

Eco-Friendly Nanomaterials for Remediation of Microplastics and Heavy Metals in Wetland Ecosystems: Emerging Technologies and Environmental Considerations

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Abstract

Microplastics (MPs) and heavy metals (HMs) are pervasive contaminants in wetland ecosystems, where their co-occurrence poses complex ecological and human health risks due to synergistic interactions. Traditional remediation strategies often target these pollutants separately, overlooking opportunities for integrated removal approaches. This review addresses the research gap by systematically synthesizing current knowledge on eco-friendly nanomaterials for simultaneous MP–HM remediation in wetlands, with a particular focus on sustainable, low-cost solutions suitable for resource-limited contexts. Following PRISMA guidelines, over 50 peer-reviewed studies were analyzed to assess nanomaterial types, physicochemical properties, contaminant removal mechanisms, and integration into wetland systems. Key findings reveal that bio-based and green-synthesized nanomaterials such as biochar composites, metal–organic frameworks, and plant-derived nanoparticles show promising efficiency in MP–HM co-remediation, while maintaining compatibility with wetland biota. Design considerations, operational challenges, and policy frameworks are critically discussed, alongside identified knowledge gaps, including limited field-scale validation and long-term ecological risk assessments. The review concludes with targeted recommendations for future research, emphasizing scalable nanomaterial development, optimized wetland–nanomaterial synergy, and inclusion of MP–HM co-remediation in environmental policy. This synthesis offers a unique, integrated perspective that bridges material science, wetland ecology, and environmental management to advance sustainable remediation strategies in the face of complex contaminant mixtures.

Keywords: Microplastics, Heavy Metals, Wetland, Wastewater, Eco-Toxicology Nanomaterials, Remediation.

Introduction

The increasing prevalence of heavy metals and microplastics in wetland ecosystems has become a significant environmental concern, necessitating the development of innovative and sustainable remediation strategies. Wetlands, as dynamic interfaces between terrestrial and aquatic environments, are particularly vulnerable to contamination due to their role in filtering pollutants and supporting diverse biological communities. The accumulation of heavy metals in these environments can lead to soil degradation, reduced agricultural productivity, water pollution, and adverse effects on wildlife and human health. These impacts underscore the urgent need for effective monitoring and remediation practices that align with both ecological and regulatory standards (Lavanya et al., 2024). Wetlands are vital ecosystems that provide a variety of ecological services, including water purification, carbon sequestration, and habitat for biodiversity (Olaoye et al. 2025). Traditional remediation methods like vitrification have limitations like high operational costs and soil loss. Sustainable alternatives like nanotechnology offer unique properties like high surface area, tunable porosity, and enhanced reactivity, making them ideal for pollutant adsorption and removal.

Nanomaterials, including those synthesized via green routes using plant extracts or microorganisms, have demonstrated remarkable efficiency in adsorbing heavy metals from aqueous solutions. These green nano-adsorbents not only offer high removal capacities but also reduce the risk of introducing additional contaminants into the environment (Bakhtiari et al., 2024). In parallel, the emergence of microplastics as a persistent pollutant in wetland and marine systems has prompted extensive research into their sources, distribution, and ecological impacts. Over the past few decades, microplastic pollution in aquatic environments has become a more pressing environmental concern (Egbuna et al. 2025). Microplastics can interact with heavy metals, altering their environmental behavior, bioavailability, and toxicity. The adsorption of heavy metals onto microplastic surfaces is influenced by factors such as polymer type, surface chemistry, and environmental conditions, which can exacerbate ecological risks in contaminated wetlands (Mozafarjalali et al., 2023).

Liu et al. (2024,) state that both phytoremediation and bioremediation, leveraging plants and microorganisms, are promising eco-friendly approaches for water cleanup, but the integration of nanotechnology further enhances the selectivity and efficiency of contaminant removal. The development of portable and smart analytical devices, including those based on nanomaterials and biosensors, has facilitated rapid, in situ detection of heavy metals and microplastics, enabling more effective monitoring and management of wetland pollution (Lia et al., 2022). These technological advancements are complemented by the application of artificial intelligence and machine learning, which provide powerful tools for identifying, tracking, and optimizing the removal of microplastics from complex environmental matrices (Das et al., 2024).

Despite the promise of nanomaterial-based remediation, it is essential to consider the potential environmental implications and risks associated with their deployment. The interactions between engineered nanomaterials, microplastics, and heavy metals are complex and may influence the fate, transport, and toxicity of these pollutants in wetland ecosystems. Mozafarjalali et al., (2023) discuss how the high adsorption capacity of nanomaterials can facilitate the removal of microplastics, but also highlight the need for further research into the long-term ecological effects and the possibility of nanomaterials acting as carriers for other contaminants. The integration of sustainable nanotechnologies with existing remediation frameworks offers a promising pathway for addressing the multifaceted challenges of wetland pollution. However, the successful implementation of these solutions requires interdisciplinary collaboration, ongoing evaluation of environmental risks, and adherence to evolving regulatory standards. The current body of research underscores the necessity for continued innovation and critical assessment to ensure that the application of nanomaterials in wetland remediation achieves both environmental protection and public health objectives (Inobeme et al., 2022) (Torimiro et al., 2021).

While extensive research exists on separate remediation strategies for microplastics (MPs) and heavy metals (HMs), studies addressing their simultaneous removal in wetland ecosystems remain scarce. Limited attention has been given to how eco-friendly nanomaterials can be tailored for MP–HM co-remediation, particularly in resource-limited and ecologically sensitive contexts. Furthermore, there is a lack of integrated synthesis linking nanomaterial properties, contaminant interactions, and wetland operational parameters. Therefore, this review systematically analyzes the current literature on eco-friendly nanomaterials for MP–HM co-remediation in wetlands, examines their physicochemical interactions and environmental behavior, evaluates design and operational considerations for wetland integration, and identifies key research gaps, challenges, and policy implications to guide future innovations in sustainable wetland remediation.

Background and Significance

Microplastic and Heavy Metal Pollution in Wetlands

Microplastic and heavy metal pollution in wetlands has emerged as a significant environmental concern, with far-reaching implications for ecosystem health, food security, and human well-being. Wetlands, due to their unique hydrological and biogeochemical characteristics, act as both sinks and conduits for a variety of contaminants, including microplastics and heavy metals. The transport and accumulation of these pollutants in wetland environments are influenced by complex interactions among water, sediments, biota, and anthropogenic activities (Egbueri et al., 2021). Microplastics, defined as plastic particles less than 5 mm in size, are increasingly detected in wetland soils, sediments, and water columns, where they can be transported via atmospheric deposition, surface runoff,

and inflow from upstream sources (Allen et al., 2022). The persistence and ubiquity of microplastics in these environments raise concerns about their ecological impacts, particularly their potential to disrupt food webs and compromise the health of aquatic organisms.

Heavy metals, such as cadmium, lead, copper, and zinc, are also prevalent in wetland ecosystems, often originating from industrial discharges, agricultural runoff, and urban effluents (Lia et al., 2022). These metals can accumulate in wetland soils and sediments, where they may persist for extended periods due to their non-biodegradable nature. The bioavailability and toxicity of heavy metals in wetlands are modulated by factors such as pH, redox potential, organic matter content, and the presence of other contaminants, including microplastics (Mozafarjalali et al., 2023).

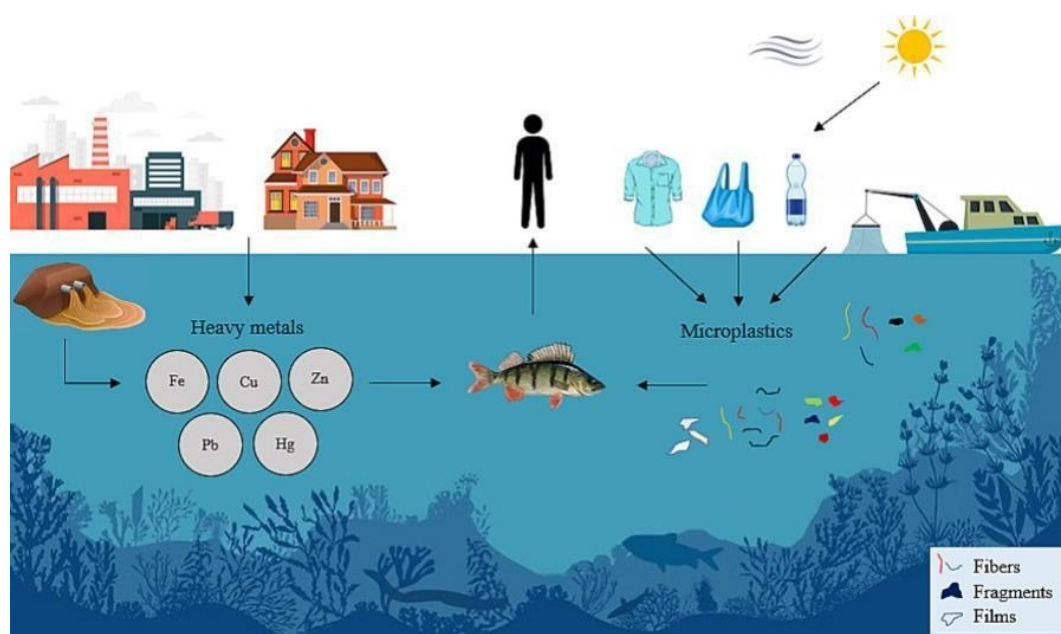


Fig. 1 Heavy metals and microplastic pollution Reprinted with permission from ref. 17. Copyright: © 2024, Elsevier B.V. All rights reserved

Microplastics and heavy metals in wetland and aquatic bodies pose a significant threat to ecosystems. Microplastics can adsorb and transport heavy metals, altering their environmental fate and toxicity. This interaction may increase trophic transfer and ecological consequences, including physical blockages, reduced feeding efficiency, and oxidative stress. The combined exposure could exacerbate risks to wetland biodiversity and ecosystem functioning. Moreover, the accumulation of these pollutants in wetland food webs poses a direct threat to food safety and human health, particularly in regions where wetlands are integral to local fisheries and agriculture (Sarker et al., 2022). Microplastics and heavy metals ingestion through water, food, or inhalation is a growing concern for human health and ecosystem services like water purification and habitat provision..

Wetlands play a crucial role in mitigating pollution by trapping and transforming contaminants; however, excessive loading of microplastics and heavy metals can overwhelm these natural attenuation processes and lead to long-term degradation of wetland functions (Lavanya et al., 2024). Wetland ecosystems face environmental risks from microplastics and heavy metals, necessitating effective monitoring, management, and remediation strategies. Understanding transport, fate, and ecological impacts is crucial for developing targeted interventions, integrating advanced techniques and ecological modeling.

Ecological and Human Health Risks

Ecological and human health risks associated with microplastics and heavy metals in wetland ecosystems are multifaceted, involving direct and indirect pathways of exposure and impact. Microplastics, due to their small size and persistence, are transported through air, soils, sediments, and wetlands, where they accumulate and interact with biota. These particles can be ingested by a wide range of organisms, including filter feeders and detritivores, leading to bioaccumulation and potential biomagnification within food webs (Egbueri et al., 2021) (Stábile et al., 2024). The ingestion of microplastics by aquatic and terrestrial organisms not only causes physical harm but also facilitates the transfer of adsorbed toxicants, such as heavy metals, into biological systems (Mozafarjalali et al., 2023). The extent of these effects depends on the concentration, type, and size of the microplastics, with potential consequences for ecosystem stability and productivity (Lia et al., 2024). Furthermore, microplastics can disrupt soil microbial communities, impairing nutrient cycling and organic matter decomposition, which are critical for wetland health (Arifa et al., 2024). These disruptions may cascade through the ecosystem, affecting higher trophic levels and overall biodiversity. Heavy metals, often co-occurring with microplastics, pose additional risks. They can degrade soils, reduce agricultural productivity, pollute water, and harm wildlife. The bioavailability and toxicity of heavy metals may be altered by their interactions with microplastics, potentially increasing ecological risks (Lavanya et al., 2024). The toxicological effects of microplastics include inflammation, oxidative stress, and potential disruption of cellular processes, while heavy metals are known to cause a range of adverse health outcomes, including neurotoxicity, carcinogenicity, and organ damage. The combined exposure to both microplastics and heavy metals raises concerns about synergistic effects that may exacerbate health risks.

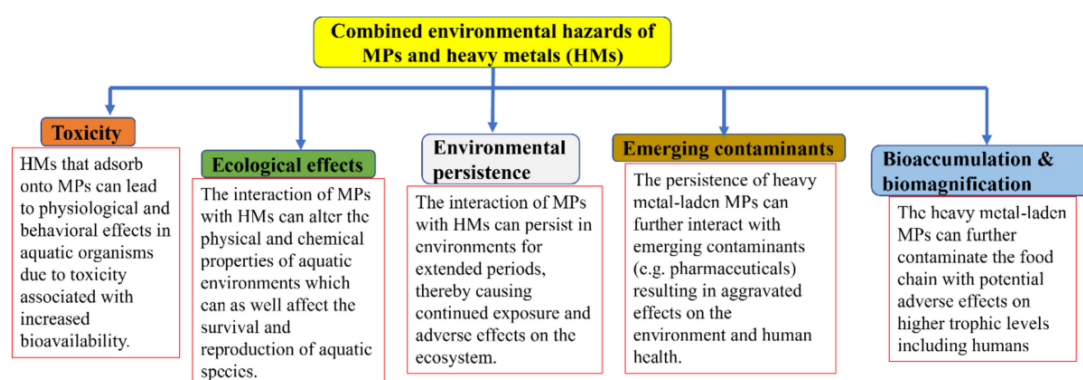


Fig. 2 The figure illustrates how MPs and HMs interact to increase toxicity, disrupt ecosystems, persist in the environment, enhance emerging contaminant risks, and lead to bioaccumulation and biomagnification, potentially impacting human health. Reprinted with permission from ref. 1. Copyright: © 2024, Springer nature

The deployment of nanomaterials for remediation introduces additional considerations. While engineered nanomaterials, such as iron oxide nanoparticles and zero valent iron nanoparticles, have demonstrated high efficiency in removing microplastics and heavy metals from contaminated environments, their own ecological and health risks must be carefully evaluated (Luo et al., 2021) (Ahmad et al., 2019). Nanoparticles in wetland systems persist and can cause toxicity or disrupt ecosystem processes. Research on their fate and transport is ongoing. Sustainable remediation practices are crucial to minimize environmental and health impacts, with regulatory frameworks and environmental standards ensuring safety. Phytoremediation is sometimes considered as an alternative to nanomaterial-based approaches, because it offers a cost-effective and environmentally friendly solution for heavy metal removal, with minimal adverse effects (Lavanya et al., 2024). However, the incomplete elimination of contaminants and the need for species-specific studies highlight the complexity of managing ecological and health risks in wetland environments. The integration of emerging nanotechnologies with established ecological restoration practices may provide a pathway toward sustainable remediation, but ongoing assessment of risks and benefits is imperative.

Importance of Wetland Ecosystems in Environmental Remediation

Wetland ecosystems are recognized as essential natural infrastructures for environmental remediation due to their unique capacity to intercept, transform, and remove a wide array of pollutants, including microplastics and heavy metals, from water and sediments. Their complex biogeochemical processes, high biodiversity, and dynamic hydrology enable wetlands to function as natural filters, thereby maintaining water quality and supporting ecosystem health (Sarkar et al., 2021) and (Chanda & Suthar, 2024). Wetland ecosystems,

with their intricate interplay of vegetation, microbial communities, and sediment, play a crucial role in mitigating anthropogenic pollution. They can reduce ecological stresses caused by microplastic pollution. Constructed wetlands, mimicking natural wetlands, are promising technologies for reducing microplastics in wastewater. They also play a crucial role in remediating heavy metal contamination. The natural processes occurring within wetland environments, such as phytoremediation and bioremediation, are eco-friendly and cost-effective strategies for the removal of toxic metals from aquatic systems (Lavanya et al., 2024) & (Liu et al., 2024). Wetland plants can accumulate and transport heavy metals, requiring species selection for remediation. Phytoremediation in wetlands reduces heavy metal concentration, minimizes pollution, and supports ecological restoration. Wetlands also provide habitat, regulate hydrology, and contribute to carbon sequestration. However, the effectiveness of wetlands in environmental remediation is influenced by several factors, including the type of wetland (e.g., salt marsh, mangrove forest, seagrass bed), the specific contaminants present, and the local environmental conditions (Lia et al., 2022).

Research trends and remediation strategies may vary across regions and wetland types, indicating the need for site-specific studies and adaptive management approaches. The integration of advanced technologies, such as nanomaterial-based filters and innovative water treatment methods, with wetland-based remediation can further enhance the removal efficiency of microplastics and heavy metals, while maintaining the ecological integrity of these systems (Bakhtiari et al., 2024). Despite their demonstrated benefits, wetlands face challenges related to the identification and quantification of emerging pollutants, such as microplastics, and the lack of standardized methodologies for monitoring and assessment. Addressing these challenges requires a multidisciplinary approach that combines ecological, technological, and regulatory perspectives to optimize the remediation potential of wetlands and safeguard their ecological functions for future generations (Marcharlaa et al., 2024). The continued exploration of wetland ecosystems as natural and constructed remediation systems is essential for advancing sustainable solutions to complex environmental pollution problems.

Table 1. Comparative Summary for Microplastics (MPs) vs Heavy Metals (HMs) in Wetlands, Based on their Sources, Behaviour, Impacts, and Remediation Approaches

Aspect	Microplastics (MPs)	Heavy Metals (HMs)
Definition	Small plastic particles (<5 mm) resulting from breakdown of larger plastics or direct release of microbeads.	Metallic elements with high atomic weight and density, toxic at low concentrations (e.g., Pb, Cd, Hg, Cr).
Primary Sources in Wetlands	Urban runoff, wastewater effluents, degraded fishing gear, industrial discharge, atmospheric deposition.	Industrial effluents, mining runoff, agricultural inputs (fertilizers, pesticides), waste leachates.
Aspect	Microplastics (MPs)	Heavy Metals (HMs)

Persistence	Highly persistent; degrade slowly into nanoplastics but not biodegradable.	Persistent and non-biodegradable; can undergo chemical transformations.
Transport & Fate	Float or sink depending on density; can adsorb contaminants; ingested by organisms and transported through trophic levels.	Bind to sediments, accumulate in biota, undergo complexation, precipitation, or remobilization under changing pH/redox.
Ecological Impact	Physical injury, blockage in organisms; vector for other pollutants; habitat alteration.	Toxic to aquatic plants and animals; disrupt enzymatic processes; bioaccumulate and biomagnify in food webs.
Human Health Impact	Potential ingestion via seafood and water; linked to inflammation, oxidative stress, and unknown long-term effects.	Neurological, renal, and reproductive damage; carcinogenic effects (e.g., Cr, Cd); chronic toxicity.
Detection Methods	FTIR, Raman spectroscopy, visual sorting under microscope, density separation.	AAS, ICP-MS, XRF, voltammetry.
Remediation Strategies	Physical removal (filters, traps), wetland plants for trapping, sediment dredging, bioremediation.	Phytoremediation, chemical precipitation, adsorption (biochar, zeolites), constructed wetlands.
Policy & Regulation	Emerging policies, less standardized regulation globally.	Well-established regulatory limits for water, sediments, and food in most countries.

Sources and Characteristics of Microplastics and Heavy Metals

Origins and Pathways in Wetland Environments

Primary Sources

Primary sources of microplastics and heavy metals in wetland environments are closely linked to anthropogenic activities and the complex interplay of environmental processes. Over the past decades, research has increasingly focused on topics such as industrial deposition, aquaculture, land use changes, mine tailings, and oil related activities, all of which introduce significant quantities of heavy metals into coastal and inland wetland systems (Lia et al., 2022). Microplastics, originating from both primary and secondary sources, are influenced by land management practices and industrialization patterns, causing spatial and temporal variability in contamination profiles. Secondary microplastics result from the fragmentation of larger plastic debris due to physical, chemical, and biological processes in the environment (Arifa et al., 2024). The omnipresence of microplastics in wetland ecosystems is largely attributed to human activities, including improper waste disposal, runoff from urban and agricultural areas, and the breakdown of consumer plastics. Rivers, uncovered landfills, and densely populated regions act as major conduits, transporting microplastics from terrestrial sources into aquatic systems, where

they accumulate in sediments and water columns (Goha et al., 2022). Environmental factors like hydrodynamics, sediment characteristics, and biological activity influence the transport and fate of contaminants like microplastics. Biofouling by microorganisms can increase microplastics' density, causing them to sink and contaminate wetland sediments. Heavy metals, introduced through industrial effluents, mining activities, and agricultural runoff, can adsorb onto plastic surfaces, enhancing their persistence and toxicity. The complexity of wetland hydrology, with its fluctuating water levels and dynamic redox conditions, can further mobilize or immobilize heavy metals, affecting their bioavailability and ecological impact (Lavanya et al., 2024). Monitoring studies have revealed that microplastics are now detected in a wide range of wetland matrices, including surface waters, sediments, and even groundwater sources (Allen et al., 2022). The persistence of both microplastics and heavy metals in these environments underscores the need for comprehensive source identification and management strategies. The type, size, and chemical composition of microplastics, as well as the speciation and concentration of heavy metals, determine their environmental behavior and potential risks (Singh et al., 2023). For example, certain forms of heavy metals are more mobile and toxic under acidic or reducing conditions, which are common in wetland soils. Similarly, the presence of nanoplastics and engineered nanomaterials introduces new dimensions to the contamination problem, as these materials may exhibit unique transport and interaction properties compared to their larger counterparts (Kokkinos et al., 2020) (Inobeme et al., 2022).

Secondary Sources

Secondary sources of microplastics and heavy metals in wetland environments are formed through the breakdown of larger contaminants and the redistribution of pollutants through environmental processes. These secondary sources are formed when larger plastic debris fragments. The fragmentation of macroplastics is accelerated by environmental factors such as ultraviolet radiation, mechanical abrasion, and microbial activity, resulting in the continuous input of MPs into wetland soils, sediments, and water columns (Arifa et al., 2024; Lia et al., 2024). The terrestrial origin of most marine plastics, with approximately 75–90% of marine plastic debris traced back to land-based activities, underscores the importance of secondary sources in the context of wetlands, which often serve as transitional zones between terrestrial and aquatic environments (Allen et al., 2022). Urban, agricultural, and industrial runoff transports plastics and contaminants into wetlands, accumulating or degrading. Wastewater treatment plants contribute to secondary MPs, introducing MPs into receiving water bodies and amplifying plastic particle input. Heavy metals also enter wetland environments. Industrial emissions, agricultural runoff, and atmospheric deposition initially introduce heavy metals into the environment, but subsequent processes such as erosion, resuspension, and leaching can redistribute these metals within wetland systems (Liu et al., 2024). For instance, heavy metals bound to soil particles or organic matter may be released into the water column during flooding events

or changes in redox conditions, thus acting as secondary sources that sustain or exacerbate contamination levels over time (Lavanya et al., 2024) (Osman et al., 2023). Heavy metal cycling in wetlands is influenced by biogeochemical processes, plant uptake, and microbial transformations. The dynamic nature of these environments further complicates secondary sources, necessitating monitoring and characterizing secondary pathways for understanding contaminants' persistence and ecological impacts, and developing effective remediation strategies.

Transport Mechanisms

Microplastics and heavy metals in wetland environments are transported through physical, chemical, and biological processes, starting from sources like industrial emissions, agricultural runoff, domestic wastewater, and solid waste discharge. These sources introduce pollutants into wetland systems, where they are subsequently mobilized through various pathways (Liu et al., 2024) (Lia et al., 2024). For microplastics, atmospheric deposition represents a significant transport route. Wind can carry microplastic particles over long distances, depositing them onto terrestrial and aquatic surfaces (Allen et al 2022). Heavy metals, on the other hand, Heavy metals are primarily transported through waterborne pathways, including industrial effluents, agricultural leachates, and atmospheric fallout, introducing them into wetland catchments and adsorbing onto suspended particulates. The partitioning between dissolved and particulate phases is strongly influenced by environmental parameters such as pH, redox potential, and the presence of complexing agents (Inobeme et al., 2022) (Ashraf et al., 2024). Biological processes also play a role in the transport and transformation of these contaminants. Microbial activity can mediate the transformation of heavy metals, altering their chemical forms and mobility (Singh et al., 2023). Plants and microorganisms in wetlands can uptake, accumulate, or transform heavy metals, thereby influencing their distribution and transport within the ecosystem (Lavanya et al., 2024). Nanomaterials themselves can be mobile within wetland systems, and their interactions with existing contaminants may alter the transport and fate of both the nanomaterials and the pollutants they are designed to remediate (Torimiro et al., 2021). Environmental factors like pH, ionic strength, and competing ions affect nanomaterial-based remediation efficiency. Adsorption on microplastics and natural particulates affects transport and distribution within wetland environments. The interplay of these factors determines the spatial and temporal distribution of contaminants.

Interactions between Microplastics and Heavy Metals

Adsorption and Desorption Mechanisms

Adsorption and desorption are crucial for removing heavy metals and MPs from wetland systems, with environmental conditions like pH, ionic strength, and competing ions triggering this process. Engineered nanomaterials like graphene oxide-based

nanocomposites and magnetic biochars enhance adsorption (Das et al., 2024). Additional materials like Al_2O_3 or MPs can affect adsorption equilibrium, while natural organic matter, co-existing ions, and aging of microplastics can alter their surface properties and adsorption behavior. Furthermore, the leaching and potential release of nanomaterials or adsorbed contaminants into the environment remain concerns, particularly due to the lack of comprehensive analytical tools for detecting and quantifying nanomaterials in complex environmental matrices (Goha et al., 2022). Most studies on leaching and dispersion are conducted under controlled conditions, but there's a gap in understanding their long-term fate in open water bodies. Adsorption efficiency is influenced by nanomaterial type (Inobeme et al., 2022). The interaction between MPs and heavy metals is further complicated by the potential for MPs to act as vectors, facilitating the transport of adsorbed heavy metals through the food web and potentially increasing their bioavailability and toxicity (Lia et al., 2024). Nano-bioremediation effectively reduces pollutants, but toxicity, recycling challenges, and ecosystem health concerns must be addressed. Eco-friendly, biodegradable nanomaterials and detection technologies are crucial for sustainable application.

Synergistic Toxicity

Wetland ecosystems are prone to synergistic toxicity when microplastics and heavy metals coexist, resulting in more severe effects than the sum of their individual toxicities. The unique physicochemical properties of MPs, such as their large surface area and hydrophobicity, enable them to adsorb and transport a variety of contaminants, including heavy metals, through aquatic environments (Xu et al., 2022). This interaction transforms MPs into vectors for heavy metals, facilitating their mobility and bioavailability, which can intensify the toxicological impact on aquatic organisms and potentially disrupt entire food webs (Arifa et al., 2024). The adsorption of heavy metals onto MPs is influenced by several factors, including the type of polymer, surface functional groups, and environmental conditions such as pH and ionic strength. For instance, the surface of aged or weathered MPs often exhibits increased roughness and the presence of oxygen-containing functional groups, which enhance their affinity for metal ions (Mandal & Mishra, 2023). MPs can accumulate heavy metals in wetland systems, acting as both sinks and sources. Ingestion of contaminated MPs by aquatic fauna results in simultaneous exposure to both particle and metal toxicity, causing oxidative stress, inflammation, and metabolic disturbances. MPs can also act as carriers for other pollutants, increasing the risk of multi-contaminant exposure in wetland environments. The persistence and bioaccumulation of MPs and heavy metals in wetland biota can disrupt metabolic and physiological functions, leading to impaired growth, reproduction, and survival of aquatic species (Narwala et al., 2023). MPs with heavy metals transport across trophic levels raises biomagnification and human exposure. They alter microbial community structure, nutrient cycling, and ecosystem health. Understanding their interactions and developing remediation strategies is crucial.

The use of advanced adsorbent materials, such as nanomaterials and biochar, has shown promise in removing both MPs and heavy metals from aquatic systems (Mulindwa et al., 2024). However, the deployment of these materials must be carefully evaluated to avoid introducing new risks, such as the release of nanomaterial residues or unintended ecological effects (Inobeme et al., 2022). The authors of (Ashraf et al., 2024) indicate that the optimal design and application of nanomaterials for pollutant removal should consider the specific interactions between MPs, heavy metals, and the wetland environment to maximize remediation efficiency while minimizing adverse outcomes. In summary, the synergistic toxicity resulting from the interplay between MPs and heavy metals in wetland ecosystems represents a significant environmental challenge. The combined effects of these pollutants can exacerbate ecological and health risks, necessitating integrated approaches for monitoring, risk assessment, and remediation.

Implications for Bioaccumulation

The implications for bioaccumulation arising from the interactions between microplastics (MPs) and heavy metals in wetland ecosystems are multifaceted and raise significant concerns for both ecological and human health. MPs, due to their small size and high surface area, act as efficient vectors for various contaminants, including heavy metals and antibiotics. This carrier effect not only facilitates the co-transport of pollutants but also modifies their bioavailability, thereby amplifying their impact on microbial function and metabolism (Lia et al., 2024). The formation of composite pollutants through the adsorption of heavy metals onto MPs can result in altered chemical speciation and increased persistence of these contaminants in the environment (Marcharlaa et al., 2024). Bioaccumulation of microplastics (MPs) is influenced by factors like their physicochemical properties, heavy metals, and the characteristics of the organisms they ingest. Smaller MPs are more easily ingested by aquatic organisms, leading to higher rates of bioaccumulation. Certain polymers can concentrate pollutants, causing physiological effects like inflammatory responses and compromised health. The interconnectedness of wetland ecosystems raises concerns about chronic exposure and biomagnification. Biofilms on MPs can also influence bioaccumulation dynamics. The presence of biofilms can enhance the adsorption of heavy metals and other contaminants, creating microenvironments that promote the persistence and transfer of pollutants within wetland ecosystems (Goha et al., 2022). The interaction between MPs, heavy metals, and microbial communities is particularly important, as it can lead to shifts in microbial structure and function, with implications for nutrient cycling and ecosystem health. The accumulation of MPs and heavy metals in wetland sediments is exacerbated by continuous inputs from sources such as wastewater and aquaculture activities. Sediments in closed wetland systems are especially prone to capturing MPs, leading to long-term contamination and increased risk of bioaccumulation in benthic organisms (Qian et al., 2020). The chronic exposure of wetland fauna to MPs and heavy metals can result in sublethal effects, including histopathological

changes, immune responses, and altered reproductive success (Mozafarjalali et al., 2023). These effects may persist across generations, raising concerns about the long-term stability and resilience of wetland populations. The use of nanomaterials for the remediation of MPs and heavy metals introduces additional complexity to bioaccumulation processes. While nanomaterials such as graphene oxide, carbon nanotubes, and metal oxide nanoparticles have demonstrated high adsorption capacities for heavy metals, their interactions with MPs and biota are not fully understood (Ashraf et al., 2024) (Inobeme et al., 2022). The potential for nanomaterials to themselves become vectors for contaminant transport, or to induce toxicity in aquatic organisms, must be carefully considered in the context of wetland remediation strategies (Narwala et al., 2023). Nanoparticles release into the environment can lead to secondary contamination and influence the bioaccumulation of MPs and heavy metals. The combined presence of these pollutants can increase contaminants' burden and toxicity, impacting ecosystem health, food web dynamics, and human exposure.

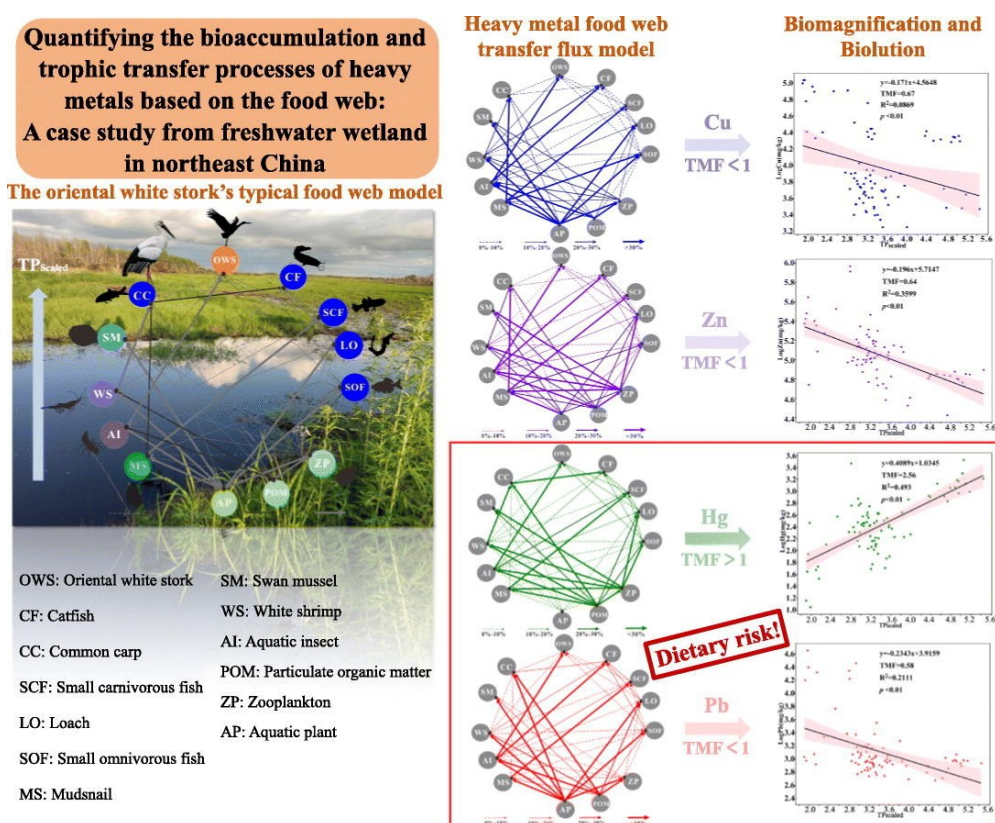


Fig. 3 This image shows how heavy metals move through a wetland food web. While copper, zinc, and lead show no biomagnification (TMF < 1), mercury (TMF > 1) accumulates up the food chain, posing a dietary risk to top predators like the oriental white stork. Reprinted with permission from ref. 20 Copyright: © 2024, Elsevier

Eco-Friendly Nanomaterials for Remediation

Types of Nanomaterials Used

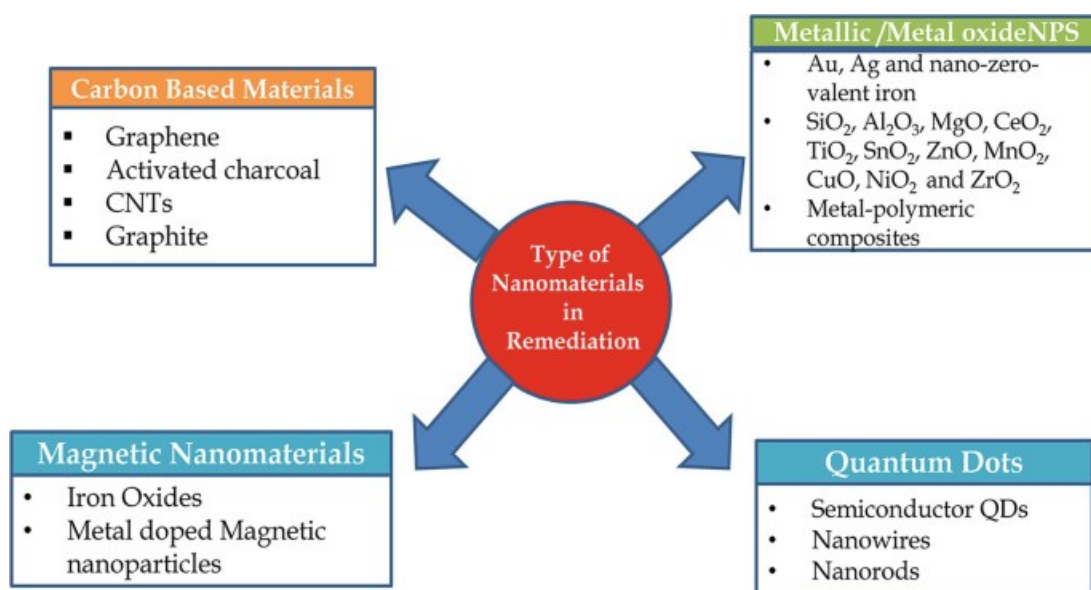


Fig. 4 Types of nanomaterials used in environmental remediation Reprinted with permission from ref. 47. Copyright: © 2022, Springer nature

Carbon-based Nanomaterials

Carbon-based nanomaterials have emerged as highly promising candidates for eco-friendly remediation of microplastics and heavy metals in wetland ecosystems. Their unique physicochemical properties, such as high surface area, tunable surface chemistry, and robust stability under diverse environmental conditions, make them particularly suitable for environmental applications (Kokkinos et al., 2020). Among the most studied carbon-based nanomaterials are carbon nanotubes (CNTs), graphene, and graphitic carbon nitride (g-C₃N₄), each offering distinct advantages for pollutant removal. CNTs and graphene possess extensive π -conjugated structures, which facilitate strong interactions with a variety of contaminants through mechanisms such as π - π stacking, electrostatic attraction, and hydrophobic interactions. These interactions are especially effective for adsorbing organic pollutants, including microplastics, as well as heavy metal ions (Thangadurai et al., 2020). The large surface area of these materials allows for a high density of active sites, enhancing their adsorption capacity and efficiency. Furthermore, the structure of CNTs and graphene can be chemically modified to introduce functional groups, such as carboxyl, hydroxyl, or amine moieties, which further improve their affinity for specific contaminants and enable selective removal processes. The eco-friendliness of carbon-based nanomaterials is underscored by their earth-abundance and the potential for synthesis from renewable resources. Their stability in harsh environmental conditions, including variable pH and temperature, ensures consistent performance in wetland settings, where such fluctuations

are common (Cai et al., 2019). Carbon-based nanomaterials, including CNTs, graphene, and their composites, offer eco-friendly and effective solutions for removing microplastics and heavy metals from wetland ecosystems. These materials exhibit high electrical conductivity, making them ideal for electrochemical remediation and catalysis. Recent advancements focus on developing carbon-based nanocomposites, which can be combined with other nanomaterials to enhance remediation performance. However, potential risks include leaching into ecosystems and potential ecological disruption. Their tunable properties, high adsorption capacities, and stability under environmental stressors position them at the forefront of sustainable nanotechnology solutions for pollution remediation (Torimiro et al., 2021).

Metal and Metal Oxide Nanomaterials

Metal and metal oxide nanomaterials have emerged as highly effective agents for the remediation of microplastics and heavy metals in wetland ecosystems due to their unique physicochemical properties. Their nanoscale dimensions confer a high surface area-to-volume ratio, which enhances their adsorption capacity and reactivity compared to their bulk counterparts (Mensah et al., 2021). This increased surface area allows for more active sites to interact with contaminants, making them particularly suitable for the adsorption and removal of heavy metals such as lead, cadmium, copper, and iron from aqueous environments (Ashraf et al., 2024). The adsorption mechanisms of metal and metal oxide nanomaterials are influenced by several factors, including surface charge, functional groups, and the presence of specific metal ions. For instance, iron oxide nanoparticles exhibit strong affinity for cationic heavy metals through electrostatic interactions and surface complexation, which can be further enhanced by surface modification or combination with other materials (Kokkinos et al., 2020). Nanoparticles, such as nanosilver and nano-TiO₂, have potential applications in water purification and photocatalytic activities. They can adsorb heavy metals and inactivate waterborne pathogens. However, their efficiency is limited to UV light, prompting the development of doped or modified TiO₂ nanocatalysts. Additionally, the interaction between microplastics and metal nanoparticles is growing. For example, polyvinyl chloride (PVC) microplastics, due to their high polarity from chlorine atoms, exhibit a greater capacity to adsorb metal nanoparticles such as Fe and Cu compared to other polymers like polypropylene (PP) and polystyrene (PS) (Mozafarjalali et al., 2023). This suggests that the type of microplastic present in wetlands can influence the fate and transport of metal nanoparticles, as well as the overall efficiency of contaminant removal. Electrochemical oxidation processes utilizing metal-based electrodes represent another promising approach for the degradation of organic pollutants, including microplastics, in wastewater. This technique generates potent oxidants such as hydroxyl radicals and hydrogen peroxide, which can mineralize contaminants without the need for additional chemical agents and without producing sludge waste (Osman et al., 2023). The sustainability and cost-effectiveness of electrochemical oxidation make it an

attractive option for largescale wetland remediation efforts. Despite their advantages, the deployment of metal and metal oxide nanomaterials in wetland environments raises important environmental considerations. Life cycle assessment (LCA) is essential to evaluate the potential impacts associated with the production, use, and disposal of these nanomaterials (Inobeme et al., 2022). Weathering processes can accumulate nanoparticles in areas, potentially affecting ecosystems. Assessing their environmental fate and potential to generate pollutants is crucial. Integrating metal and metal oxide nanomaterials with advanced materials like MOFs and COFs enhances adsorption capacities and selectivity for heavy metals and radionuclides. However, their application requires understanding their environmental behavior, potential risks, and sustainable design and deployment strategies.

Biopolymer and Natural Nanomaterials

Biopolymer and natural nanomaterials are promising eco-friendly remediation strategies for wetland ecosystems, particularly for removing microplastics and heavy metals. Chitosan, a biopolymer from chitin, has high adsorption capabilities for heavy metals due to amino and hydroxyl functional groups. Chemical modifications can enhance their structural stability and binding capacity. For instance, chitosan nanoparticles have shown significant potential in absorbing heavy metals like Pb(II), and when combined with zinc oxide, they can achieve high removal rates for organic pollutants such as permethrin, as well as dyes like AO12 and acid green 25 (Ashraf et al., 2024). Biodegradation using microbial consortia and biopolymer matrices can effectively remove microplastics in wetlands. These materials offer low toxicity, biodegradability, and minimal contamination risk, but their performance is influenced by environmental factors. For example, the adsorption of heavy metals onto biopolymer nanomaterials is highly pH-dependent, with optimal removal typically occurring near neutral pH, where electrostatic interactions and surface coordination are maximized (Inobeme et al., 2022). This necessitates careful consideration of site-specific conditions when designing and implementing remediation strategies. Advances in the extraction and functionalization of natural nanomaterials, such as the use of eco-friendly solvents and techniques to minimize leaching risks, have further improved their applicability and safety in environmental remediation (Lavanya et al., 2024). The integration of nanomaterials and biopolymers in composite systems has improved stability and longevity, addressing limitations in traditional remediation methods. Genetically engineered microorganisms and biopolymer matrices enable targeted degradation of pollutants. These versatile materials can be tailored for specific applications, offering potential for sustainable and effective wetland remediation.

Performance Assessment in Wetland Ecosystems

The simultaneous presence of microplastics (MPs) and heavy metals (HMs) in wetland ecosystems presents a complex challenge for remediation, as these co-contaminants can interact in ways that amplify ecological risks and complicate removal strategies. MPs, due

to their high surface area and hydrophobicity, can adsorb and transport HMs, facilitating their migration and bioavailability within wetland environments. This interaction not only increases the spatial extent of contamination but also enhances the potential for trophic transfer, as MPs ingested by aquatic organisms can introduce adsorbed HMs into the food web, leading to bioaccumulation and biomagnification (Lia et al., 2024) (Xu et al., 2022). Recent eco-friendly nanomaterials, such as magnesium oxide nanoparticles, have shown promise in combining remediation approaches for MPs and HMs in wetland systems, achieving removal rates exceeding 80%. Notably, the use of MgO-NPs resulted in low metal concentrations in plant roots, suggesting effective immobilization or transformation of HMs, thereby reducing their bioavailability and ecological risk (Nguegang et al., 2022). The study suggests that nanomaterials can mediate the fate of HMs in plant-based remediation strategies, enhancing co-contaminant removal. Plants, like hyperaccumulators, can reduce HM and MP concentrations through natural absorption and nanomaterials' breakdown. (Lavanya et al., 2024). Coagulation and flocculation, when combined with nanomaterials, can significantly improve the capture and removal of MPs from aqueous environments (Goha et al., 2022). Nanomaterials offer dual-functionality for wetland remediation by adsorbing MPs and degrading them, while immobilizing HMs, despite challenges in deployment in wetland ecosystems. The performance of these materials can vary depending on environmental conditions, such as pH, organic matter content, and the presence of competing ions or natural colloids (Liu et al., 2024). Emerging research also points to the importance of understanding the interactions between MPs, HMs, and nanomaterials at the microbial and enzymatic levels. MPs can influence the activity of soil enzymes and the composition of microbial communities, which in turn affects the biogeochemical cycling of HMs and the overall remediation performance (Ma et al., 2022). Comprehensive studies are needed to optimize microbial, plant, and nanomaterial interactions in wetland remediation strategies, considering the complexity of co-contaminant remediation due to diverse pollutant sources and dynamic ecosystems. Anthropogenic activities remain the dominant drivers of HM and MP pollution, necessitating adaptive and site-specific remediation approaches (Lia et al., 2022). Hybrid systems combining phytoremediation, nanomaterial-assisted adsorption, and microbial transformation are being developed for contaminated wetlands. These systems must be tailored to specific contaminant profiles and ecological characteristics, considering pollutant interactions and minimal environmental disturbance. Further research is needed to optimize nanomaterial properties and assess long-term environmental impacts.

Table 2. Peer-reviewed studies that provide strong quantitative evidence on the use of eco-friendly nanomaterials for remediation of microplastics and heavy metals

Study Title	Nanomaterial Type	Key quantitative findings	References
Metal and Metal Oxide Nanomaterials for Heavy Metal Remediation	Graphene oxide, CNTs, MOFs	Adsorption capacity: Pb ²⁺ = 250 mg/g; Cd ²⁺ = 180 mg/g; Selectivity enhanced by surface functionalization	Olawade <i>et al.</i> , 2024
Nanomaterials for the Removal and Detection of Heavy Metals	Cellulose nanofibers, chitin-based nanomaterials	Removal efficiency: >90% for Pb ²⁺ and Hg ²⁺ ; Detection limit: <10 ppb	De Silva <i>et al.</i> , 2025
Biomass-Derived Carbon Nanotubes for Heavy Metal Removal	Bio-CNTs	Adsorption capacity: Cu ²⁺ = 160 mg/g; Zn ²⁺ = 140 mg/g; Reusability: >5 cycles with >80% retained efficiency	De Silva <i>et al.</i> , 2025
Microplastic Pollutant Degradation in Water Using Modified TiO ₂ Photocatalyst Under UV-Irradiation	TiO ₂	Composites degraded polyethylene under UV radiation, with Ag/TiO ₂ /RGO catalyst showing a 76% higher degradation percentage compared to pure TiO ₂ and Ag/TiO ₂	Fadli <i>et al.</i> , 2021
Green synthesis of a silver nanoparticle using <i>Moringa oleifera</i> seed and its applications for antimicrobial and sun-light mediated photocatalytic water detoxification	AgNPs from <i>Moringa oleifera</i>	MOS-AgNPs demonstrated significant photocatalytic activity against organic dyes and removed 80% of toxic Pb metal ions from treated water, maintaining efficiency after 10 cycles under sunlight irradiation.	Mehwish <i>et al.</i> , 2021
Green synthesis of spongy Nano-ZnO productive of hydroxyl radicals for unconventional solar-driven photocatalytic remediation of antibiotic enriched wastewater	ZnO nanoparticles	Bulk ZnO exhibits 41.46% photodegradation efficiency, while biosynthesized ZnO has 97.6%. Highly acidic or alkaline media hinder FL photodegradability, with holes playing a significant role.	Essawy <i>et al.</i> , 2020

Environmental Implications and Safety Concerns
Potential Ecotoxicological Effects of Nanomaterials

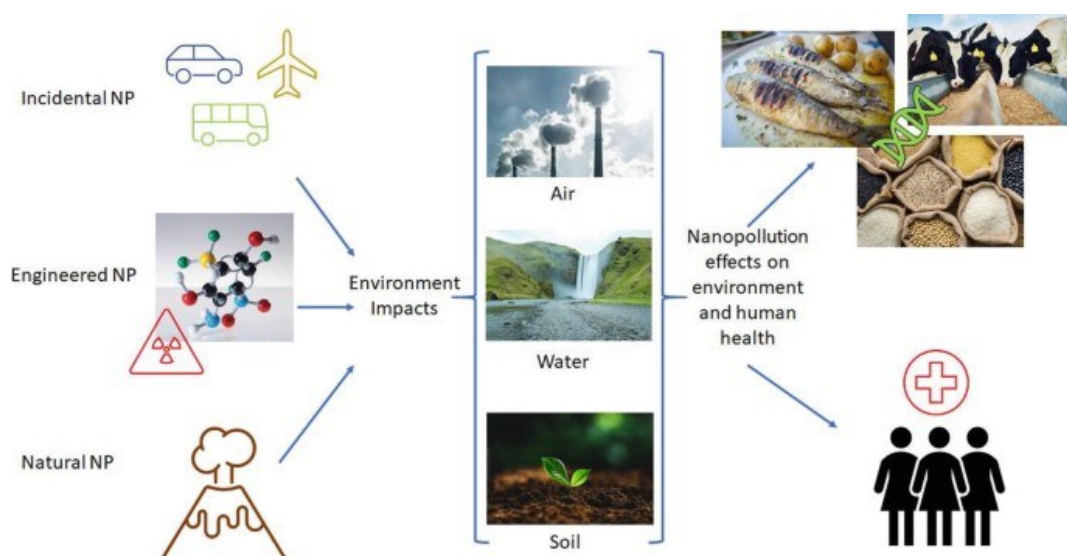


Fig. 5 Collateral effects of nanopollution on human and environmental health Reprinted with permission from ref. 14. Copyright: © 2023, Springer nature

The deployment of nanomaterials for the remediation of microplastics (MPs) and heavy metals in wetland ecosystems introduces a complex array of potential ecotoxicological effects on aquatic organisms. The interaction between nanomaterials and aquatic biota is multifaceted, influenced by the physicochemical properties of the nanomaterials, the characteristics of the surrounding environment, and the biological traits of the organisms themselves (Das et al., 2024). The adsorption and removal of MPs using advanced nanomaterials, such as functionalized 2D structures, can alter the bioavailability and distribution of these pollutants in aquatic systems. While this can reduce direct exposure to MPs, it may also lead to the formation of new contaminant-nanomaterial complexes whose biological effects are not yet fully understood (Marcharlaa et al., 2024). Aquatic organisms, including fish, shellfish, and invertebrates, are vulnerable to MPs and contaminants, leading to physical blockages, reduced feeding efficiency, and impaired growth. The introduction of nanomaterials may complicate these effects, potentially causing bioaccumulation and biomagnification, posing risks to higher trophic levels and ecosystem stability. The fate and transport of nanomaterials in aquatic environments are governed by their density, surface chemistry, and interactions with natural organic matter and biota (Arifa et al., 2024). Nanomaterials with lower densities may interact with planktonic organisms, while denser materials may impact benthic communities. Long-term ecological impacts and toxicological effects on aquatic organisms are concerns. These effects may include oxidative stress, membrane disruption, and interference with normal physiological processes (Osman et al., 2023). The potential for nanomaterials to act as carriers for other pollutants, such as heavy metals or persistent organic compounds, further amplifies the risk of combined or synergistic toxicity (Allen et al., 2022). Therefore, there is a need for

comprehensive safety assessments before large-scale deployment of nanomaterials in natural ecosystems. The presence of MPs and nanomaterials can disrupt ecological interactions and food web dynamics, impairing predatory species' health and reproductive success. Current knowledge gaps hinder accurate assessment of environmental hazards in wetland ecosystems. Robust risk assessment frameworks are essential for safeguarding aquatic organisms and maintaining ecosystem integrity.

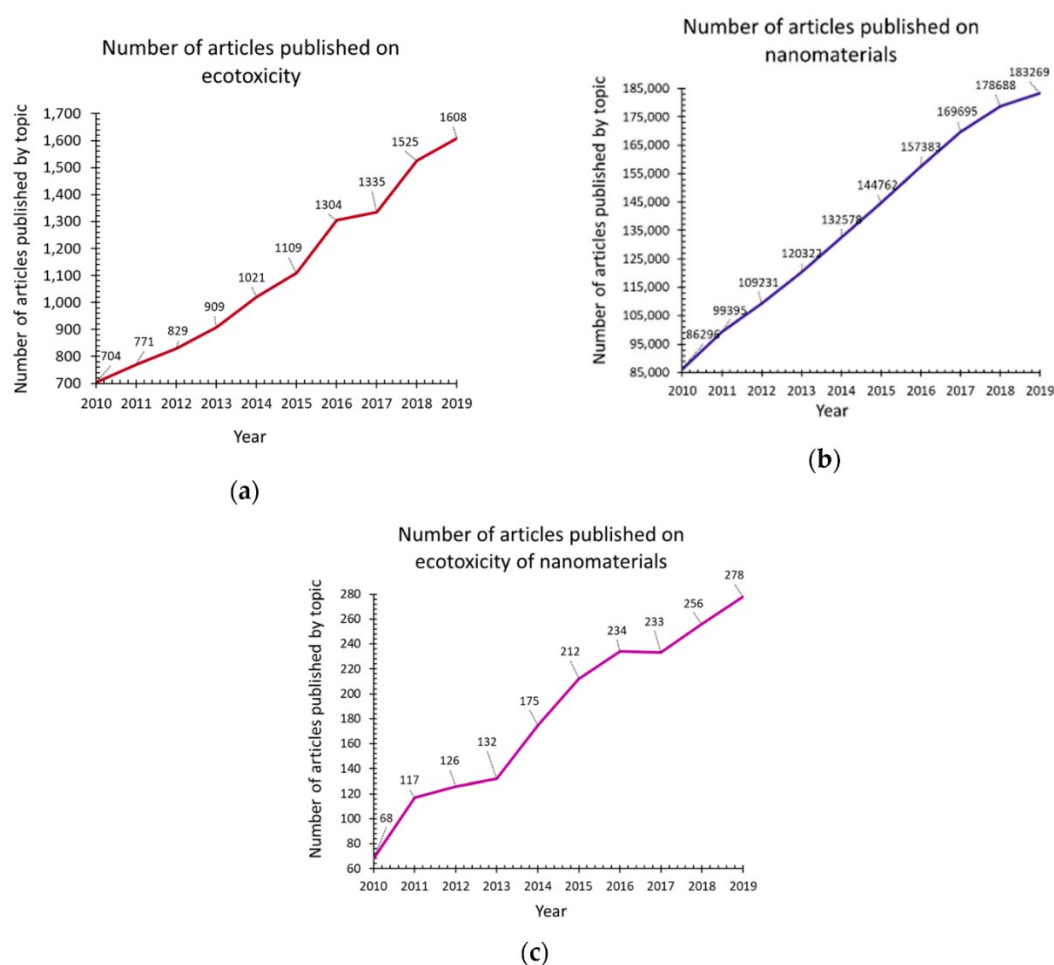


Fig. 6 Bibliometric analysis of research in 2010–2019 from Web of Science Core Collection (Web of Science, Clarivate Analytics) on (a) ecotoxicity (search strategy: topic search (TS)=(Ecotox*)) (containing “ecotox” in the topic of the articles)); (b) nanomaterials (search strategy: TS=(Nano*)) and (c) ecotoxicity of nanomaterials (search strategy: TS=(Ecotox* AND Nano*)). Reprinted with permission from ref. 8, Copyright: © 2020, MDPI

Integration with Constructed and Natural Wetlands

Applications in Engineered Wetland Systems

Design Considerations

Designing eco-friendly nanomaterial-based systems for the removal of microplastics and heavy metals in engineered wetland environments requires a multifaceted approach that balances efficiency, sustainability, and ecological safety. The selection of nanomaterials must consider not only their adsorption or catalytic capabilities but also their long-term stability, reusability, and potential for secondary pollution. For instance, the use of regenerated nano-adsorbents and magnetically separable multifunctional nanomaterials has been shown to maintain high activity over multiple reuse cycles, which is essential for cost-effective and sustainable operation in wetland settings (Kokkinos et al., 2020). The application of lower-purity nanomaterials, such as amino fullerene photocatalysts derived from fullerene soot, can significantly reduce costs while maintaining high removal efficiencies, supporting the feasibility of large-scale deployment in constructed wetlands (Inobeme et al., 2022). Integration of nanomaterials into wetland systems must also address the compatibility with existing biological and physicochemical processes. Constructed wetlands (CW) rely on the synergistic action of wetland flora, soils, and associated microbial communities to achieve pollutant removal (David et al., 2023). The design must ensure that these materials are retained within the wetland matrix and do not leach into downstream environments, which could pose ecological risks (Narwala et al., 2023). Membrane technologies with nanomaterials enhance conductivity and antifouling properties, beneficial for bioelectrochemical systems. Tuning membrane permeability and selectivity maintains hydraulic performance and contaminant removal. The use of conductive membranes that facilitate redox reactions on their surfaces can further promote the transformation of refractory pollutants, reducing the burden on biological processes and minimizing membrane fouling (Morin-Crini & Crini, 2022). The spatial arrangement and retention of nanomaterials in wetland substrates are crucial. Magnetically recoverable nanomaterials like iron oxide allow targeted deployment, minimizing environmental release. Adsorption kinetics and isotherms should be considered in design to optimize loading. Plant species influence microplastics and heavy metals transport (Gecheva et al., 2025). The use of nanomaterials in wetland environments is crucial due to potential toxicity to aquatic organisms. Risk assessment and monitoring are necessary, and strategies like encapsulation or biocompatible coatings should be used. Long-term reusability and regeneration are essential for cost reduction and environmental impact. The system should also consider potential accumulation in plant biomass and sediments. The use of eco-friendly synthesis methods, such as microbial production of silver nanoparticles, can further reduce the environmental burden. Combining phytoremediation with biomass cogeneration can significantly reduce environmental impacts, highlighting the importance of integrating nanomaterial applications with broader sustainability strategies in wetland engineering (Lavanya et al., 2024). In summary, the design of nanomaterial-enhanced

wetland systems for microplastic and heavy metal remediation must integrate material selection, system configuration, ecological compatibility, operational practicality, and environmental safety. This holistic approach ensures that the benefits of advanced nanotechnologies are realized without compromising the integrity and sustainability of wetland ecosystems.

Operational Challenges

Operational challenges in integrating eco-friendly nanomaterials into engineered wetland systems for microplastics and heavy metal remediation include limited adsorption capacity of certain nanomaterials, limiting their effectiveness in large-scale applications. Additionally, under specific environmental conditions, there is a risk that previously adsorbed pollutants could be released back into the wetland, undermining long-term remediation goals (Liu et al., 2024). Wetland substrates, dynamic and complex, pose operational challenges in nanomaterial deployment and heavy metal removal due to pollutant loading, plant uptake, rhizofiltration, precipitation, and sedimentation. These processes are not always predictable, and the efficiency of nanomaterial-based remediation can be influenced by the interplay between these biogeochemical mechanisms (Nguegang et al., 2022). The use of nanomaterials in wetlands raises concerns about metal removal due to their catalytic properties, but also the potential release of contaminants due to environmental factors like pH and redox conditions. Shifts in pH can reduce adsorption efficiency or even trigger the release of previously sequestered metals, complicating operational management (Bakhtiari et al., 2024). Sustainability and safety are further complicated by the risk of secondary pollution. For example, constructed wetlands filled with conductive materials can effectively remove antibiotics and antibiotic resistance genes (ARGs), but there is a potential for ARGs to be re-released into the effluent, raising concerns about the long-term containment of these pollutants. The operational challenge here lies in balancing effective removal with the prevention of secondary emissions, which requires careful monitoring and adaptive management strategies (Lia et al., 2024). The heterogeneity of wetland environments also poses a challenge for the uniform distribution and retention of nanomaterials. Variability in hydrology, plant density, and microbial community structure can lead to uneven exposure of pollutants to the nanomaterials, reducing overall treatment efficiency. For example, the presence of microplastics and nanoplastics can directly affect the composition and function of microbial communities, which are essential for nutrient cycling and organic matter decomposition. Changes in microbial community structure, such as increased abundance of stress-tolerant taxa, may indicate environmental stress and could impact the overall performance of the wetland system (Ma et al., 2022). Operational scalability in full-scale wetland systems is challenging due to the need for large quantities of nanomaterials, potential clogging, and environmental conditions. The long-term fate and transformation of nanomaterials in wetland environments remain uncertain. The potential for nanomaterial aggregation,

transformation, or degradation could alter their remediation efficacy and environmental impact, necessitating robust monitoring and risk assessment frameworks (Padervand et al., 2020). Addressing these operational challenges requires a multidisciplinary approach, combining advances in nanotechnology, wetland ecology, and environmental engineering. Adaptive management, continuous monitoring, and the development of responsive operational protocols are essential to ensure that the deployment of eco-friendly nanomaterials in engineered wetland systems achieves both effective pollution remediation and environmental safety.

Table 3: Operational Challenges in Integrating Eco-Friendly Nanomaterials into Wetland Systems

Operational Challenge	Underlying Cause	Relevant Nanomaterial Property	Possible Mitigation Measures
Material aggregation in water	High surface energy and particle–particle attraction	Particle size, surface charge	Use of surface functionalization or biodegradable stabilizers
Reduced adsorption in variable pH	pH-dependent ionization of functional groups	Surface chemistry, pH sensitivity	Select pH-stable coatings or mixed-functionalized materials
Biofouling and microbial colonization	Organic matter and microbial growth on nanomaterial surfaces	Surface roughness, hydrophobicity	Anti-biofouling coatings; periodic wetland flushing
Transport limitation in sediment	Poor mobility in porous wetland media	Particle size, distribution, density	Optimize particle size; use slow-release carriers
Nanomaterial degradation in harsh conditions	UV, oxidation, or microbial breakdown	Photostability, biodegradability	Choose materials with controlled degradation rates
Potential ecotoxicity to wetland biota	Release of reactive species or toxic intermediates	Redox activity, dissolution rate	Pre-deployment ecotoxicity testing; controlled dosing
High operational cost	Complex synthesis or scarce raw materials	Synthesis method, feedstock source	Utilize locally available agricultural/biowaste precursors

Broader Applications and Future Prospects

The transition from wetland-focused remediation to broader aquatic ecosystems necessitates a nuanced understanding of both the unique challenges and the transferable opportunities presented by eco-friendly nanomaterials. Wetlands, while critical as natural filters and biodiversity hotspots, share several pollution dynamics with other aquatic systems such as rivers, lakes, and estuaries. The persistent nature of microplastics and

heavy metals, their tendency for bioaccumulation, and their movement through trophic levels are not confined to wetlands but are also observed in diverse aquatic environments (Osman et al., 2023). The stability and resistance to degradation of microplastics, for instance, enable their transport from terrestrial and wetland sources into larger water bodies, where they can enter food webs and accumulate in biota, ultimately impacting ecosystem health and human consumers (Qian et al., 2020). Expanding the application of nanomaterial-based remediation strategies to these systems requires careful consideration of the physicochemical properties of both the contaminants and the receiving environments. The effectiveness of nanomaterials such as graphene, graphene oxide, and transition metal dichalcogenides in adsorbing microplastics and heavy metals has been demonstrated in controlled settings, largely due to their high surface area, mechanical strength, and chemical reactivity (Das et al., 2024). These properties suggest that such materials could be adapted for use in rivers and lakes, where dynamic flow conditions and variable contaminant loads present additional challenges. The adaptability of nanomaterials, including their potential for surface modification and functionalization, allows for the tuning of their interactions with specific pollutants, which is essential for addressing the heterogeneity of aquatic environments (Cai et al., 2019). The migration and transformation of microplastics and nanoplastics in aquatic systems are influenced by episodic events such as rainfall and stormwater runoff, which can introduce pulses of contaminants into surface waters (Stábile et al., 2024). The temporal fluctuations in nanoplastic concentrations, as well as the complexity of natural waters, highlight the need for remediation technologies that are robust under variable conditions. The use of nanomaterials in these contexts must account for the potential for aggregation, dissolution, and changes in reactivity due to environmental factors such as pH, ionic strength, and the presence of natural organic matter (Kokkinos et al., 2020). Nanoparticle immobilization can reduce risks and improve stability in open water systems, but ecological implications must be carefully assessed, as nanoplastics can disrupt biogeochemical processes like nitrification and denitrification. (Lia et al., 2024). Microplastics and nanoplastics can disrupt microbial communities in rivers and lakes, highlighting the need for understanding nanomaterial removal efficiency and their impact on ecosystem processes and dynamics. Legal and regulatory frameworks for the responsible use and disposal of nanomaterials are currently underdeveloped, particularly for applications beyond wetlands (Narwala et al., 2023). The expansion of nanomaterials into aquatic systems necessitates guidelines for their unique properties, proper disposal methods, and scalability and sustainability for remediation, preventing secondary contamination and promoting broader application. Conventional methods for heavy metal removal, such as chemical precipitation and ion exchange, often face limitations in cost, efficiency at trace concentrations, and secondary pollution (Inobeme et al., 2022). Nanomaterial-based adsorption offers an economical and effective alternative, but large-scale implementation requires advancements in material synthesis, deployment technologies, and post-

treatment recovery. Customization of nanomaterials for specific ecosystem types is crucial. The integration of phytoremediation with nanotechnology, for example, could offer synergistic benefits by combining biological uptake with nanomaterial-enhanced adsorption or catalysis (Lavanya et al., 2024). Understanding the interactions between nanomaterials, contaminants, and biota across different aquatic systems will be essential for optimizing remediation strategies and minimizing unintended impacts (Lia et al., 2022). Eco-friendly nanomaterial applications in aquatic ecosystems offer sustainable pollution control, but require a holistic approach balancing technological innovation, ecological risk assessment, regulatory development, and long-term monitoring for effective and environmentally responsible solutions.

Emerging Trends in Eco-Friendly Nanomaterials

Smart and Responsive Nanomaterials

Smart nanomaterials are revolutionizing eco-friendly remediation technologies, specifically for removing microplastics and heavy metals from wetland ecosystems, by exhibiting dynamic behaviors based on environmental stimuli. Their ability to adapt and modulate their physicochemical properties under varying conditions enhances both selectivity and efficiency in pollutant capture and degradation (Kokkinos et al., 2020). Nanotechnology integration with interdisciplinary approaches creates nanomaterials for environmental pollutants detection, photocatalytic degradation, and large-scale remediation. These smart materials are being developed for genetically modified organisms and bio-hybrid systems. These systems can be engineered to sense the presence of microplastics or heavy metals and initiate targeted responses, such as the release of degradative enzymes or the activation of pollutant-adsorbing surfaces (Marcharlaa et al., 2024). The study of plant-microbe-nanomaterial interactions is crucial for phytoremediation strategies, utilizing artificial intelligence and robotics for smart detection and remediation, but environmental fate and ecotoxicity must be assessed. The interaction of responsive nanomaterials with non-target organisms and their potential to introduce new risks into wetland ecosystems are areas that require further investigation (Aryal et al., 2020) and (Stábile et al., 2024). Understanding nanoplastic transport and behavior is improving, but the true scale of nanomaterial pollution and ecological consequences is still unknown. The future of smart nanomaterials in wetland remediation depends on developing effective, selective, safe, and biodegradable materials. The convergence of nanotechnology, biotechnology, and digital technologies holds promise for next-generation materials.

Hybrid Systems and Multi-Functional Materials

Hybrid systems and multi-functional materials are at the forefront of eco-friendly nanotechnology for wetland remediation, offering synergistic properties that surpass those

of single-component materials. These advanced materials are engineered to address the complex mixture of contaminants typically found in wetland ecosystems, such as microplastics and heavy metals, by integrating multiple functionalities into a single platform (Mensah et al., 2021) (Ashraf et al., 2024). Nanomaterials, when combined with biopolymers or substrates, improve the removal of pollutants, enhancing efficiency and selectivity. Chitosan-based nanocomposites, magnetic nanoparticles, and multifunctional nanomaterials can adsorb and degrade pollutants. Ideal nanoadsorbents should exhibit strong affinity, stability, reusability, and ease of separation (Liu et al., 2024). For example, innovative materials that combine cyclodextrins with carbon nanotubes or other nanostructures can encapsulate and immobilize microplastic particles, preventing their further dissemination in aquatic environments (Chanda & Suthar, 2024)(Narwala et al., 2023). Hybrid nanomaterials, combining cyclodextrins' molecular recognition properties with carbon-based nanomaterials' high adsorption capacity, enhance removal efficiencies in wetland systems. These advanced materials, guided by green chemistry and sustainability principles, are biocompatibility and biodegradable. However, their long-term environmental fate and potential ecotoxicological impacts remain a concern. The high reactivity and persistence of some nanomaterials may pose risks to non-target organisms or disrupt ecological processes if not properly managed (Stábile et al., 2024). Research is focusing on optimizing materials for wetland remediation, balancing efficacy with environmental safety. Hybrid systems and multi-functional materials enable efficient removal of multiple pollutants, utilizing sustainable synthesis methods and complementary nanomaterial properties.

Integration with Digital Monitoring

The integration of eco-friendly nanomaterials with digital monitoring systems is rapidly transforming the landscape of wetland pollution remediation. The convergence of advanced nanotechnologies and real-time sensing platforms enables not only the efficient removal of microplastics and heavy metals but also the continuous assessment of environmental health. Digital monitoring, when coupled with nanomaterial-based remediation, provides a feedback loop that enhances both the precision and adaptability of treatment strategies (Marcharlaa et al., 2024). Recent developments in magnetic nanomaterials, such as iron oxide nanoparticles, have demonstrated the potential for remote manipulation and targeted pollutant removal. These materials can be guided and recovered using external magnetic fields, which is particularly advantageous for site-specific interventions in complex wetland matrices (Luo et al., 2021). The ability to control the spatial distribution and retrieval of nanomaterials is further amplified when integrated with digital monitoring systems that track contaminant hotspots and nanomaterial dispersion in real time. Digital platforms equipped with sensor arrays and data analytics are increasingly being deployed to monitor the fate and transport of both microplastics and heavy metals in wetland environments. These systems can detect fluctuations in pollutant

concentrations, track the performance of nanomaterial-based adsorbents, and provide early warnings of system failures or contaminant breakthroughs (Padervand et al., 2020). Membrane bioreactors can be optimized with digital sensors for real-time monitoring of fouling, flow rates, and effluent quality, ensuring sustained removal efficiency under varied environmental conditions. The environmental implications of deploying nanomaterials in wetlands necessitate robust monitoring frameworks to assess potential risks. Digital monitoring systems can be programmed to track not only the removal of target pollutants but also the persistence, transformation, and possible ecotoxicological effects of nanomaterials themselves (Bakhtiari et al., 2024). Digital platforms integrate nanotechnology with digital monitoring to manage wetland biota and ecosystem functions. This allows for predictive modeling, real-time information dissemination, community participation, and policy development, ensuring environmental safety and stakeholder engagement.

Policy, Regulation, and Public Perception

International Regulatory Landscape

The international regulatory landscape addressing the use of eco-friendly nanomaterials for the remediation of microplastics and heavy metals in wetland ecosystems is characterized by a complex interplay of policy development, scientific uncertainty, and evolving public awareness. Regulatory frameworks for microplastics and associated contaminants have historically lagged behind the rapid pace of scientific discovery and technological innovation, particularly in the context of emerging nanotechnologies. This gap is evident in the limited harmonization of standards and guidelines across different jurisdictions, which complicates the global management of microplastic pollution and the deployment of novel remediation materials (Marcharlaa et al., 2024). The lack of standardized testing protocols and risk assessment methodologies for nanomaterials further complicates regulatory oversight, as the unique physicochemical properties of these materials may lead to unforeseen ecological and health impacts (Morin-Crini & Crini, 2022). International organizations and scientific bodies are advocating for unified guidelines for the safe and effective use of nanotechnologies in environmental remediation due to recent trends in wastewater treatment. Nevertheless, the translation of scientific advances into policy is often hindered by uncertainties related to the long-term behavior, toxicity, and bioaccumulation potential of both microplastics and nanomaterials in complex wetland ecosystems (Allen et al., 2022). Public perception and awareness are crucial for shaping international regulatory responses to microplastic pollution. Educational campaigns and media outreach are essential for increasing public understanding. Policymakers must prioritize research on environmental and health implications before widespread deployment. The current regulatory landscape is marked by a tension between sustainable pollution solutions and ecosystem and human health protection.

Societal Acceptance and Ethical Considerations

Societal acceptance and ethical considerations are central to the successful implementation of ecofriendly nanomaterials for the remediation of microplastics and heavy metals in wetland ecosystems. Public perception of nanotechnology is shaped by a combination of perceived benefits, potential risks, and the transparency of information provided by researchers and policymakers. The integration of nanomaterials into environmental applications, particularly in sensitive habitats such as wetlands, raises questions about long-term ecological safety, human health implications, and the adequacy of current regulatory frameworks (Kokkinos et al., 2020; Sharma et al., 2022). One of the primary factors influencing societal acceptance is the perceived environmental and health safety of nanomaterials. While nanotechnology offers promising solutions for pollutant removal, concerns persist regarding the fate, transport, and potential toxicity of engineered nanoparticles once released into natural systems (Marcharlaa et al., 2024). The lack of comprehensive data on the long-term effects of nanomaterials in complex wetland environments can lead to public apprehension and resistance. This is compounded by the fact that many nanomaterials, despite their eco-friendly design, may still interact with biota in unforeseen ways, potentially leading to bioaccumulation or disruption of ecosystem functions (Xu et al., 2022). The authors emphasize the importance of compatibility with existing water and wastewater treatment infrastructure, ethical considerations of equity, justice, and informed consent, and the deployment of advanced nanotechnologies in wetlands. This entails ensuring that the benefits and risks of remediation technologies are distributed fairly and that vulnerable populations are not disproportionately exposed to potential hazards (Bakhtiari et al., 2024). Public engagement and transparent communication are crucial for trust and informed decision-making. Green chemistry principles in nanomaterial synthesis can enhance societal acceptance by minimizing toxic byproducts and environmental footprint. However, regulatory gaps persist in monitoring, risk assessment, and post-deployment surveillance. The absence of standardized protocols for evaluating the safety and efficacy of nanomaterials in wetlands can hinder public confidence and slow the adoption of innovative solutions (Rashed et al., 2023). Furthermore, the integration of nanotechnologies into existing policy frameworks requires interdisciplinary collaboration among scientists, regulators, and stakeholders to ensure that ethical considerations are embedded in technology development and deployment. Public perception is further shaped by the visibility of successful case studies and the demonstration of tangible benefits. When communities observe measurable improvements in water quality and ecosystem health resulting from nanomaterial-based interventions, acceptance tends to increase (Arifa et al., 2024) (Osman et al., 2023). Conversely, high-profile failures or reports of unintended consequences can erode trust and fuel opposition. Therefore, ongoing monitoring, transparent reporting of outcomes, and adaptive management are critical components of responsible nanotechnology deployment in wetlands (Lia et al., 2024). Eco-friendly nanomaterials in wetland ecosystems require

robust risk assessment, transparent communication, equitable distribution of benefits and risks, and evolving regulatory frameworks to ensure responsible development and application.

Stakeholder Engagement and Collaboration

Stakeholder engagement and collaboration are essential components in advancing the development and deployment of eco-friendly nanomaterials for the remediation of microplastics and heavy metals in wetland ecosystems. The complexity of wetland environments, combined with the multifaceted nature of pollution sources and the diversity of affected communities, necessitates a coordinated approach that brings together scientists, policymakers, industry representatives, local communities, and non-governmental organizations. Monitoring standards, and acceptable contamination levels is critical for effective international cooperation (Marcharlaa et al., 2024). This consensus is particularly important given the rapid evolution of industrial activities and the emergence of novel microplastic pathways that may not be adequately addressed by current regulations. International agreements, like Basel Convention modifications, emphasize cross-border collaboration in managing plastic waste and microplastic pollution. These require consent from importing countries, highlighting shared responsibility and transparency in global waste management (Osman et al., 2023). Engagement of local communities is especially important in wetland regions, where residents often have direct experience with the impacts of pollution and may possess valuable traditional knowledge regarding ecosystem management. Liu et al. suggest prioritizing sustainability and equality in environmental cleanups to ensure equitable distribution of remediation technologies, particularly among disproportionately affected communities, and to enhance social acceptability of new technologies (Liu et al., 2024). Their involvement in collaborative research and development initiatives can accelerate the translation of laboratory-scale innovations into scalable, cost-effective solutions suitable for real-world application (Inobeme et al., 2022). Industry participation in multistakeholder dialogues helps identify barriers to implementation, while academic and research institutions generate scientific knowledge, develop nanomaterials, and conduct risk assessments. Collaboration with regulatory agencies ensures rigorous safety evaluations and updated regulatory frameworks. International organizations and non-governmental organizations can act as intermediaries, promoting knowledge exchange, capacity building, and the harmonization of standards across regions (Allen et al., 2022). In summary, the successful application of eco-friendly nanomaterials for wetland remediation depends on robust stakeholder engagement and collaboration at local, national, and international levels. This collaborative approach enhances the legitimacy, effectiveness, and sustainability of remediation efforts, while also supporting the development of adaptive policies that can keep pace with technological and environmental change (Lia et al., 2024).

Conclusion and Future Directions

This review has highlighted the dual threat posed by microplastics (MPs) and heavy metals (HMs) in wetland ecosystems, underscoring their intertwined ecological impacts and the pressing need for integrated remediation approaches. While eco-friendly nanomaterials offer promising solutions for contaminant removal, current research largely focuses on single-pollutant systems, with minimal emphasis on their co-remediation in complex wetland environments, particularly in developing countries. This paper addressed this gap by synthesizing evidence on pollutant interactions, evaluating nanomaterial-based interventions, and outlining key challenges to scalability and field application.

Targeted Future Research and Policy Priorities:

- **Mechanistic Studies:** Investigate the interaction pathways between MPs and HMs in wetland matrices to inform co-remediation strategies.
- **Field-Scale Validation:** Move beyond lab trials to pilot projects in real wetland systems, especially in Global South regions.
- **Material Optimization:** Develop low-cost, biodegradable nanomaterials tailored to local environmental and socio-economic conditions.
- **Policy Integration:** Embed nanomaterial-based co-remediation approaches into wetland management plans and national pollution control policies.

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