

EMERGING ROLE OF BIOCHAR IN MICROPLASTIC REMEDIATION: MECHANISMS, APPLICATIONS, AND FUTURE PERSPECTIVES

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ABSTRACT

Microplastics (MPs) are emerging contaminants widely distributed in soil and aquatic environments, posing risks to ecosystem stability, soil functionality, and aquatic biota due to their persistence and pollutant-carrying capacity. Conventional remediation methods remain limited in efficiency and sustainability, particularly for smaller particles. Biochar, a carbon-rich material derived from biomass pyrolysis, has recently gained attention as a promising, eco-friendly solution for Microplastic (MP) remediation. This review synthesises current knowledge on the sources, distribution, and environmental impacts of MPs in terrestrial and aquatic systems. It further evaluates the physicochemical properties of biochar that enable effective interactions with MPs, including high surface area, porosity, and functional groups. Key remediation mechanisms such as adsorption, pore entrapment, electrostatic attraction, hydrophobic interactions, and $\pi-\pi$ interactions are discussed. The application of biochar in soil and water systems demonstrates significant potential in reducing MP mobility, toxicity, and associated contaminants while improving soil health and microbial activity. Advances in engineered and magnetic biochar for enhanced removal efficiency and recovery are also highlighted. However, challenges related to scalability, regeneration, and long-term environmental impacts persist. Future research should focus on field-scale validation and the development of tailored biochar systems for sustainable MP management.

KEYWORDS: Adsorption mechanisms; Aquatic systems; Biochar; Engineered biochar; Microplastic remediation; Microplastics; Soil systems

Graphical Abstract



Figure 1. Biochar-mediated mechanisms and applications for microplastic remediation in soil and aquatic environments.

1. INTRODUCTION

Microplastics (MPs), which are typically defined as plastic particles smaller than 5 mm, have emerged as widespread contaminants in both terrestrial and aquatic ecosystems due to the large-scale production and improper disposal of plastic materials (1). MPs arise from two primary sources: primary MPs, which are deliberately produced at microscopic sizes for instance, microbeads found in cosmetics and secondary MPs, which are formed from the breakdown of larger plastic debris through various physical, chemical, and biological processes (1,2). Due to their diminutive size, durability, and significant surface area-to-volume ratio, MPs can be easily transported by wind, water, and living organisms, resulting in their extensive distribution from agricultural fields to freshwater and marine environments. Their persistence in the environment and resistance to degradation render them a long-term ecological concern (3).

In aquatic environments, MPs affect both physical and biological processes (4). They diminish light penetration, which in turn impacts photosynthesis in aquatic plants and phytoplankton, and can be consumed by a variety of organisms, including zooplankton, fish, and benthic fauna (5). This consumption may lead to physical blockages, decreased feeding efficiency, and toxicological consequences due to the release of additives and absorbed pollutants (5,6). Furthermore, MPs serve as vectors for heavy metals, persistent organic pollutants, and pathogenic microorganisms, enhancing their transport and increasing their bioavailability within aquatic food webs (7). In soil systems, especially agricultural soils that receive plastic mulch, sewage sludge, or wastewater irrigation, MPs significantly modify soil characteristics (8). Research has indicated alterations in bulk density, porosity, water retention capacity, and aggregate stability as a result of MPs presence. These changes can adversely affect root development, soil aeration, and water movement (9). Additionally, MPs disrupt soil enzyme activities and the structure of microbial communities, thereby interfering with nutrient cycling and soil fertility (10,11).

The increasing awareness of the detrimental effects of MPs in both terrestrial and aquatic systems has amplified the quest for effective remediation methods (12). Nevertheless, traditional approaches such as filtration, sedimentation, and chemical treatments frequently exhibit limitations in efficiency, especially concerning smaller particles, and may incur substantial operational costs or lead to secondary pollution (13). Consequently, there is a pressing necessity to devise sustainable, cost-efficient, and eco-friendly strategies to address Microplastic (MP) contamination (2).

In this context, biochar has emerged as a promising candidate for environmental remediation. Biochar is a stable, carbon-rich substance produced from the thermochemical conversion of biomass in oxygen-limited environments (6,14). It possesses numerous beneficial properties, including a highly porous structure, a large specific surface area, and a variety of surface functional groups such as hydroxyl, carboxyl, and aromatic moieties (15). These attributes enable biochar to interact effectively with a broad spectrum of pollutants, including MPs and their associated contaminants (16,17). The potential of biochar in the remediation of MPs is rooted in its capacity to adsorb, immobilise, and modify the environmental behaviour of MPs (18).

In soil systems, the application of biochar has demonstrated improvements in soil structure, increased water retention, and enhanced microbial activity, thereby mitigating some of the adverse effects caused by MPs (19). Biochar can adsorb organic pollutants and heavy metals linked to MPs, thereby decreasing their bioavailability and toxicity (20). Moreover, its porous matrix may facilitate the physical entrapment of MPs, restricting their mobility within the soil profile (21). In aquatic environments, biochar can aid in the removal of MPs through adsorption and aggregation processes, promoting the sedimentation of particles (22). MP contamination has emerged as a significant threat to crop productivity and soil-plant interactions. MPs can alter soil physical and chemical properties, impair root growth, reduce nutrient and water uptake, and negatively affect seed germination and plant development (11,19). Their accumulation in the rhizosphere may induce phytotoxic effects, including oxidative stress, disruption of photosynthetic activity, and reduced biomass production (2). Furthermore, MPs can influence the uptake and translocation of contaminants and nutrients within plants, potentially affecting crop quality and food safety (23). Recent studies have also shown that MPs disturb beneficial plant-microbe interactions by altering rhizosphere microbial communities and nutrient cycling processes (17). In this context, biochar offers a promising plant-focused remediation strategy by improving soil structure, enhancing nutrient availability, stimulating beneficial microbial populations, and restoring plant growth under microplastic stress. Through its ability to adsorb and immobilize MPs while promoting healthy soil-plant-microbe interactions, biochar has considerable potential for maintaining agricultural productivity and sustainability in MP contaminated environments.

2. METHODOLOGY

This review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, reproducibility, and systematic selection of the literature. Relevant peer-reviewed articles published between 2010 and March 2026 were retrieved from major scientific databases, including Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar.

A comprehensive search strategy was employed using combinations of keywords and Boolean operators such as “biochar” AND “MPs”, “biochar” AND “Nanoplastics (NPs)”, “MP remediation”, “biochar adsorption”, “soil remediation”, “water treatment”, “engineered biochar”, and “magnetic biochar”. Additional studies were identified through backward reference screening of selected papers and review articles.

Initially, approximately 320 records were identified from different databases. After removing duplicate publications, 275 records remained for title and abstract screening. Based on their relevance, 185 articles were subjected to full-text assessment, and finally, 79 studies that fulfilled the inclusion criteria were selected for detailed analysis (Fig. 1). Eligible studies investigated the occurrence, transport, fate, or environmental impacts of MPs and NPs, evaluated pristine,

modified, magnetic, or engineered biochar for MP remediation in soil or aquatic environments, and reported experimental findings, adsorption characteristics, removal efficiencies, or remediation mechanisms. Studies lacking sufficient methodological details or quantitative data, focusing on remediation approaches unrelated to biochar, or consisting of conference abstracts, editorials, patents, theses, and other non-peer-reviewed documents were excluded.

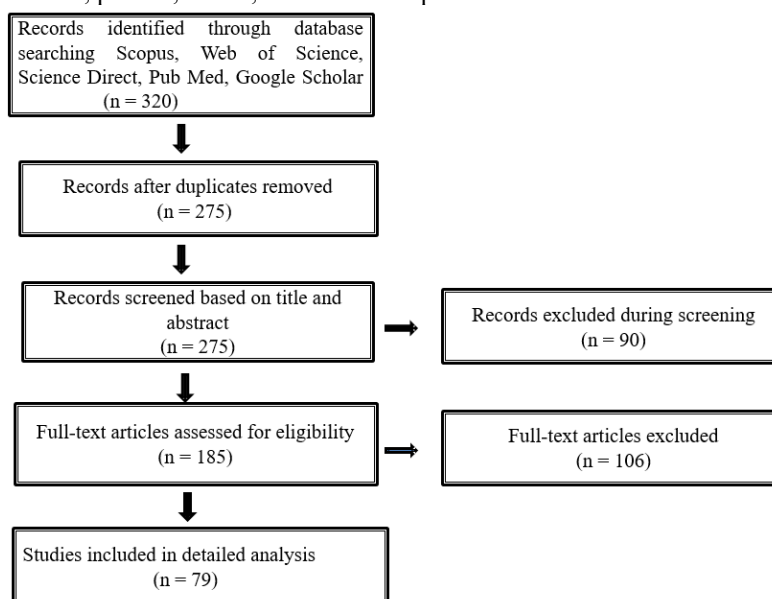


Figure 2. PRISMA flow diagram illustrating the identification, screening, eligibility assessment, and final selection of studies included in this review on biochar-mediated remediation of microplastics and nanoplastics.

From each selected study, information regarding biochar feedstock, pyrolysis conditions, physicochemical properties, characteristics of MPs and NPs, adsorption mechanisms, removal efficiencies, experimental conditions, and environmental implications was extracted. The collected information was critically synthesized and comparatively evaluated to identify the mechanisms, applications, advantages, limitations, and future prospects of biochar-based technologies for MP remediation in soil and aquatic systems.

3. Sources and Distribution of Microplastics in Soil and Water

Agricultural plastic mulch, compost, sewage sludge, and atmospheric deposition serve as key inputs to soils, in addition to synthetic fertilisers, contaminated irrigation water, slow-release fertilisers, and irrigation pipes (24) (Fig. 3). Sewage sludge is found to contain between 5,972 and 7,771 MPs per kilogram of dry weight, resulting in their accumulation with repeated applications; for instance, 40 tons per hectare of dry weight can increase the concentration from 1.1 to 3.5 particles per gram of soil after 1 to 5 applications (25,26). Street runoff, flooding, wastewater irrigation, and littering further contribute to this issue, with vertical transport occurring through ploughing (at depths of 10 to 40 cm), bioturbation, and leaching into groundwater (27). The use of plastic mulching contributes to the introduction of MPs through degradation caused by UV exposure, mechanical wear during tillage, and weathering (19,28). Research has quantified this effect, the average macroplastic residue is 35.7 kg ha⁻¹, which shows a positive correlation with the intensity of mulch usage, reaching up to 432.8 kg ha⁻¹ (29). Furthermore, the abundance of MPs in mulched agricultural lands can reach 22,675 particles per kg of soil, significantly greater than that found in non-mulched control areas at depths of 0-10 cm after extended use (30).

Rivers carry 80-94 % of plastic debris to oceans through mechanisms such as runoff, atmospheric deposition, and inadequate waste management (7). Surface waters and sediments (Table 1) are repositories for fragmented MPs, with global estimates ranging from 82 to 358 trillion pieces, corresponding to a total mass of 1.1 to 4.9 million tonnes in the surface layer alone (4). Along the Rhine River, surface MPs were quantified at median concentrations of 4.48 particles/m³ over a period of 22 months in proximity to Basel, with stormwater runoff contributing the highest average concentrations of 676 particles/L, surpassing wastewater treatment plant effluent (6,11).

Compartment	Concentrations	Dominant Polymers	Reference
Oceans – Surface Water	0.002-62.5 items m ⁻³	PE, PP, PS	(63)
Freshwater – Rivers/Lakes	0.67-376 particles L ⁻¹	PET, PP, PE	(21)
Sediments – Marine/Fresh	8.1-7588 particles kg ⁻¹	PP, PS, PE, PET	(38)
Biota – Fish GIT	0.5-98 particles/individual	PE (31 %), PP (28 %)	(16)
Wastewater (Influent/Effluent)	10 ³ -10 ⁶ particles m ⁻³	PE, PP, PET, PVC	(7)
Drinking Water (Tap/Bottled)	10-10 ⁴ particles L ⁻¹	PET, PP, PE	(7)

PE – Polyethylene, PET – Polyethylene Terephthalate, PP – polypropylene, PS – Polystyrene, PVC – Polyvinyl Chloride

Table 1. Concentration of microplastics in the aquatic environment.

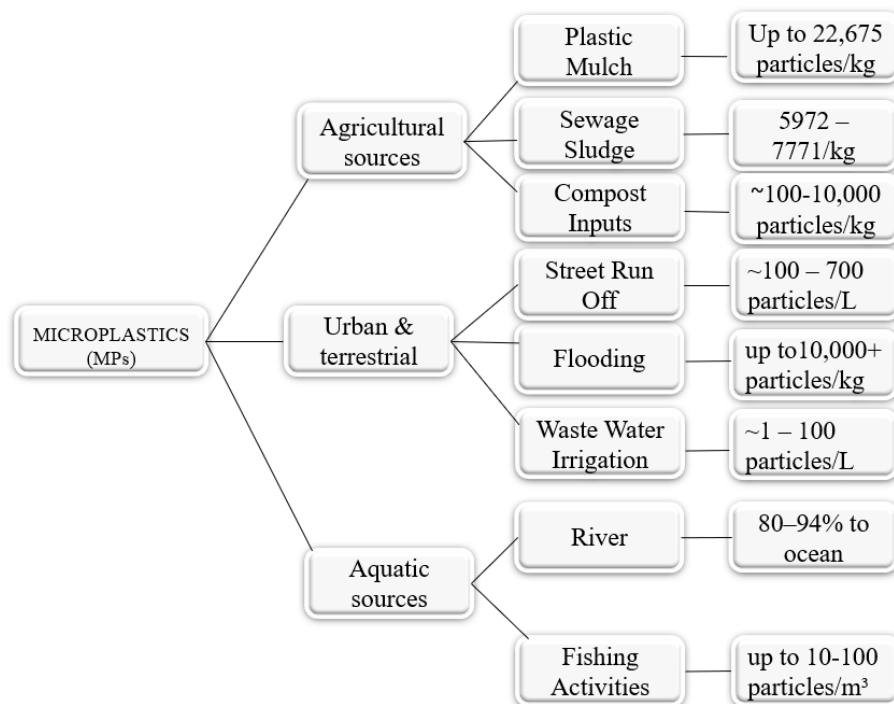


Fig. 3: Sources of Microplastics

4. Impacts of Microplastics on Soil Systems

MPs have a profound impact on the chemical composition and nutrient equilibrium of soils (31). The presence of MPs can elevate soil pH by 2.04 %, enhance soil organic carbon (SOC) by 17.8 %, while simultaneously diminishing critical nitrogen forms such as ammonium ($\text{NH}_4^+\text{-N}$) by 40.06 % and nitrate ($\text{NO}_3^-\text{-N}$) by 8.42 %, along with available phosphorus by 7.16 % (25,32). MPs disrupt biogeochemical cycles, particularly those of nitrogen and carbon, by affecting microbial genes that play a role in nitrogen cycling (*nirK*, *amoA*, *nifH*) and modifying processes related to carbon cycling, including litter decomposition and microbial respiration (24,33).

MPs have a significant impact on soil microbial communities. In comparison to control soil, the Ace index experienced a reduction of 1.68 %, the Shannon diversity index decreased by 1.70 %, and the Chao index was reduced by 0.35 % (34,35). These declines suggest that MP presence leads to a slight reduction in both microbial richness and diversity within the rhizosphere soil ecosystem (4,36). Furthermore, 56 bacterial genera exhibited an increase in abundance while 66 bacterial genera showed a decrease in abundance, reflecting significant alterations in the structure of microbial communities as a result of MP contamination (16,32). In paddy soil experiments with polystyrene (PS) MPs, MP addition significantly increased methane (CH_4) emissions, with the highest emissions occurring at 30 and 70 days after rice planting, corresponding to the tillering and heading stages (20,37).

5. Impacts of Microplastics on Aquatic Ecosystems

Ingestion of MPs leads to intestinal obstructions and misleading feelings of fullness, resulting in a 32 % decrease in growth within the foregut muscularis of zebrafish and affecting reproduction in *Daphnia magna* (8). Fish demonstrate an 85.7 % retention of fibre (ranging from 100 to 330 μm), which causes abrasions (38). The adsorption of persistent organic pollutants (POPs), including polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs), along with heavy metals and various additives such as phthalates and bisphenol A (BPA), induces oxidative stress characterised by increased levels of superoxide dismutase (SOD) and catalase (13). This process leads to inflammation and immunotoxic effects. In zebrafish, the liver accumulates PS particles ranging from 5 to 70 nm, resulting in lipid peroxidation and disruption of energy metabolism (5).

MPs diminish transparency, which hampers algal photosynthesis and leads to premature sinking (16,39). Fish behaviours change hyperactivity with a 1.3-2.4 fold increase in swimming distance in zebrafish resulting in heightened predation risk; corals are at risk of bleaching and necrosis (7). Carbon sequestration declines as MPs interfere with the sinking of faecal pellets and disrupt nutrient cycling (13).

6. Biochar: Properties and Environmental Significance

Biochar is a material abundant in carbon, created through the pyrolysis of biomass in environments with limited oxygen (15) (Table 2). It provides advantages for improving soil quality and facilitating environmental cleanup (17). The characteristics of biochar differ depending on the methods of production and the types of feedstocks used, which in turn affects its applications in agricultural practices and efforts to mitigate climate change (18).

Biochar possesses a significant surface area conducive to adsorption, along with porosity that facilitates water retention and aeration, and a low density that affects its integration into soil. The specific surface area (SSA) of biochar varies between 50 and 100 $\text{m}^2 \text{g}^{-1}$, which can increase cation exchange capacity (CEC) in soils by as much as 183 % (40). The

production process through pyrolysis at different temperatures (ranging from 350 to 700 °C) results in the formation of porous structures characterised by macropores that promote water movement and micropores that retain nutrients, as evidenced by Scanning Electron Microscope (SEM) imaging (14). Biochar is characterised by a high carbon content (up to stable aromatic forms), the presence of functional groups (such as hydroxyl and carboxyl), and an alkaline pH, which enhances its CEC for nutrient retention (19,31). Higher pyrolysis temperatures lead to increased carbon stability and pH levels, effectively reducing nutrient leaching, particularly nitrates, by 50 % (39,41). Fourier-transform infrared (FTIR) spectroscopy analysis indicates that these functional groups promote metal sorption, while the alkaline pH contributes to the neutralisation of acidic soils (20,28).

Feedstock	Preparation Conditions	Carbon Content	Application of Biochar	Reference
Banana peels	Hydrothermal carbonization, 230 °C, 2 h	71.38 %	Soil remediation of MP contamination	(18)
Pig manure	Hydrothermal carbonization, 240 °C, 2 h	23.9 %	Soil remediation of MP contamination	(52)
Rice husk	Slow pyrolysis, 500 °C, 2 h	~60-70 %	Adsorption and immobilization of MPs in soil	(68)
Corn straw	Slow pyrolysis, 450 °C, 1.5 h	~55-65 %	Improvement of soil structure and reduction of MP mobility	(49)
Wood chips	Slow pyrolysis, 600 °C, 2 h	~70-80 %	High surface area sorbent for MP retention and contaminant adsorption	(44)
Wheat straw	Slow pyrolysis, 500–550 °C, 2 h	~60-75 %	Enhances soil aggregation and reduces MP transport	(70)
Sewage sludge	Pyrolysis, 500–700 °C	~40-60 %	Sorption of MPs and co-contaminants (heavy metals, organics)	(10)
Sugarcane bagasse	Pyrolysis, 600–750 °C	~65-80 %	High porosity biochar for nanoplastic adsorption in water	(62)
Bamboo	Slow pyrolysis, 500–700 °C	~70-85 %	High surface area and aromaticity for MP adsorption	(35)
Coconut shell	Pyrolysis, 700–800 °C	~75-90 %	Strong adsorption capacity due to microporous structure	(71)
Algae biomass (<i>Ulva</i> , <i>Chlorella</i>)	Hydrothermal carbonization/pyrolysis (200–500 °C)	~50-65 %	Removal of nanoplastics via aggregation and adsorption	(4)
Sawdust	Slow pyrolysis, 400–600 °C	~65-75 %	Improves soil carbon stability and reduces MP bioavailability	(2)

Table 2. Types of feedstocks and preparation conditions of biochar.**7. Mechanisms of Microplastic Remediation by Biochar**

Biochar effectively eliminates MPs via various adsorption mechanisms, frequently attaining efficiencies exceeding 95 % in laboratory environments, especially for PS and polyethylene (PE) particles less than 10 μm (2). Various types of feedstocks are used for the production of biochar and, based on their composition and pyrolysis temperature, their removal efficiencies differ (42) (Table 3).

Physical processes play a crucial role in the removal of MPs by biochar, mainly through mechanisms such as pore filling and mechanical interception, which involve the capture of MPs within the biochar's complex honeycomb-like porous structure (22). Smaller particles often show higher adsorption due to larger surface area (2). Larger particles were removed through filter columns due to mechanical straining (35,42). This process is particularly effective for MPs larger than 1 μm , as evidenced by corn straw biochar pyrolysed at 500 $^{\circ}\text{C}$, which successfully traps 10 μm PS spheres via a three-stage immobilisation process: stuck, trapped, and entangled (43) (Fig. 4).

Chemical interactions play a crucial role in enhancing the removal of MPs by biochar, supplementing physical trapping through specific molecular forces that achieve over 90 % adsorption for various polymers (3,44). These interactions encompass electrostatic attraction resulting from zeta potential mismatches, for instance, PS nanoplastics (PSNPs) at $\zeta = -34.5$ mV interacting with Fe-modified biochar at $\zeta = +30$ mV, leading to a 99 % removal rate at pH 6–8, hydrogen bonding facilitated by the oxygen-rich functional groups of biochar ($-\text{OH}$, $-\text{COOH}$; 2–5 mmol g^{-1} following HNO_3 treatment), π – π stacking interactions between the graphitic domains of biochar and the benzene rings of PS; and hydrophobic partitioning that preferentially targets nonpolar PE/polypropylene (PP) through London dispersion forces (45) (Fig. 5).

High-temperature pyrolysis (exceeding 600 $^{\circ}\text{C}$) facilitates the aromatisation of biochar, resulting in an increase of aromatic carbon by 70–90 %, allowing π – π electron donor–acceptor (EDA) stacking with PS aromatics. X-ray photoelectron spectroscopy (XPS) analysis reveals shifts in the C1s π^* peak from 284.5 to 285.2 eV (29,46). Nonpolar MPs (PE, PP) distribute into the hydrophobic core of biochar, adhering to linear free energy relationships ($\log K_{ow} \propto \log q_e$, $r^2 = 0.92$), with rice straw biochar (700 $^{\circ}\text{C}$) attaining 99.96 % removal of 300 nm PSNPs through multilayer hydrophobic stacking (47).

Biochar Type	Pyrolysis Temp ($^{\circ}\text{C}$)	Pore Distribution	MP Size Retained	Efficiency (%)	Reference
Corn straw	500	Meso > micro	10 μm PS	~95	(49)
Hardwood	400-500	Macro > meso	10 μm PS	~93	(22)
Pine sawdust	550	Micro > meso	1 μm PS	94.8	(4)
Rice husk	700	Micro-dominant	300 nm PSNPs	99.6	(68)
Corn cob biochar	500	Meso-micro	PSNPs (~100 nm)	~90	(72)
Woodchip biochar	700	Macro-meso porous	1 μm PS	~85	(46)
Sugarcane bagasse biochar	750	Micro-meso dominant	<500 nm PSNPs	~99	(21)
Jujube biomass biochar	700	Micro–meso	PE MPs	>99	(17)
Banana peel biochar	500-600	Meso–macro	PS MPs (μm range)	>90	(55)
Sludge + red mud biochar (magnetic)	700	Macro–meso	100 nm PS	~90-98	(61)

Mg/Zn modified magnetic biochar	~600	Micro-meso enhanced	1 μ m PS	98.7-99.5	(44)
Fe-modified lignin biochar	600-700	Micro-meso	PS MPs	~99	(73)
Rice straw biochar	700	Micro-dominant	300 nm PSNPs	89.9	(74)
Pinewood biochar	550	Micro-meso	1 μ m PS	~94.8	(75)
Corn stem	650	Meso-micro	1 μ m PE, PP	90-95	(38)

PP – polypropylene, PS – Polystyrene, PSNPs – Polystyrene Nanoplastics, PE – Polyethylene

Table 3. Effect of biochar feedstock, pyrolysis conditions, and pore structure on microplastics retention efficiency.

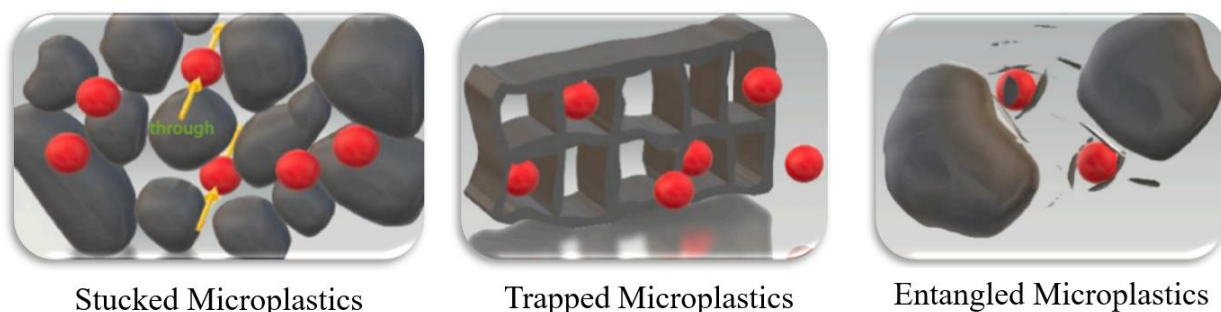


Fig 4: Removal mechanism of biochar to MPs

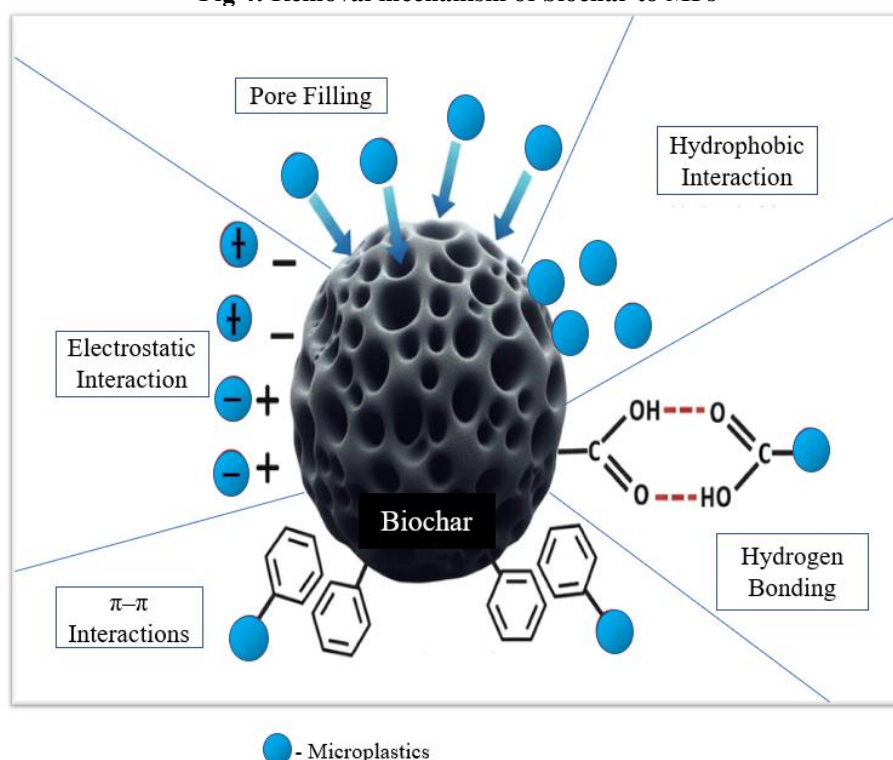


Fig. 4: Schematic representation of the multifaceted mechanisms underlying biochar-mediated microplastic remediation in soil and aquatic environments.

8. Biochar-Based Remediation in Soil Systems

Biochar effectively mitigates the negative impacts of MPs within soil-plant-microbe systems by improving nutrient cycling, enzyme activities, and microbial functions (9,48). The specific mechanisms involved encompass the adsorption of MPs, the facilitation of degradation processes, and the rejuvenation of soil fertility, with the quantitative advantages differing according to the type of MPs (Table 4) and the rates of application (25,32).

Microplastic	Biochar Feedstock	Preparation Condition	Duration of Cultivation	Interaction Mechanism	Reference
LDPE	Oilseed rape (OSR), soft wood pellet (SWP)	550 °C, 700 °C	100 days	Soil properties	(32)
PE	Straw biochar, pig manure biochar	500 °C, 4 h	45 days	Reducing greenhouse gas emissions	(52)
PVC	Cotton stalks	650-750 °C	21 days	Soil properties	(38)
PVC	Corn cob	500 °C, 3 h	14 days	Enzyme activities	(76)
PS	Food waste	500 °C, 20 min	5 weeks	Soil properties	(10)
PS	Peanut	450 °C, 4 h	80 days	Soil microorganisms	(77)
PVC	Corn cob biochar	–	20 days	Plants	(37)
PE	Corn stalk biochar	600 °C	300 days	Soil micro-organism	(45)
PS	Wheat straw and cow dung	500-700 °C	24 h	Soil properties	(78)

LDPE - Low-Density Polyethylene, PE – Polyethylene, PS – Polystyrene, PVC – Polyvinyl Chloride

Table 4. Effects of biochar feedstock and pyrolysis conditions on microplastic interactions in soil.

8.1 Plant Growth Advantages

The application of biochar has been shown to enhance the dry matter of wheat shoots in soil contaminated with polyvinyl chloride (PVC-MPs) (0.25-0.5 % w/w), effectively mitigating the adverse effects of PVC-MPs on urease (11.93-18.75 %) and dehydrogenase (5.98-9.11 %) activities (42,48). In the case of sugarcane, the introduction of 2 % biochar resulted in an increase in aboveground biomass, counteracting the reductions caused by MPs of 4.2-8.6 % for aboveground and 22.6-37.9 % for belowground biomass, while also enhancing total nitrogen content (1.46-1.66 g kg⁻¹) and microbial biomass C/N ratios (29,49). For peanuts, the use of 2 % peanut-shell biochar combined with 1.5 % PS-MPs led to significant increases in root biomass (37.35 %), root length (up to 1.68-fold), root volume, and surface area, alongside a decrease in reactive oxygen species (ROS) accumulation (32,50).

8.2 Soil Property Enhancements

Biochar has been shown to elevate soil pH from a range of 3.96-4.08 to 7.94, increase organic carbon content from 12.71–19.14 g kg⁻¹, and enhance nutrient levels, with total nitrogen rising from 33.96-40.77 % (12,49). This improvement counteracts the pH reductions (0.39-0.48 units) and decreases in microbial biomass carbon (MBC) by 12-17 % associated with MP presence (25,33). In soils containing low-density polyethylene MPs (LDPE), biochar treatment modified pH, electrical conductivity, and total electrical conductivity during wetting and drying cycles, effectively reducing microplastic penetration; specifically, the addition of 15 % biochar reduced the escape of MPs to approximately 2 % compared to 8.74 % without biochar (12,15).

8.3 Microbial Community Shifts

Biochar enhanced bacterial diversity (OTUs/Chao1/Shannon increased), promoting *Actinobacteria* while mitigating the reductions of gram-negative bacteria (10.09-12.97 %) and *Pseudomonas* (23.31-41.24 %) caused by MPs; arbuscular mycorrhizal fungi (AMF) increased by 7-13 % (14,23). In peanuts, biochar reinstated the diversity suppressed by PS-MPs (Ace/Chao1/Shannon decreased by 1.68-1.70 %) and enriched nitrogen cycle genera (e.g. *Nitrospira*) with *nifH*/*nirK* genes increased (47,51). Biochar stimulated the growth of *phoD*-bacteria (such as *Amycolatopsis* and *Bradyrhizobium*) and associated functions including aerobic NH₃ oxidation and denitrification (23,26).

9. Biochar-Based Remediation in Aquatic Systems

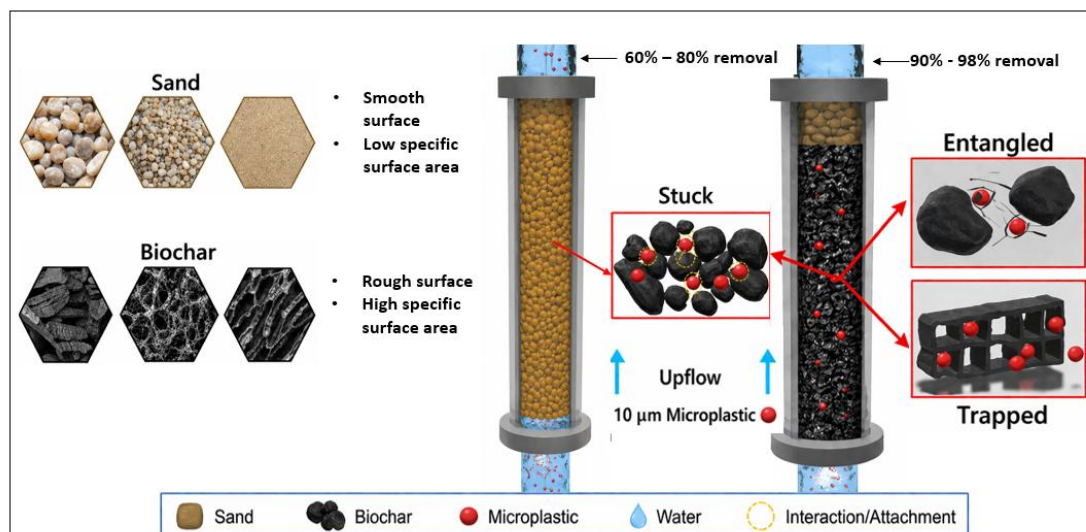
Biochar effectively eliminates 90-99 % of MPs under laboratory conditions (2). However, in real water scenarios, the removal rate decreases to 15-40 % due to the presence of dissolved organic matter (DOM) and ions (9,41). Modified biochar forms, such as magnetic, CTAB, and nZVI, demonstrate superior performance, achieving removal rates of 95-100 % for PS, PE and polyamide (PA) particles ranging from 1 to 15 µm (33,52). Notably, the combination of pine biochar and persulfate results in complete mineralisation of PA MPs within 6.76 days (34,53).

Continuous-flow biochar columns demonstrate remarkable efficiencies in MP removal (Table 5) (Fig. 6), frequently surpassing 90-99 % when conditions are optimised (46,7). Among the different types, woodchip-derived biochar produced at 700 °C in thin layers exhibits superior performance, successfully retaining 100 % of 1 µm MPs even at a flow rate of 160 m d⁻¹ or after processing 100 pore volumes (15,55). Thin layers of biochar (0.5-1 wt%) in sand columns enhance retention by decreasing porosity, modifying effluent chemistry, increasing pH and ionic strength, and improving adsorption capabilities (39,46).

The surface area and pore structure of biochar are significantly influenced by pyrolysis temperature (22,56). An increase in pyrolysis temperature enhances the porosity, aromaticity, and adsorption capabilities of biochar, indicating that the development of surface area and pore structure plays a crucial role in the removal of MPs (14,57). Surface functional groups, including oxygen-containing groups such as Fe–O, C–O, and C=O, have been identified as crucial for MP removal due to their facilitation of surface complexation, hydrogen bonding, and electrostatic interactions (56,58).

Smaller MP particles tend to exhibit greater removal efficiency, as adsorption is more effective for finer particles; a particular study revealed a significantly enhanced removal rate when PA particles measured less than 75 µm (12,23). The process of ageing and weathering has led to an increase in surface roughness, a decrease in particle size and crystallinity, and the introduction of additional oxygen-containing groups on PA MPs, resulting in an enhancement of removal efficiency from approximately 25 % for pristine particles to around 97 % for aged particles (27,59). pH level influences the surface charge and the strength of interactions; an increase in pH may lead to a decrease in adsorption capacity (15,59). The ionic strength, the presence of dissolved substances, nutrients, humic compounds, and the composition of the water matrix can influence electrostatic repulsion, competitive interactions, and the overall retention of MPs on biochar (20,60).

Biochar Type/Source	Preparation/Modification	MP Type/Size	Efficiency (%)	Matrix/Conditions	Reference
Woodchip biochar	700 °C	PS-COOH (1 µm)	~94 %	Thin layer (1 wt%), 4-160 m d ⁻¹	(46)
Banana peel biochar	–	PS (150-300 µm)	~92 %	Fixed-bed column, 6 cm bed	(4)
Hardwood activated carbon	–	PS (10-15 µm), PET (6-9 µm)	96.8 %, 95.5 %	Sand filtration column, 180 mL h ⁻¹	(36)
Corn straw biochar	500 °C	PS (10 µm)	>95 %	Column filtration, 180 mL h ⁻¹	(74)
Cellulose-derived biochar	400–700 °C	PS (1 µm)	~95-98 %	Thin permeable layer	(28)
Lignin-derived biochar	400–700 °C	PS (1 µm)	90-98 %	Thin-layer filtration	(46)
Pinewood biochar	900 °C	Mixed MPs (PE, PS, PET)	85-90 %	Packed column (20-30 cm)	(75)
Sugarcane biochar	500 °C	Mixed MPs	~70-90 %	Column system (20 cm bed)	(75)
Macadamia shell biochar	–	PE (50-300 µm)	78-96 %	Fixed-bed column	(62)
Biochar–kaolin composite	–	Mixed MPs	~97 %	Bioretention column	(71)
Fe–Mn modified biochar	–	PS MPs (µm range)	>90 %	Fixed-bed column	(30)
CTAB-modified magnetic rice husk biochar	Chemical modification	PS (15 µm)	95.7 %	Batch system, DI water	(44)
Sugarcane bagasse biochar	Functionalized	Nanoplastics (<1 µm)	>90 %	Lab-scale aqueous system	(62)
Magnetic Fe-modified biochar	–	PHBV MPs	>90 %	Wastewater reusable system,	(70)
Sludge-derived magnetic biochar	–	PSNPs (~100 nm)	~95–98 %	Batch + magnetic separation	(55)
Rice straw biochar	700 °C	PSNPs (300 nm)	89-93.9 %	Batch aqueous system	(60)

Table 5. Removal efficiency of microplastics by biochar-based materials under various experimental conditions.**Fig. 6: Schematic Illustration of Microplastic Capture Mechanisms in Biochar- Amended Filtration Systems****10. Modified and Engineered Biochar**

Magnetic biochar is a composite material characterised by a carbon-rich porous structure that incorporates magnetic recovery agents, typically iron-based nanoparticles such as magnetite (Fe_3O_4) or hematite (Fe_2O_3) (53,61). This composition enables the adsorbent to be efficiently separated from aqueous solutions through the application of an external magnetic field (35,62). This process is often preceded by pre-treatment or co-precipitation with metal salts (e.g. FeCl_3 or MgCl_2) to enhance the magnetic properties and surface functionality of the resulting char (41,59).

To mitigate the impacts of MPs and NPs in aquatic environments, magnetic biochar employs a synergistic approach combining physical and chemical mechanisms (60,63) (Table 6). These include electrostatic attraction between the biochar surface and plastic particles, π - π interactions involving the aromatic rings of polymers such as PS, and surface complexation through oxygen-containing functional groups (21,27). In soil ecosystems, modified biochars can function as catalysts that promote the generation of ROS, including hydroxyl radicals ($\cdot\text{OH}$), which facilitate the oxidative fragmentation and transformation of MPs while concurrently modifying the rhizosphere microbiome to support bacteria that can withstand plastic-induced stress (9,64).

Biochar Type	Target Plastic	Efficiency/Capacity	Key Mechanism(s)	Reference
Magnetically Modified Hemp Straw	1 μm PS	89.97 % removal (9.3 $\times$ higher than pristine)	Electrostatic interaction, chemical bonding, π - π interactions	(44)
Mg/Zn Modified Magnetic Biochar	1 μm PS	98.75 % (Mg) & 99.46 % (Zn) removal	Electrostatic & chemical bonding; catalytic degradation for regeneration	(72)
Rice Husk + CTAB Magnetic Biochar	1 μm PS	98 % removal; 247.52 mg/g capacity	Predominantly chemisorption, surfactant-enhanced attraction	(79)
Iron-Modified (<i>Ulva prolifera</i>) Biochar	NPs	V-shaped removal (pH 2-11)	pH-dependent: transition from adsorption to heterogeneous aggregation	(30)

Magnetic Rice Husk (MRB)	Microplastics	Up to 99.96 % removal	Spontaneous process; hydrogen bonding and surface complexation	(54)
Sugarcane Bagasse Biochar	NPs	>99 % removal (at 750 °C pyrolysis)	Pore abundance and high surface area from high-temp pyrolysis	(69)
Iron-Modified Magnetic Biochar (FB-850)	NPs (30-1000 nm)	225.11 mg g ⁻¹ capacity	Ultrafast removal (<10 min); heterogeneous surface interaction	(30)

PS – Polystyrene, NPs – Nanoplastics

Table 6. Modified biochar for microplastic removal

11. CHALLENGES AND LIMITATIONS

Although biochar is relatively inexpensive to produce on a small scale, the volumetric demands for treating hectares of contaminated land or millions of litres of wastewater are immense (34,65). The development of infrastructure capable of consistently producing and applying biochar at this scale, without exacerbating the carbon footprint associated with transportation, presents a significant logistical challenge (53,58). Furthermore, biochar is not a homogeneous product. Its efficacy is influenced by the type of feedstock used and the pyrolysis temperature (63,66). Differences in pore size can hinder the entrapment of larger MPs, and variability in aromaticity and functional groups imply that one batch may effectively bind MPs while another may not (26).

Once biochar reaches a state of saturation, it transforms into a waste product (67,68). If biochar is left in the soil, MPs may eventually leach back into the environment as the biochar deteriorates (69). The process of cleaning biochar for reuse necessitates high temperatures, which are energy-intensive and may compromise structural integrity (20,40). Magnetic biochar, often enhanced with iron oxides, is advantageous for recovery; however, the chemical precursors and energy required for this synthesis can increase costs by 200–500 % (34,67). Even when MPs are deemed immobilised, they are merely adhered and not eliminated activities such as tilling fields can physically disrupt the bonds between biochar and MPs (36,65). In actual environmental contexts, MPs are seldom the sole contaminant; Natural Organic Matter (NOM) and DOC frequently compete with MPs for the same pores and functional groups (48,56). Over time, bacteria and algae develop biofilms on the biochar's surface, obstructing pores and hindering interaction with MPs. Low-quality biochar may unintentionally introduce its own contaminants, including PAHs or heavy metals, into the soil (29,51).

12. CONCLUSIONS AND FUTURE PERSPECTIVES

This review provides an overview of the utilisation and mechanisms of biochar in the removal of MPs from both water and soil environments. Biochar acts as a remediation agent for MPs in soils, alleviating the negative impacts of MPs on soil and water properties, enzyme activities and the soil microbial community. Nevertheless, large-scale application is hindered by obstacles such as limited recovery and regeneration of exhausted biochar, potential secondary pollution risks arising from modification techniques and uncertainties regarding end-of-life management.

Future investigations should prioritise the enhancement of predictive and high-throughput methodologies, incorporating machine learning-assisted design and molecular-level simulations, to create precision-engineered biochars specifically designed for various polymer types. Additionally, it is crucial to assess biochar efficacy within complex real-world environments, particularly in light of eco-corona formation and interactions with co-contaminants. Integrated remediation approaches, such as microbe-biochar composites and coupling with phytoremediation, present considerable promise for synergistic MP removal. Life cycle assessments and principles of the circular economy are vital to guarantee both environmental and economic sustainability, particularly through the use of waste-derived feedstocks. Ultimately, the establishment of standardised recovery systems, including magnetic biochar technologies, along with safe disposal or regeneration protocols, is essential for facilitating the practical and responsible use of biochar in the remediation of MPs.

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