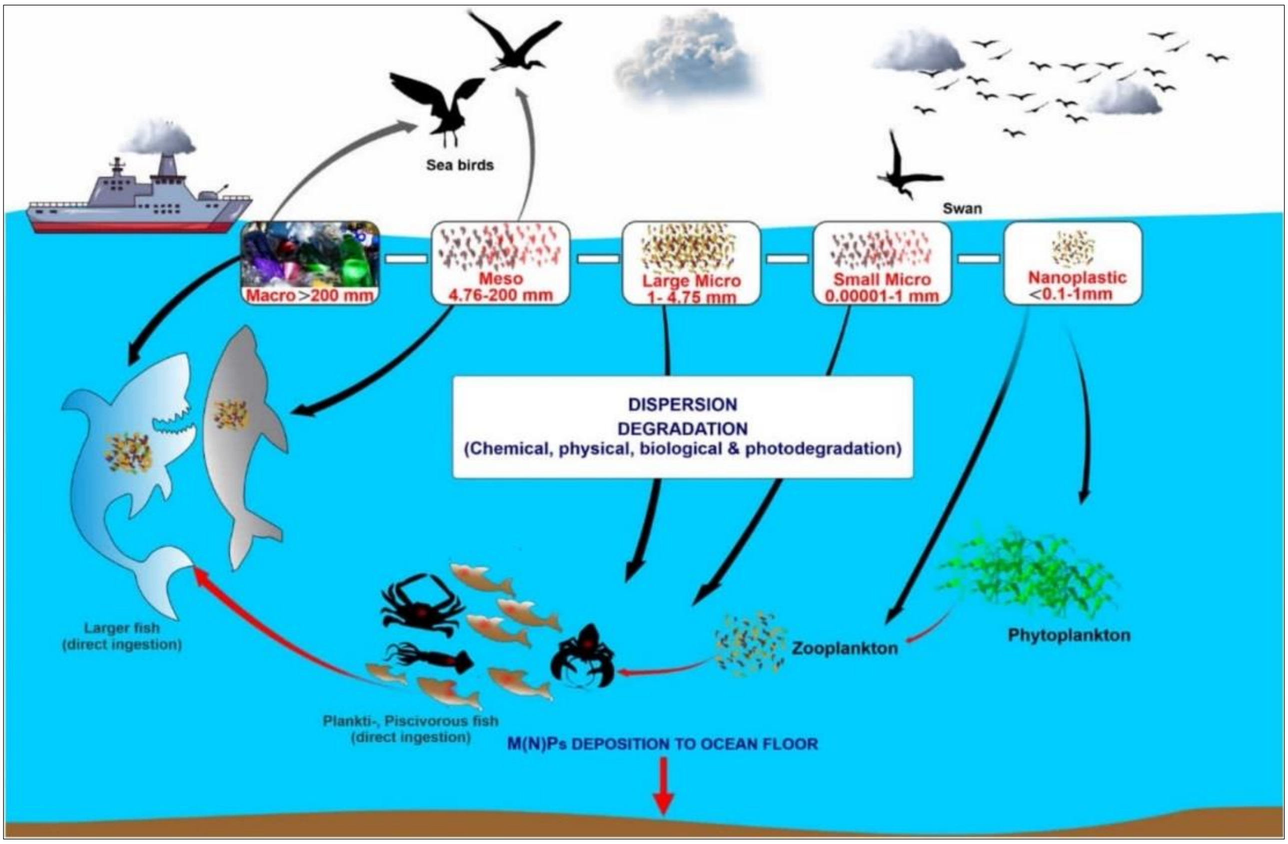

Figure 2: Fate and impacts of nanoplastics (NPs) in aquatic species (Stapleton and Hai, 2023)

Toxicity mechanisms

The physiological and biochemical ramifications arising from nanoplastic exposure constitute a well-substantiated domain within the realm of scientific inquiry. In-depth examinations led by (Jin, Y.; Lu, L.; Tu, W.; Luo, T.; Fu, 2018; Qiao, R.; Sheng, C.; Lu, Y.; Zhang, Y.; Ren, H.; Lemos, 2019) have delineated a spectrum of adversative effects, encompassing inflammatory responses, oxidative stress, perturbations in immune and enzyme activities, as well as disruptions in metabolic and neurotransmitter functions. These findings underscore the intricate and multifaceted nature of nanoplastic-induced toxicity, engendering cascading impacts on the sophisticated physiological processes governing various aquatic organisms (Jamil *et al.,* 2025).

Adverse effects at the population level have been meticulously documented in a diverse array of laboratory studies, particularly under conditions of heightened doses exceeding 1 mg/L, as expounded in the works by (Prokić, M.D.; Radulović, V.; Grujić, S.; Jaćimović, M.; Vukašinović-Pešić, V.; Borković-Mitić, S.; Gačić, Z.; Lazarević, K.B.; Jarić, 2022; Wang, J.; Peng, J.; Tan, Z.; Gao, Y.; Zhan, Z.; Chen, Q.; Cai, L.; Huang, 2017). Such repercussions encompass a spectrum of manifestations, including feeding inhibition, disruptions in reproductive processes, occurrences of larval abnormalities, and elevated mortality rates (Yi *et al.,* 2024). The manifestation of these effects is intricately linked to pivotal particle properties, most notably surface charge and age, which wield significant influence over processes such as agglomeration and the adsorption of co-occurring contaminants. These nuanced interactions contribute substantively to the complexities inherent in nanoplastic toxicity, thereby elucidating the intricate mechanisms that underlie the adverse impacts on both individual organisms and broader populations (Yee *et al.,* 2021).

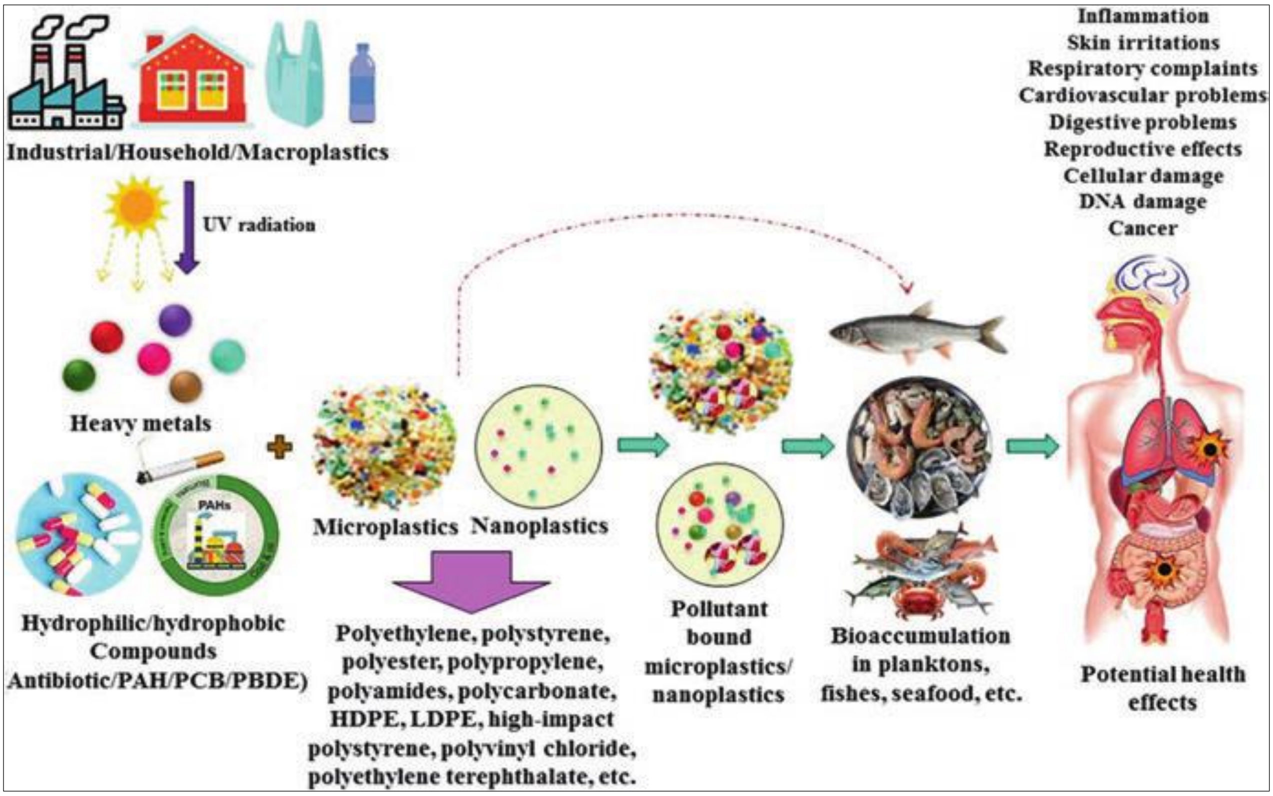

Figure 3: Pathways of nanoplastic toxicity from sources to human health via bioaccumulation in aquatic food web (Benson *et al.,* 2022)

Environmental fate and behavior

The distribution, transport and persistence of nanoplastics within aquatic ecosystems depend on various intrinsic particle properties alongside external environmental conditions mediating key processes of sedimentation, bioaccumulation and trophic transfer (Galloway, T.S.; Cole, M.; Lewis, 2022). A predominant early phase for marine plastics is buoyancy enabling long-range oceanic dispersal. However, at nano-dimensions below 80 nm, density exceeds that of seawater causing sinking estimated at 0.03–10 m/day governed by surface functionalization (Jiang, W.; Wu, M.; Li, Z.; Hu, S.; Liu, H.; Wang, Z.; Hu, J.; Chen, M.; Wang, S.; Jin, 2021). Still, organic matter facilitates refloating through aggregation actually increasing bioavailability to pelagic feeders (Kooi, M.; Reisser, J.; Slat, B.; Ferrari, F.F.; Schmid, M.S.; Cunsolo, S.; Brambini, R.; Noble, 2018). Acid-base modeling reveals nanoplastics accumulate protons and cations from seawater, acquire negative surface charge and stabilize using divalent cations as counterions - all influencing agglomeration, gel formation and sorption phenomena (Wang, X.; Ma, J.; Li, S.; Luo, J.; He, C.; Wei, H.; Sun, C.; Liu, W.; Chen, 2022). Sedimentation also depends on particle shape with elongated high-aspect ratio nanofibers subsiding slower than spherical particles at identical densities (Vendel, A.L.; van der Zande, M.; Lamoree, M.H.; ter Halle, 2022). Across lacustrine settings, seasonal stratification and turnover mixing cycles spur variable vertical transport (Käppler, A.; Fischer, D.; Oberbeckmann, S.; Schernewski, G.; Labrenz, M.; Eichhorn, 2022). At the nano-bio interface, mucus secretions facilitate nanoplastics retention on aquatic vegetation surfaces where herbivores graze (Windsor, F.M.; Durance, I.; Ormerod, 2022). In wastewater treatment plants, microorganisms internalize then egest nanoparticles during sludge stabilization contributing terrestrial outputs (Li, L.; Zhou, C.; Jiang, J.; Wu, Y.; Shang, C.; Zhang, Q.; Qiu, J.; Zhou, Y.; Qiu, 2021).

While pristine particles demonstrate limited persistence undergoing microbial mineralization, aged nanoplastics from environmental weathering prove more recalcitrant (Kole, P.J.; Löhr, A.J.; Van Belleghem, F.G.; Ragas, A.M.J.; Van Brussel, S.; Pereira, A.R.; Schuurmans, J.M.; de Franscisco-Mora, B.; Leslie, H.A.; An, 2022). Across food chains, durable accumulation has been experimentally verified from zooplankton to fish over chronic exposures (Mattson, K.; Weis, E.; Trebitz, A.; Wiley, 2022). Between surface water and organisms, bioconcentration factors reach thousands suggesting high bioavailability, subsequently transferring up trophic levels (Wang, Y.; Zhu, F.; Zhao, J.; Wang, Y.; Li, W.; Sun, C.; Guo, Z.; Wang, T.; Liu, H.; Ma, 2020). Elucidating such combination of nanoplastics physicochemical alterations over their lifecycle alongside complex environmental interactions and organismal trophodynamics can best illuminate contamination timescales.

Emerging Technologies

Recent advances in sensor instrumentation and spectroscopic techniques showcase promise for enhanced identification and quantification of nanoplastic pollution in environmental matrices. Novel hyperspectral imaging instrumentation uses ultraviolet-visible-near infrared wavelengths (400-1000 nm) to obtain detailed optical fingerprints of particles down to 10 µm facilitating polymer classification of microfibers and fragments (Peng, C.; Guo, X.; Wang, M.; Huang, Y.; Xiang, Z.; Li, X.; Yao, P.; Li, 2022) .Coupling near infrared chemical imaging with multivariate curve resolution achieves rapid in-situ chemical maps differentiating nanoplastic particles from background interferences in complex sediment samples (Turner, A.; Hirai, H.; van den Berg, C.; Tucker, T.; Verkuijlen, 2021). Infrared photoacoustic spectroscopy method detects polystyrene nanospheres to levels of 1 ng/L in water demonstrating sensitivity outpacing conventional FT-IR (Chen, Y.; Gao, X.; Li, J.; Chen, H.; Zheng, H.; Li, J.; Zhou, H.; Liu, J.; Li, Y.; Chen, 2021). Another vibrational technique, surface enhanced Raman spectroscopy facilitated detection down to 11 nm polystyrene beads using gold-silica coated magnetic nanoparticles (Su, Y.; Yan, M.; Wang, H.; Li, S.; Sun, L.; Liu, Y.; Li, 2022). Such ultrasensitive spectroscopic sensor and microscopy innovations show promise for comprehensive nanoplastics occurrence data.

Microfluidic and nanomaterials-enabled lab-on-a-chip devices also continue rapid development. For example, nano-porous anodized aluminum oxide immobilized TiO2 nanosheets facilitated photoelectrochemical detection of polyethylene microplastics down to 10 nm through oxidation current signals sensitive to transparent particle surface area (Zhang, L.; Gao, R.; Li, H.; Sun, S.; Jiang, H.; Wang, P.; Hu, 2022). Further incorporation of machine learning pattern recognition models can support automated analyses (Xiong, Q.; Sun, Y.; Qiao, H.; Jin, Z.; Wang, Y.; Yang, F.; Yu, Y.; Wang, C.; Chen, L.; Zhou, 2021). Ultimately interfacing ongoing instrumentation refinements with environmental sampling protocols promises accelerated progress.

Future Research Directions

Our study into the quantification and distribution of nanoplastics in aquatic environments illuminates a pathway for future research, marked by innovation and interdisciplinary collaboration. A critical frontier is the advancement of detection methodologies. We advocate for the exploration of multivariate discriminatory algorithms integrated with hyperspectral imaging to enhance the molecular and morphological characterization of nanoplastics in situ. This approach promises a leap forward in environmental monitoring, potentially eliminating the need for complex extraction processes. Furthermore, the development of portable microfluidic lab-on-a-chip platforms, incorporating advanced sensor technologies, could revolutionize real-time nanoplastic detection in diverse aquatic settings.

An equally pressing research avenue is the application of multi-omics techniques to reveal the biological impacts of nanoplastic exposure. Future studies should focus on leveraging proteomic, genomic, and metabolomic profiling to uncover mechanisms of toxicity and identify biomarkers of exposure, providing insights critical for ecological risk assessments. The establishment of standardized reporting guidelines and methodologies for nanoplastic research is imperative to unify and advance our understanding of their global impacts. Moreover, longitudinal studies examining trophic transfer, biomagnification, and the broader ecological consequences of nanoplastics are vital for filling existing knowledge gaps and developing predictive models for their environmental fate.

Addressing these challenges necessitates an interdisciplinary approach, weaving together expertise from environmental chemistry, engineering, ecotoxicology, and policy-making. Such collaborations are crucial for devising effective strategies to mitigate the environmental and health impacts of nanoplastics. By setting a clear agenda for future research, our study not only contributes to the scientific discourse on nanoplastic pollution but also paves the way for meaningful advancements in environmental protection and sustainability.

Policy implications

Addressing the issue of nanoplastic pollution requires a comprehensive approach that goes beyond scientific research. Effective policy and regulatory frameworks are essential to mitigate the risks posed by these particles. The following **Table 3** highlights the key policy implications and recommendations.

Table 3: Policy Implications and Recommendations of Nanoplastic Pollution

Policy Issue	Description	Impact	Recommendations	References
Regulation of Nanoplastic Production and Use	Current regulations do not specifically target nanoplastics or address the additives used in plastics.	Nanoplastics continue to be released into the environment without proper controls, contributing to long-term pollution.	- Implement regulations to limit the production of nanoplastics. - Reduce toxic additives in plastics to minimize risk.	(Abdolahpur Monikh *et al.,* 2022; Allan *et al.,* 2021; Walker and Fequet, 2023b)
Monitoring and Surveillance of Nanoplastics	Lack of global monitoring systems for nanoplastic concentrations in different environmental matrices.	Inadequate data hinders the ability to track the extent of contamination, making mitigation efforts less effective.	- Develop standardized protocols for nanoplastic detection. - Establish international monitoring programs for aquatic environments.	("Advancing Global Microplastics Detection Technologies → Scenario," n.d.)
Funding for Nanoplastic Research	Limited funding for nanoplastic-specific research compared to microplastics.	Slower progress in understanding the full extent of nanoplastic pollution and its impacts on ecosystems and health.	- Increase funding for nanoplastic research. - Prioritize research on detection methods, toxicity, and environmental impact.	(Hale *et al.,* 2020; Winiarska *et al.,* 2024)
Public Awareness and Education	Public knowledge about nanoplastics and their risks is limited.	Lack of awareness results in ineffective waste management practices and continued release of nanoplastics into the environment.	- Launch public education campaigns on nanoplastic pollution. - Integrate nanoplastic awareness into environmental curricula.	(Christopher *et al.,* 2024; Kibria *et al.,* 2023b)
International Collaboration and Policy Alignment	Fragmented policies across regions and countries lead to inconsistent approaches to nanoplastic pollution.	Disjointed regulations make global efforts to address nanoplastic pollution ineffective and slow.	- Develop international agreements on nanoplastic pollution. - Promote global research collaboration on nanoplastic impacts.	(Nielsen *et al.,* 2023; Osuna-Laveaga *et al.,* 2023; Usman *et al.,* 2022)
Development of Mitigation Strategies	Effective technologies for removing or reducing nanoplastics in aquatic and terrestrial systems are lacking.	Nanoplastics will continue to accumulate in the environment, affecting biodiversity and ecosystem services.	- Invest in the development of nanoplastic removal technologies. - Promote sustainable practices to prevent nanoplastic release.	(Kumar *et al.,* 2021b; Rashed *et al.,* 2023)

CONCLUSION

In conclusion, Nanoplastics, a by-product of large plastic waste degradation, pose a significant threat to aquatic ecosystems. Despite their pervasive presence, challenges in quantification lead to an underestimation of their environmental levels. They are found in various environments, including oceans, the Arctic, Great Lakes, and wastewater effluents, and can be ingested by various taxa, indicating potential bioaccumulation pathways. However, analytical limitations hinder precise quantification and understanding of their geographic dynamics.

The future of microplastic research holds promise in reshaping our understanding of the environmental implications and persistence of these artificial particles. Integrating emerging technologies, such as hyperspectral imaging, infrared photoacoustic spectroscopy, and surface-enhanced Raman spectroscopy, offers opportunities for enhanced identification and quantification of microplastics. Interdisciplinary approaches are imperative for grappling with the multifaceted challenges posed by microplastic pollution. Collaborations among environmental scientists, ecologists, chemists, engineers, and social scientists are essential to holistically assess the ecological, chemical, and societal dimensions of microplastic issues.

Collaborative global efforts are imperative in addressing the pervasive nature of microplastic pollution. The interconnectedness of ecosystems and the transboundary transport of microplastics mandate international cooperation in research, monitoring, and policy development. The establishment of standardized protocols for sample collection, analysis, and reporting is essential to enhance comparability across studies and regions. The future of microplastic research hinges on integrating cutting-edge technologies, fostering interdisciplinary collaboration, and promoting global cooperation to unravel the complexities of microplastic pollution and develop effective strategies for mitigation and prevention.

While crucial to future monitoring and policy efforts, equally vital are revelations on biological impact severities. Initial toxicological evidence points to enzyme dysregulation, neurotransmitter interference, tissue damage, and even mortality implications under high experimental doses unlikely to replicate field exposures. Yet, extrapolation of effects to vulnerable populations and commercially relied upon fisheries remains speculative absent additional chronic assays on key species.

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