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REVIEW

Advancements in Nanomaterial-Enhanced Biochar for Microplastic Remediation: A Comprehensive Review of Environmental Impact and Remediation Strategies

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Abstract

Microplastics (MPs) and nanoplastics (NPs) pollution represents a critical environmental crisis, yet conventional remediation techniques are frequently constrained by low removal efficiencies and high secondary-pollutant risks. This review critically evaluates nanomaterial-enhanced biochar as a superior, synergistic solution to these limitations. We identify the primary technical challenges in current remediation, specifically the kinetic barriers of sub-micron particle capture and the recovery of spent adsorbents from complex aquatic matrices. The key contribution of this work lies in detailing the transition from general adsorption to precision-engineered nano-interfaces, highlighting mechanisms such as π-π electron donor-acceptor interactions, Fe_3O_4-driven magnetic separation, and Reactive Oxygen Species (ROS)-mediated catalytic degradation. We further analyze hybrid innovations, including graphene oxide-functionalized biochar and enzyme-immobilized composites, which bridge the gap between physical entrapment and chemical mineralization. To facilitate the transition from laboratory-scale proof-of-concept to industrial restoration, we provide three main recommendations: (1) the adoption of standardized ecotoxicity assessments for spent nano-composites to prevent secondary contamination; (2) the development of AI-driven synthesis for polymer-specific biochar targeting; and (3) the integration of circular-economy frameworks to valorize agricultural waste into high-value remediation tools. By synthesizing recent advancements, this review provides a strategic roadmap for the scalable deployment of nano-biochar technologies in wastewater treatment and soil remediation.

Keywords Pollution · Environmental remediation · Regulatory challenges · Sustainable nanotechnology · Emerging contaminants

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1 Introduction

The rapid rise in global plastic production, exceeding 450 million tons annually, has led to severe environmental contamination, with projections estimating 11 billion tons of plastic waste accumulation by 2025 [52]. A significant fraction of this plastic degrades into microplastics (MPs) (< 5 mm), which are now ubiquitous in marine, freshwater, soil, and even atmospheric environments, undergoing fragmentation, biofouling, and long-range transport to remote ecosystems, including polar regions and deep sea sediments [166]. While MPs are defined by a diameter of less than 5 mm, their further degradation leads to the formation of nanoplastics (NPs), typically categorized by a size range of 1 to 1000 nm [40]. These smaller particles exhibit higher surface-to-volume ratios and increased Brownian motion, which enhances their bioavailability and potential for cellular penetration compared to larger MPs. Consequently, effective remediation requires nano-engineered biochar composites that can target these sub-micron pollutants through specialized pore-filling and molecular-level adsorption. Unlike MPs, which are primarily governed by gravitational settling and hydrodynamic transport, NPs exhibit Brownian motion and high colloidal stability, allowing them to remain suspended in aquatic matrices for extended periods [162]. Their extremely high surface-to-volume ratio results in a greater capacity for adsorbing hazardous co-pollutants and interacting with biological membranes, facilitating cellular internalization and potential transgenerational toxicity. Furthermore, the sub-micron scale of NPs makes them largely immune to conventional mechanical filtration, necessitating the development of nano-engineered biochar composites [75]. These advanced materials leverage molecular-level mechanisms, such as π-π electron donor-acceptor interactions and electrostatic attraction, to effectively trap NPs within the biochar's hierarchical pore structure [27, 104]. Their persistence and bioavailability pose serious ecological and human health risks. Marine and terrestrial organisms ingest MPs and NPs, leading to toxicity bioaccumulation and food web disruptions, while chemical additives and adsorbed pollutants exacerbate their harmful physiological impacts on aquatic biota [185]. A recent study introduced the term plasticosis to describe fibrosis caused by MPs in seabirds affecting digestion and overall health [28]. In humans, MPs have been detected in the lungs, liver, placenta, bloodstream, and even the brain, raising concerns about their potential role in inflammatory diseases, carcinogenesis, and neurodegeneration with dementia patients exhibiting significantly higher MPs concentration in brain tissue [43]. The detection of such ubiquitous contaminants in human blood and placentas underscores the critical need for advanced removal and detection technologies. While traditional biomass-derived carbon provides a low-cost and sustainable pathway for remediation, emerging two-dimensional (2D) materials like MXenes (transition metal carbides) and Metal-Organic Frameworks (MOFs) have demonstrated exceptional potential for the simultaneous detection and catalytic degradation of MPs and co-contaminants like PFAS [61, 62, 119, 144, 169]. These nanomaterials provide high surface area and specialized functional sites that address the methodological challenges of identifying and removing sub-micron particles from complex aqueous environments. Given their environmental persistence and adverse health impacts, urgent action is needed to develop sustainable alternatives, efficient waste management, and innovative remediation technologies [163].

Conventional remediation methods frequently utilized in wastewater treatment plants (WWTPs), including physical processes such as filtration and skimming, chemical oxidation, and biological enzymatic treatments, exhibit prominent limitations in efficiency, cost, and environmental impact when applied to plastic contaminants [6, 24]. Chemical oxidation methods such as advanced oxidation process generate toxic byproducts and require high energy inputs limits their sustainability and large-scale application [66, 88]. Biological treatment, particularly enzymatic degradation, presents promising eco-friendly alternatives but faces challenges related to enzyme stability and degradation efficiency in wastewater matrices [84, 142]. Furthermore, the high operational costs, maintenance requirements, and potential secondary pollution associated with approaches for effective microplastic remediation [6, 92].

The rising amount of microplastic in the environment requires new remediation techniques with nanotechnology, and biochar demonstrates potential as an effective solution. Engineered nanomaterials, including metal-based and carbonaceous structures, exhibit high surface area reactivity and exceptional adsorption properties [77, 78, 137]. These unique physicochemical traits enable them to effectively sequester or degrade persistent environmental contaminants, such as microplastics and heavy metals, within the biochar matrix. The carbon-rich material known as biochar attracts microplastics in aquatic environments through its ability to derive from biomass through pyrolysis. The combination of porous structure and surface functional groups on biochar enables it to effectively retain pollutants, thus making it an effective tool for microplastic remediation [99]. Biochar integration with nanomaterials presents a synergistic approach that enhances remediation procedures. Biochar-supported nanoparticles effectively remove microplastics and emerging contaminants, as studies demonstrate improved contaminant removal through biochar adsorption properties along with nanomaterial reactivity [123]. This hybrid approach not only facilitates microplastic degradation, but it also addresses a wide range of pollutants, which offers a sustainable and scalable remediation technique for polluted environments.

MPs pollution is a major threat that threatens both ecosystems and human well-being. The current remediation practices demonstrate weak performance alongside additional environmental hazards during treatment [7, 136]. The scientific field now focuses on biochar and nanomaterials as sustainable options for environmentally friendly microplastic remediation [74]. The organic waste-derived biochar material shows potent adsorption properties that enable it to successfully extract microplastics from water bodies. Quantum dots and carbon nanotubes, along with nano-based sponges, demonstrate exceptional efficiency in microplastic extraction because they achieve extraction rates reaching 99.9% [35, 143]. While recent studies have highlighted the severity of microplastics (MPs) contamination, a significant research gap remains in transitioning from laboratory observation to field-scale remediation. This systematic review addresses this gap by critically examining the synergistic effectiveness of nano-engineered biochar composites. Unlike existing literature, this work provides a novel integrated analysis of the physicochemical absorption behaviors at the nano-biochar interface and evaluates the recent advancements in sustainable materials. Furthermore, we contribute a Strategic Research Roadmap that prioritizes future research imperatives, ranging from toxicity standardization to industrial-scale engineering, offering a clear framework to bridge the 'lab-to-field' divide in combating global MPs pollution.

2 Review Methodology

To ensure a high-quality and comprehensive synthesis of microplastic (MPs) remediation, this review followed a structured literature selection process. We conducted a systematic search across major databases, including Web of Science, Scopus, and Google Scholar, using keywords such as "Microplastic remediation," "Biochar-nanomaterial composites," and "Nanotoxicity." The selection criteria prioritized: (i) Peer-reviewed articles published between 2020 and 2026 to ensure the inclusion of the most recent advancements; (ii) Studies reporting quantitative removal efficiencies and specific physicochemical mechanisms; and (iii) Research addressing both laboratory-scale successes and identified field-scale limitations. This methodology allowed us to move beyond a simple descriptive summary and instead provide a critical evaluation of the "lab-to-field" gap currently hindering large-scale implementation.

3 Microplastics Pollution and Remediation Strategies

Microplastics pollution represents an emerging component of global environmental change characterized by widespread ubiquity in water (sea, sediment, and freshwater), food, and air and a forbidding attitude for ecological and human health [14, 181]. Conventional treatment methods do not effectively remove MPs and NPs, which demands new approaches [115]. With continuous research, biochar and nanomaterials have emerged as superior remediation candidates. The high adsorption capacity of biochar is attributed to its high specific surface area and the presence of oxygen-containing functional groups that facilitate multi-mechanism interactions with microplastics, such as π-π bonding and electrostatic attraction [198]. Furthermore, biochar offers a sustainable and low-cost alternative to traditional adsorbents because it is synthesized from abundant agricultural waste through energy-efficient pyrolysis, effectively sequestering carbon while reducing waste management expenses [187]. Biochar, produced from biomass remnants like agricultural plant residues, along with nanomaterials such as carbon nanostructures (including carbon nanotubes and quantum dots), have been found in the scientific literature to effectively remove microplastics from fluids via adsorption, filtration, and aggregation, thus presenting an environmentally friendly means to reduce this long-lasting pollutant [168].

3.1 Sources, Transport, and Removal Mechanisms of MPs

Microplastics contamination is becoming a major environmental threat, arising from multiple sources and leading to its widespread distribution in terrestrial and aquatic ecosystems [53]. MPs originate from both primary and secondary sources. Primary microplastics are intentionally manufactured for specific applications, such as personal care products (e.g., exfoliating beads in cosmetics) and industrial processes (e.g., plastic pellets used in manufacturing). Secondary microplastics, on the other hand, result from the breakdown of larger plastic items, such as bottles, packaging, and fishing nets, due to exposure to environmental factors like UV radiation, wind, and mechanical abrasion [108]. Over time, these larger plastics fragment into smaller particles that contribute to the widespread presence of microplastics in both terrestrial and aquatic ecosystems. The sources of microplastics are diverse, making their management and removal particularly challenging [110].

The transport of MPs is primarily influenced by their size, shape, and density [156]. In aquatic environments, MPs are transported through water currents, with their movement determined by factors such as water flow velocity, turbulence, and the microplastic's buoyancy [98]. In terrestrial environments, MPs can be carried by wind or runoff, with some being absorbed into the soil, where they may affect agricultural productivity and soil health [54, 118]. Microplastic contamination in agricultural soils disrupts soil physicochemical properties, such as water retention and porosity, which negatively affects crop growth and soil fertility. It also serves as a carrier for harmful pollutants, further compromising soil health. MPs can harm soil biota, including earthworms and soil microbes, impairing nutrient cycling and plant growth [37, 54]. These effects emphasize the urgent need for research and strategies to mitigate microplastic pollution in agricultural systems. The global spread of MPs can also occur through atmospheric deposition, where fine particles are carried over long distances. As MPs are transported, they pose significant environmental threats, especially to marine life, as many organisms mistake them for food. The ingestion of MPs can lead to physical harm, chemical exposure, and biomagnification within the food chain, ultimately affecting both wildlife and humans [13]. Figure 1 shows that the holistic cycle of MPs contamination is an integrated process ranging from initial generation to advanced remediation. The framework identifies the distinction between primary microplastics, such as manufactured microbeads and industrial pellets, and secondary microplastics resulting from the environmental fragmentation of larger debris like plastic bottles and tires. Once released, these particles migrate through multiple transport pathways, including wind-driven atmospheric deposition, surface runoff into riverine systems, and eventual sedimentation in marine environments. These pathways lead to critical ecological risks, such as ingestion by aquatic and terrestrial biota, which can result in specific health conditions like plasticosis and the subsequent trophic transfer of pollutants through the food chain. To address these threats, the remediation strategy utilizing nano-enhanced biochar is highlighted, demonstrating how the incorporation of magnetic nanoparticles (e.g., Fe_3O_4) amplifies removal efficiency. The detailed molecular view confirms that the synergy between physical entrapment in porous structures, electrostatic attraction, and π- π interactions between the biochar's delocalized systems and the plastic's carbon backbone facilitates the restoration of clean water and healthy soil.

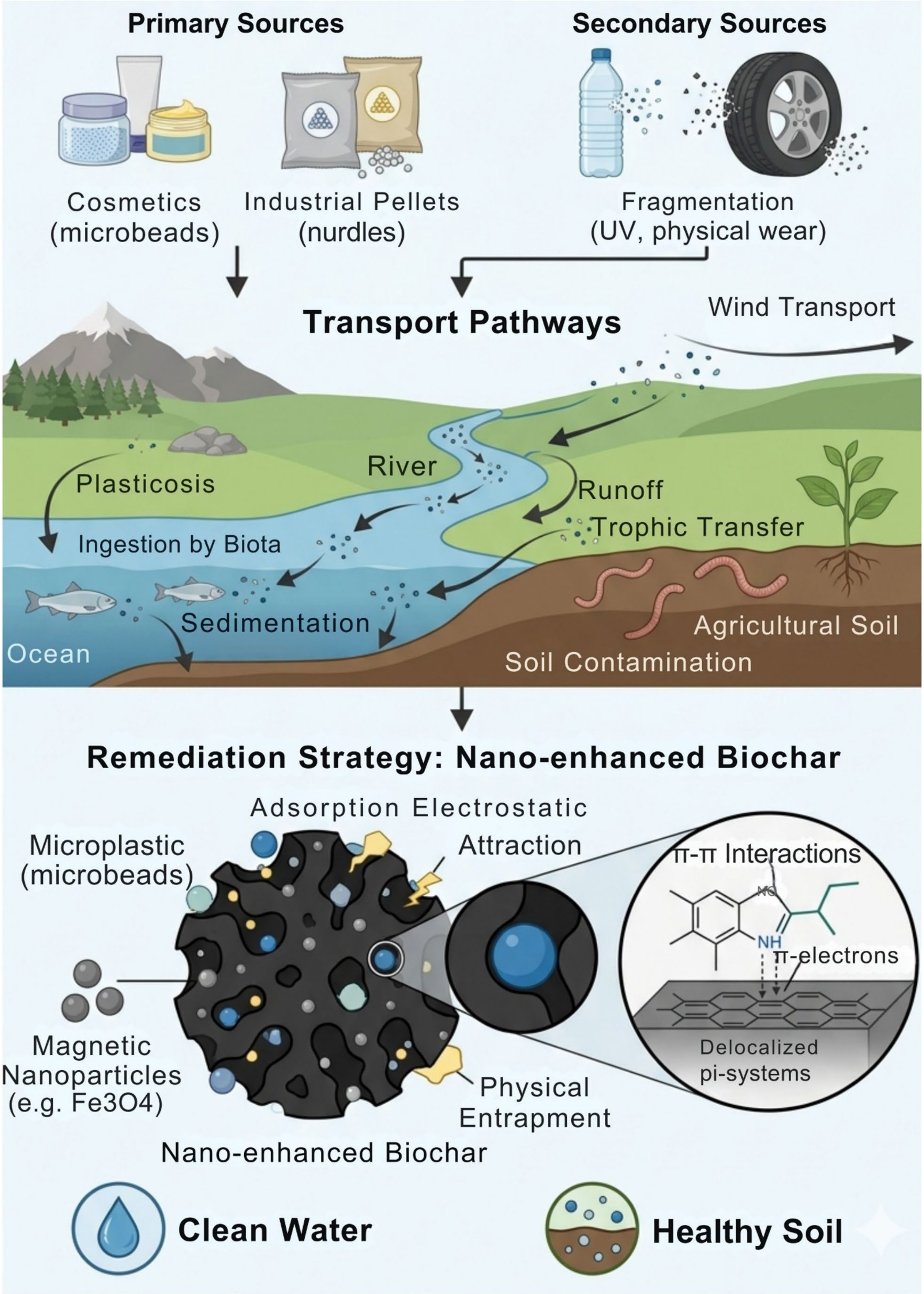
The removal of MPs from the environment has become a critical issue in recent years, with various strategies being explored to address the growing pollution [19]. Among these, biochar and nanomaterials have shown promising potential in mitigating the impact of microplastic contamination. Biochar, a sustainable material derived from biomass, has proven effective in adsorbing MPs from aqueous environments due to its high surface area and porosity. It works by trapping MPs onto its surface, preventing further spread, and can be considered an eco-friendly and cost-effective solution, although its application on a larger scale still requires optimization [68]. On the other hand, nanomaterials, including nanoparticles, nanocomposites, and nanofibers, offer another innovative approach to microplastic removal. Their high reactivity and large surface areas enable them to effectively capture MPs from water and soil [63]. Magnetic nanoparticles, for instance, can use magnetic fields to facilitate the separation and removal of MPs, while functionalized nanocomposites enhance adsorption at the molecular level [141]. Despite their promising capabilities, the use of nanomaterials raises significant concerns regarding their potential toxicity and long-term environmental fate. The high surface reactivity of nanocomposites can trigger the production of ROS, leading to oxidative stress, membrane damage, and genetic toxicity in non-target environmental organisms [1, 80, 169]. Furthermore, the small particle size of these materials facilitates their translocation across biological barriers, posing a risk of bioaccumulation and biomagnification within the food chain [25, 56, 64]. These environmental hazards, combined with the potential leaching of secondary pollutants from metal-based nanoparticles, necessitate comprehensive life-cycle assessments and further research to ensure their safe and sustainable implementation in remediation practices [86, 165]. Both biochar and nanomaterials present viable alternatives for microplastic removal, each with unique strengths and limitations [36]. Biochar is a more environmentally friendly and sustainable option, suitable for large-scale applications, while nanomaterials offer high efficiency and precision in capturing MPs. However, both approaches require further refinement and research to optimize their effectiveness and ensure minimal ecological impact, highlighting the need for continued innovation in microplastic remediation technologies.

Fig. 1 Life cycle of environmental microplastics (MPs) and the integrated role of nano-enhanced biochar in sustainable remediation ▶

4 Characterization of Microplastics and Their Environmental Behavior

4.1 Microplastics Properties Affecting Their Fate

The behavior of MPs in aquatic environments, including polymer density, surface charge, and biofilm formation, directly dictates the design and selection of biochar-based remediation agents. Low-density polymers like polyethylene (PE) and polypropylene (PP) maintain buoyancy, which necessitates the use of floating biochar or surface-integrated biochar filters for effective capture. Conversely,


Primary Sources
Secondary Sources
Cosmetics (microbeads)
Industrial Pellets (nurdles)
Fragmentation (UV, physical wear)
Transport Pathways
Wind Transport
River
Plasticosis
Runoff
Trophic Transfer
Ingestion by Biota
Sedimentation
Ocean
Agricultural Soil
Soil Contamination
Remediation Strategy: Nano-enhanced Biochar
Adsorption Electrostatic
Attraction
Microplastic (microbeads)
π-π Interactions
NH
π-electrons
Magnetic Nanoparticles (e.g. Fe3O4)
Delocalized pi-systems
Physical Entrapment
Nano-enhanced Biochar
Clean Water
Healthy Soil

high-density polyvinyl chloride (PVC) tends to sink, requiring heavy, mineral-rich biochars for sediment-level remediation [102, 157]. Furthermore, the surface charge of MPs is a critical factor for adsorption, as negatively charged MPs interact with biochar through cation bridging or electrostatic attraction when the biochar surface is modified with metal oxides like Fe_2O_3 or ZnO [42, 58, 182]. The hydrophobic organic pollutants, such as polycyclic aromatic hydrocarbons (PAHs) and persistent organic pollutants (POPs), are transported by MPs through both van der Waals forces and hydrophobic interactions [116, 131]. Additionally, the formation of "eco-corona" biofilms on MPs increases their surface roughness and oxygenated functional groups, which enhances their affinity for hydrophilic hydrochars produced via hydrothermal carbonization (HTC) [87, 126]. Understanding these property-specific interactions is essential for tailoring the pore size and surface chemistry of biochar to maximize MPs sequestration. Heavy metals in aquatic environments become more accessible to biological systems because of biofilm-secreted extracellular polymeric substances (EPS), which increase metal retention and modify the movement patterns of contaminants [158, 202]. These MPs-based vector consists of biofilm coatings that function as toxic material conveyors to enable entry points for aquatic food chains but present substantial ecological dangers [131]. Scientists need to know how MPs respond to environmental conditions based on their physical and chemical properties to evaluate their extended ecological risks.

4.2 Microplastics Transport and Accumulation in Aquatic Systems and Sediments

MPs have been studied for their persistence and mobility across different environments, especially terrestrial freshwater and marine ecosystems. Their small dimensions, along with their buoyancy, enable these particles to travel extensive distances by allowing wind transport and water flow, and soil movement until they settle in aquatic systems and sediments [128]. The environmental fate and movement of MPs depend heavily on their interactions with natural organic materials as well as soil minerals [138]. Marine ecosystems experience POPs bioaccumulation because MPs function as carriers that enhance their availability and toxicity for aquatic life [176]. Additionally, MPs persist within the environment over the long term because they experience slow degradation from physical, chemical, and biological processes [21]. The widespread distribution and complex behavioral patterns of MPs require additional scientific investigation to create effective mitigation methods and assess their lasting environmental effects.

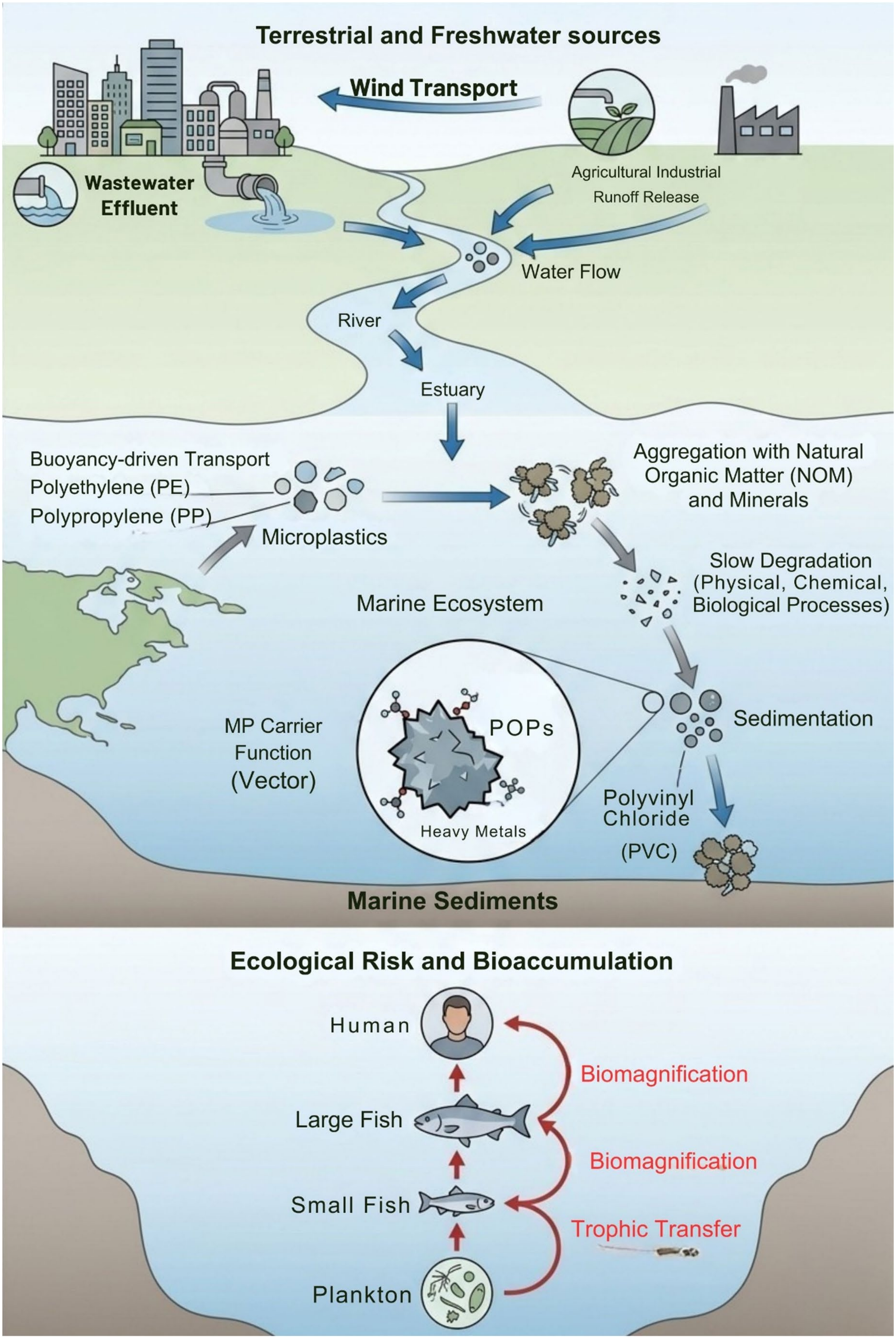
Fig. 2 Conceptual model of microplastics transport pathways from terrestrial sources to marine sinks and their subsequent trophic accumulation ▶

4.3 Emerging Analytical Techniques for Microplastics Detection

The detection of MPs and NPs relies on emerging analytical techniques that combine AI-assisted imaging with nanoparticle tracking analysis (NTA) and machine learning algorithms to improve identification efficiency. Advanced deep learning models have demonstrated the capacity to automate the quantification of MPs in environmental samples with high precision [178]. Similarly, NTA provides a standard method for determining the size and concentration of NPs in aqueous phases by measuring Brownian motion [147]. While advanced spectroscopic (FTIR) and thermal methods (DSC) continue to refine identification [190], the integration of mass spectrometry with chemometrics offers a more nuanced detection capability in complex matrices [41]. However, despite the development of these tools and the potential of remediation materials like biochar, significant hurdles remain. The standardization of field sensors and the cost-effectiveness of large-scale monitoring are major ongoing difficulties [130], suggesting that while laboratory-scale results are encouraging, the practical application of both detection and remediation technologies requires further optimization. Figure 2 shows that the environmental behavior of microplastics is governed by a complex "source-to-sink" transport model. As illustrated, MPs migrate from terrestrial environments via wastewater discharge and agricultural runoff into freshwater and marine systems. Their spatial distribution is significantly influenced by polymer density; low-density polymers like polyethylene (PE) exhibit buoyancy-driven transport, while higher-density polyvinyl chloride (PVC) undergoes sedimentation into marine sediments. Furthermore, the figure depicts the "carrier function" of MPs, where they act as vectors for heavy metals and persistent organic pollutants (POPs), facilitating their entry into the food chain. This leads to trophic transfer and biomagnification, posing a systemic risk to organisms ranging from plankton to humans.

5 Role of Nanomaterials in Microplastics Remediation

Nanotechnology refers to the manipulation and application of materials at the nanoscale (typically between 1 and 100 nanometers) [79, 169]. This field leverages the unique properties of nanomaterials, such as increased surface area, reactivity, and strength, to create advanced solutions for a variety of challenges, including environmental remediation


Terrestrial and Freshwater sources
Wind Transport
Wastewater Effluent
Agricultural Industrial Runoff Release
Water Flow
River
Estuary
Buoyancy-driven Transport
Polyethylene (PE)
Polypropylene (PP)
Microplastics
Aggregation with Natural Organic Matter (NOM) and Minerals
Slow Degradation (Physical, Chemical, Biological Processes)
Marine Ecosystem
MP Carrier Function (Vector)
POPs
Heavy Metals
Sedimentation
Polyvinyl Chloride (PVC)
Marine Sediments
Ecological Risk and Bioaccumulation
Human
Large Fish
Small Fish
Plankton
Biomagnification
Biomagnification
Trophic Transfer

[20, 76]. Nanotechnology has shown significant potential in improving the efficiency of current waste management practices, particularly in the removal of MPs and NPs from environmental systems [34]. Nanomaterials have emerged as a promising solution to enhance the effectiveness of traditional microplastic removal technologies and address the challenges associated with plastic waste management. Their unique properties, such as high surface area, porosity, and physicochemical stability, allow them to interact effectively with MPs, improving removal efficiency [26, 191]. Nanoparticles, for example, have shown the ability to act as catalysts in the degradation process, facilitating the breakdown of plastic polymers by influencing the growth of microorganisms involved in plastic degradation. This ability to accelerate microbial activity makes nanomaterials a valuable tool in addressing plastic contamination in aquatic and terrestrial environments [8, 81, 82].

The high reactivity and stability of nanomaterials, combined with their capacity for large surface area interactions, significantly enhance plastic waste degradation [71]. Nanoparticles can degrade plastic materials more efficiently than traditional methods, acting not only as catalysts but also as agents that boost the overall degradation process [4]. Additionally, these materials are being integrated into innovative approaches, such as bio-nanomaterial composites, that enhance the removal and degradation of MPs and NPs [18]. Their role in improving the efficiency of existing removal techniques while offering new avenues for plastic waste management highlights the potential of nanotechnology as a key player in environmental remediation efforts.

5.1 Types of Nanomaterials Used in Microplastics Removal

The unique properties of nanomaterials enable them to serve as highly efficient agents that remove microplastic from water environments. Fe_3O_4 and ZnO and TiO_2 metallic nanoparticles serve as essential elements for water source microplastic extraction through magnetic separation while achieving catalytic degradation [49, 139]. The pollutant capture abilities of graphene oxide and carbon nanotubes (CNTs) and fullerene reach high levels due to their strong microplastic interactions and intrinsic stability and high adsorption capacity [192, 201]. Additionally, starch-based and cellulose nanofibers serve as biodegradable nanomaterials to promote microplastic degradation in an environmentally friendly manner without creating additional environmental risks [18, 124]. The incorporation of such advanced nanomaterials within remediation approaches boosts the effectiveness of microplastic elimination by maintaining environmental sustainability.

5.2 Nanomaterials-Based Mechanism of Microplastics Removal

Nanomaterials have been increasingly employed in the removal of MPs from aquatic and terrestrial environments due to their high surface area, reactivity, and stability. For instance, graphene oxide has been used to efficiently adsorb MPs due to its large surface area and hydrophilic properties [160]. Magnetic nanoparticles such as core-shell mesoporous Si@Fe have been utilized for microplastic removal through magnetic separation, achieving significant removal efficiencies [10]. Carbon nanotubes (CNTs) have shown exceptional adsorption capabilities, especially for small microplastic particles, by interacting through van der Waals forces and electrostatic interactions [9]. TiO_2 nanoparticles, when applied in photocatalytic processes, facilitate the degradation of MPs under UV light, leading to the breakdown of polymer chains [67]. QDs have demonstrated the ability to adsorb and degrade MPs in water due to their high surface reactivity and catalytic properties [101]. Nanocellulose and starch-based nanomaterials have been explored for their biodegradability and efficiency in capturing MPs, particularly in wastewater treatment [199]. Silica nanoparticles have been used to remove MPs by acting as effective adsorbents through surface functionalization [46]. Silver nanoparticles (AgNPs) have been applied in combination with other materials to degrade MPs by enhancing catalytic reactions that break down polymer structures [167]. Chitosan nanoparticles, derived from natural biopolymers, have been shown to bind to MPs and effectively remove them from aquatic systems [12]. Zinc oxide (ZnO) nanoparticles have been employed in advanced oxidation processes to degrade MPs in aqueous solutions [161]. These nanomaterials offer promising solutions for enhancing the efficiency and sustainability of microplastic removal technologies.

The combination of nanomaterials has provided effective solutions for microplastic elimination by using electrostatic adsorption and magnetic separation, and photocatalytic degradation at once. The adsorption process heavily relies on electrostatic interactions because nanomaterials with charge-bearing surfaces effectively capture MPs from the aqueous ecosystem [5]. The use of Fe_3O_4 nanoparticles with magnetic separation improves microplastic removal efficiency because the technique enables the external magnetic field-powered collection of MPs without creating secondary pollution [2]. Under solar irradiation, TiO_2 nanoparticles, through photocatalytic degradation, produce reactive ROS that break MPs into smaller, less dangerous fragments [152]. Figure 3 shows that while nanomaterial-assisted strategies offer diverse pathways for microplastics mitigation, their practical application is governed by a distinct set of performance metrics and operational trade-offs. Magnetic

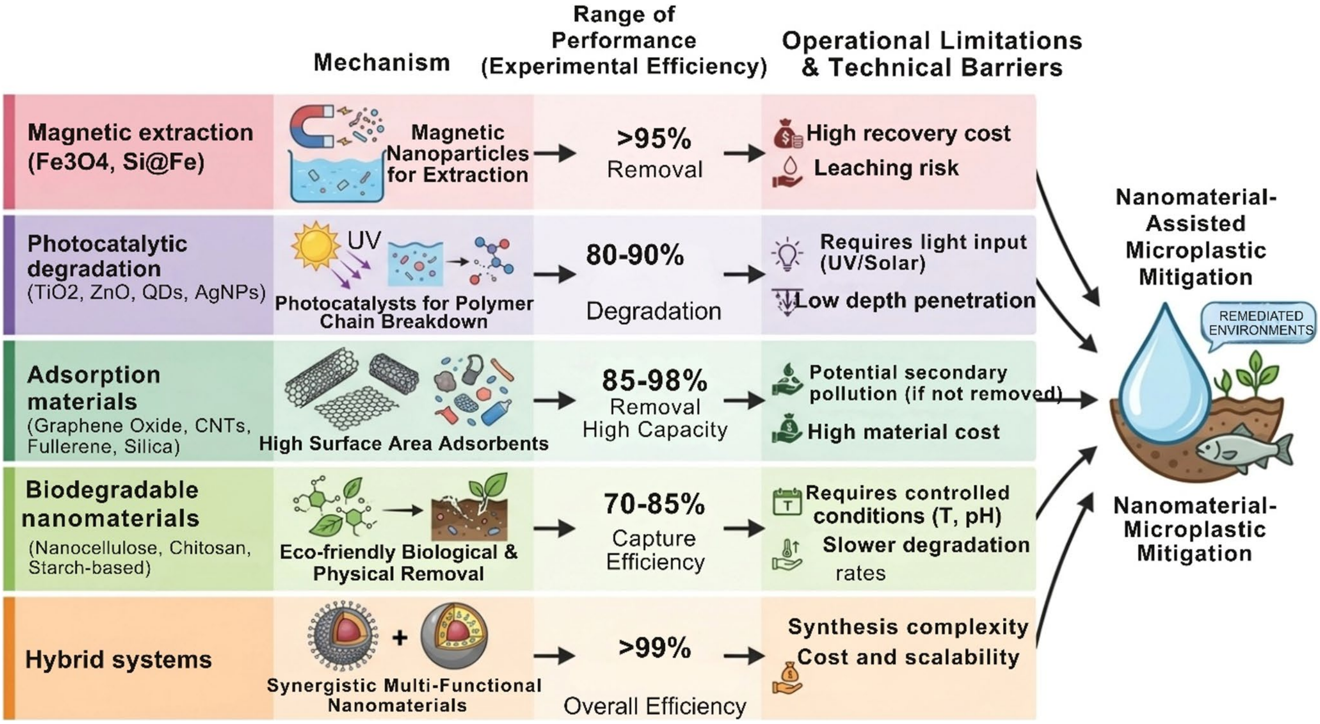


Fig. 3 Comparative analysis of nanomaterial-assisted MP mitigation strategies, illustrating performance efficiencies and operational barriers

extraction techniques using Fe_3O_4 and Si@Fe nanoparticles consistently achieve high removal efficiencies, often exceeding 95%, yet they are frequently constrained by high recovery costs and the potential risk of metal leaching into the treated media. In contrast, photocatalytic degradation using TiO_2 or ZnO provides a destructive solution with 80–90% degradation of polymer chains; however, this mechanism is highly dependent on UV or solar light input and suffers from low depth penetration in turbid environments. Adsorption materials, such as graphene oxide and carbon nanotubes, offer an expansive surface area resulting in 85–98% removal capacity, but their use necessitates careful secondary recovery to prevent the adsorbents themselves from becoming a source of secondary pollution. Biodegradable nanomaterials, including nanocellulose and chitosan, present an eco-friendly alternative with a 70–85% capture efficiency, although they often exhibit slower degradation rates and require strictly controlled environmental conditions, such as specific temperature and pH levels, to maintain structural integrity. Finally, hybrid systems represent the most advanced approach, merging multiple functionalities to reach overall efficiencies greater than 99%, though their widespread implementation remains limited by synthesis complexity and high scalability costs. By evaluating these strategies collectively, it becomes clear that the selection of a remediation technology must balance experimental removal rates against the specific technical barriers inherent to the target environment.

6 Biochar as an Eco-Friendly Microplastics Remediation Agent

Biochar, a carbon-rich material produced through thermochemical processes such as pyrolysis, hydrothermal carbonization (HTC), and gasification, is tailored for microplastic remediation based on synthesis parameters and feedstock. Pyrolysis, conducted at 300–900 °C in oxygen-limited conditions, yields biochar with properties dependent on heating rate and residence time: slow pyrolysis (400–600 °C, hours) prioritizes carbon stability, while fast pyrolysis (≥ 700 °C, seconds) favors bio-oil production [115, 150, 151]. HTC processes wet biomass under subcritical water (180–250 °C, 2–10 MPa), generating hydrochar rich in oxygenated functional groups (–OH, –COOH) effective for polar contaminant adsorption [60]. Gasification, involving partial oxidation at 700–1200 °C, produces biochar with lower carbon content but higher mineral ash, suitable for catalytic roles [38]. Feedstock choice further diversifies biochar: lignocellulosic variants (wood, bamboo) offer high porosity (> 500 m^2/g) for physical microplastic entrapment, manure-based types leverage cation exchange capacity (CEC) to bind charged plastics, and engineered biochars, modified via $ZnCl_2$ activation or Fe_3O_4 impregnation, enhance porosity or enable magnetic recovery [31, 69].

The porous structure and high surface area, along with adjustable surface chemistry in biochar, make it an effective sustainable adsorbent for aquatic environment MP and NPs removal [36, 68]. The adsorption capacity of biochar results from its complex pore network that creates better microplastic capture mechanisms, and surface modifications enhance its plastic polymer binding ability [15]. Biochar remediation capabilities have seen significant improvements through recent modifications such as magnetic biochar and biochar-based composite, which enable efficient separation and recovery [93]. Additionally, Biochar stands as a cost-effective sustainable solution for plastic remediation because of its environmentally friendly characteristics [175]. The studies demonstrate how biochar interacts through physicochemical processes with MPs to capture and degrade them, which helps reduce their lifespan in water systems [45]. The combination of biochar with existing water treatment systems creates a practical solution to fight plastic pollution, which meets both sustainable environmental management requirements [9].

Furthermore, the modified biochar system demonstrates dual functionality because specific modifications enable it to break down MPs/NPs into harmless byproducts while simultaneously adsorbing them [114]. Comparative studies on different biochar types indicate that nano-sized biochar types demonstrate better adsorption properties because their small size enhances surface reactivity and functional group availability [105]. Additionally, the implementation of biochar filtration systems for treating MP-contaminated stormwater and wastewater has shown promising scalability potential for practical applications [94]. The implementation of biochar into current water treatment facilities, together with progress in biochar modification and hybrid biosorbent development, leads to efficient, environmentally sustainable, and cost-effective MP/NP remediation [50].

6.1 Biochar Production and Modification Strategies

To optimize biochar for microplastic remediation, production parameters must be precisely tailored to the target polymer's characteristics. High-temperature pyrolysis (> 700 °C) is specifically employed to increase microporosity and graphitization, which facilitates the physical entrapment of nanoplastics and enhances π-π interactions with aromatic plastics like polystyrene (PS) [113, 184]. In contrast, low-temperature pyrolysis (300–500 °C) is preferred when the target MPs require hydrogen bonding, as these biochars retain a higher density of oxygenated functional groups (–OH, –COOH) [95]. Beyond temperature, heteroatom doping, such as Nitrogen or Sulfur, is utilized to modify the biochar's electron density, creating "active sites" that improve the catalytic degradation of polymer chains through the generation of ROS [32]. By specifically engineering the feedstock and thermal conditions, biochar can be transformed from a general adsorbent into a selective remediation agent optimized for complex microplastic matrices [115]. The transformation of agricultural residues into high-value remediation tools represents a critical advancement in sustainable wastewater treatment. As highlighted by Chaudhary et al. [29], converting abundant agricultural waste into biochar mitigates the environmental degradation associated with open-field burning while providing renewable adsorbents characterized by high specific surface areas and chemically active functional moieties. To optimize these materials for microplastics removal, advanced surface modifications are employed to create specialized composites, including metal-doped, magnetic, mineral-based, and layered double hydroxide (LDH) biochars. These modifications are specifically designed to address the ubiquity of MPs in aquatic ecosystems by enhancing surface reactivity and magnetic recoverability. Furthermore, the integration of nanosized biochar composites supports the principles of the circular economy by promoting waste valorization [57]. By tailoring biomass conversion routes to produce these advanced materials, researchers can bridge existing knowledge gaps regarding MPs adsorption mechanisms, ultimately improving the real-world performance of biochar-based systems in diverse environmental remediation scenarios [33]. Production of biochars used for specific environmental applications such as pollutant adsorption and catalysis can be achieved by tailoring pyrolysis conditions [109]. Among the doped biochar's, nitrogen (N)-doped biochar, have shown superior adsorption capacity, catalytic activity and electronic properties. However, N-type doping in this regard is normally pursued through either in situ or post-pyrolysis modification with nitrogen-containing precursors such as ammonia, urea, or melamine; these molecules eventually enhance surface functionality and enrich the presence of pyrrolic, pyridinic and graphitic nitrogen fractions [73, 172]. These changes will modify the charge distribution and enhance the electron density, which improves the interaction with contaminants, especially in areas such as waste water treatment and energy storage [205]. Metal-doped biochar served as a superior phosphate recovery (e.g., Fe, Mn, and Ca) and selective pollutants removal reagents due to the raise of ionic exchange abilities and enhanced redox properties [133]. The combined use of heteroatom doping and structural engineering strategies shows great potential in constructing high-performance biochar's for environmental and energy-related [132].

6.2 Biochar-Microplastic Interaction and Mechanisms of Action

The interaction between biochar and microplastic is dynamic and complex, affecting environmental pollutant behavior, soil and water quality, and greenhouse gas emission. Biochar has shown an effective ability to absorb MPs based on the hydrophobic effect, electrostatic attraction, and hydrogen bond, thereby improving the capacity of removing MPs from the aqueous ecosystem [100, 183]. In addition, the co-presence of biochar and MPs has been reported to affect organic matter decomposition, pollutant adsorption, and microbial activity, thus changing the fates of nutrients and contaminants in soil and aquatic ecosystems [149]. Interactions of MPs with biochar have also been shown to alter the sorption behavior of other environmental pollutants like heavy metals and organic contaminants through the formation of new surface characteristics that maximize adsorption dynamics [89, 111]. The aging of both MPs and biochar can be concurrent, leading to changes in their structures and chemistry and associated alteration in their interactions in the environment, with potential implications for long-term ecological consequences [189]. These findings indicate that biochar applications could provide a promising approach to removing MPs from the environment but also highlight the need for further exploration of optimizing biochar applications for microplastic remediation while avoiding potential side effects within the environment.

Biochar removes MPs and NPs through synergistic mechanisms driven by its physicochemical properties and environmental interactions [115]. Its porous structure and high surface area enable physical adsorption via pore filling, hydrophobic interactions (e.g., van der Waals forces with polyethylene), and hydrogen/electrostatic bonding with polar plastics (e.g., PET) through oxygenated functional groups (–OH, –COOH). Engineered biochars, such as Fe_3O_4-modified variants, enhance adsorption via magnetic separation or surface complexation, while aromatic carbon domains engage π–π interactions with polystyrene. Biochar also facilitates degradation through catalytic processes: Fe-loaded biochar triggers Fenton-like reactions, generating hydroxyl radicals ($^\bullet$OH) that oxidize MPs/NPs into harmless byproducts, while persistent free radicals (PFRs) and graphitic structures enable photocatalytic breakdown under light. Additionally, biochar supports microbial colonization, hosting enzymes (e.g., esterases) that depolymerize plastics like polyester. Immobilization occurs through co-sedimentation, where biochar-MPs aggregates settle in aquatic systems, or soil aggregation, binding MPs to organic matter. Alkaline biochars hydrolyze ester-containing plastics (e.g., PET), while $ZnCl_2$-activated biochar traps NPs in ultra-micropores. Integrated approaches, such as coupling biochar with filtration systems or electro-Fenton processes, enhance removal efficiency. Performance depends on feedstock (e.g., lignocellulosic vs. manure-based), pyrolysis temperature (high temperatures favor hydrophobicity; low temperatures retain functional groups), and environmental aging. Challenges include field-scale validation, ecotoxicity of spent biochar, and standardization for specific plastics. Mota et al. [115] emphasize biochar's role as a sustainable, multifunctional material aligned with circular economic principles.

Biochar's effectiveness in microplastic removal is attributed to various mechanisms depending on its composition and modifications. Lignocellulosic biochars, such as those made from wood and bamboo, offer high surface area and porosity, which allow for the physical entrapment of MPs, especially those with larger sizes [206]. Manure-based biochars, with their high CEC, attract and bind negatively charged MPs, making them effective in environments where plastics carry a charge [117]. Engineered biochars, modified through methods such as Fe_3O_4 impregnation, possess magnetic properties that enable the magnetic recovery of MPs, facilitating easy separation from contaminated water bodies [69]. Additionally, surface functionalization techniques like $ZnCl_2$ activation enhance the surface area and reactivity of biochar, improving its ability to adsorb MPs through both physical and chemical interactions [200]. The synergistic efficiency of hybrid composites is driven by the multifaceted interplay between the biochar scaffold and integrated nanoparticles [154, 187]. While the biochar acts as a robust, porous template that prevents nanoparticle aggregation and provides foundational hydrophobic capture sites, the nanoparticles (e.g., Fe_3O_4 or TiO_2) introduce catalytic and magnetic functionalities absent in pristine biochar [204]. This synergy is most evident in the "electron shuttle" mechanism, where the graphitic layers of the biochar facilitate rapid electron transfer to the nanoparticle surface, significantly accelerating the generation of ROS (•OH, $•O_2^-$). This integrated "adsorption-degradation" pathway allows for the localized concentration of MPs at the biochar interface, followed by immediate chemical mineralization at the nanoparticle active sites, a dual-functionality that drastically reduces the activation energy required for polymer chain scission and exceeds the cumulative performance of the individual components. Figure 4 illustrates the three-stage transformation of biomass into "smart" remediation tools, beginning with feedstock selection and tailored thermochemical conversion (pyrolysis, HTC, or gasification) to pre-define foundational porosity and oxygenated functionality. These materials undergo advanced surface engineering, such as Fe_3O_4 impregnation for magnetic recovery or $ZnCl_2$ activation, to enhance selectivity for complex microplastics and nanoplastics matrices. The resulting composites drive remediation through synergistic mechanisms, including physical pore-filling, π-π interactions, and catalytic degradation via hydroxyl radical (•OH) generation. This integrated approach effectively neutralizes sub-micron pollutants through concurrent adsorption and depolymerization, providing a scalable, circular-economy solution for environmental restoration.

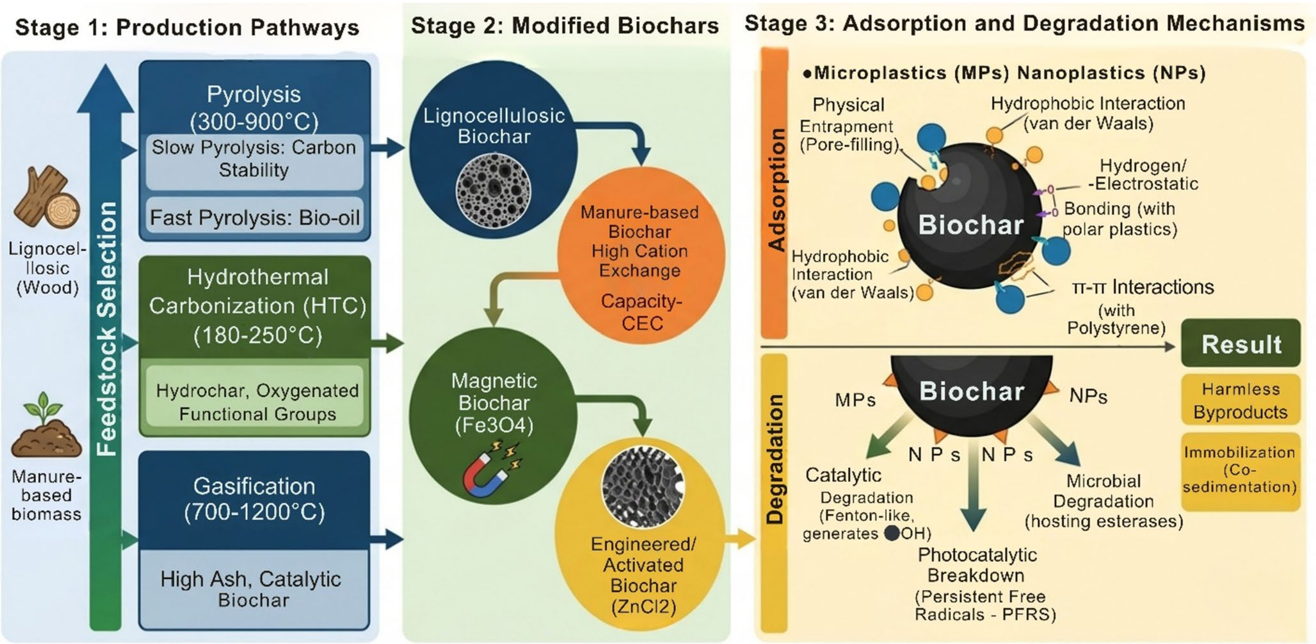


Fig. 4 Integrated framework for biochar-mediated microplastics and nanoplastics remediation, illustrating the progression from tailored production and surface modification to synergistic adsorption and catalytic degradation mechanisms

7 Hybrid Nanomaterial-Biochar Composites for Enhanced Microplastics Remediation

While nano-biochar systems demonstrate exceptional laboratory performance, their transition to industrial-scale microplastic remediation is hindered by significant techno-economic and operational barriers. The synthesis of advanced composites, particularly those involving MXenes, MOFs, or nZVI, requires high-purity precursors and specialized equipment, leading to production costs that can be 5–10 times higher than those of pristine biochar. Furthermore, the energy-intensive nature of high-temperature pyrolysis (> 700 °C) and the multi-step functionalization processes pose a challenge to the overall carbon-neutrality goals of these materials [135]. Operationally, the integration of nano-biochar into existing wastewater treatment plants (WWTPs) requires a significant redesign of filtration and sedimentation units to ensure the complete recovery of spent adsorbents and prevent secondary nanopollution. The regeneration and reuse of these materials also remain a critical bottleneck; while thermal regeneration can restore adsorption sites, it often degrades the integrated nanoparticles, leading to a loss of catalytic activity after 3–5 cycles [180, 186]. Currently, most nano-engineered biochar systems occupy a Technology Readiness Level (TRL) of 3 to 4 (Experimental Proof of Concept), lagging behind pristine biochar which has reached TRL 7–8 in soil and basic water filtration. Pilot-scale successes, such as the use of magnetic biochar for PFAS removal from biosolids [90], suggest that commercialization is possible, but only if future research prioritizes cost-efficient "green" synthesis and the development of high-throughput magnetic recovery systems capable of handling large-volume hydraulic flows. The remediation efficiency of nano-biochar is heavily dictated by the inherent heterogeneity of microplastics (MPs). Polymer composition determines the primary adsorption mechanism; for instance, Polystyrene (PS) exhibits superior removal via π-π electron donor-acceptor interactions with the aromatic carbon skeleton of biochar, whereas Polyethylene (PE) and Polypropylene (PP) rely predominantly on weaker hydrophobic partitioning and van der Waals forces [32]. Furthermore, the environmental aging (weathering) of MPs significantly alters their fate. Natural UV-induced oxidation and mechanical abrasion increase the surface area and the density of oxygen-containing functional groups (e.g., carboxyl and hydroxyl) on the MP surface. This "weathering" increases the polarity of the particles, often enhancing their affinity for nano-biochar composites through hydrogen bonding and electrostatic attraction, resulting in removal efficiencies up to 97% for aged polyamide (PA) compared to only 25% for pristine counterparts [97]. Conversely, biofouling, the formation of a microbial "eco-corona", can hinder remediation. While biofilms may provide additional sorption sites, they often shield the polymer core from ROS generated by catalytic nano-biochar, thereby reducing the rate of actual polymer mineralization and increasing the complexity of material recovery.

7.1 Recent Innovations in Nanomaterial-Functionalized Biochar

Nanomaterial-functionalized biochar has emerged as a pivotal tool for microplastic removal. For instance, Fe_3O_4-loaded biochar forms magnetic microspheres with high specific surface areas; these serve as effective materials for microplastic removal through magnetic separation, becoming a research hotspot in magnetically-assisted adsorption [164]. Graphene oxide-enhanced biochar also showed high-capacity adsorption, which was mainly due to its expanded surface area, the presence of oxygen-containing functional groups, and better microplastic interaction [96]. In addition, the incorporation of enzyme-immobilized biochar, which is especially effective when combined with laccase enzymes, represents a novel approach for the biodegradation of MPs, wherein enzymatic cleavage of polymer chains results in the formation of smaller, environmentally benign compounds [188]. Furthermore, the incorporation of enzyme-immobilized biochar, particularly when combined with laccase, represents a novel approach for biodegradation, wherein enzymatic cleavage of polymer chains results in the formation of smaller, environmentally benign compounds [196].

7.2 Mechanism of Hybrid Material Performance

Hybrid material exhibits superior performance due to their unique charged based adsorption and hydrophobic interactions, which enable efficient pollutant to capture and degradation. π-π interactions and electrostatic forces significantly enhance adsorption efficiency by facilitating electron transfer as observed in donor acceptor g-C_3N_4 system [197]. Multifunctional hybrid material integrates adsorption, separation, and catalytic degradation into a single system, thus improving water purification and pollutant removal [171]. Advanced membranes, such as polyacrylonitrile-based nanofibrous structure, utilize pH responsive surface charge regulation for selective separation and sustained catalytic activity [91]. Additionally, biochar-based composites and graphene derivatives enhance adsorption and oxidative degradation via synergistic charge interactions and hydrophobic forces [16, 72]. Figure 5 delineates the transition from raw biochar to multifunctional hybrid composites through the integration of Fe_3O_4 for magnetic separation, Graphene Oxide for expanded surface reactivity, and immobilized laccase enzymes for targeted biodegradation. These hybrid systems achieve superior performance by merging pH-responsive surface charge regulation with synergistic π-π donor-acceptor interactions and hydrophobic forces. Consequently, this integrated approach facilitates a simultaneous "capture-and-catalyze" process, wherein microplastics are adsorbed via electrostatic attraction and subsequently mineralized through oxidative degradation.

As shown in Table 1, a comparative analysis of various microplastic remediation strategies utilizing nanomaterials, biochar, and hybrid composites is presented. The table

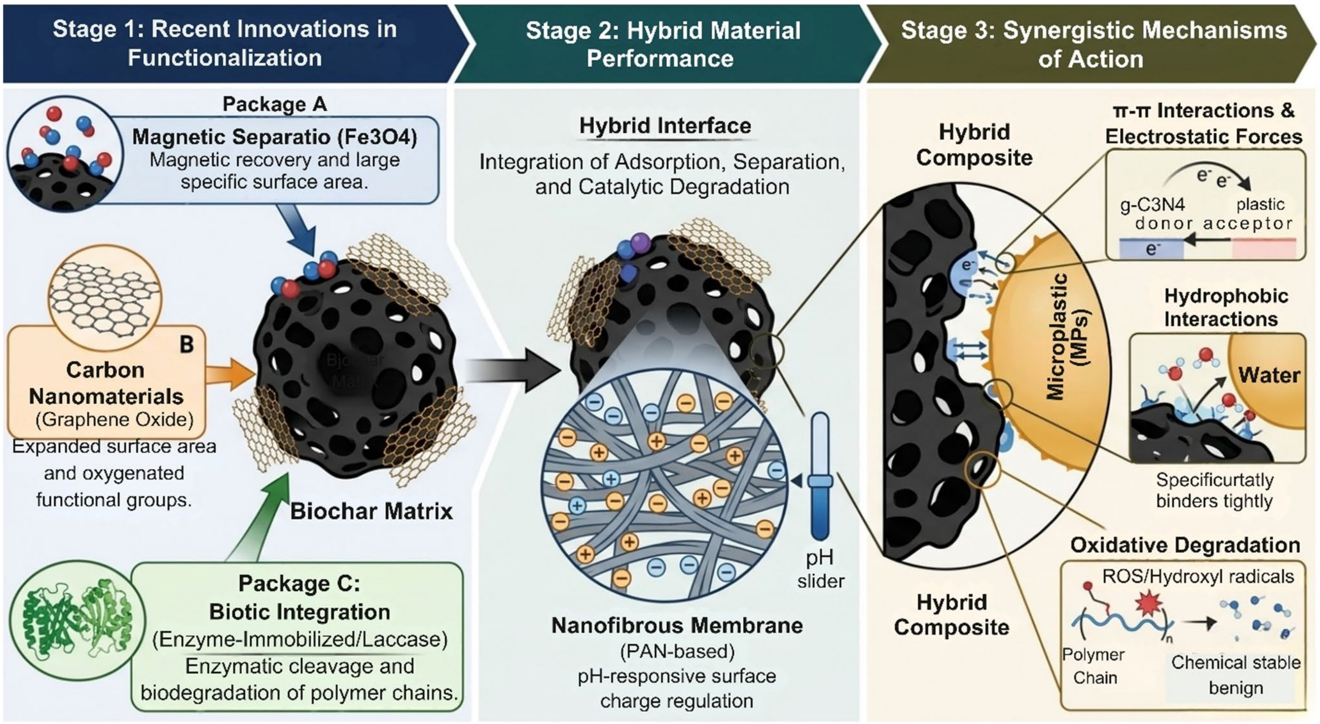


Fig. 5 Synergistic framework of hybrid nano-biochar composites, illustrating functionalization via Fe_3O_4, graphene oxide, and enzymes alongside integrated π-π electron transfer, hydrophobic attraction, and oxidative degradation mechanisms for enhanced MPs remediation

Table 1 Comparative analysis of microplastic remediation strategies using nanomaterials, biochar, and hybrid composites

Remediation Strategy	Key Mechanism	Advantages	Limitations	Applications	References
Metallic Nanoparticles (Fe_3O_4, ZnO, TiO_2)	Electrostatic adsorption, magnetic separation, photocatalytic degradation	High removal efficiency, catalytic oxidation, magnetic recovery potential	Potential toxicity, high production cost, stability concerns in real environments	Wastewater treatment, industrial effluent purification	Hasan et al. [55], Lu, [103]
Carbon-based Nanomaterials (Graphene Oxide, CNTs Fullerenes)	High surface area adsorption, π-π interactions, hydrophobic interactions	Strong adsorption capability, lightweight, stable, under extreme conditions	High synthesis cost, possible environmental persistence	Water filtration, advanced industrial applications	Goswami et al. [51], Zhou, [203]
Biodegradable Nanomaterials (Starch-based, Cellulose Nanofibers)	Biodegradable adsorption, biofilm formation, electrostatic bindings	Eco-friendly, sustainable, naturally decomposable	Lower efficiency compared to metallic nanomaterials, scalability issues	Soil and agricultural water remediation	Esteves et al. [44], Sarvi, [146]
Biochar (Pristine and modified with Fe, Zn, Ti, etc.)	Porous structure adsorption, surface functionalization, cation exchange	Cost-effective carbon sequestration, customizable surface chemistry	Variability in adsorption efficiency, long term stability concerns	Agriculture, soil remediation, municipal wastewater treatments	Pallewatta et al. [125], Wang, [173]
Hybrid Nanomaterial Biochar Composites	Multifunctional adsorption, catalytic degradation, enhanced reactivity	High efficiency magnetic separability, combined benefits of biochar and nanomaterials	Complex fabrication process, scaling challenges	Advanced wastewater treatment, pilot-scale industrial applications	Khanzada et al. [85], Pallewatta, [125]
Ultrafiltration and Reverse Osmosis Membranes	Size-exclusion filtration	High efficiency, removes nanoscale plastics	Membrane fouling, high maintenance costs	Desalination, water purification	Acarer, [3]
Photocatalytic Degradation (TiO_2, ZnO, $BiVO_4$-based Systems)	Light-driven oxidation and degradation	High efficiency, non-toxic byproducts	Limited efficiency in dark conditions requires UV light	Advanced oxidation processes for wastewater	Ferreira & Azenha, [47], Vallarasu, [170]
Coagulation-Flocculation with Bio-Based Agents (Chitosan, Plant Extracts)	Flocculation, charge neutralization	Eco-friendly, safe, cost-effective	Lower efficiency in complex matrices	Municipal wastewater treatment	Khan et al. [83]
Clay-Based Nanomaterials (Montmorillonite, Kaolinite, Bentonite)	Electrostatic adsorption, intercalation	Abundant, cost-effective	Lower adsorption efficiency than carbon-based materials	Soil and sediment remediation	Arun et al. [11], Mapossa, [107]
Metal-Organic Frameworks (MOFs)	Porous adsorption, molecular sieving	Extremely high surface area, selective adsorption	High cost, stability concerns	Water purification, industrial effluent treatment	Nikhar et al. [122]
Hydrothermal Carbonization (HTC) of Plastic Waste	High-temperature decomposition and carbonization	Converts plastic into useful carbon materials	Energy-intensive requires specialized reactors	Recycling of plastic waste	Shekoohiyan et al. [150]
Ozonation-Based Treatments (Nanocarbon-based catalytic ozonation)	Oxidative degradation of plastic polymers	High efficiency, no secondary pollution	High operational costs, require controlled conditions	Municipal water treatment	Wang et al. [177]
Biochar from Biomass Waste (Rice husk, Coconut shells, Wood chips)	High porosity adsorption, surface functionalization	Low cost, renewable, high adsorption capacity	Risk of leaching contaminants (PAHs, metals)	Water filtration, soil remediation	Ji et al. [68], Mota, [115]
Magnetic Nanoparticles (Fe_3O_4, $CoFe_2O_4$)	Magnetic separation, electrostatic interactions	Reusable, effective for water purification	High material costs, limited large-scale application	Industrial wastewater treatment	Shi et al. [153]

provides an overview of the key mechanisms, advantages, limitations, applications, and references for each strategy. For instance, metallic nanoparticles (Fe_3O_4, ZnO, TiO_2) are effective due to electrostatic adsorption, magnetic separation, and photocatalytic degradation, offering high removal efficiency and magnetic recovery potential, though concerns about toxicity and cost remain. Carbon-based nanomaterials, such as graphene oxide and CNTs, offer strong adsorption capabilities under extreme conditions, but their high synthesis costs and potential environmental persistence limit their practical use. Biodegradable nanomaterials, like starch-based and cellulose nanofibers, present an eco-friendly solution, yet they have lower efficiency compared to metallic counterparts. Biochar, both pristine and modified with metals like Fe and Zn, offers a cost-effective, sustainable solution, but faces variability in adsorption efficiency and long-term stability concerns. Hybrid nanomaterial-biochar composites combine the advantages of both, showing high efficiency, though the fabrication process is complex. Other strategies such as ultrafiltration membranes, photocatalytic degradation systems, and coagulation-flocculation with bio-based agents also provide promising solutions for microplastic removal, each with unique strengths and limitations.

Table 2 provides a comprehensive comparative analysis of various nano-engineered composites, highlighting their performance in removing diverse MPs, NPs, and associated industrial pollutants from aqueous matrices. These primary experimental data demonstrate that the integration of nanomaterials, such as MXenes, MOFs, and magnetic Fe_3O_4@TiO_2/Ag heterostructures, significantly enhances remediation through synergistic mechanisms. For instance, while catalytic biochar utilizes radical generation (•OH) to achieve up to 92% degradation of polypropylene, magnetic photocatalysts like Fe_3O_4@TiO_2/Ag offer a dual benefit of enhanced visible light absorption and easy recovery, achieving 15.54% degradation of polyethylene under optimized conditions. Additionally, chemically synthesized metal oxides like ZnO and NiO show high efficacy (up to 96.1 mg/g) in removing anionic co-pollutants, which often coexist with MPs in industrial effluents. Despite these impressive laboratory metrics, a critical analysis of the experimental conditions reveals a significant 'lab-to-field' gap. Most studies, such as the high-efficiency removal of PS-MPs in seawater (93.4%), were conducted in controlled batch systems. The reliance on uniform spherical polymers and specific pH optimizations (e.g., pH 2.0 for oxalic acid-modified biochar) may not fully reflect the behavior of irregularly shaped fibers or the competing ionic interference found in real-world wastewater. These factors suggest that while current performance metrics are promising, transitioning to continuous-flow systems and complex environmental matrices remains a priority for achieving technological readiness.

7.3 Comparative Analysis of Remediation Technologies

To contextualize the role of nano-engineered biochar within the broader landscape of water and soil treatment, a structured comparison with conventional and emerging technologies is presented in Table 3. This evaluation highlights a significant "performance-practicality trade-off" across current remediation strategies. Physical and chemical methods, such as horizontal sand filtration and optimized coagulation, remain the industry standard due to their high scalability and low relative cost. However, as demonstrated by Rullander et al., [140], sand filtration efficiency drops significantly for particles smaller than 50 μm, leading to the potential bypass of nanoplastics. Similarly, while machine-learning-optimized coagulation can predict removal efficiencies up to 96% [59], the process generates substantial chemical sludge, increasing the secondary environmental footprint. Advanced Oxidation Processes (AOPs), including Photocatalysis (TiO_2) and Fenton-based systems, offer the advantage of actual polymer mineralization rather than simple phase transfer. However, these are often constrained by specific operational requirements; for instance, Fenton

Table 2 Performance of nano-engineered composites for MPs/NPs and co-pollutant remediation

Composite Type	Nanomaterial Component	MPs/NPs Type & Size	Experimental Conditions (pH, Temp, Time)	Removal Efficiency/ Adsorption Capacity	Primary Mechanism	References
Magnetic Biochar	Fe_3O_4	PS (500 nm)	pH 6.5, 25 °C, 24 h	98.5% Removal	Magnetic separation & Electrostatic	Jin et al. [70]
Metal Oxide Nano-adsorbent	ZnO	Reactive Red Dye (RRMe4BL)	(RRMe4BL)pH 2.0, 25 °C, 90 min	96.1 mg/g	Electrostatic attraction & Chemisorption	Zaheer et al. [193]
Magnetic Photocatalyst	Fe_3O_4@TiO_2/Ag	PE (Polyethylene)	Optimized via RSM	15.54% (Photodegradation)	Synergistic Charge Transfer & ROS Generation	Wei & Zheng, [179]
Catalytic Biochar	nZVI/Persulfate	PP (20 μm)	pH 4.0, 30 °C, 4 h	92% Degradation	ROS generation (•OH)	Nawab et al. [119]
Doped Hybrid	N-doped/ZnO	PVC (100 nm)	pH 8.0, 20 °C, 6 h	89.2% Removal	π-π interactions	Nguyen et al. [120]
MOF-Biochar	MIL-101(Fe)	PET (50 μm)	pH 5.5, 25 °C, 10 h	210 mg/g	Metal-coordination & Chelation	Sajid et al. [144]
Modified Nano-BC	Oxalic Acid @ Pineapple (OA@NBP)	PS-MPs (68–105 nm)	pH 2.0, 40 min	87.4% (Seawater)	Adsorptive removal; Endothermic	Mahmoud et al. [106]
Modified Nano-BC	Oxalic Acid @ Artichoke (OA@NBA)	PS-MPs (9.8–16.1 nm)	pH 2.0, 40 min	93.4% (Seawater)	Adsorptive removal; Endothermic	Mahmoud et al. [106]
Surfactant-Modified MBC	CTAB/Fe_3O_4	Polystyrene (NPs)	pH 7.0	234 mg/g (Adsorption Capacity)	Electrostatic attraction, Hydrophobic interaction & Surface complexation	Fu et al. [48]

Table 3 Comparative evaluation of MPs and nanoplastics remediation technologies

Technology	Primary Mechanism	Removal Efficiency	Relative Cost	Environmental Footprint	Scalability	References
Sand Filtration (Horizontal)	Straining & Sedimentation	> 98% (for particles > 50 μm)	Very Low	Low	High	Rullander et al. [140]
Coagulation (Optimized)	Charge Neutralization/Bridging	High (Up to 96% Predicted)	Moderate	High (Chemical Sludge)	High	Hosseinzadeh et al. [59]
Microbial Biodegradation	Enzymatic Mineralization	Moderate (Variable)	Low	Very low	Low (Slow Kinetics)	Dey et al. [39]
A/O-MBR System	Microbial Colonization & Bio-degradation	High (Variable)	Moderate to High	Moderate (Biofilm growth)	High	Wang et al. [174]
Electro-Coagulation (EC)	Electro-flotation & Radical Oxidation	High (> 90–95%)	Moderate	Moderate (Low Sludge)	Moderate	Zhang et al. [199]
Photocatalysis (TiO_2)	ROS-Driven Mineralization	High (Mass loss 10–98%)	High	Moderate	Low (Light-limited)	Canovi et al. [23]
Fenton/Photo-Fenton	Radical Oxidation	High (Material degradation)	Moderate	Moderate (Sludge/UV energy)	Moderate	Bule Možar et al. [22]
Magnetic Nano-Biochar	Adsorption & Magnetic Separation	High (Up to 97% for Aged MPs)	High	Low (Waste Valorization)	Emerging (TRL 3–4)	Li et al. [97]
Nano-Biochar (Soil)	HGT Inhibition & Niche Competition	High (Superior to Bulk-BC)	Moderate	Very Low (Carbon Sink)	High	Su et al. [159]

processes require highly acidic conditions (pH 3) and are polymer-specific, showing high degradation for LDPE but relative insensitivity for PP [22]. Furthermore, biological systems like A/O-MBR provide high removal but introduce risks such as the enrichment of antibiotic resistance genes (ARGs) on the biofilm-coated microplastic surfaces [174]. Nano-biochar systems emerge as a superior middle ground. In aqueous matrices, magnetic nano-biochar achieves up to 97% removal efficiency for aged microplastics, utilizing a dual mechanism of adsorption and magnetic separation that outperforms pristine [97]. In terrestrial applications, nano-sized biochar significantly outperforms bulk biochar in inhibiting the horizontal gene transfer (HGT) of ARGs in contaminated soils [159]. While these nano-engineered systems currently face higher synthesis costs and lower TRLs compared to conventional methods, their ability to combine high-efficiency "capture-and-catalyze" functionality with waste valorization makes them the most promising candidate for the next generation of microplastic remediation.

8 Real-World Applications and Implementation Challenges

8.1 Pilot-Scale Studies and Industrial Applications

In recent years, biochar-based nanomaterials have been increasingly explored for environmental remediation, as they can effectively remove contaminants from soil and water. Studies have shown biochar-supported nanoscale zerovalent iron is an effective persulfate activator for aromatic hydrocarbon degradation on contaminated soil, and in-situ pilot scale studies have shown evidence that the dispersion of nanoparticles in heterogeneous soil systems is successful [194]. Furthermore, modified biochar-based nanomaterials such as magnetic biochar nano-metal catalytic micro-device demonstrated superior capability in adsorbing pollutants in wastewater treatment and in improving soil remediation [103, 196]. The combination of biochar and iron oxide nanoparticles has also been reported to enhance the removal efficiency of pharmaceutical contaminants, indicating the multifunctional character of biochar-based composites [155]. In addition, there are studies on the use of biochar to remove per- and polyfluoroalkyl substances (PFAS) from biosolids on a pilot scale, which indicate its potential application in the field [90]. Developments toward hydrochar–nanoparticle hybrids, engineered biochar with mesoporous architectures, and biochar-based nanocomposites are advancing pollutant binding mechanism, kinetics, and efficiency in remediation technologies [85, 203]. These findings further corroborate biochar as a sustainable, scalable and effective material for tackling environmental pollution challenges.

8.2 Challenges in Field Deployment

There are major barriers associated with deploying nanotechnology-based solutions in environmental remediations, including cost reduction, scalability, regulatory approval, and long-term environmental risk. High production costs of engineered nanomaterials (ENMs) and the extreme complexity of scaling up from laboratory-scale use to industrial applications are major economic and technical barriers [134]. The limited regulatory frameworks have raised unclear guidelines on the environmental release, disposal, and monitoring of nanomaterial, which has become a hindrance in their widespread adoption [112]. Environmental toxicity, bioaccumulation, and persistence of ENMs in the ecosystem dictating potential long-term environmental risk need complete risk assessments for secure applications [145]. Beyond these general barriers, several MPs-specific technical hurdles remain critical. First, the lack of standardized detection methods for sub-micron plastics (NPs) complicates the quantification of removal efficiencies. Second, the interference of complex wastewater matrices, including natural organic matter (NOM) and competing ions, often masks biochar active sites, reducing adsorption capacity in real-world scenarios compared to laboratory deionized water studies. Third, the disposal and regeneration of spent adsorbents present a major sustainability gap; without cost-effective thermal or chemical regeneration protocols, spent nano-composites risk becoming secondary plastic-laden waste. Finally, a more granular understanding of the interfacial interactions between diverse polymer types (e.g., weathered vs. pristine plastics) and heterogeneous adsorbent surfaces are required to move toward targeted, molecular-level design. Moreover, the disposal and degradation of nanomaterials raise questions about sustainability and call for developing sustainable design strategies to minimize environmental burdens. Developing cost-efficient production methods, establishing clear and concise regulatory practices, and implementing comprehensive risk assessment protocols to ensure successful and safe insertion of nanotechnology within environmental remediation are all challenges that will require input from researchers, industry leaders, and regulatory experts alike [129].

8.3 Ecotoxicological Risks and Material Stability

While nano-engineered biochars (NBCs) demonstrate superior microplastic removal, their large-scale deployment introduces a secondary layer of environmental risk that remains largely under-monitored. The potential for these remediation agents to become secondary pollutants is governed by the critical interplay of material leaching, chronic toxicity, and trophic transfer. The stability of the bond between the biochar scaffold and integrated nanomaterials, such as nZVI or metal oxides, is highly dependent on environmental chemistry; under conditions of high salinity or fluctuating pH, the weakening of electrostatic and coordinative bonds can trigger the release of free nanoparticles into the water column [61, 148]. Recent studies by Mota et al. [115] indicate that the aging of the biochar matrix, driven by UV exposure and microbial mineralization, can lead to surface "sloughing," which releases both the adsorbed plastics and the engineered nanomaterials as secondary pollutants. If released, these suspended nanocomposites can exhibit deleterious effects on non-target aquatic organisms, ranging from respiratory distress in filter-feeders which inhibit photosynthetic activity. Furthermore, the high surface area of NBCs may facilitate the "Trojan Horse" effect, where the biochar "shuttles" co-existing heavy metals into the cells of aquatic life, significantly amplifying the inherent toxicity of the nanomaterials [135]. In terrestrial applications, the accumulation of metal-doped biochars has been shown to alter the gut microbiota of soil invertebrates and hinder the development of beneficial mycorrhizal fungi [65, 127]. A critical concern remains the potential for trophic transfer, where nano-biochar particles laden with adsorbed plastics are ingested by primary consumers, potentially moving up the food chain and increasing the risk of biomagnification in higher trophic levels, including humans [100, 195].

8.4 Societal and Policy Implications

Effective global regulations are necessary to avoid any environmental and health risks with nano-based remediation approaches, including nano-biochar applications [17]. Now, regulators are developing frameworks, including the U.S. Toxic Substance Control Act (TSCA), to bridge the gap, but there is an overwhelming need for harmonized international guidelines to foster the safe development of these technologies [30]. The acceptance of nano-biochar solutions depends heavily on public perception. The study showed varying levels of public awareness and comfort with biochar use, especially biochar sourced from waste, which subsequently impacts the social acceptance of the technology [121]. Society and policy implications need to be addressed to support the responsible advancement of nano-based environmental remediation.

9 Future Perspectives and Strategic Research Roadmap

First, future research should employ machine learning optimization and predictive modeling to forecast biochar performance. Algorithms such as Random Forest and Neural Networks can be trained to correlate feedstock properties, such as lignin or cellulose ratios, and pyrolysis parameters with resultant adsorption capacities. This allows for the preselection of optimal chemical dopants, including nitrogen or phosphorus, to maximize specific molecular interactions with target polymers like polystyrene or polyethylene

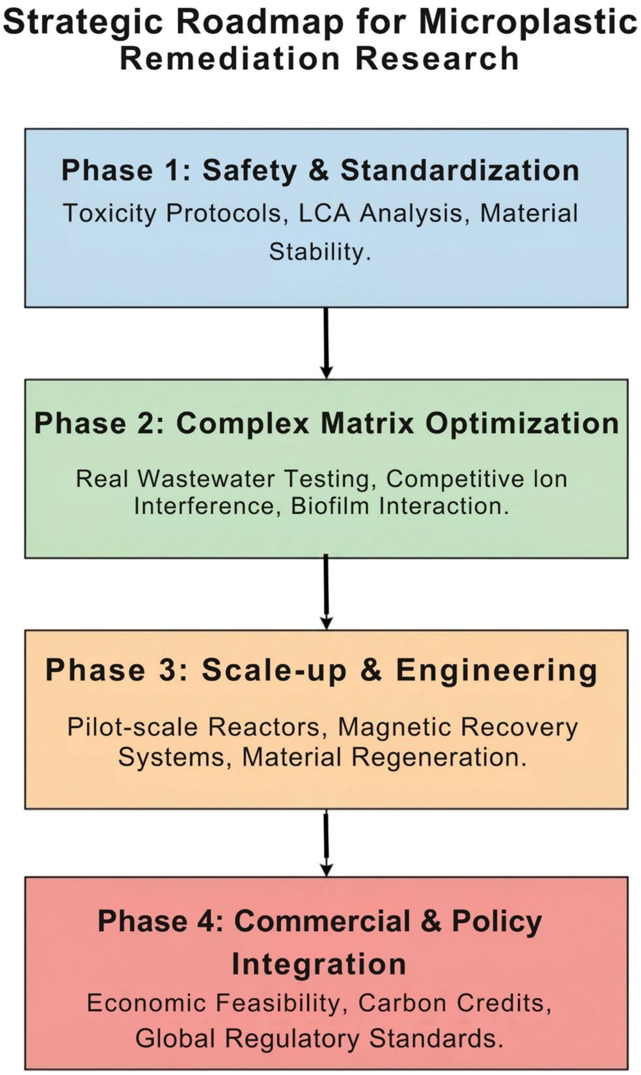


Fig. 6 Strategic research roadmap for the transition of biochar-nanomaterial composites from laboratory to real-world application

before synthesis even begins. Second, a strategic future direction involves the integration of digital twins, virtual replicas of wastewater treatment plants, that utilize reinforcement learning to simulate and optimize nano-biochar performance under fluctuating hydraulic loads. Such AI-enabled systems could dynamically adjust biochar dosages in response to real-time competition from dissolved organic matter, potentially enhancing removal efficiency while significantly reducing operational waste. Finally, advanced image processing and deep learning can be applied to automated spectral analysis, such as Raman or IR, to identify the weathering state of microplastics in situ. This enables the deployment of smart biochar surfaces that are specifically tailored to match the surface polarity and functional group density of aged environmental pollutants in real-time. By prioritizing these AI-assisted designs, the strategic roadmap ensures that advanced high-cost composites are deployed only when predictive models indicate that conventional pristine biochar will be insufficient for the targeted microplastic matrix. This structured approach moves the field toward a precision remediation model, which is essential for scaling nano-biochar from the laboratory to industrial applications. The transition of nano-based remediation from laboratory success to real-world impact requires a structured, sequential approach rather than the simultaneous pursuit of all research goals. As illustrated in the Strategic Roadmap **(**Fig. 6**)**, the research community must prioritize these challenges in an ordered manner to bridge the gap between "smart" bench-scale results and true environmental restoration.

9.1 Phase 1: Safety and Standardization (Immediate Priority)

The first prerequisite for moving beyond the laboratory is the establishment of standardized Life Cycle Assessments (LCA) and chronic toxicity protocols. While nano-enhanced biochar shows promising removal rates, its long-term interactions within different environmental matrices remain underexplored. Addressing the lack of standardized methodologies for toxicity testing is fundamental to ensuring that these materials do not create secondary pollution or unforeseen ecological risks across diverse ecosystems.

9.2 Phase 2: Complex Matrix and Environmental Optimization

Once safety benchmarks are established, research must shift toward understanding the degradation kinetics and efficacy of next-generation materials, such as AI-engineered biochar and plant-derived nanostructures, in non-effective conditions. This includes evaluating performance in the presence of competitive ions, organic matter, and microbial biofilms, which currently hinder the "real-world" efficacy of even the most advanced self-assembling nanostructures.

9.3 Phase 3: Scale-up and Pilot-Scale Engineering

The field currently suffers from a scale-of-impact barrier; laboratory results are often minimally felt in true, real-scale dimensions. Future efforts must focus on Pilot-Scale Engineering, developing reactors and magnetic recovery systems capable of handling large volumes of water or soil. This phase addresses the mechanical and structural stability of biochar composites under hydraulic flow and environmental stress.

9.4 Phase 4: Policy, Economics, and Global Integration

The final phase of the roadmap addresses the fragmented regulatory landscape. A well-defined policy framework and cost-benefit analysis (including carbon credit potential) are essential to ensure public acceptance and industrial-scale deployment. By following this ordered priority, placing safety and matrix-testing before commercialization, nano-biochar technology can be transformed into a scalable, effective, and globally accepted solution for environmental remediation.

10 Conclusion

The integration of nanomaterial and biochar presents a promising and sustainable approach for microplastic remediation, leveraging their high surface area adsorption capacity and catalytic properties. While significant progress has been made in developing hybrid-biochar systems for microplastic removal, several challenges remain in their large-scale development, including cost-effectiveness, scalability, regulatory approval, and long-term environmental impacts. Recent advancements in AI-designed biochar material, self-assembling nanostructure, and green synthesis approaches have paved the way for next-generation solutions with enhanced efficiency and sustainability. Additionally, global regulatory frameworks must be established to facilitate responsible implementation and public acceptance of nano-based remediation strategies. Future research should focus on optimizing nanomaterial-functionalized biochar for selective microplastic detention, improving degradation pathways, and addressing potential secondary pollution concerns. By filling the existing research gaps and fostering interdisciplinary collaboration between scientists, policymakers, and industries, nanotechnology-enhanced biochar can be transformed into a scalable and effective solution for mitigating microplastic contamination and promoting environmental sustainability.

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