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Micro- and nano-plastics: detection and remediation strategies with insights into occurrence and health impacts

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ABSTRACT

Micro- and nanoplastics (MNPs) are emerging contaminants whose physico-chemical characteristics govern their environmental fate, bioavailability, degradation, and transport into biota, positioning them as potential vectors for other environmental pollutants. Advanced analytical techniques, including matrix-assisted laser desorption/ionization time-of-flight mass spectrometry, Raman spectroscopy, and micro-Fourier transform infrared spectroscopy, have significantly improved MNP identification and quantification. Increasing evidence links MNP exposure to oxidative stress, inflammation, and immune dysregulation in critical organs, including the liver, kidney, brain, and gastrointestinal tract. However, most ecotoxicological studies remain laboratory-based, limiting their environmental relevance. Critical gaps persist regarding co-contaminant interactions, bioaccumulation, trophic transfer, and long-term field-scale impacts. Conventional wastewater treatment systems can remove a substantial fraction of microplastics, although smaller particles, particularly nanoplastics, often evade treatment. Advanced remediation approaches, including membrane filtration, adsorption, and oxidation processes, provide enhanced removal efficiency but are constrained by fouling, energy demand, and operational costs. Consequently, integrated and hybrid treatment systems combining physical, chemical, and biological mechanisms are increasingly recognized as promising strategies for effective MNP management. Continued interdisciplinary research and coordinated policy interventions are essential to mitigate the ecological and human health risks associated with MNPs contamination.

Key words: bioaccumulation, detection, microplastics, nanoplastics, remediation, toxicity

HIGHLIGHTS

- MNPs infiltration poses escalating ecological and human health risks.
- Toxicity depends on physicochemical properties of MNPs.
- MALDI-TOF-MS, μ-FTIR, and Raman spectroscopy enable robust MNP identification and quantification.
- MNP exposure triggers oxidative stress, inflammation, and immune dysregulation.
- Key gaps include non-standardized methods, scarce bioaccumulation/epidemiological data, and weak global policy coordination.

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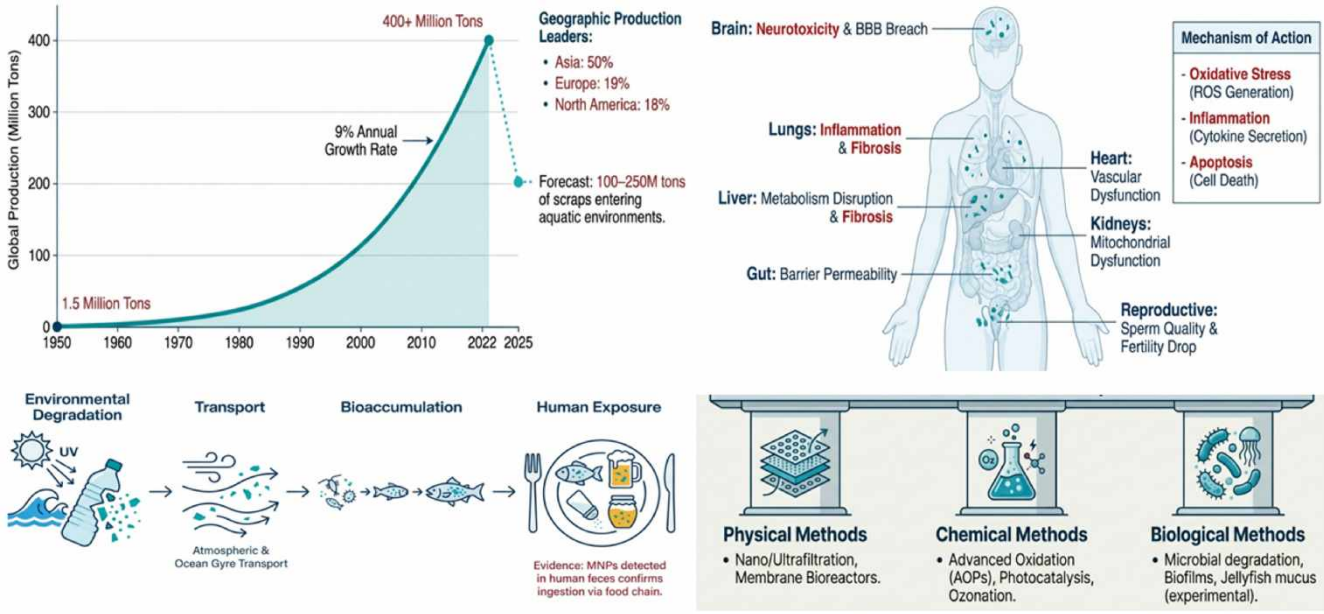
GRAPHICAL ABSTRACT



1. INTRODUCTION

Plastics have become a significant global concern due to their durability, widespread use, and resistance to degradation. In diverse ecosystems, microplastics (1–5,000 μm) and nanoplastics (<1 μm) have become ubiquitous secondary pollutants, primarily produced by the physical, chemical, and biological degradation of larger plastics. According to recent data, approximately 60% of the plastics produced globally are currently in the form of debris in the ocean, on land, at dumping sites, and in other locations, such as the Arctic frozen region and the snow-covered Himalayas (Geyer *et al.* 2017). This increase indicates that plastic contamination is not only persistent but also has the potential to affect a variety of systems. Since their industrial inception in the 1940s, the proliferation of plastics has transformed global production, with annual output rising at an exponential rate. A staggering 9% growth worldwide, with global production surging from 1.5 million tons in 1950 to over 400 million tons in 2022 (Figure 1) (Geyer *et al.* 2017). Moreover, in 2010, 4.8–12.7 million tons of

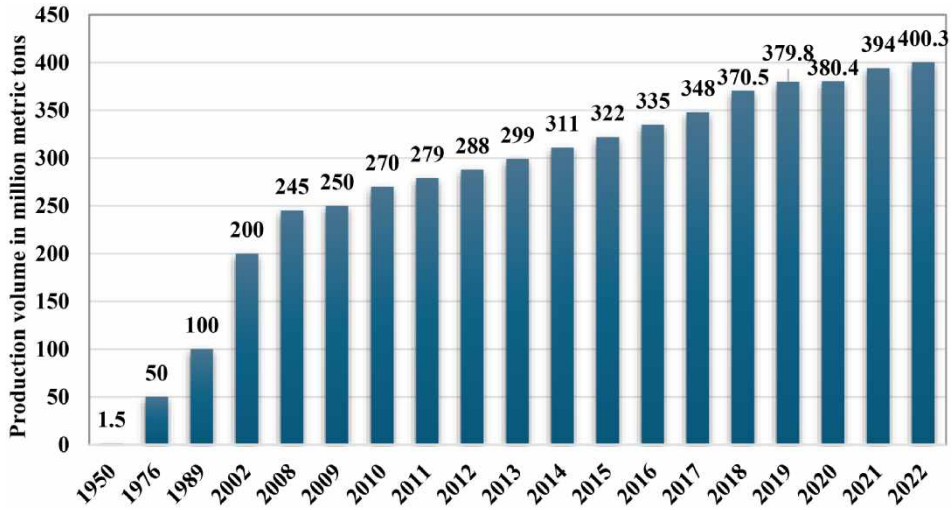


Figure 1 | Annual plastic production on a global scale from 1950 to 2022.

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plastic scrap were discarded into the aquatic environment, and it is forecast that approximately 100–250 million tons will enter the aquatic environment in 2025. It has also been estimated that Asia is the biggest manufacturer of plastic products (50%), followed by Europe (19%), North America (18%), the Middle East and Africa (7%), and Latin America (Ali *et al.* 2021).

Once the plastic scraps are discarded, they accumulate in various natural habitats. Thus, plastic waste is a threat not only to the environment but also to humans. After being exposed to ultraviolet radiation, plastic debris undergoes a photo-oxidation process, causing it to become brittle. The fragmented plastic circulates in different environments, and as a result, numerous species are affected by both its chemical and physical impacts (Pilapitiya & Ratnayake 2024). MNPs infiltration into ecosystems poses severe ecological and health risks. From zooplankton to fish, evidence abounds of their bioaccumulation and biomagnification within food chains, resulting in physical harm, immune system disruption, and even mortality in exposed organisms (Liang *et al.* 2023). Concurrently, human history intertwines with plastic usage, dating back to prehistoric Mesoamerica, culminating in the mass production of Bakelite in 1907 and the subsequent exponential growth of plastic consumption, particularly in single-use packaging (Gautam *et al.* 2024).

It is crucial to note that the existing literature on MNPs exhibits substantial variability in the quality of evidence and methodological consistency. Many studies rely on laboratory-scale experiments, under controlled conditions, especially toxicological studies and remediation methods (Zhang *et al.* 2022). Although the studies are very informative in terms of their mechanistic nature, their direct relevance to natural environments is limited. Conversely, long-term, field-based studies, which are more ecologically relevant, are relatively limited. Moreover, variations in experimental conditions, particle properties, and analytical methods often lead to discrepancies in reported results. As such, the results of controlled laboratory research must be viewed with skepticism, and greater emphasis should be placed on research that includes environmentally relevant conditions and validated procedures.

In this context, the present review offers a distinct and integrative contribution by bridging the critical gap between detection and remediation of MNPs. In contrast to previous reviews, which focused on occurrence patterns or toxicological effects, the current review is more focused and systematic on micro- and nanoplastics (MNPs), with special emphasis on detection and remediation measures. It critically evaluates the strengths and weaknesses of existing detection techniques across various environmental matrices and identifies issues related to sensitivity, standardization, and matrix interference. Simultaneously, the review examines remediation pathways based on their governing mechanisms, scalability, and operational feasibility. Importantly, the review synthesizes emerging trends in advanced materials, hybrid treatment systems, and process integration to outline a coherent framework for efficient and scalable MNP management. By aligning analytical capabilities with treatment innovations, this study advances a more application-oriented perspective and identifies priority research directions necessary for translating laboratory findings into real-world solutions.

2. CHARACTERISTICS AND BEHAVIOR OF MNPS

Physical-chemical properties of MNPs are very important in defining their environmental transport, distribution, and biological effects. They can serve as vectors for other pollutants, enhancing their overall toxicity (Ali *et al.* 2025). In the real world, MNPs typically consist of irregularly shaped particles and fibers, with microfibers being a common contaminant that can penetrate the lung and evade macrophage engulfment (Yang *et al.* 2023a, 2023b). Likewise, other physical and chemical properties of MNPs, such as size, color, chemical additives, crystallinity, surface area, surface chemistry, surface roughness, and surface charge, will influence their toxicity, as outlined in Table 1.

The complex behavior of MNPs is determined by their transport, distribution, degradation, bioavailability, and interactions with biota. The physical-chemical characteristics of MNPs and environmental conditions regulate this behavior. Water currents, wind, and biota facilitate the long-range transport of MNPs, thereby extending their distribution throughout oceans and seas. Ocean gyres, such as the Great Pacific Garbage Patch, serve as major collection zones for floating microplastics like polyethylene (PE) and polypropylene (PP). Research estimates that over 5 trillion plastic pieces accumulate in these gyres due to ocean currents, wind patterns, and the Coriolis effect, functioning as dynamic sinks that can also re-release microplastics under varying conditions (Eriksen *et al.* 2014). Nanoplastics can be dispersed over long distances and deposited in different environments far from human reach through wind and atmospheric transport processes, even in the polar regions. Photodegradation, mechanical abrasion, and microbial biodegradation can modify the properties of MNPs over time. Photodegradation refers to breaking the polymer chains upon exposure to UV irradiation. It produces

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Table 1 | Physical-chemical characteristics of MNPs and their impact on toxicity

Characteristic	Description	Impact on toxicity	Reference
Shape	Forms include beads, fibers, fragments, films, foams, etc.	Irregular shapes, such as fibers, can penetrate lungs and evade immune responses	Yang *et al.* (2023a, 2023b)
Size	Range: 1 μm to 5 mm for microplastics and ~100 nm for nanoplastics.	Smaller particles (<150 μm) can cross gastrointestinal epithelium, leading to systemic exposure. Larger particles cause local inflammation.	Hirt & Body-Malapel (2020)
Color	Various colors, including red, orange, yellow, blue	Brightly colored MNPs are easily ingested by marine organisms	Benson *et al.* (2022)
Chemical Additives	Additives include bisphenol A, phthalates, heavy metals	Leaching of toxic additives disrupts endocrine systems and causes various health issues	Jiang *et al.* (2020)
Crystallinity	Ordered structural linkages within polymers, affecting density and permeability	Increased crystallinity leads to smaller, sharper particles, causing more physical damage upon ingestion	Umrai Shariff *et al.* (2025)
Surface Area	Higher surface area with decreasing particle size.	Increased surface area enhances pollutant adsorption and interaction with cells	Wu *et al.* (2019)
Surface Chemistry	Photo- and oxidative degradation alter surface properties.	Changes in surface chemistry modify biological interactions, potentially increasing toxicity	Kumar *et al.* (2021)
Surface Roughness	Surface texture impacts adhesion and colonization of microbes.	Rough surfaces enhance microbial colonization and influence environmental behavior	Martin *et al.* (2022)
Surface Charge	Functional groups can modify surface charge.	Surface charge affects dispersion, aggregation, and cell interactions, influencing toxicity	Ali *et al.* (2024a, 2024b)

small particles with a higher specific surface area and, therefore, higher reactivity (Andrady 2011). Mechanical abrasion, due to physical forces such as wave action and sediment mobilization, is a constant source of MNPs (Alimi *et al.* 2018). Although microbial degradation is slow, it causes fragmentation and mineralization of plastics, forming MNPs. These degradation mechanisms result in modifications to the physical, chemical, and mechanical properties, as shown in Figure 2. Further fragmentation and mechanization processes will result in the production of carbon-dioxide and biocompatible products.

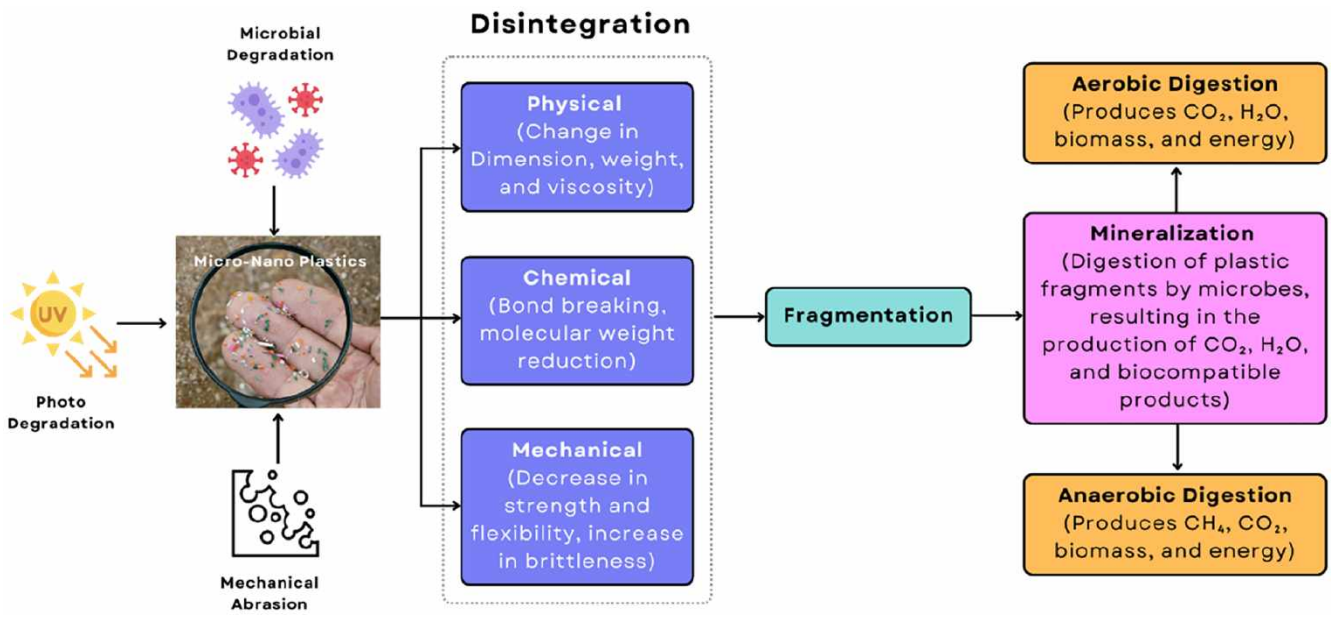

Figure 2 | Impact of degradation on MNPs characteristics.

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3. HUMAN HEALTH IMPACTS OF MNPS

MNPs are ubiquitous environmental contaminants and represent potential human health risks. They can enter the human body through different pathways, such as the oral, respiratory, and dermal routes, and can easily traverse biological barriers, such as the respiratory and gastrointestinal tracts, gain access to the circulatory system, and further accumulate in secondary organs. After exposure, bioavailable particles that enter the bloodstream can move to secondary organs, where they may build up to concentrations that could lead to negative effects at the cellular level.

Evidence across studies suggests a coherent progression from exposure to systemic distribution and organ-specific toxicity (Ali *et al.* 2024a, 2024b). For instance, a study conducted on mice co-exposed to polystyrene MNPs (PS50 and PS500) found increased intestinal permeability and greater particle accumulation, highlighting the underestimated health risks of mixed-size MNP exposure in the gastrointestinal tract (Liang *et al.* 2021). Notably, a recent study detected plastic particles (1.60–5.58 μm) in over 50% of human lung samples, confirming inhalation as a key exposure route and the lungs as a site of MNP accumulation (Amato-Lourenço *et al.* 2021). Airborne particulate matter is also known to impairs cardiovascular function, causing vascular dysfunction, hypertension, and myocardial infarction (Brook *et al.* 2010). Consistently, MNPs have been identified in human cardiac tissues, with particles ranging from 20-469 μm detected across all five tissue types examined. Nine MP types were identified, dominated by PET (77%) and PU (12%), together accounting for ~90%, while PE was present in all tissues but comprised only 1%. Experimental evidence indicates that MNPs exposure induces severe neurotoxicity, including cerebral hemorrhage, microthrombosis, and Purkinje cell loss, driven by inflammatory infiltration and ASC–NLRP3–GSDMD-mediated pyroptosis. Disruption of mitochondrial function and AMPK signaling further exacerbates damage, while mice studies report amygdala inflammation, neuronal apoptosis, and elevated neurodegeneration (Yin *et al.* 2022; Jiang *et al.* 2023). MNP toxicity in liver cells is strongly size-dependent: smaller particles (50–100 nm) exhibit greater cellular uptake and dose-dependent cytotoxicity, whereas larger particles (500–5,000 nm) show lower acute toxicity but induce apoptosis (e.g., Caspase-3) and inflammation (e.g., IL-8), especially with prolonged exposure (Banerjee *et al.* 2022). Oral exposure to polystyrene particles (50 nm–4 μm) in mice showed clear size-dependent nephrotoxicity, with higher mortality in smaller particle groups. Effects included reduced body and kidney weights, decreased ALB and ALP levels, elevated BUN and CRE levels, and tubular damage with inflammation, indicating significant renal impairment (Meng *et al.* 2022). A study by Jin *et al.* (2021) found that polystyrene microplastics (0.5–10 μm) accumulate in testes, reducing sperm quality and testosterone even after short-term exposure. MNPs are widely detected in maternal and infant matrices (placenta, meconium, breast milk), predominantly 20–50 μm and mainly polyamide- and polyurethane-based, indicating early-life exposure from diverse sources (Liu *et al.* 2023). Importantly, microplastics, alongside other endocrine-disrupting chemicals, interfere with steroidogenic pathways, leading to adrenal dysfunction and potential transgenerational effects (Li & Robaire 2025). Notably, smaller particles exhibit greater bioavailability and acute toxicity, whereas larger particles tend to elicit chronic inflammatory and apoptotic responses, highlighting a size-dependent yet mechanistically convergent toxicity profile. While the detection of MNPs in human tissues provides compelling evidence of internal exposure, these studies remain largely observational and do not establish causal links with disease outcomes. Despite these converging findings, significant limitations constrain their interpretation. Much of the evidence is derived from controlled *in vivo* and *in vitro* models, often employing high doses, short exposure durations, and uniform particle types that do not reflect the complexity of real-world environmental exposures. Comparative inconsistencies in particle size ranges (nm to μm), polymer composition, and exposure routes further hinder cross-study synthesis and risk extrapolation. Consequently, although MNPs demonstrate clear multi-organ toxic potential, their actual contribution to human disease burden remains uncertain and likely underestimated, underscoring the need for standardized methodologies and long-term, real-world investigations.

Across organ systems, a consistent pattern emerges: MNPs induce toxicity through shared mechanisms, including oxidative stress, mitochondrial dysfunction, and inflammatory signaling (e.g., NLRP3-mediated pathways), leading to neurotoxicity, hepatotoxicity, nephrotoxicity, and reproductive impairment. A structured synthesis of these mechanisms is presented in Table 2, and the impacts of MNPs on different organ systems are depicted in Figure 3.

4. DETECTION AND CHARACTERIZATION TECHNIQUES FOR MNPS

The selection of the appropriate detection methods for MNPs depends on particle size, environmental matrix, and analytical objectives (Ivleva 2021). MNPs are small in size and are characterized by complex compositions that make detection and

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Table 2 | Effects of micro- and nanoplastics (MNPs) across different cell types, highlighting particle characteristics, size distribution, cellular targets, and observed toxicological responses

Characteristics of Tested Particles	Particle Size	Target Cells	Effect of MPs and/or NPs on Organisms	References
NH_2-PS-MPs	103.3 nm	BEAS-2B	Increased ROS generation, induced autophagic cell death, increased IL-1β expression	Jeon *et al.* (2023)
PS, PS-COOH, PS-NH_2	50 nm	HepG2 cells	Inhibited cell viability, caused oxidative stress, reduction in antioxidant capabilities	He *et al.* (2020)
PS MPs	1 μm	HEK 293 (human embryonic kidney)	Significant reduction in cellular proliferation, no significant decrease in cell viability, increased levels of ROS, decreased gene expression of glycolytic enzyme and antioxidant enzymes	Goodman *et al.* (2022)
PET microsieves	8 ± 0.5 μm	DU 145 human prostate cancer cells	High efficiency capture of live cells without damage; cells remained viable and proliferated in culture.	Osuchowska *et al.* (2019)
PVC MPs	25–75 μm	PBMCs, HMCs-1, HDFs, HeLa cells	IL-6 and TNF-α release, immune response	Han *et al.* (2020)
PP particles, prepared by ball milling	~20 μm, 25–200 μm	PBMCs, Raw 264.7, HMC-1 cells	Low cytotoxicity in both size and concentration; at high concentration, small-sized PP particles stimulated the immune system and enhanced hypersensitivity via increased cytokines and histamines.	Hwang *et al.* (2019)
PMMA NPs	144 nm	IMR-90	Similar cytotoxic effects as PVC, but with slightly less impact on cell viability	Mahadevan & Valiyaveettil (2021);
PS-MPs	1 μm	Caco-2	Slight uptake by cultured cells, no inflammatory response	Winiarska *et al.* (2024)
PS-NPs	20 nm	Human monocytes (Mo)	High cytotoxicity effect, stimulation of pro-inflammatory cytokines (IL-6, IL-8) secretion	Winiarska *et al.* (2024)
PE-MPs	300 nm–10 μm	NHBC (human bone-derived cells)	Increased expression of osteocyte markers, enhanced osteoclast activity	Winiarska *et al.* (2024)

characterization challenging under variable conditions. Raman spectroscopy (RS) and Fourier transform infrared spectroscopy (μ-FTIR) techniques are widely used to characterize MNPs. μ-FTIR has limited sensitivity to particles below 20 μm and is susceptible to interference from organic matter, whereas RS struggles with fluorescence interference and weaker signals from nanoplastics (Liu *et al.* 2022). Thermogravimetric analysis (TGA) is a simple technique used to study the thermal decomposition behavior of MNPs coupled with gas chromatography-mass spectrometry (GC-MS). However, it is time-consuming and often requires extensive chemical extraction and derivatization steps. It struggles with accurately identifying mixed polymers and smaller nanoplastics, as some may degrade or be lost during sample processing, leading to underestimation of particle concentrations (Li *et al.* 2022). Matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF-MS) can identify polystyrene and polyethylene terephthalate (PET) particles by improving the signal intensity under optimized conditions (Liu *et al.* 2022). But it requires extensive sample preparation, is costly, and lacks morphological insights. Additionally, Fourier transform ion cyclotron resonance mass spectrometry (FTICR-MS) was applied for untargeted profiling of complex biomolecule and polymer samples, which is essential for the structure elucidation of MNPs due to its superior mass resolution among existing mass spectrometric techniques (Liu *et al.* 2022). However, the technique's sensitivity can be affected by matrix interference, making it less effective in complex environmental samples. More advanced methods like scanning electron microscopy-Raman spectroscopy (SEM-Raman) enable simultaneous acquisition of morphological and chemical data at the nanoscale. SEM-Raman can identify individual MNPs (e.g., polystyrene or poly-methyl methacrylate) down to a size of 500 nm or 300 nm, respectively, however, it is expensive, complex, and time-

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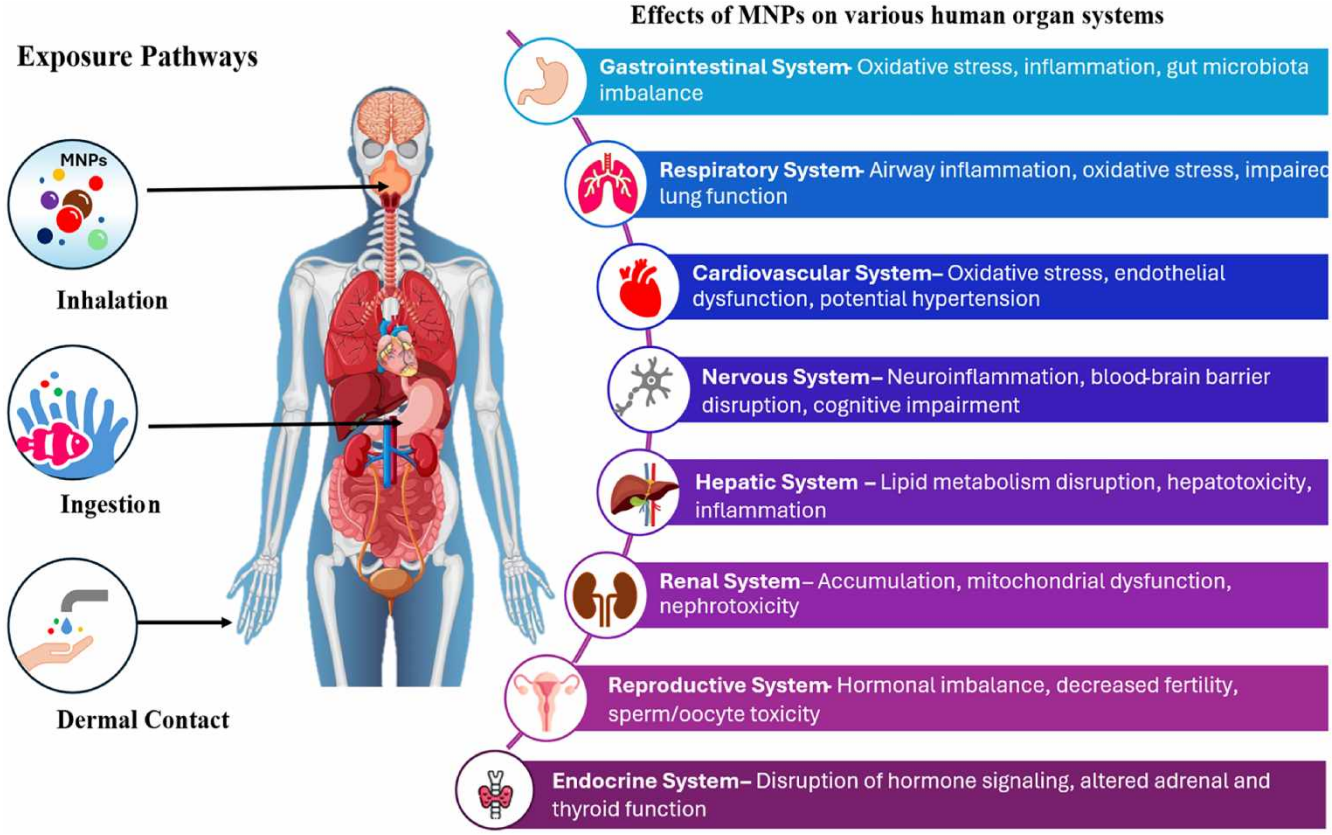

Figure 3 | Schematic representation of exposure pathways and physiological impacts of micro- and nanoplastics (MNPs) on human organ systems.

consuming, making it less feasible for use (Li *et al.* 2022). One promising approach is Asymmetric Flow Field-Flow Fractionation (AF4) coupled with Multi-Angle Light Scattering (MALS) for size fractionation and identification of nanoplastics. However, low recovery rates, high light scattering backgrounds, and difficulty in detecting smaller particles limit the use of this method (Caldwell *et al.* 2022). Terahertz (THz) spectroscopy and hyperspectral imaging (HSI) are being explored to monitor the process in real time. Although THz spectroscopy offers the highest sensitivity and penetration depth, HSI spectroscopy has been limited to lower resolution, shallower penetration, and a narrow particle size range (above 300 μm), and must be further improved to better penetrate and broaden its applicability. Advanced techniques offer better sensitivity for smaller particles but require high-cost equipment and complex sample preparation. Despite these advancements, low recovery rates and variable detection efficiencies hinder accurate quantification, especially for NPs (Caldwell *et al.* 2022).

These constraints imply that there is no single method that is universally applicable, and multi-method analytical frameworks are usually needed to fully characterize it (Table 3). Similarly, an analytical method based on matrices is necessary to characterize MNPs properly. An example would be aqueous samples analyzed by AF4-MALS with spectroscopic method, and soil and sediment samples that need to be pre-treated and then analyzed by μ-FTIR or thermal analysis (Hossain & Sahajwalla 2026). Raman spectroscopy combined with electron microscopy is a better method to define airborne microplastics (Yoo *et al.* 2023). Thus, as mentioned above, combined multi-technique solutions are required to enhance detection accuracy and address the shortcomings of the single techniques.

5. MITIGATION AND REMEDIATION STRATEGIES

Despite the availability of multiple remediation techniques, large-scale implementation remains constrained by technical complexity and economic limitations (Prakash *et al.* 2026). The effective removal of MNPs from environmental matrices

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Table 3 | Comparative analysis of major detection techniques for MNPs

Technique	Typical Size Range	Principle	Sample Preparation	Strengths	Limitations	References
μ-FTIR	Typically >20 μm	Infrared absorption (molecular vibrations)	Moderate (filtration, drying)	Reliable polymer identification; widely used	Limited sensitivity for smaller particles; interference from organic matter	Rathore *et al.* (2023)
Raman Spectroscopy	~1 μm (submicron possible under optimized conditions)	Inelastic scattering of light	Minimal to moderate	High spatial resolution; suitable for smaller particles	Fluorescence interference; weak signal for nanoplastics	Iqrar (2025)
MALDI-TOF MS	Nano-scale (polymer fragments)	Mass spectrometry (ionization and detection)	High (matrix addition, extraction)	High sensitivity; polymer-specific identification	Expensive; lacks morphological information	Hossain & Sahajwalla (2026)
SEM-Raman	~300–500 nm (reported)	Combined imaging + spectroscopy	High	Simultaneous morphology and composition	Time-consuming; high operational cost	Zhao *et al.* (2025)
AF4-MALS	Submicron to nano-scale	Size fractionation + light scattering	Complex	Effective for nanoplastics in aqueous systems	Low recovery rates; signal interference	Hossain & Sahajwalla (2026)
TGA–GC-MS	Bulk analysis	Thermal degradation + gas analysis	High	Quantitative polymer mass estimation	Destructive; no particle-level information	Primpke *et al.* (2020)

is governed not only by the choice of treatment technology but also by the underlying physicochemical and biological interactions between particles and treatment media. These mechanisms operate at multiple scales and include charge-based destabilization, hydrophobic partitioning, size exclusion, and oxidative or enzymatic degradation. Understanding these pathways is critical, as MNP removal efficiency is strongly influenced by particle size, surface functionality, polymer composition, and surrounding environmental conditions (Rout *et al.* 2022).

5.1. Mechanisms of MNP removal

Physical removal is primarily governed by particle separation driven by size, density, and surface charge. Filtration processes operate via size exclusion and retention within porous media, where particles larger than the pore size are physically trapped, whereas membrane systems (MF, UF, NF, RO) enhance removal through fine sieving and cake layer formation. However, high operational costs, membrane fouling, and limited efficiency for nanoplastics remain key constraints (Hamedi *et al.* 2019; Mousazadehgavan *et al.* 2024). Centrifugation exploits density-dependent sedimentation to separate heavier or aggregated particles under centrifugal force. Electrostatic separation relies on differences in surface charge, where particles are attracted or repelled under an applied electric field, facilitating selective removal. However, magnetic separation involves functionalizing or associating MNPs with magnetic materials, enabling rapid extraction under an external magnetic field. Overall, performance depends on particle characteristics and operational parameters such as flow rate, field strength, and residence time (Enyoh *et al.* 2025).

Chemical removal involves transformation or destabilization of polymeric structures through coagulation–flocculation, oxidation, and adsorption pathways. Coagulation–flocculation operates via charge neutralization and hydroxide precipitate formation (e.g., $Al3+$, $Fe3+$), which destabilize colloidal MNPs and promote aggregation through van der Waals forces and polymer bridging, enabling subsequent removal by sedimentation (Mohamed Noor *et al.* 2022). Advanced oxidation processes, such as photocatalysis, ozonation, and Fenton reactions, generate reactive oxygen species (e.g., hydroxyl radicals) that induce polymer chain scission, surface oxidation, and fragmentation; however, process optimization is required to enhance efficiency and limit byproduct formation (Hamd *et al.* 2022; Wang *et al.* 2023, 2024). Adsorption relies on hydrophobic interactions, electrostatic attraction, and surface complexation between MNPs and sorbents such as activated carbon, biochar, or nanomaterials, facilitating their immobilization and separation. These chemical pathways not only remove MNPs but can also modify them, increasing their susceptibility to subsequent treatments (Dung *et al.* 2026).

Biological removal mechanisms are driven by microbial colonization and enzymatic degradation of polymer structures. Microorganisms form biofilms on MNP surfaces and secrete extracellular enzymes that introduce functional groups (e.g., carbonyl, hydroxyl), increasing polymer hydrophilicity and enabling subsequent depolymerization into smaller oligomers and monomers (Das *et al.* 2024). These degradation products may then be assimilated by microbial communities as carbon sources. Biological pathways often follow sequential stages, including surface modification, fragmentation, and mineralization, although the process is generally slow and dependent on polymer type and environmental conditions. Consequently, biological mechanisms are frequently integrated with physicochemical treatments to enhance overall removal efficiency and achieve more complete degradation of persistent plastic pollutants. A comparative assessment of these approaches, including performance, scalability, and limitations, is provided in Table 4.

5.2. Technological advances and system integration

Recent advancements in microplastic remediation of water and wastewater streams have increasingly focused on improving removal performance, scalability, and compatibility of advanced technologies with existing water and wastewater treatment infrastructure (Tiwari & Arya 2026). In wastewater treatment plants (WWTPs), conventional methods such as primary sedimentation and secondary biological treatment have been reported to remove a large fraction of microplastics (~85–90% removal); however, complete removal remains challenging, particularly for smaller fractions, such as nanoplastics (Carnevale Miino *et al.* 2024; Rawat *et al.* 2025; Pérez-López *et al.* 2026). Nevertheless, conventional treatment systems often transfer microplastics to sludge rather than fully eliminating them, underscoring the need for improved system design (Rim *et al.* 2025).

These limitations have driven the development of more advanced, targeted treatment strategies to overcome them. Among these, advanced membrane-based systems, including membrane bioreactors (MBRs) and dynamic membranes, have demonstrated improved retention of microplastics through combined physical separation and biofilm-assisted filtration mechanisms, with removal efficiencies approaching ~99% (Khan *et al.* 2025; Rawat *et al.* 2025). Electrocoagulation has

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Table 4 | Comparative analysis of remediation strategies for MNPs

Method	Mechanism	Reported Performance	Energy Requirement	Scalability	Key Challenges	References
Filtration (UF/NF/MBR)	Physical separation	High removal efficiency reported	Moderate to high	High	Membrane fouling; operational cost	Shen *et al.* (2023)
Advanced Oxidation Processes (AOPs)	Radical-driven degradation	Effective degradation under optimized conditions	High	Moderate	Energy intensive; formation of byproducts	Easton (2025)
Adsorption (Biochar, MOFs)	Surface interaction	Moderate to high efficiency reported	Low to moderate	Moderate	Regeneration and disposal challenges	Das *et al.* (2024)
Bioremediation	Microbial degradation	Limited efficiency due to slow kinetics	Low	Low	Environmental dependency; slow degradation rates	Hadian-Ghazvini *et al.* (2022)
Coagulation/Flocculation	Particle aggregation	Moderate removal efficiency	Low	High	Less effective for nanoplastics	Hanif *et al.* (2026)

also emerged as a promising approach, enabling *in situ* generation of coagulant species that destabilize and aggregate microplastics, thereby facilitating their removal (Zhang *et al.* 2025). Similarly, magnetic nanoparticle-assisted separation has demonstrated removal efficiencies exceeding 99% under controlled conditions, driven by hydrophobic and electrostatic interactions (Rawat *et al.* 2025). In parallel, engineered adsorbents, including functionalized biochar, graphene-based materials, and metal-organic frameworks, offer high adsorption capacities due to their large surface area and tunable surface functionalities (He & Chen 2025).

Despite these advancements, no single technology ensures complete removal across all particle sizes. Operational challenges, including energy demand, fouling, cost, and long-term stability, continue to limit large-scale application (Table 5). Consequently, recent studies emphasize on integrated and hybrid treatment systems with synergistic interactions among physical, chemical, and biological processes to achieve more comprehensive and practical MNP control (Lu *et al.* 2023; Dayal *et al.* 2024; Dung *et al.* 2026). Emerging approaches, such as electrochemical advanced oxidation processes (EAOPs), enable the in-situ generation of reactive species for effective mineralization with reduced secondary pollution (Rim *et al.* 2025). In addition, nanomaterial-based and bio-nanotechnological innovations are enhancing adsorption and catalytic efficiency, offering promising pathways toward scalable and sustainable remediation (Koul *et al.* 2025).

Table 5 | Applicability of MNP remediation technologies under different environmental conditions

Technology	Suitable Environment	Strengths	Limitations	Recommended Application Scenario	References
Membrane Filtration (UF/NF/MBR)	Wastewater, drinking water	High removal efficiency; reliable	Fouling; high energy cost	WWTP polishing stage; drinking water treatment	Bodzek & Bodzek (2025)
Coagulation–Flocculation	Surface water, wastewater	Simple; cost-effective	Less effective for nanoplastics	Pre-treatment step before filtration	Ojha *et al.* (2025)
Adsorption (Biochar, MOFs)	Wastewater, industrial effluents	Flexible; tunable properties	Regeneration issues	Targeted removal of specific polymers/contaminants	Wang *et al.* (2021)
Advanced Oxidation Processes	Wastewater, industrial streams	Effective degradation of polymers	High energy; byproducts	Post-treatment for persistent microplastics	Kim *et al.* (2021)
Bioremediation	Soil, sediments, low-flow water systems	Environmentally friendly	Slow kinetics	Long-term natural attenuation	Puteri *et al.* (2025)

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Overall, MNP remediation is shifting toward integrated, mechanism-driven strategies addressing diverse particle sizes and conditions. Despite advances in membranes, adsorption, and oxidation, challenges of cost, energy use, and scalability remain. Future work should focus on optimizing hybrid systems, standardizing evaluation methods, and developing efficient, cost-effective technologies for large-scale implementation (Nasir *et al.* 2024).

6. KNOWLEDGE GAPS AND FUTURE RESEARCH

Significant knowledge gaps remain in MNPs research, particularly in detection, impact assessment, and large-scale management. Current analytical limitations stem from the lack of standardized protocols, leading to inconsistent results across studies and environmental matrices. There is a pressing need for high-resolution, reliable analytical methods, particularly ones which are capable of detecting nanoplastics in complex samples. Moreover, most ecotoxicological studies are conducted under controlled laboratory conditions, limiting their applicability to real-world environments. Key uncertainties remain regarding interactions with co-contaminants, long-term bioaccumulation in food webs, and ecosystem-level impacts under field conditions. Human health hazards, especially those associated with chronic exposure through ingestion, inhalation, and dermal exposure, remain insufficiently understood. Epidemiological studies are urgently needed to establish links between MNP exposure and health outcomes, including their potential role in pathogen transport and the spread of antibiotic resistance. In addition, the lack of globally harmonized policies and regulatory frameworks hampers effective management. Coordinated international guidelines, along with the promotion of sustainable materials, are essential. Addressing these challenges requires interdisciplinary collaboration across materials science, toxicology, environmental engineering, and policy domains.

Recent advancements in detection and remediation emphasize improved sensitivity, scalability, and real-time monitoring. Techniques such as hyperspectral imaging and terahertz spectroscopy offer rapid, non-destructive analysis, although challenges related to spatial resolution and cost persist. In parallel, engineered materials, including functionalized biochar, nanocomposites, and metal–organic frameworks, have demonstrated enhanced adsorption capacity and selectivity. Hybrid treatment systems that integrate physical, chemical, and biological processes are also emerging as promising strategies for improving removal efficiency across a wide range of particle sizes. However, translating these innovations from laboratory to field-scale applications remains a major bottleneck.

Future research should prioritize the development of standardized and universally accepted detection protocols to improve comparability across studies. Enhancing the sensitivity and reliability of analytical techniques, particularly for nanoplastics, is equally important. On the remediation front, efforts must focus on scaling up laboratory technologies to pilot- and full-scale systems, with emphasis on operational stability and long-term performance. Comprehensive techno-economic and life-cycle assessments are needed to evaluate feasibility and sustainability. Additionally, long-term field-based studies under realistic environmental conditions are essential for validating laboratory findings. Collectively, these efforts will be critical for advancing MNP management toward practical, scalable, and sustainable solutions.

7. CONCLUSION

MNPs have emerged as an environmental/human health issue due to their widespread occurrence as secondary contaminants. The review highlights the complexity of MNPs, their interactions with other contaminants, and the potential health risks, all of which require effective mitigation strategies and detection methods. The existing detection strategies and remediation technologies are promising but have shortcomings in scalability, sensitivity, and cost-effectiveness. To address these difficulties, an interdisciplinary approach that combines advances in materials science, toxicology, environmental science, and data analytics is needed. This method can be used to improve the detection of MNPs, forecast their environmental performance, and create new solutions to remediation. The existing treatment processes of filtration, adsorption, and advanced oxidation exhibit excellent removal capabilities, yet they are highly sensitive to particle size, environmental, and operational factors. No single technology can be applied to eliminate all of the particle sizes, thus emphasizing the need to have an integrated and hybrid treatment system. In addition, cost issues, energy use, material stability, and secondary pollution continue to constrain large-scale implementation. To address these problems, a coordinated, interdisciplinary solution is needed that involves innovation in materials science, environmental engineering, and policy frameworks. The policies should not focus solely on restricting the use of toxic plastics, but also on promoting the production and adoption of biodegradable substitutes, implementing extended producer responsibility (EPR), and improving

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waste management facilities. Scientists, politicians, business sectors, and the entire community should collaborate to establish a sustainable control regime that will encompass the entire life cycle of plastics. By aligning scientific innovation with policy implementation, it is possible to reduce the ecological and health impacts of MNPs and contribute to a more resilient environment.

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AUTHOR CONTRIBUTIONS

Conceptualization: RS, VKT, YRSR, AM; Data curation: JS, MC; Formal analysis: JS, MC; Funding acquisition: RS; Investigation: JS, MC; Methodology: JS, MC; Project administration: RS, VKT; Resources: RS; Supervision: RS, VKT, AM; Validation: JS; Visualization: RS, VKT; Writing – original draft: JS, MC; and Writing – review & editing: RS, VKT, YRSR, KC, AM.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT and Grammarly to improve the scientific language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Ali, I., Cheng, Q., Ding, T., Yiguang, Q., Yuechao, Z., Sun, H., Peng, C., Naz, I., Li, J. & Liu, J. (2021) Micro-and nanoplastics in the environment: occurrence, detection, characterization and toxicity–a critical review, *Journal of Cleaner Production*, **313**, 127863.

Ali, I., Tan, X., Peng, C., Naz, I., Zhang, Y., Hernández, A., Marcos, R., Pervez, R., Duan, Z. & Ruan, Y. (2024a) Eco-and bio-corona-based microplastics and nanoplastics complexes in the environment: modulations in the toxicological behavior of plastic particles and factors affecting, *Process Safety and Environmental Protection*, **187**, 356–375.

Ali, N., Katsouli, J., Marczylo, E. L., Gant, T. W., Wright, S. & De La Serna, J. B. (2024b) The potential impacts of micro-and-nano plastics on various organ systems in humans, *EBioMedicine*, **99**, 104901.

Ali, N., Katsouli, J., Auyang, E. & de la Serna, J. B. (2025) Microplastic and nanoplastic pollution and associated potential disease risks, *The Lancet Planetary Health*, **9** (12).

Alimi, O. S., Farner Budarz, J., Hernandez, L. M. & Tufenkji, N. (2018) Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport, *Environmental Science & Technology*, **52** (4), 1704–1724.

Amato-Lourenço, L. F., Carvalho-Oliveira, R., Júnior, G. R., dos Santos Galvão, L., Ando, R. A. & Mauad, T. (2021) Presence of airborne microplastics in human lung tissue, *Journal of Hazardous Materials*, **416**, 126124.

Andrady, A. L. (2011) Microplastics in the marine environment, *Marine Pollution Bulletin*, **62** (8), 1596–1605.

Banerjee, A., Billey, L. O., McGarvey, A. M. & Shelver, W. L. (2022) Effects of polystyrene micro/nanoplastics on liver cells based on particle size, surface functionalization, concentration and exposure period, *Science of the Total Environment*, **836**, 155621.

Benson, N. U., Agboola, O. D., Fred-Ahmadu, O. H., De-la-Torre, G. E., Oluwalana, A. & Williams, A. B. (2022) Micro (nano) plastics prevalence, food web interactions, and toxicity assessment in aquatic organisms: a review, *Frontiers in Marine Science*, **9**, 851281.

Bodzek, M. & Bodzek, P. (2025) Remediation of micro- and nanoplastics by membrane technologies, *Membranes (Basel)*, **15**, 82.

Brook, R. D., Rajagopalan, S., Pope III, C. A., Brook, J. R., Bhatnagar, A., Diez-Roux, A. V., Holguin, F., Hong, Y., Luepker, R.V., Mittleman, M. A., Peters, A., Siscovick, D., Smith, S. C., Whitsel, L. & Kaufman, J. D. (2010) Particulate matter air pollution and cardiovascular disease: an update to the scientific statement from the American Heart Association, *Circulation*, **121** (21), 2331–2378.

Caldwell, J., Taladriz-Blanco, P., Lehner, R., Lubskyy, A., Ortuso, R. D., Rothen-Rutishauser, B. & Petri-Fink, A. (2022) The micro-, submicron-, and nanoplastic hunt: a review of detection methods for plastic particles, *Chemosphere*, **293**, 133514.

Carnevale Miino, M., Galafassi, S., Zullo, R., Torretta, V. & Rada, E. C. (2024) Microplastics removal in wastewater treatment plants: a review of the different approaches to limit their release in the environment, *Science of the Total Environment*, **930**, 172675.

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by IIT Roorkee user

Das, K. P., Chauhan, P., Staudinger, U. & Satapathy, B. K. (2024) Exploring sustainable adsorbents to mitigate micro-/nano-plastic contamination: perspectives on electrospun fibrous constructs, biochar, and aerogels, *Environmental Science: Advances*, **3**, 1217–1243.

Dayal, L., Yadav, K., Dey, U., Das, K., Kumari, P., Raj, D. & Mandal, R. R. (2024) Recent advancement in microplastic removal process from wastewater-a critical review, *Journal of Hazardous Materials Advances*, **16**, 100460.

Dung, T. N. B., Nguyen, T. T. H., Ly, Q. V., Ong, H. L. & Truong, H. B. (2026) Recent advances and challenges in advanced oxidation processes for degradation of nano-and microplastics in water: a critical review, *RSC Advances*, **16**, 11874–11896.

Easton, T. (2025) Microplastic degradation and interaction with organic micro-pollutants within wastewater treatment systems. Doctoral thesis Edinburgh, UK: University of Edinburgh. https://era.ed.ac.uk/server/api/core/bitstreams/7320725d-9adc-474f-b46f-1f773cbd4caa/content.

Enyoh, C. E., Devi, A., Maduka, T. O., Tyagi, L., Rana, S., Akuwudike, I. S. & Wang, Q. (2025) A Review of Materials for the Removal of Micro- and Nanoplastics from Different Environments, *Micro*, **5** (2), 17.

Eriksen, M., Lebreton, L. C., Carson, H. S., Thiel, M., Moore, C. J., Borerro, J. C., Galgani, F., Ryan, P. G. & Reisser, J. (2014) Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea, *PLoS One*, **9** (12), e111913.

Gautam, B. P. S., Qureshi, A., Gwasikoti, A., Kumar, V. & Gondwal, M. (2024) Global scenario of plastic production, consumption, and waste generation and their impacts on environment and human health. In: Soni, R., Debbarma, P., Suyal, D. C. & Goel, R. (eds) *Advanced Strategies for Biodegradation of Plastic Polymers*, Cham Springer Nature Switzerland, pp. 1–34.

Geyer, R., Jambeck, J. R. & Law, K. L. (2017) Production, use, and fate of all plastics ever made, *Science Advances*, **3** (7), e1700782.

Goodman, K. E., Hua, T. & Sang, Q. X. A. (2022) Effects of polystyrene microplastics on human kidney and liver cell morphology, cellular proliferation, and metabolism. *ACS omega*, **7** (38), 34136–34153.

Hadian-Ghazvini, S., Hooriabad Saboor, F. & Safaee Ardekani, L. (2022) Bioremediation techniques for microplastics removal. In: Sillanpää, M., Khadir, A. & Muthu, S. S. (eds) *Microplastics Pollution in Aquatic Media: Occurrence, Detection, and Removal*, Singapore: Springer.

Hamedi, H., Ehteshami, M., Mirbagheri, S. A., Rasouli, S. A. & Zendehboudi, S. (2019) Current status and future prospects of membrane bioreactors (MBRs) and fouling phenomena: a systematic review, *The Canadian Journal of Chemical Engineering*, **97**, 32–58.

Hamd, W., Daher, E. A., Tofa, T. S. & Dutta, J. (2022) Recent advances in photocatalytic removal of microplastics: mechanisms, kinetic degradation, and reactor design, *Frontiers in Marine Science*, **9**, 885614.

Han, S., Bang, J., Choi, D., Hwang, J., Kim, T., Oh, Y., Hwang, Y., Choi, J. & Hong, J. (2020) Surface pattern analysis of microplastics and their impact on human-derived cells, *ACS Applied Polymer Materials*, **2** (11), 4541–4550.

Hanif, M., Ibrahim, N., Azhari, A., Dahalan, F., Hasan, M., Lutpi, N., Othman, N. & Isa, M. (2026) Natural-based coagulants/flocculants for microplastics and nanoplastics removal via coagulation–flocculation: a systematic review, *International Journal of Environmental Science and Technology*, **23**, 313.

He, Y., Li, J., Chen, J., Miao, X., Li, G., He, Q., Xu, H., Li, H. & Wei, Y. (2020) Cytotoxic effects of polystyrene nanoplastics with different surface functionalization on human HepG2 cells, *Science of the Total Environment*, **723**, 138180.

He, L. & Chen, Z. (2025) Emerging porous materials for adsorptive removal of microplastics and nanoplastics from aquatic environments: a review, *ACS Applied Materials & Interfaces*, **17**, 67457–67488.

Hirt, N. & Body-Malapel, M. (2020) Immunotoxicity and intestinal effects of nano-and microplastics: a review of the literature, *Particle and Fibre Toxicology*, **17** (1), 57.

Hossain, R. & Sahajwalla, V. (2026) A comprehensive toolkit for micro-to manoplastic analysis, *Environmental Science: Nano*, **13**, 122–149.

Hwang, J., Choi, D., Han, S., Choi, J. & Hong, J. (2019) An assessment of the toxicity of polypropylene microplastics in human derived cells, *Science of the Total Environment*, **684**, 657–669.

Iqrar, S. A. (2025) *Detection and Characterisation of Micro-and Nano-Plastics in Water Using Optical Spectroscopy*. Birmingham, UK: Aston University.

Ivleva, N. P. (2021) Chemical analysis of microplastics and nanoplastics: challenges, advanced methods, and perspectives, *Chemical Reviews*, **121**, 11886–11936.

Jeon, M. S., Kim, J. W., Han, Y. B., Jeong, M. H., Kim, H. R., Sik Kim, H., Park, Y. J. & Chung, K. H. (2023) Polystyrene microplastic particles induce autophagic cell death in BEAS-2B human bronchial epithelial cells, *Environmental Toxicology*, **38** (2), 359–367.

Jiang, B., Kauffman, A. E., Li, L., McFee, W., Cai, B., Weinstein, J., Lead, J. R., Chatterjee, S., Scott, G. I. & Xiao, S. (2020) Health impacts of environmental contamination of micro-and nanoplastics: a review, *Environmental Health and Preventive Medicine*, **25** (1), 29.

Jiang, W., Hu, C., Chen, Y., Li, Y., Sun, X., Wu, H., Yang, R., Tang, Y., Niu, F., Wei, W. & Sun, C. (2023) Dysregulation of the microbiota-brain axis during long-term exposure to polystyrene nanoplastics in rats and the protective role of dihydrocaffeic acid, *Science of The Total Environment*, **874**, 162101.

Jin, H., Ma, T., Sha, X., Liu, Z., Zhou, Y., Meng, X., Chen, Y., Han, X. & Ding, J. (2021) Polystyrene microplastics induced male reproductive toxicity in mice, *Journal of Hazardous Materials*, **401**, 123430.

Khan, S., Kalsoom, U., Kashif, M., Hussain, S. A., Gul, M., Azizi, S. & Maaza, M. (2025) Smart and sustainable microplastic removal: hybrid systems, Bio-Inspired technologies, real-time sensing, and policy integration, *Water, Air, & Soil Pollution*, **236**, 900.

Kim, S., Sin, A., Nam, H., Park, Y., Lee, H. & Han, C. (2021) Advanced oxidation processes for microplastics degradation: a recent trend, *Chemical Engineering Journal Advances*, **9**, 100213.

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Koul, S., James, A., Suvedi, D., Shard, S., Nanda, R. R., Verma, S., Sharma, A. & Nagraik, R. (2025) From source to solution: addressing microplastic pollution through advanced remediation strategies, *Journal of Applied Biology & Biotechnology*, **13** (5), 56–70.

Kumar, M., Chen, H., Sarsaiya, S., Qin, S., Liu, H., Awasthi, M. K., Kumar, S., Singh, L., Zhang, Z., Bolan, N. S. & Pandey, A. (2021) Current research trends on micro-and nano-plastics as an emerging threat to global environment: a review, *Journal of Hazardous Materials*, **409**, 124967.

Li, Z. & Robaire, B. (2025) Effects of endocrine-disrupting chemicals on adrenal function, *Endocrinology*, **166** (4), bqaf045.

Li, G., Yang, Z., Pei, Z., Li, Y., Yang, R., Liang, Y., Zhang, Q. & Jiang, G. (2022) Single-particle analysis of micro/nanoplastics by SEM-Raman technique, *Talanta*, **249**, 123701.

Liang, B., Zhong, Y., Huang, Y., Lin, X., Liu, J., Lin, L., Hu, M., Jiang, J., Dai, M., Wang, B. & Zhang, B. (2021) Underestimated health risks: polystyrene micro-and nanoplastics jointly induce intestinal barrier dysfunction by ROS-mediated epithelial cell apoptosis, *Particle and Fibre Toxicology*, **18** (1), 20.

Liang, J., Xiong, S., He, C., Song, Z., Yang, S., Ma, D., Yan, W., Wang, H., Tahir, R. & Han, M. (2023) The organism fate of inland freshwater system under micro-/nano-plastic pollution: a review of past decade, *Aquatic Toxicology*, **265**, 106774.

Liu, S., Zhao, H., Liu, Z., Zhang, W., Lai, C., Zhao, S., Cai, X., Qi, Y., Zhao, Q., Li, R. & Wang, F. (2022) High-performance micro/nanoplastics characterization by MALDI-FTICR mass spectrometry, *Chemosphere*, **307**, 135601.

Liu, S., Guo, J., Liu, X., Yang, R., Wang, H., Sun, Y., Chen, B. & Dong, R. (2023) Detection of various microplastics in placentas, meconium, infant feces, breastmilk and infant formula: a pilot prospective study, *Science of the Total Environment*, **854**, 158699.

Lu, Y., Li, M. C., Lee, J., Liu, C. & Mei, C. (2023) Microplastic remediation technologies in water and wastewater treatment processes: current status and future perspectives, *Science of the Total Environment*, **868**, 161618.

Mahadevan, G. & Valiyaveettil, S. (2021) Comparison of genotoxicity and cytotoxicity of polyvinyl chloride and poly (methyl methacrylate) nanoparticles on normal human lung cell lines, *Chemical research in toxicology*, **34** (6), 1468–1480.

Martin, L. M., Gan, N., Wang, E., Merrill, M. & Xu, W. (2022) Materials, surfaces, and interfacial phenomena in nanoplastics toxicology research, *Environmental Pollution*, **292**, 118442.

Meng, X., Zhang, J., Wang, W., Gonzalez-Gil, G., Vrouwenvelder, J. S. & Li, Z. (2022) Effects of nano-and microplastics on kidney: physicochemical properties, bioaccumulation, oxidative stress and immunoreaction, *Chemosphere*, **288**, 132631.

Mohamed Noor, M. H., Wong, S., Ngadi, N., Mohammed Inuwa, I. & Opotu, L. A. (2022) Assessing the effectiveness of magnetic nanoparticles coagulation/flocculation in water treatment: a systematic literature review, *International Journal of Environmental Science and Technology*, **19** (7), 6935–6956.

Mousazadehgavan, M., Khademi, S., Naeini, A. M., Yoosefdoost, I., Vashisht, V., Hashemi, M., Manouchehri, M. & Hashim, K. (2024) Fate of micro-and nanoplastics in water bodies: a critical review of current challenges, the next generation of advanced treatment techniques and removal mechanisms with a special focus on stormwater, *Journal of Water Process Engineering*, **67**, 106159.

Nasir, M. S., Tahir, I., Ali, A., Ayub, I., Nasir, A., Abbas, N., Sajjad, U. & Hamid, K. (2024) Innovative technologies for removal of micro plastic: a review of recent advances, *Heliyon*, **10**, 4.

Ojha, P. C., Satpathy, S. S., Ojha, R., Dash, J. & Pradhan, D. (2025) A brief concept on the physical remediation of microplastics and nanoplastics from water environment, *Environmental Technology Reviews*, **14**, 933–950.

Osuchowska, P. N., Ostrowski, R., Sarzyński, A., Strzelec, M., Mierczyk, Z. & Trafny, E. A. (2019) Microstructured polyethylene terephthalate (PET) for microsieving of cancer cells, *Results in Physics*, **15**, 102612.

Pérez-López, A., Cotillas, S., Santos, A. & Domínguez, C. M. (2026) Micro- and nanoplastics removal from water and solid matrices: technologies, challenges, and future perspectives, *Environmental Research*, **299**, 124295.

Pilapitiya, P. N. T. & Ratnayake, A. S. (2024) The world of plastic waste: a review, *Cleaner Materials*, **11**, 100220.

Prakash, J., Sharma, N., Sharma, R., Thakur, S., Sharma, S., Kumar, P., Fitria, F., Gandhi, S., Devi, K. S. & Kuramitz, H. (2026) Identification and removal of nano/micro-plastics using nanostructured materials: from fundamentals to environmental applications, *Environmental Science: Nano*, **13**, 2164–2210.

Primpke, S., Christiansen, S. H., Cowger, W., De Frond, H., Deshpande, A., Fischer, M., Holland, E. B., Meyns, M., O'donnell, B. A. & Ossmann, B. E. (2020) Critical assessment of analytical methods for the harmonized and cost-efficient analysis of microplastics, *Applied Spectroscopy*, **74**, 1012–1047.

Puteri, M. N., Gew, L. T., Ong, H. C. & Ming, L. C. (2025) Technologies to eliminate microplastic from water: current approaches and future prospects, *Environment International*, **199**, 109397.

Rathore, C., Saha, M., Gupta, P., Kumar, M., Naik, A. & De Boer, J. (2023) Standardization of micro-FTIR methods and applicability for the detection and identification of microplastics in environmental matrices, *Science of the Total Environment*, **888**, 164157.

Rawat, M., Kumar, D. & Sharma, R. (2025) Micro plastics: a deep insight into occurrence, classification, and remediation techniques using nanomaterials from water and wastewater streams, *Journal of Environmental Chemical Engineering*, **13**, 118955.

Rim, T., Xing, Y., Kang, M., Li, W., Chen, Y., Zhang, D., Li, W., Guo, Y., Zhang, X., Wang, S. & Qian, Z. (2025) Microplastic pollution remediation: a comprehensive review on electrochemical advanced oxidation processes (EAOPs) for degradation in wastewater, *Environmental Science: Water Research & Technology*, **6**, 100070.

Rout, P. R., Mohanty, A., Sharma, A., Miglani, M., Liu, D. & Varjani, S. (2022) Micro-and nanoplastics removal mechanisms in wastewater treatment plants: A review, *Journal of Hazardous Materials Advances*, **6**, 100070.

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Shen, M., Zhao, Y., Liu, S., Hu, T., Zheng, K., Wang, Y., Lian, J. & Meng, G. (2023) Recent advances on micro/nanoplastic pollution and membrane fouling during water treatment: a review, *Science of the Total Environment*, **881**, 163467.

Tiwari, B. & Arya, R. K. (2026) Removal of microplastics from wastewater: various methods and functional coating materials, *Reviews in Chemical Engineering*, **42** (4), 307–332.

Umrai Shariff, K., Le, A., Goodwin-Loughton, E., Chung, M., Ali, A., Farella, M. & Venugopal, A. (2025) Microplastics and nanoplastics in clinical dentistry and orthodontics: leaching, health implications, and future directions: a narrative review, *Progress in Orthodontics*, **26** (1), 49.

Wang, J., Sun, C., Huang, Q.-X., Chi, Y. & Yan, J.-H. (2021) Adsorption and thermal degradation of microplastics from aqueous solutions by Mg/Zn modified magnetic biochars, *Journal of Hazardous Materials*, **419**, 126486.

Wang, X., Ren, X. M., He, H., Li, F., Liu, K., Zhao, F., Hu, H., Zhang, P., Huang, B. & Pan, X. (2023) Cytotoxicity and pro-inflammatory effect of polystyrene nano-plastic and micro-plastic on RAW264. 7 cells, *Toxicology*, **484**, 153391.

Wang, X., Dai, Y., Li, Y. & Yin, L. (2024) Application of advanced oxidation processes for the removal of micro/nanoplastics from water: a review, *Chemosphere*, **346**, 140636.

Winiarska, E., Jutel, M. & Zemelka-Wiacek, M. (2024) The potential impact of nano-and microplastics on human health: Understanding human health risks, *Environmental Research*, **251**, 118535.

Wu, K., Su, D., Liu, J., Saha, R. & Wang, J. P. (2019) Magnetic nanoparticles in nanomedicine: a review of recent advances, *Nanotechnology*, **30** (50), 502003.

Yang, Y., Xie, E., Du, Z., Peng, Z., Han, Z., Li, L., Zhao, R., Qin, Y., Xue, M., Li, F. & Hua, K. (2023a) Detection of various microplastics in patients undergoing cardiac surgery, *Environmental Science & Technology*, **57** (30), 10911–10918.

Yang, Z., DeLoid, G. M., Zarbl, H., Baw, J. & Demokritou, P. (2023b) Micro-and nanoplastics (MNPs) and their potential toxicological outcomes: state of science, knowledge gaps and research needs, *NanoImpact*, **32**, 100481.

Yin, K., Lu, H., Zhang, Y., Hou, L., Meng, X., Li, J., Zhao, H. & Xing, M. (2022) Secondary brain injury after polystyrene microplastic-induced intracerebral hemorrhage is associated with inflammation and pyroptosis, *Chemico-Biological Interactions*, **367**, 110180.

Yoo, H., Kim, M., Lee, Y., Park, J., Lee, H., Song, Y.-C. & Ro, C.-U. (2023) Novel single-particle analytical technique for inhalable airborne microplastic particles by the combined use of fluorescence microscopy, Raman microspectrometry, and SEM/EDX, *Analytical Chemistry*, **95**, 8552–8559.

Zhang, Q., He, Y., Cheng, R., Li, Q., Qian, Z. & Lin, X. (2022) Recent advances in toxicological research and potential health impact of microplastics and nanoplastics in vivo, *Environmental Science and Pollution Research*, **29**, 40415–40448.

Zhang, S., Wang, S., Liu, Z., He, X., Shi, L., Liu, Y. & Wang, H. (2025) Mechanism and improvement of electrocoagulation technology for removing microplastics from wastewater-current status and future directions, *Water, Air, & Soil Pollution*, **236**, 990.

Zhao, J., Lan, R., Tan, H., Wang, J., Ma, Y., Chen, Q., Jiang, F., Wang, Z. & Xing, B. (2025) Detection and characterization of microplastics and nanoplastics in biological samples, *Nature Reviews Bioengineering*, **3**, 1019–1033.

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