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Review

Dynamics and Impacts of Microplastics (MPs) and Nanoplastics (NPs) on Ecosystems and Biogeochemical Processes: The Need for Robust Regulatory Frameworks

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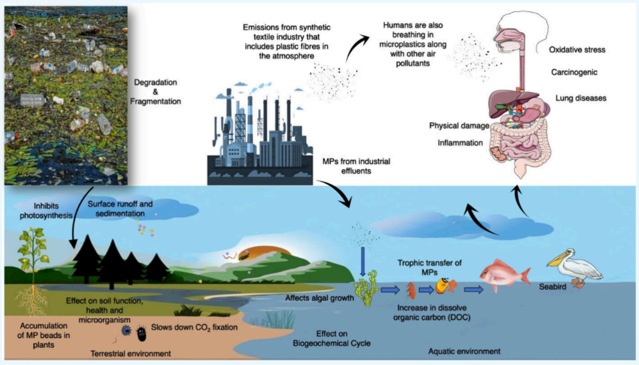

ABSTRACT: Microplastics (MPs) and nanoplastics (NPs) pose significant threats to aquatic and terrestrial ecosystems, disrupting nutrient cycling, altering soil properties, and affecting microbial communities. MPs and NPs bioaccumulate and contribute to global nutrient and water cycle disruptions, intensifying the impact of climate change. Despite the widespread use of plastics, inadequate plastic waste management leads to persistent environmental pollution. Toxic compounds are transported by MPs and NPs, affecting food chains, nutrient cycles, and overall ecosystem health. MPs impact soil biogeochemistry, microbial activity, and greenhouse gas emissions by altering the nitrogen and carbon cycles. One of the largest gaps in microplastic (MP) research today is the lack of standardized sampling and analytical methods. This lack of standardization significantly complicates the comparison of results across different studies. Multidisciplinary research and strict regulatory measures are needed to address MP pollution. This review highlights the critical need for mitigation methods to maintain ecosystem integrity and suggests standardization of sampling and data analysis. It offers insights into MP distribution, best practices for data analysis, and the impacts and interactions of MPs with biogeochemical processes. The Environmental Protection Agency has identified a critical need to improve the identification of nanoplastics. Particles smaller than 10 μm become increasingly difficult to quantify using standard MP detection practices.

1. INTRODUCTION

The worldwide production output of plastics, estimated to be 391 million tons for the year 2021, has steadily increased, thereby exacerbating environmental pollution.[1] Plastics pose enduring ecological challenges due to their slow degradation, along with the mismanagement of plastic waste. As plastic waste significantly remains uncollected, its breakdown into Microplastics (MPs) and Nanoplastics (NPs) adversely affects the ecosystem.[2] Common MPs include polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), polyester (PES), polyethylene terephthalate (PET), polyamide (PA), and polyurethane (PUR).[3] MPs are defined as plastic particles less than 5 mm in size,[4] originating from the breakdown of more oversized plastic items that are manufactured for various purposes, such as household goods, chemical fertilizers, and personal care products.[5,6] On the other hand, NPs are 1 nm to 1 μm in size and add to a newer dimension of plastic pollution.[7] Microplastics (MPs), originating from diverse sources, can be classified into two main forms: primary and secondary. Primary microplastics are deliberately produced small particles, such as resin pellets and exfoliators, which are found in pharmaceuticals and personal care products (PPCPs), and they often originate from industrial processes, synthetic fibers, and 3D printing waste.[8,9] In contrast, secondary microplastics are generated from the fragmentation of larger plastic items due to environmental factors like UV exposure, mechanical abrasion, and chemical degradation. Sunlight induces photooxidation, altering the chemical structure and increasing fragility; while physical forces such as transportation and weathering contribute to their breakdown. The aging or weathering process significantly modifies plastics, breaking down larger items into smaller fragments. MPs undergo degradation through mechanical, chemical, and biological processes, influenced by polymer structure, environ-

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mental conditions (humidity, temperature, and sun exposure), and the depositional matrix (water, soil, sand, or terrestrial vs aquatic environments).[10,11] Exposure to UV radiation induces surface oxidation, altering the specific surface area of MPs and enhancing protein binding through the production of carboxylic acid.[12] This photooxidation process occurs in the C−C backbone of plastics via initiation, transmission, and termination steps. Chromophoric groups absorb light energy, breaking C−C and C−H bonds and generating free radicals, which react with oxygen to form peroxy radicals and peroxides, leading to chemical modifications, fragility, and fragmentation.[13,14] Mechanical abrasion is another mechanism for generating microplastic particles. Prolonged abrasion increases surface area loss, while transportation through pipelines and riverbeds subject plastics to varying shear stresses, accelerating fragmentation.[15,16]

Moreover, chemical degradation due to humidity and temperature further accelerates the fragmentation process, introducing MPs into terrestrial and aquatic ecosystems, where they disrupt biogeochemical cycles and harm ecosystems.[17] In aquatic environments, microplastics are transported from terrestrial sources via surface runoff, river systems, and wastewater effluents. Coastal regions with high human activity experience substantial plastic degradation, producing fragments with higher surface areas. These particles leach toxic chemicals, such as per- and poly fluoroalkyl substances (PFAS), and act as vectors for contaminants like heavy metals and hydrophobic organic substances.[18] In aquatic environments, microplastics originate from terrestrial sources and eventually find their way into the sea via streams and rivers, with ocean basins acting as the primary reservoir for micro and nanosized particles.[19] These microplastics, detected in marine habitats,[20] possess the ability to absorb environmental chemicals, potentially carrying diseases and contaminants into marine ecosystems, thereby altering pollutant behavior and causing harmful impacts that pose a public health risk.[21] During the COVID-19 pandemic, many microplastics, including around 12,000 tons, were released into the oceans globally.[22] Literature highlights river systems as temporary storage sites for microplastics and floating plastics, emphasizing plastic's lifecycle and ultimate fate.[23] In water environments, microplastics such as PP, PS, and PE can also assemble possible pathogens[24] that further aggravate environmental hazards.

MPs also impact carbon cycling in freshwater ecosystems, revealing inhibitory effects on primary producer growth and photosynthetic activity.[25] Beyond their direct impacts on marine ecosystems, microplastics threaten terrestrial environments and biogeochemical cycles.[26,27] MPs and NPs negatively affect the environment by impacting the functioning of the ecosystem at various stages. They disrupt nutrient cycles by increasing soil toxicity and damaging organisms.[28−30] A study reveals that PE and polylactic acid (PLA) MPs altered soil multifunctionality and nitrogen cycling processes under different nitrogen diffusion (ND) conditions, affecting bacterial communities involved in nitrogen fixation and nitrate reduction.[31] A meta-analysis revealed that microplastic (MP) exposure significantly increased soil N_2O emissions and denitrification rates, impacting nitrogen cycling processes. Studies on PVC, PLA, and PP MPs in freshwater sediments noted significant effects on microbial communities during nitrogen and phosphorus dynamics. MP biofilms on polypropylene squares were found to promote ammonia oxidation and denitrification in aquatic systems, altering nitrogen and phosphorus cycling. Different MP types in saltmarsh sediments influenced nitrification and denitrification processes as well as sediment microbial communities. PE MPs was reported to affect submerged plants and sediment nutrient cycling in freshwater ecosystems, leading to a reduction in plant biomass and nutrient release from sediment.[32−35] Furthermore, microplastics interfere with carbon conversion and the carbon cycle in soil environments, affecting soil microbial biomass, enzyme activity, and carbon sequestration.[36,37] MPs also retards plant growth by blocking water and nutrient uptake, inducing drought, and causing excessive reactive oxygen species (ROS) production. It also alters ionome, impairs hormonal regulation, and reduces chlorophyll and photosynthesis, affecting overall plant health.[38,39] MPs influence the soil nitrogen cycle, facilitating biological nitrogen fixation and altering microbial community structure and enzyme activity.[40] According to Li et al. (2021)[41] global MP pollution jeopardizes soil ecosystem diversity and function by altering pH levels. The unique challenges posed by MPs and NPs, due to their small size and capacity to absorb harmful substances, present urgent issues that potentially pose more significant risks than larger plastic debris. It has been linked to harmful effects on aquatic organisms, including acute poisoning and physiological damage, highlighting their significance as a global hazard affecting ecosystems, biodiversity, and human health.[42,43] The detrimental effects of microplastics on soil ecosystems underscore the urgent need for mitigation strategies and regulatory measures to curb plastic pollution and safeguard soil health. This review, therefore, provides an in-depth analysis of microplastic (MP) and nanoplastic (NP) pollution and its effects on ecosystems. A key challenge in this field is the lack of standardized sampling and analytical methods, which limits the comparability of findings across studies. This review examines the presence, distribution, and impacts of MPs and NPs in terrestrial and marine environments, highlighting their disruption of biogeochemical cycles and contamination of natural ecosystems. While significant progress has been made in understanding the short-term effects of MPs and NPs, their long-term impacts remain unclear. Addressing these gaps is crucial to understanding the broader implications of MPs and NPs for ecosystem stability and informing effective mitigation strategies. Our methodology for this would be a critical review of existing literature that familiarizes how MPs and NPs get introduced into the Ecosystem, followed by its impact, analysis of the regulatory framework, and possible mitigation strategies.

2. PENETRATING THE WEB-OF-LIFE: MPS AND NPS ENTERING THE ECOSYSTEM

The dispersion of microplastics (MPs) into the environment, mainly through atmospheric transport, is influenced by various factors, including the degradation of household items, laundering of textiles, industrial emissions from vinyl and polyvinyl chloride production, clothing abrasion, and urban dust contamination.[44] Over time, plastics degrade due to environmental factors such as UV radiation, mechanical wear, and chemical weathering, leading to an increase in MP abundance and alterations in their physical and chemical properties.[12] Weathering drives MP formation through mechanical, chemical, and biological processes, with degradation influenced by polymer composition, environmental conditions, and surrounding matrices like water, soil, and sand.[13] UV-induced photooxidation initiates polymer break-

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down, producing free radicals that react with oxygen, leading to further fragmentation and chemical modifications.[14]

MPs originate from primary sources, including artificial turfs, paints, textiles, wastewater, personal care products, and industrial emissions (e.g., micropolyester, Fe_3O_4, SiO_2 from printing toners).[45−47] Secondary sources result from larger plastic debris degrading via UV exposure, mechanical stress, and environmental transport. Improper waste disposal allows rainwater runoff to carry MPs from land to water bodies.[48,49] Once formed, MPs remain suspended in the air and are transported by wind patterns, leading to their widespread distribution across land and oceans.[50] Their continuous degradation ensures a persistent influx of MPs, making their accumulation a growing concern in both terrestrial and aquatic ecosystems.

2.1. Terrestrial Impact. Once in soil, MPs from urban, agricultural, and industrial activities disrupt microbial communities, nutrient cycling, and soil structure. Agricultural inputs such as sewage sludge and compost contribute to MP contamination. Weathering releases nanoplastics and facilitates chemical leaching.[51−53] Microplastics, particularly micronanoplastics, have emerged as a concerning physical soil contaminant with multifaceted implications for terrestrial ecosystems. Micronano plastics alter soil aggregation, release toxic plastic leachate, decrease soil bulk density, and may impede root penetration resistance while also enhancing soil aeration, water flow, and evaporation.[54,55] The accumulation of plastic litter on the ground, stemming from the disposal of single-use plastics and domestic activities such as tourism, exacerbates this issue.[56] In agricultural soils, sewage sludge application contributes to the buildup of fragmented-dominated microplastics, which are subsequently absorbed by plants and enter the food chain.[57] Earthworms, such as *Lumbricus terrestris*, facilitate the transportation of microplastics through cutaneous transportation and mechanical injection into deeper soil strata.[58] Urban areas may exhibit significantly higher microplastic concentrations than coastal soil and estuaries due to various channels like landfills, air fallout, and agricultural practices such as plastic mulching.[59] MP exposure can disrupt terrestrial organism's development, reproduction, and behavior (Table 1).[60]

Furthermore, the influence of MPs on microbial communities varies depending on factors such as type, size, concentration, polymer composition, surface features, microbial composition, and exposure duration. These effects can range from favorable to detrimental or negligible, affecting enzyme activities, fungal populations, bacterial communities, and even pathogen assemblages in soil and water environments. For instance, microplastics like PE, PS, and PVC have been shown to influence enzyme activities, bacterial populations, and fungal communities and even increase harmful fungus in sandy loam.[61,62] In soil, PE microplastics have been found to increase ammonium concentration and alter the nitrogen cycle, while both PE and PVC are capable of influencing bacterial community structure.[63,64] The interaction between micro/nanoplastics and plants is a complex process that has significant implications for plant health, growth, and human exposure through the food chain. Due to their small size, nanoplastics can penetrate plant tissues with ease, leading to phytotoxic effects that compromise plant vitality.[65] The journey of these particles often begins at the roots, as they represent the primary entry point for MPs/NPs into plants. Plant roots are highly vulnerable to the uptake of MPs/NPs.

Table 1. Impact of Microplastic on Terrestrial Plants

Species	Concentrations	MPs/NPs	Effects	Ref
Lentil (*Lens culinaris* L.)	10, 50, and 100 mg L^{-1}	Polyethylene (PE)	Seed germination and seedling growth.	74
Summer squash (*Cucurbita pepo* L.)	<0.5 mg kg^{-1}	Polypropylene (PP), polyethylene (PE), and polyvinyl chloride (PVC)	Reductions in leaf size, chlorophyll content, and photosynthetic efficiency.	75
Lettuce (*Lactuca sativa* L.)	0, 0, 1 and 1 mg/L	Polystyrene (PS)	Foliar exposure to PSNPs at 1 mg/Lreduced growth, pigments, antioxidant capacity, and micronutrients in lettuce.	78
Garlic (*Allium sativum* L.)	0.05, 0.1, 0.25, 0.5, 1.0 mg/g	Polystyrene (PS)	Photosynthetic pigments, antioxidant enzyme activities, phytohormones, styrene content, and nutritional quality were notably affected. High PSNP exposure altered photosynthetic pigments, induced oxidative stress, and reduced the nutritive quality.	79
Arabidopsis (*Arabidopsis thaliana* L.)		Polystyrene (PS)	Decreased seed viability, growth, chlorophyll content, accumulation of root reactive oxygen species, and root exudates.	80
Palmer pigweed (*Amaranthus palmeri*)	0.1%, 0.5%, and 1%.	Polyethylene (PE) and polypropylene (PP)	Height and biomass, and altered community structure.	81
Ajwain (*Trachyspermum ammi* L.)	0, 25, and 50 $\mu g\ mL^{-1}$	Polyvinyl chloride (PVC)	At concentrations of 25 and 50 $\mu g\ mL^{-1}$, the effects are noted on plant sugars, nutrients, photosynthetic pigments, gas exchange, growth, and biomass.	82
Solanum lycopersicum	0.01, 0.1, and 1 g kg^{-1}	Polyethylene nanoplastics (PE-NPs)	PE-NPs pollution reduced biomass, delayed flowering, and caused abnormal fruit development. It induced oxidative stress, altered gene expression, and increased proline, phenols, and flavonoids. Photosynthesis and transpiration were reduced, and fruit quality was affected.	83

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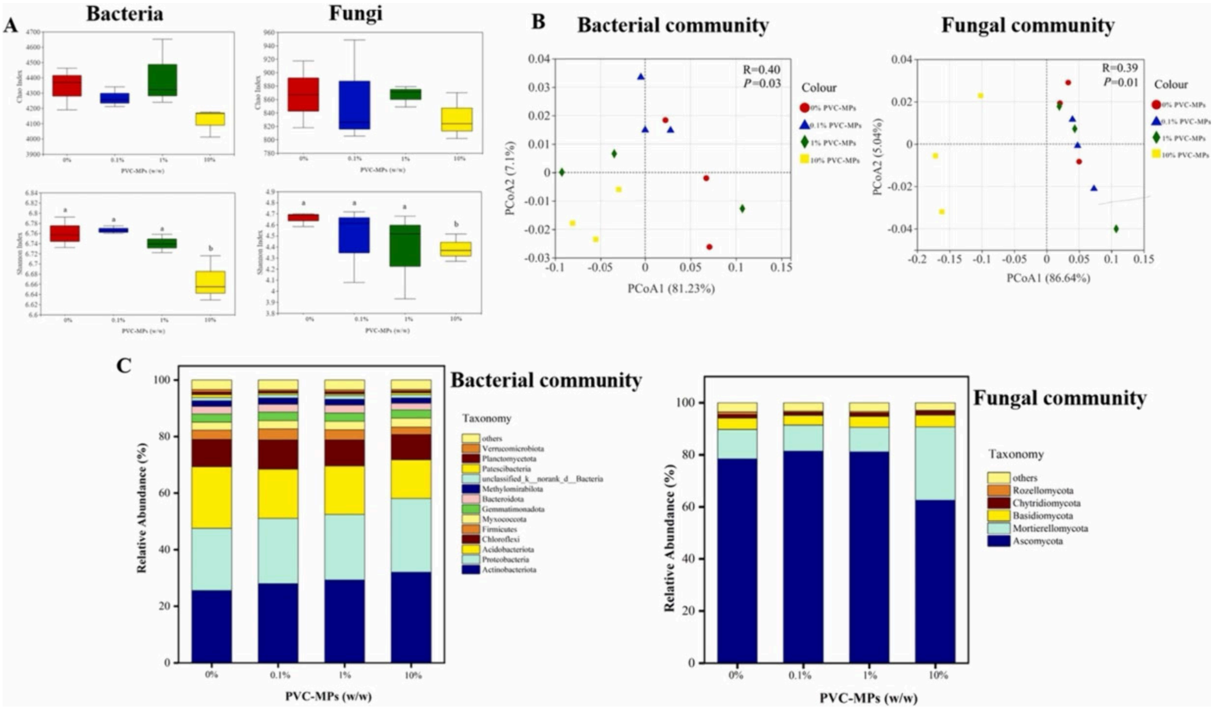

Figure 1. (A) The graph illustrates the decrease in bacterial and fungal richness, alongside the decline in alpha diversity, as PVC microplastics (PVC-MPs) content increases. (B) PCoA (Principal Coordinates Analysis) plot displaying distinct clustering patterns of microbial communities at varying concentrations of PVC microplastics (PVC-MPs). (C) Taxonomic analysis reveals shifts in bacterial and fungal phyla composition following exposure to PVC microplastics (PVC-MPs).[31] Reprinted with permission from Zhang et al. (2023). Copyright 2023 Elsevier. License No. 5997500925679.

These particles are absorbed directly through the plasma membrane and subsequently translocated to aerial parts such as stems, leaves, and fruits via the xylem.[66] This root-to-leaf movement can result in the accumulation of MPs/NPs in edible tissues, posing potential risks to human health throughout the food chain.[67] However, the interaction between these particles and roots triggers various adverse effects. For example, polystyrene microplastics (PS-MPs) can infiltrate root hairs and vascular bundles, disrupting root growth and nutrient absorption. This blockage reduces the translocation of essential macronutrients such as nitrogen, potassium, and phosphorus, further impairing plant health.[68] Moreover, the presence of MPs/NPs in the root zone induces oxidative stress, alters soil properties, and disrupts microbial communities, which collectively hinder nutrient uptake and plant development.[69] Studies on strawberries have highlighted the extent of these impacts. Exposure to polyethylene microplastics (PE-MPs) in soil, particularly smaller particles (35 μm in diameter) at higher concentrations (0.2% w/w), led to oxidative stress, reduced water uptake, and impaired root function. These physiological disruptions manifested as limited CO_2 assimilation reduced stomatal efficiency, and diminished fruit quality, characterized by lower fruit weight, soluble solid content, and anthocyanin levels.[70] In addition to root uptake, NPs can also enter plants through their leaves. Foliar uptake primarily occurs via stomatal pores, driven by the transpiration pull that facilitates the entry of these particles into the leaf tissue.[71] The ability of NPs to penetrate plant cell walls more effectively than MPs is largely attributed to their smaller size. Once inside, these particles can move through additional pathways such as endocytosis and apoplastic transport, with factors like particle size, surface charge, and plant physiology influencing their distribution.[72] The dual pathways of nanoplastic uptake roots and leaves allow these particles to integrate into plant systems, ultimately accumulating in edible parts. This accumulation threatens plant growth shown in Table 1.

The effects of polyvinyl chloride microplastics (PVC-MPs) on maize seedlings and soil properties have also been investigated (Figure 1). PVC-MPs primarily impacted shoot biomass and antioxidant enzyme activity in leaves. Bacterial and fungal richness decreased, while alpha diversity declined with increasing PVC-MP content (Figure 1A). Principal coordinate analysis (PCoA) showed distinct clustering of microbial communities at different PVC-MP concentrations (Figure 1B). Taxonomic analysis revealed shifts in bacterial and fungal species with PVC-MP exposure (Figure 1C). Bug base analysis indicated significant changes in soil microorganism phenotypes, favoring certain aerobic, Gram-positive, and stress-tolerant traits while inhibiting others. Biofilm formation varied slightly among treatments. Moreover, the RDA analysis studied soil factors and microbial traits for their impact on maize seedlings under PVC-MP stress. Soil NO_3-N and NH_4-N were the most influential, explaining 87.4% and 7.7% of the variation in seedling traits, respectively.[31]

2.2. Aquatic Impact. MPs in aquatic environments originate from terrestrial sources and are transported via surface runoff, river systems, and wastewater effluents. Coastal regions with high human activity experience substantial plastic degradation, producing fragments with increased surface area.[18] Due to their resemblance to natural food sources, MPs are ingested by marine organisms, leading to bioaccumulation and trophic transfer within aquatic food webs.[84]

Table 2. Impact of Microplastic on Aquatic Organisms

Species	Concentrations	MPs/NPs	Effects	Ref
Scenedesmus (*Scenedesmus obliquus*)	(30−103 mg/L)	Polystyrene (PS)	Reduction in chlorophyll.	94
Curly pondweed (*Potamogeton crispus* L.)	0.5, 5, and 50 mg/L)	Polystyrene (PS)	Alterations in the metabolic profile were identified in leaves, particularly in secondary metabolic pathways and ATP-binding cassette transporters.	95
Common duckmeat (*Spirodela polyrhiza* L.)	10, 100, and 1000 mg/L	Polyvinyl chloride (PVC)	Decreased the adventitious root elongation, affects carbon metabolism, nitrogen metabolism, amino acid metabolism, and lipid metabolism, and inhibits the synthesis of anthocyanins.	96
Oriental river prawn (Macrobrachium nipponense)	20, 40 mg/L	Polystyrene (PS)	Reduces nutrient buildup and suppresses gonadal growth in juvenile.	97
White leg shrimp (*Litopenaeus vannamei*)	0.1, 1, 5, and 10 mg/L	Polystyrene (PS)	Gut immune enzyme activity, cell shape, apoptosis, and microbial diversity.	98
Dunaliella (*Dunaliella tertiolecta*)	250 mg/mL	Polystyrene (PS)	Effect on the microalgae's growth and development.	99
Tape grass (*Vallisneria natans*)	1%	Polystyrene (PS)	Lowered the height, total biomass, root activity, and relative growth rate, as well as dissolved oxygen (DO).	100
Chlamydomonas (*Chlamydomonas reinhardtii*)	50 to 500 mg L $^{-1}$	Polystyrene (PS)	Biomass, photosynthetic pigment, oxidative stress, and cell morphology.	101
Water spinach (*Ipomoea aquatica*)	10, 20, 30, and 50 mg L^{-1}	Polystyrene (PS)	Growth uptake of water and nutrients by the roots.	102
Microcystis (*Microcystis aeruginosa*)	200 mg^{-1}	Polylactic acid (PLA)	Induced oxidative stress and caused membrane damage.	103
Zebrafish (*Danio rerio*)	0.04, 34 ng L^{-1} and 34 μg L^{-1}	Polystyrene (PS)	Damage to development, vasotoxicity, cytotoxicity, production of reactive oxygen species, and behavioral deficits.	104

Through processes like wave action, UV light exposure, and microbiological degradation, plastics break down into minute fragments, contributing to the formation of secondary microplastics in water.[85,86] These MPs, often as small as 5 mm, are detected in marine habitats[20] and possess the ability to absorb environmental chemicals, potentially carrying diseases and contaminants into marine ecosystems, thereby altering pollutant behavior and causing harmful impacts that pose a public health risk (Table 2).[21] Various factors, such as air movements, ocean currents, and surges, influence the distribution and quantity of MPs in marine ecosystems, enabling their long-distance transport.[87] During the COVID-19 pandemic, many MPs, including around 12,000 tons, were released into the oceans globally.[22] MPs enter freshwater and marine environments through multiple pathways, including wind dispersal, discharge from wastewater treatment plants (WWTPs), industrial and domestic runoff, and road runoff.[23] Their presence threatens marine ecosystems by potentially blocking digestive tracts and transferring toxins to marine organisms.[88] Literature highlights river systems as temporary storage sites for microplastics and floating plastics, emphasizing plastic's lifecycle and ultimate fate.[89] In water environments, MPs such as PP, PS, and PE can also assemble possible pathogens.[24]

MPs have been observed to be mistaken for food and consumed by various aquatic organisms, ranging from tiny zooplankton to large marine mammals. Their high affinity for hazardous environmental pollutants poses chemical and physical threats to biota.[90] Despite these threats, some organisms exhibit remarkable resilience to Tris(methylphenyl)-phosphate (TMPP) exposure. The ingestion of microplastics (MPs) in *Daphnia magna* during 48-h exposure has been reported. Both live and dead daphnids showed red MPs in their guts, confirmed as PET material via Attenuated Total Reflectance-Fourier Transform Infrared Spectroscopy (ATR FT-IR) microscopy (Figure 2). Deceased daphnids consistently exhibited full guts of MPs, while live individuals displayed varying gut contents, categorized as empty, partially filled, or filled. Despite repeated doses, the relationship between MP exposure and gut content was inconsistent, with no significant difference observed with or without algae prefeeding. Notably, surviving daphnids expelled MPs entirely after a 24-h recovery in MP-free conditions, demonstrating resilience, whereas deceased daphnids retained MPs.[91]

Studies on *Macrobrachium rosenbergii*, an ecologically significant freshwater prawn, reveal distinct responses to NP exposure. Transcriptomic analysis identified 918 differentially expressed unigenes (DEGs) after 30 days of exposure (356 upregulated, 562 downregulated) and 2376 DEGs after 96 h (1541 upregulated, 835 downregulated). Acute NP exposure enhanced carbohydrate transport, metabolism, and extracellular matrix processes, while chronic exposure induced nucleolar stress, impairing ribosome development and mRNA maturation without affecting glucose metabolism. These findings highlight the species' adaptive mechanisms under acute and chronic NP exposure, contributing to our understanding of how aquatic organisms respond to NP pollution.[92] Further, multigenerational resilience was explored in *Brachionus plicatilis*, a marine rotifer, under high temperature (HT), high salinity (HS), and NP exposure. While HT alone initially reduced lifespans and increased daily offspring production, combined HT/HS and HT/HS/NP exposure led to further declines in longevity, reproduction, and fatty acid profiles, with notable upregulation of antioxidant defenses. Multigenerational studies revealed rapid recovery from HT alone, whereas the combined stressors required four generations for complete recovery. This research underscores the resilience of aquatic organisms and the complex interplay of abiotic stressors and plastic pollution.[93]

Despite these findings, studies investigating the resilience of MPs and NPs in aquatic organisms remain limited. The evidence of adaptive mechanisms and recovery observed in gastropods, prawns, and rotifers underscores the importance of understanding resilience as a critical factor in assessing the ecological impacts of emerging contaminants. These insights pave the way for a deeper exploration of how aquatic

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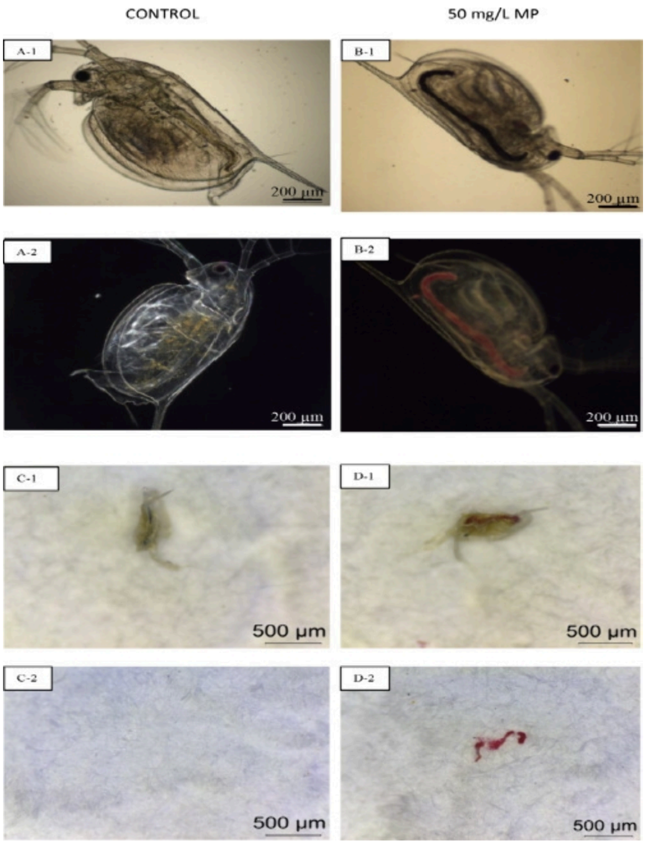

Figure 2. Microplastic (MP) ingestion and decomposition in *Daphnia magna*. The left panel (A, C) represents control D. magna without MP exposure, while the right panel (B, D) shows D. magna exposed to 50 mg/L MP. Images were captured using a light microscope at 5× magnification under bright field illumination (A-1, B-1) and dark field illumination (A-2, B-2), highlighting MP accumulation in the gut. Panels C-1 and D-1 depict daphnids before H_2O_2 decomposition, while panels C-2 and D-2 show the remains after decomposition, confirming MP retention. Scale bars: 200 μm (A-1, A-2, B-1, B-2); 500 μm (C-1, C-2, D-1, D-2).[91] Adapted with permission from Li et al. (2016). Copyright 2016 Elsevier. License No. 5997490383405.

ecosystems can withstand and adapt to the growing threat of micro- and nanoplastic pollution.

Environmental MPs and NPs form a diverse mixture of polymer particles of varying sizes and chemical properties.[105] To address this diversity, standardized approaches for monitoring nanoplastics should incorporate equipment capable of quantifying nanomaterials, such as dynamic light scattering (DLS).[17] Additional methods recommended by The Environmental Protection Agency (EPA) for tracking nanoplastics include electron microscopy (TEM/SEM), nanoparticle tracking analysis, atomic force microscopy coupled with infrared spectroscopy (AFM-IR), and energy-dispersive X-ray spectroscopy (EDX). Examples of nanoparticle tracking analysis, such as ATR-FTIR, are discussed in this paper (Figure 3). Another emerging technique highlighted by the EPA is pyrolysis gas chromatography−mass spectrometry (Pyrolysis GC/MS), which facilitates the characterization of various nanoplastics, including complex composites.

The EPA also underscores the critical role of wastewater treatment plants in mitigating the release of MPs and NPs into the environment. Furthermore, the inclusion of NPs in research is vital due to their potentially greater harm compared to MPs, stemming from their tendency to aggregate and interact with living organisms, and their higher numbers. Thus, the lack of standardized sampling and analytical methods for studying NPs represents a significant research gap.

3. IMPACTS ON BIOGEOCHEMICAL PROCESSES

3.1. Carbon Cycle. MPs significantly influence the carbon cycle by altering soil characteristics and microbial dynamics, which are crucial to carbon processes.[45] The fossil carbon content in plastics, a dominant component of MPs, positions them as key contributors to changes in soil ecosystems. MPs affect soil structure and microbial activity, leading to alterations in carbon dynamics.[106,107] In aquatic environments, weathered MPs form biofilms that disrupt feeding patterns and carbon transfer within marine food webs.[108] For instance, ingestion of MPs by zooplankton impairs carbon absorption and reduces sinking rates, impacting the biological pump responsible for transporting carbon to ocean depths.[109,110]

Photodegradation of plastics generates dissolved organic carbon (DOC), modifying microbial activity and enhancing CO_2 emissions.[36,111] In terrestrial ecosystems, MPs inhibit carbon sequestration by disrupting photosynthesis and nutrient transport in plants, reducing biomass accumulation.[112] Pollutant transport from roots to leaves further affects plant growth and carbon fixation.[113,114] Similarly, in marine ecosystems, MPs negatively impact phytoplankton by reducing chlorophyll production and photosynthetic efficiency. For instance, MPs at 250 mg/L decreased phytoplankton photo-

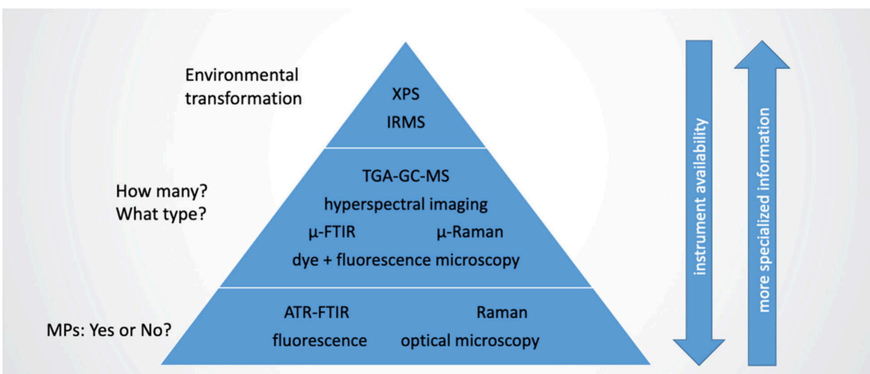

Figure 3. MPs and NPs methodologies utilized for environmental tracking, quantification, and characterization of nanoplastics as retrieved from The Environmental Protection Agency (EPA) reference.

synthetic rates by 45%, while a one mg/L increase in PS-NP concentration reduced fixed carbon dioxide by 0.0023 ppm.[115,116]

It has been demonstrated that CO_2 emissions in high-tide sediment over 28 days varied with microsized polypropylene (mPP) particle concentrations. Emissions were recorded as 496.86 ± 2.07 mg kg^{-1} for 0.1% mPP, 430.38 ± 3.84 mg kg^{-1} for 1% mPP, and 447.09 ± 1.72 mg kg^{-1} for 10% mPP, indicating a dose-dependent relationship. The results showed increased CO_2 emissions at a 0.1% mPP concentration, but a decline at higher concentrations of 1% and 10%, suggesting that tide levels and microplastic dosage significantly influence CO_2 dynamics in mangrove sediments.[117]

In marine environments, MPs aggregate with organic matter to form structures known as marine plastic snow, which sink and affect the biological carbon pump. These aggregates act as hotspots for microbial activity, facilitating organic matter decomposition and the cycling of carbon-derived compounds. Furthermore, additives leached from MPs, such as bisphenol A (BPA) and diethylhexyl phthalate (DEHP), detrimentally affect autotrophic bacteria like Cyanobacteria, thereby increasing CO_2 emissions.[118]

MPs alter soil physiochemical properties, such as structure, water retention, and hydraulic conductivity, which disrupt soil microbiomes and organic matter decomposition.[119,120] Specific MPs, such as phenol-formaldehyde-based plastics, significantly reduce microbial diversity by altering the available carbon sources.[121] Solar radiation and microbial degradation of MPs produce oligomers that serve as microbial carbon sources, affecting growth and enzyme activity.[122] Reaction mechanisms play a pivotal role in these disruptions. For example:

- **Surface Oxidation and Aggregation**: Oxidation of MPs, such as polystyrene (PS), alters their surface properties, enhancing their interaction with dissolved organic matter (DOM) and microorganisms. These interactions occur through electrostatic forces and chemical bonding, facilitating the aggregation of MPs into larger complexes. This aggregation impacts microbial access to carbon sources, reducing CO_2 emissions. Studies show that oxidized PS reduced CO_2 emissions by 23.76% at 0.1 mg/L and 44.97% at 10 mg/L compared to controls without MPs.[123]
- **Photo-Oxidation and DOC Formation**: MPs undergo photodegradation, breaking into smaller particles and releasing plastic-derived DOC (pDOC). The degradation involves chain scission and cross-linking reactions, which generate intermediate oxygenated compounds. These intermediates influence microbial metabolism, increasing DOM utilization and altering carbon cycling dynamics.[118]
- **Priming Effects**: MPs influence the mineralization of native soil organic carbon (SOC) through priming effects. Positive priming occurs when MPs enhance microbial cometabolism, increasing SOC breakdown. Conversely, negative priming arises from the adsorption of SOC onto MP surfaces, reducing its bioavailability. Both effects depend on MP concentration, type, and surface chemistry.[125]
- **Microbial Enzymatic Pathways**: MPs stimulate microbial metabolic pathways, including the tricarboxylic acid (TCA) cycle. By providing carbon substrates, MPs enhance enzyme activity and DOM biodegradation. However, this process produces transformed DOM that is more aromatic, less bioavailable, and more stable, significantly reshaping aqueous carbon dynamics.[126]

Thus, MPs disrupt carbon cycling by altering soil and aquatic systems, microbial dynamics, and biogeochemical processes. They interfere with carbon storage, emissions, and sequestration, highlighting the need for further investigation into their ecological impacts, including mechanisms like surface oxidation, photo-oxidation, and microbial interactions.

3.2. Nitrogen Cycle. The nitrogen cycle is a vital ecological process influenced by various factors, including MPs. Several metabolic processes, including nitrification, denitrification, assimilation, ammonification, and nitrogen fixation, are essential for managing soil nitrogen dynamics.[127] MPs have been found to increase dissolved organic carbon (DOC) in soil, potentially impacting the nitrogen cycle.[128]

The abundance of nitrogen-fixing microorganisms, including free-living diazotrophs and plant symbionts, can be affected by microplastic exposure.[129,130] For instance, the relative abundances of denitrifying Cupriavidus were enhanced by MPs/NPs + Ag (silver) NPs. At the same time, those of nitrogen-fixing functional microorganisms of *Microvirga*, *Bacillus*, and *Herbaspirillum* were decreased.[131] Additionally, adding PE-MPs to soil increased nitrogen fixation gene abundance (nifD, nifH, and nifX).[127,132] Furthermore, introducing polyamide microplastics increased the abundance of certain bacteria, contributing to nitrogen fixation gene enrichment in sandy loam soils.[62]

MPs can impact nitrification and denitrification process exposure.[133] For example, PE-MPs were found to improve soil aeration, limiting the denitrification process and reducing N_2O emission.[134] In freshwater sediments, the presence of microplastics led to a decrease in NO_3^- concentrations and an increase in denitrification rates.[135] Polylactic acid MPs were also observed to reduce nitrification while increasing the denitrification process, leading to ammonia nitrogen buildup and release.[132] Various types of microplastics, such as PLA, PE, and PVC, were found to increase N_2O production through interactions with carbon and nitrogen substrates, affecting the concentrations of nitrifying and denitrifying bacteria and related functional genes.[136]

Smaller PS particles hindered the NH_4^+ to NO_2 oxidation, impacting nitrification.[137] Additionally, the abundance and community composition of ammonia oxidizers were affected by MPs, leading to decreased gross nitrification rates.[138] Denitrification was improved by adding microplastics, particularly polyvinyl chloride and polyester. At the same time, MPs influenced NO_3^- metabolism by controlling the quantity of Nitrospirae and specific genes.[139] Polyvinyl chloride microplastics with plasticizer reduced NO_3^--N levels significantly and increased NH_4^+-N content in the soil.[140] Different types of MPs, such as PLA, high-density polyethylene (HDPE), and PS, had varying effects on soil nitrogen content, with some reducing NO_3^--N concentration and others enhancing NH_4^+-N content.[141] Microplastics exert diverse effects on the nitrogen cycle, influencing nitrogen fixation, nitrification, and denitrification processes, significantly affecting soil health and ecosystem functioning.

3.3. Phosphorus Cycle. The proliferation of biofilms significantly influences the phosphorus (P) cycle in terrestrial and aquatic ecosystems. However, there is limited research on the effects of microplastics (MPs) on the P cycle.[63] PP and

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PVC increased enzyme activity for certain biogeochemical processes, such as alkaline phosphatase activity, while decreasing activity for other processes.[142]

In microcosms, MP biofilms enhanced alkaline phosphatase activities, consequently increasing total P concentration in water after 25 days due to changes in biofilm adhesion and breakdown.[33] PVC-MPs were also observed to increase the activity of polyphosphoric bacteria, thereby promoting phosphorus uptake and release in aquatic environments.[143] In rice soils containing amino acids and arsenic residues, PS and polytetrafluoroethylene (PTFE) microplastics led to decreased phosphorus content and phosphatase activity. In contrast, PE and PVC microplastics increased phosphatase activity.[144]

The conversion of inorganic P into soluble phosphate ions (PO_4^{3-}) is mainly dependent on phosphorus-solubilizing microorganisms, particularly phosphate-solubilizing bacteria (PSB). The addition of 5% PVC (18 μm) and 1% and 5% PE (678 μm) microplastics to acid-loamy soils significantly increased the relative abundance of PSB Burkholderiaceae, leading to increased acid phosphatase activity in the soils altered with MPs.[62] It has been stated that PP and PE microplastics have the potential to drastically reduce soil-accessible phosphate content from 122.61 mg P L^{-1} to 63.43 mg P L^{-1} by altering microbe-mediated solubilization of inorganic P.[145]

4. BIOLOGICAL UPTAKE AND TROPHIC TRANSFER

4.1. Direct Ingestion by Organisms. Due to their low density and wide range of sizes, MPs are frequently consumed by many organisms that mistake them for food. Seabirds, fish, marine mammals, crustaceans, and other species that feed on deposits and suspensions are among hundreds that are impacted by MPs; at least 10% of these species are known to absorb MPs.[146] Whales, seabirds, bivalves, zooplankton, and fishes have been found to contain MPs.[147] Certain colors of plastic debris attract animals that eat it. For example, seabirds like the larger shearwater, red phalarope, and parakeet auklet are attracted to dark-colored, opaque plastics that look like jellyfish.[148]

Some mussels, such as quagga and zebra mussels, which filter food from the water, may consume microplastics floating in the water and then release them into the food chain of benthic organisms through their pseudofaeces or excretion.[149] It is seen that in the North Tyrrhenian Sea and the Ionian Sea, the marine species *Mullus barbatus* and *Merluccius merluccius* consume microplastics.[150] The water flea *Daphnia magna* was found to die after 48 h of ingesting polyester fibers from the water column.[151]

The Franciscana dolphin (*Pontoporia blainvillei*) found in southern Brazil is more likely to consume plastic than the *sotalia guianensis*, a species of pelagic-feeding Guiana dolphin. Also, while feeding on benthic vegetation, a large number of adult green turtles (*Chelonia mydas*) seem to have swallowed plastic.[152] Ragworms, or *Hediste diversicolor*, can feed from either the substrate or the water column, depending on the distribution and availability of food.[153] Some foods, such as commercial salts, honey, and beer, can be a direct source of plastic particles for humans to consume; research has shown that these foods contain MPs and NPs.[154]

4.2. Absorption through Biological Membranes. MPs and NPs can enter the bloodstream and cause damage to specific cells once they have crossed biological barriers. For MPs to enter cells and exert any biological effects, cell membranes are an essential first barrier. As a result of their critical function in controlling the distribution of substances via active transport, infiltration, and diffusion, they ensure that cellular metabolism remains normal.[155] Nanoparticles and all other substances attempting absorption by plants, including algae, face a formidable challenge from the complex cellulose-rich cell wall matrix. If the size of the plastic nanoparticles is larger than the pore size in the cell wall, they will likely just stick to the surface instead of penetrating the algal cells.[156] Microplastics in waterways have the potential to reduce the abundance of algae, an essential food source for many marine animals. Algae like *Dunaliella tertiolecta, Scenedesmus quadricauda*, and *Chlorella vulgaris* have been found to absorb and accumulate microplastics, according to multiple studies.[157−159] Algae suffer from oxidative stress and reduced photosynthetic activity due to microplastics. One example is the dinoflagellate *Karenia mikimotoi*. Algae can absorb and accumulate microplastics because their negative charges interact with the positive ones.[160] In addition, coralline algae have been found in Asian clams' (*Corbicula fluminea*) mantles, which means that NPs can be absorbed by aquatic organisms by adhesion instead of digestion.[161]

4.3. Bioaccumulation and Biomagnification. Bioaccumulation and biomagnification can occur when organisms at different trophic levels of food webs consume pollutants.[162] MPs build up in the organs of mice that undergo toxicological testing, which raises the possibility that animals at higher trophic levels can consume and accumulate MPs in their tissues.[163] It has been reported that MPs can affect the functions and characteristics of plant organs and tissues when they enter through surface exposure and root system uptake.[164] It has been demonstrated that *Arabidopsis thaliana* consumed functionalized polystyrene (PS) nanoparticles such as polystyrene sulfonic acid (PS-SO_3H) and amino-modified PSNPs (PS-NH_2), which then accumulated in the root steles.[165] Similarly, the accumulation of styrene maleic anhydride (SMA) particles in the stem of *Murraya exotica* was directly correlated with the exposure concentration, indicating that plants passively absorb these plastic particles.[166] Using fluorescence imaging, researchers found that seedlings of different plant species exposed to Polystyrene doped with Europium (PS-Eu) mainly accumulated in the intercellular space and were transported from the roots to the leaves via the apoplastic route and vascular bundle.[167] Environment plays a significant role in determining whether fish with small planktonic feeders are more likely to consume microplastics, which could increase the concentration of microplastics in their digestive systems.[168] Furthermore, it has been discovered that killer whales, like *Chinook salmon*, can acquire microplastics by trophic transfer from the food they consume.[169] It has also been reported that microplastics in the stomachs of seabirds like short-tailed shearwaters (*Puffinus tenuirostris*) could raise the bioaccumulation of polybrominated diphenyl ethers (PBDEs) in their abdominal adipose tissue.[170]

5. FORMATION OF SECONDARY POLLUTANTS

5.1. Release of Leachates and Additives. MPs undergo various weathering processes in soil and water that lead to their structural degradation and the release of leachates- dissolved organic compounds, including additives and residual monomers, that are not covalently bonded to the polymer matrix.[171,172] Additives, such as pigments, flame retardants,

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plasticizers, heat stabilizers, and antioxidants, are intentionally incorporated into plastics to enhance their properties during molding. However, degradation mechanisms like fragmentation and surface cracking increase the likelihood of additive leaching into the environment.[173,174]

Chemical leachates from microplastics, including bisphenol A (BPA) and phthalates, are a significant concern due to their potential to act as endocrine disruptors and cause harmful effects on ecosystems and human health.[175] For instance, photoaging of PVC-MPs enhances the leaching of di(2-ethylhexyl) phthalate (DEHP) and its toxic byproducts, such as mono(2-ethylhexyl) phthalate and phthalic acid, into aquatic environments, contributing to secondary pollution.[176] The extent of additive release is influenced by environmental factors, including particle size, UV irradiation, temperature, dissolved organic matter (DOM), and pH. Additionally, the polymer's structure and environmental salinity play crucial roles.[177] Research on the leaching kinetics of organophosphate esters (OPFRs) from polypropylene (PP) and polystyrene (PS) microplastics reveals significant variations based on polymer type, environmental conditions, and biotic interactions. Studies demonstrate that ingestion of polyethylene (PE) MPs notably contributes to the bioaccumulation of OPFRs in marine organisms, with minimal contributions from PP and PS-MPs.[178] Similarly, phthalates, widely detected in the environment, exhibit long-term release from PVC-MPs due to their hydrophobic nature and diffusion-limited leaching, with desorption half-lives exceeding 500 years under certain conditions.[179]

Oxidative degradation processes further intensify the release of additives and the formation of secondary micro- and nanoparticles. For example, studies show that hydrogen peroxide (H_2O_2) in aquatic environments can accelerate the oxidative degradation of PE, producing nanoscale particles and releasing toxic additives like butylated hydroxytoluene.[180] This highlights the need to better understand the role of naturally occurring oxidants, such as hydroxyl radicals (·OH), in driving plastic degradation.

Weathering processes, including UV radiation, exacerbate the release of toxic leachates. A study on MPs derived from marine antifouling paints and unplasticized PVC showed that leachates from weathered MPs were significantly more toxic than those from nonweathered materials. The increased toxicity was attributed to the higher concentrations of heavy metals and additives in the leachates, which inhibited algae growth and disrupted aquatic ecosystems.[181]

Furthermore, landfill sites contribute to the release of MP-associated leachates. Around 40% of the world's plastic waste ends up in landfills, where chemical, physical, and biological processes degrade plastics into MPs, which accumulate in landfill leachates. These leachates are highly variable, depending on landfill conditions and waste types, and can pose risks to human and environmental health.[182]

Despite advancements in understanding the toxicity of MPs and their leachates, significant knowledge gaps remain. Studies have shown that leaching contributes significantly to the overall toxicity of MPs, yet experimental variability and nonstandardized methods hinder reliable risk assessment.[183]

5.2. Contaminant Adsorption. MPs can adsorb a variety of contaminants, including organic chemicals, heavy metals, polycyclic aromatic hydrocarbons (PAHs), and antibiotics, depending on their pollutant distribution coefficient.[184] This adsorption process plays a significant role in the formation of secondary pollutants, as adsorbed contaminants may transform due to environmental factors. Factors influencing the sorption capacity of microplastics include the presence of biofilms, the physical properties of plastics (e.g., color, density, and age), and environmental conditions such as pH, salinity, and dissolved organic matter.[185]

Darker plastics, often containing more additives, and smaller or irregularly shaped particles exhibit higher sorption rates due to their larger surface area-to-volume ratios.[186] Biofilms can enhance adsorption by altering the surface properties of microplastics, such as hydrophobicity and electric charge, and can also catalyze chemical transformations, potentially leading to the formation of secondary pollutants like oxidized or degraded contaminants.[187] For example, hydrophobic interactions improve the adsorption of bisphenols onto PVC-MPs, which may later desorb or degrade under environmental stressors.[188] The interactions between microplastics and contaminants, such as pharmaceuticals and personal care products (PPCPs), further highlight the risks of secondary pollutant formation. Studies have shown that traditional and biodegradable plastics can adsorb hydrophilic PPCPs, with biodegradable plastics such as polylactic acid (PLA) demonstrating higher adsorption potential. Adsorption mechanisms, including electrostatic interactions, hydrogen bonding, and hydrophobic forces, vary with environmental conditions like pH and ionic strength, influencing the transformation and desorption of contaminants.[189]

Environmental processes such as UV exposure, temperature fluctuations, and microbial activity can degrade adsorbed contaminants, generating secondary pollutants that may have increased toxicity or mobility. For example, persistent organic contaminants like polycyclic aromatic hydrocarbons and pesticides adsorbed onto microplastics can undergo photochemical reactions, releasing harmful byproducts into the environment.[190] Similarly, contaminants adsorbed onto polyethylene terephthalate (PET) microplastics in marine environments are subject to adsorption−desorption cycles that may exacerbate pollution risks.[191]

Overall, the ability of MPs and NPs to adsorb and transform pollutants highlights their role in the formation of secondary pollutants, which pose significant ecological and human health risks. Addressing these challenges requires a deeper understanding of the interactions between microplastics, adsorbed contaminants, and environmental conditions to develop effective mitigation strategies.

6. HUMAN HEALTH IMPLICATIONS

Humans are exposed to MPs through multiple routes, including ingestion, inhalation, and skin contact, all of which pose potential health risks.[192] MPs can enter the body through contaminated food, water, or air, increasing the risk of immune reactions, inflammation, and cell damage.[193]

Inhalation is considered a primary route of exposure, as airborne MPs from indoor and outdoor sources such as textile production and polyvinyl chloride manufacturing can be easily inhaled.[194,195] Fine particulate matter (PM 2.5), which includes MPs, can penetrate the respiratory and circulatory systems, increasing the risk of bladder cancer, hematological disorders, and breast cancer.[196] Contamination of food chains is a major challenge, especially in coastal areas where seafood remains a major food source for humans.[197] Consumption of seafood, including mussels, shrimp, and fish, poses the danger of ingesting microplastic particles.[198] Polystyrene and plastic

Table 3. Impacts on Human Health

MPs/NPs	Concentration	Effects	Ref
Polystyrene (PS) (50 nm)	10 and 100 μg/mL	Apoptosis of cells and the inflammatory response (intestinal organoids).	208
PS (1 and 10 μm)	100, 50, and 5 μg/mL	Impacted the patterning of brain tissue and the gene expression of DNA damage (forebrain organoid).	209
PS (0.5 μm)	100 μg/mL	Harmful effects on the plasma membrane.	210
PS (1 μm)	100 μg/mL	Reduced the levels of the antioxidant enzymes CAT and SOD, as well as the glycolytic enzyme glyceraldehyde-3-phosphate dehydrogenase, hence decreasing their capacity to detoxify reactive oxygen species (kidney and liver).	211
PS (0.05 to 0.1 μm)	100 μg mL^{-1}	ROS production rises along with genotoxicity, oxidative DNA damage, and the expression of genes linked to stress (intestinal epithelial Caco-2 cell).	212

teabags are other examples of packaging materials that can contaminate food and expose people to MPs even more.[199,200] Because MPs are part of the atmospheric particulate matter, they can be found both indoors and outdoors, which raises the risk of inhalation.[201] Inhalation exposure to polypropylene (PP) fibers found in indoor air may be a contributing factor, according to studies.[202] NPs in particular pose a threat to human health when they come into contact with skin.[203,204] This is because these tiny particles can eventually cross the blood-brain barrier and enter the body via contaminated water or personal care items. Possible entry points include hair follicles, sweat glands, or damaged skin.[205] Studies have shown that MPs may have toxicological effects on human health, including disturbances to energy balance, metabolism, and the immune system when ingested.[206,207] The results in Table 3 highlight the need to understand and address the health risks of MP exposure to protect human health.

7. MITIGATION AND REMEDIATION STRATEGIES

7.1. Mechanical Methods. Magnetic extraction relies on the electrostatic attraction between microplastic particles and silanized iron nanoparticles. MP removal techniques have evolved to leverage physical, chemical, and biological mechanisms for enhanced efficiency. Magnetic extraction, for instance, utilizes iron nanoparticles due to their ferromagnetic properties, large surface area, and cost-effectiveness.[213] This method was further refined by introducing a hydrophobic layer of hexadecyltrimethoxysilane, improving microplastic separation through enhanced attraction and extraction.[214]

Electrocoagulation offers another promising approach, where metal electrodes trigger the aggregation of MPs, simplifying their removal. This technique is valued for its cost-effectiveness, high efficiency, and ability to degrade charged pollutants.[215] Its growing application in wastewater treatment highlights its effectiveness in addressing microplastic contamination.[216]

Membrane filtration, a widely used physical method, effectively separates MPs from water. However, while it efficiently removes larger particles, smaller ones can lead to membrane fouling. Interestingly, larger particles contribute to the formation of a porous filter cake, reducing water flow resistance.[217] Complementing this, biofiltration integrates biological and physical mechanisms, where biofilms play a crucial role in microplastic entrapment. The presence of microbial films on nonreactive filter materials significantly enhances surface area, facilitating the removal of larger particles.[218,219]

Adsorption-based strategies further contribute to MP removal by employing materials like metal−organic frameworks, activated carbon, and biochar. The effectiveness of these adsorbents stems from intermolecular interactions, including hydrophobic forces, hydrogen bonding, and electrostatic attractions, making them highly efficient in capturing MPs from contaminated environments.[220]

7.2. Biological Degradation Methods. Biological degradation involves the utilization of different microorganisms, some of which exhibit potential for bioremediation.[221] Two commonly used techniques for biological separation are bioactive sludges and biodegradation. While these techniques may possess lower levels of efficiency, they are typically cost-effective and viable for various environments. Given the inherent constraints of traditional methods, there is an increasing fascination with alternative strategies to efficiently eliminate MPs.[222]

Multiple studies have shown the degradation of microparticles, specifically Polyethylene (PE), Polypropylene (PP), and Polyethylene terephthalate (PET), using microorganisms like bacteria and fungi. After 14 days of growth, the fungus *Zalerion maritimum* decomposed PE particles by 43%. A separate investigation employing a bacterial strain called *Rhodococcus* discovered that 6.4% of the polymer mass of PP degraded within 40 days. In contrast, *Ideonella sakaiensis* achieved complete degradation of PET film within 6 weeks after exposure.[223] In addition, a study conducted by Pathan et al. (2020)[224] found that *Bacillus* sp., *Pseudomonas* sp., *Streptococcus* sp., and *Fusarium* spp. were able to completely degrade plastic polymers after 120 and 75 days, respectively, when screening bacteria from different dumping grounds at various time intervals. *Ideonella sakaiensis* is a bacterium in the Comamonadaceae family and the genus Ideonella. It can break down and consume PET as its only carbon and energy source. These microorganisms are essential in plastic recycling, as they use two enzymes to convert PET into terephthalic acid and ethylene glycol.[223,225] Microbial communities that can utilize xenobiotics as growth and energy sources are essential for the degradation of synthetic plastics. These organisms employ enzyme systems to decompose polymers into intermediate substances, which are subsequently absorbed and metabolized to obtain energy. The latest studies have specifically examined actinomycetes, algae, bacteria, and fungi that possess the ability to break down plastic polymers.[226] Macroplastics undergo a complex process of physical or biological degradation, resulting in the formation of microplastics and nanoplastics.[227]

When cyanobacteria such as *Phormidium* colonized low-density PE film, they were able to metabolize approximately 4% of the carbon present in the film, resulting in the biodegradation of the film. The biodegradability of low-density polyethylene (LDPE) was assessed under different growth conditions of *Anabaena spiroides* (cyanobacteria), *Navicula pupula* (diatoms), and *Scenedesmus dimorphus* (green algae), resulting in degradation rates of 8.18%, 4.44%, and 3.74%, respectively[228] over 180 days. Two types of bacteria

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(*Pseudomonas aeruginosa* and *Achromobacter* sp.) that were obtained from soil contaminated with oil showed the capability to break down epoxidized vegetable oil containing PVC, with the PVC making up 75% of the weight. As a consequence, the alteration in the material's surface topography led to a reduction in its tensile strength.[229] Fungi such as *Aspergillus, Cladosporium, Fusarium*, etc., possess strong enzyme systems and are capable of surviving in challenging environmental conditions with limited nutrient and water availability. In addition, the hyphae of these organisms can penetrate the openings and cracks on the plastic surface, allowing them to spread extensively.[230]

Bioremediation and mechanical extraction demonstrate significant potential for addressing MP pollution, with their effectiveness influenced by environmental conditions and the specific types of microplastics involved.[231] Bioremediation relies on microorganisms to degrade plastics, offering an eco-friendly solution for smaller or more complex particles. In contrast, mechanical extraction efficiently removes larger plastic particles from environments such as soil and water systems.[232]

8. POLICY AND REGULATORY FRAMEWORKS

Various global agreements and programs have been created to mitigate plastic pollution and its effects on the environment. The London Convention and MARPOL (73/78) were among the first international agreements to address the issue of plastic debris.[233] In March 2022, the United Nations Environment Assembly (UNEA) made a notable advancement by adopting a resolution that urges negotiations for the establishment of a universally binding mechanism to address the issue of plastic pollution.[234] The International Union for Conservation of Nature (IUCN), the Life Cycle Initiative, and the United Nations Environment Program (UNEP) have developed guidelines that provide a standardized method for identifying areas with high concentrations of plastic pollution, tracking the effects of plastic throughout its lifecycle, and determining the most important actions to take.[235] The National Guidance for Plastic Pollution Hot Spotting and Shaping offers nations, regions, and cities specific strategies and frameworks designed to suit their circumstances. This allows them to set initial benchmarks and assess the effectiveness of their interventions. The Paris Agreement, established within the framework of the United Nations Framework Convention on Climate Change (UNFCCC), acknowledges the correlation between plastic pollution and climate change. Its objective is to achieve net carbon neutrality by 2050 by regulating the entire life cycle of plastic.[236] Global voluntary initiatives, such as guidelines on monitoring marine litter and promoting responsible fishing practices, actively discourage pollution and waste.[237] The United Nations Environment Program seeks to tackle the primary factors contributing to the generation of plastic waste by the year 2022.[238] The primary objective of the European Union's Common Fisheries Policy is to specifically address the issue of chemical and nutrient pollution by implementing targeted reduction measures. The Water Framework Directive simultaneously aims to attain optimal water quality within specified timeframes by implementing emission restrictions and simplifying legislation. The United States Agency for International Development (USAID) initiated the Municipal Waste Recycling Program (MWRP) in October 2016 as part of its commitment to reducing plastic pollution.[239]

Effective management of plastic waste necessitates the implementation of national and regional initiatives, which entail the development of physical and technical infrastructure, as well as the cultivation of organizational, economic, and political capabilities.[240] Governments are progressively implementing legislation to prohibit or impose taxes on disposable plastic items, in line with worldwide initiatives spearheaded by the United Nations (UN) to mitigate the release of plastic into the environment. The efforts mentioned, including the UN Environment Assembly Resolutions on Marine Litter and Microplastics, Addressing Single-Use Plastic Product Pollution, and the UN Sustainable Development Goals (SDGs), demonstrate this undertaking.[241]

Several governing bodies are enacting regulations to limit the use of disposable plastic bags to prevent their buildup in coastal waters. Although efforts to reduce primary microplastics include policies such as microbead bans the main emphasis is on regulating plastic bag usage through measures such as bans, pricing, or taxes. Several nations, in North America, Europe, Australia, South Africa, India, and Bangladesh, have implemented prohibitions or implemented programs where consumers are charged for each plastic bag used, to tackle the issue of plastic bag consumption.[242] Regional initiatives such as the Action Plan for the Protection, Management, and Development of the Marine and Coastal Environment of the Northwest Pacific Region (NOWPAP) aim to protect marine environments from activities that originate on land. NOWPAP engages in annual Tripartite Environment Ministers Meetings and scientific research to tackle marine debris in the Northwest Pacific Region.[243] Although India and Costa Rica have enforced partial prohibitions on plastic bags and have set targets to eliminate all disposable plastics by 2022 and 2021, respectively,[244] in reality, has not been proven effective because of poor implementation policies. In addition, the United States Environmental Protection Agency (USEPA) has expressed interest in tackling microplastic pollution through its Draft National Strategy to Prevent Plastic Pollution. The strategy focuses on preventing the entry of microplastics and nanoplastics into waterways.[245]

9. CONCLUSIONS

The amalgamation of current research highlights the significant and diverse effects of MPs and NPs on biogeochemical cycles and fundamental Earth processes. These minute particles, widely distributed in both terrestrial and marine environments, pose serious risks to ecosystem health, species diversity, and human well-being. MPs and NPs disrupt nutrient cycling, soil properties, microbial activity, and the availability of nutrients in ecosystems. Furthermore, they affect energy transfer within food webs, leading to pollutant accumulation in organisms and increasing concentrations as these pollutants move up the food chain. The detrimental impacts of MPs on aquatic ecosystems are particularly alarming, affecting primary producers such as phytoplankton and higher trophic levels like fish and seabirds. Ultimately, these effects have direct implications for human health, particularly through the consumption of contaminated seafood. Additionally, MPs alter global nutrient and water cycles, hinder nutrient availability for plants and animals, and exacerbate climate change by releasing greenhouse gases. Despite significant progress in understanding MP pollution, key research gaps remain, particularly regarding the effects of MPs on land-based ecosystems and the harmful effects of NPs

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on cellular structures. Addressing these gaps requires interdisciplinary collaboration and the adoption of innovative research methods. The United States Geological Survey (USGS) has called for the establishment of standardized methods for quantifying and analyzing MPs and NPs, incorporating microscopy techniques as well as size-dependent methodologies, such as Raman spectroscopy for particles larger than 20 μm and infrared spectroscopy for those above 50 μm. Efficient mitigation strategies necessitate policy interventions at multiple levels of government to regulate plastic production, enhance waste management, and promote a circular economy. The National Oceanic and Atmospheric Administration (NOAA) outlines key steps to standardize methods across governments and laboratories, which include: 1) separation from the surrounding environment, 2) detection and measurement of physical particles, 3) chemical analysis of the material (polymer), and 4) identification and measurement of both inherent and external chemicals that have accumulated on microplastics. Comprehensive mitigation of MP pollution demands collective action from policymakers, communities, and individuals worldwide. Intervention from the Humanities and Social Sciences disciplines would also help in analyzing the problem from a cultural perspective. Since modern technologies have promoted a culture of pollution in the Global South, oneedseed to investigate the ethical and moral dimension that governs the society where scientific inventions are negatively impacting human and nonhuman life forms. However, this study emphasizes the urgent need to address the complex challenges posed by plastic pollution across the globe. By closing knowledge gaps, advancing scientific understanding, and implementing robust mitigation strategies, we can move toward a sustainable and resilient future for ecosystems and human societies. Resolute measures must be taken to alleviate the widespread effects of microplastic pollution and ensure the health of our planet for future generations. While notable advances have been made in understanding the short-term effects of MPs and NPs, the long-term impacts remain unclear. Critical questions, such as how species adapt to sustained exposure, how ecosystems maintain resilience amid persistent plastic pollution, and whether recovery is possible once pollution levels decrease, still require answers. Addressing these issues is vital for understanding the broader implications of MPs and NPs on ecosystem stability and developing effective strategies to mitigate their impact.

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Notes

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