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Biochar-Based Adsorbents for Micro- and Nanoplastics Removal from Water: A Critical Review on Mechanistic Insights, Challenges, and Future Perspectives

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ABSTRACT

Micro- and nanoplastics (MNPs) have emerged as persistent and ubiquitous contaminants in aquatic environments due to their small size, chemical stability, and strong affinity for toxic pollutants, posing significant risks to ecosystems and human health. Conventional water treatment technologies are largely ineffective for their removal, necessitating the development of innovative and sustainable remediation strategies. Among emerging solutions, biochar has gained considerable attention as a low-cost, eco-friendly, and efficient adsorbent. This review critically evaluates recent advances in biochar-based adsorbents for the removal of MNPs from water systems. Particular emphasis is placed on the role of physicochemical properties, including surface area, porosity, surface functional groups, and pyrolysis conditions, as well as the impact of modification techniques on adsorption performance. Key removal mechanisms, such as pore filling, electrostatic attraction, hydrophobic interactions, surface complexation, and π–π electron donor–acceptor interactions, are systematically analyzed. Comparative assessment of different biochar types indicates that iron-modified and corncob-derived biochars exhibit superior adsorption efficiencies. However, despite promising laboratory-scale performance, several challenges remain, including limited regeneration capacity, potential secondary pollution, and reduced efficiency under complex environmental conditions. Future research should focus on optimizing biochar modification, integrating adsorption with complementary treatment technologies, and conducting life cycle and techno-economic assessments. Overall, biochar represents a promising and sustainable approach for mitigating micro- and nanoplastic pollution in aquatic systems, although further research is required to enable large-scale application. However, the lack of standardized evaluation frameworks and limited validation under realistic environmental conditions restrict the comparability and scalability of current findings.

Keywords: Nanoplastics; Microplastics; Removal; Biochar; Plastic Pollution; Water Pollution; Electrostatic Attraction; Hydrophobic Interaction.

1. Introduction

Micro- and nanoplastics (MNPs) have emerged as persistent and ubiquitous contaminants in aquatic environments, drawing increasing global concern due to their ecological and human health implications [1–2]. These particles originate from both primary sources (e.g., personal care products and industrial applications) and secondary sources, including the fragmentation of larger plastic debris [3–4]. Owing to their small size, chemical stability, and hydrophobic nature, MNPs resist natural degradation and are inadequately removed by conventional wastewater treatment processes [5]. Consequently, they accumulate in aquatic organisms and may enter the human food chain through bioaccumulation, raising concerns regarding long-term toxicological effects [6–7].

MNPs, commonly composed of polymers such as polypropylene (PP), polystyrene (PS), polyethylene (PE), and polyamide (PA), have been widely detected in water bodies, sediments, and biological tissues [8]. Their environmental distribution is facilitated by diverse pathways, including surface runoff, atmospheric deposition, tire abrasion, industrial discharge, and wastewater effluents [9]. Once in aquatic systems, these particles undergo physicochemical and biological transformations that alter their surface properties, reactivity, and interaction with co-existing pollutants [10]. Such transformations complicate their environmental behavior and challenge the predictability of removal processes under realistic conditions. The widespread occurrence and persistence of MNPs necessitate the development of efficient and sustainable remediation strategies [11–12]. However, conventional treatment technologies, including filtration, sedimentation, and coagulation, are often ineffective due to the small size, low density, and colloidal stability of these particles [13–14]. Adsorption has emerged as a promising alternative, particularly using carbon-based materials with high surface area and tunable surface chemistry [15–16]. Nevertheless, widely studied adsorbents such as activated carbon and carbon nanotubes, while effective, are often limited by high production costs, energy-intensive synthesis, and potential environmental risks, thereby constraining their large-scale application.

In comparison, biochar offers a more sustainable and cost-effective alternative due to its derivation from abundant biomass waste and relatively simple production via pyrolysis [17–18]. Unlike activated carbon, biochar can achieve comparable adsorption performance with lower energy input and without extensive activation processes. Moreover, its hierarchical pore structure, surface functional groups, and modifiable surface chemistry enable tailored interactions with MNPs [19]. However, current studies reveal significant variability in adsorption performance depending on feedstock type, pyrolysis conditions, and surface modifications, highlighting a lack of standardization and comparability across the literature.

Critically, while mechanisms such as electrostatic attraction, hydrophobic interactions, pore filling, and π–π stacking are frequently reported, their relative contributions remain largely qualitative and context-dependent. For instance, high-temperature biochars tend to favor hydrophobic and π–π interactions, whereas chemically modified biochars enhance electrostatic interactions; however, these findings are often derived under simplified laboratory conditions that do not reflect the complexity of real water matrices. Furthermore, the presence of competing ions and natural organic matter can significantly suppress adsorption efficiency, yet such effects are insufficiently addressed in existing studies.

Therefore, despite the growing body of research, key gaps remain in understanding the mechanistic dominance, scalability, and environmental sustainability of biochar-based systems. This review critically evaluates recent advancements in biochar-mediated removal of MNPs, with particular emphasis on mechanistic insights, performance variability, and practical limitations. It further identifies research gaps and outlines future directions aimed at developing scalable, efficient, and environmentally sustainable biochar-based water treatment technologies.

1.1. Study Objectives

(1) To critically evaluate recent research advancements in biochar-based adsorbents for the removal of micro- and nanoplastics from aqueous systems. (2) To assess the influence of physicochemical properties of biochar on adsorption efficiency and removal performance. (3) To compare the effectiveness of biochar derived from different feedstocks and synthesis methods in micro- and nanoplastics removal. (4) To identify key challenges and limitations associated with the large-scale application of biochar in water treatment systems. (5) To propose future research directions for enhancing the sustainability, scalability, and practical implementation of biochar-based technologies in water treatment.

2. Biochar-Adsorbent Technology

Biomass biochar (BC) is inexpensive, possesses a high capacity to adsorb environmental pollutants due to its large surface area, porosity, eco-friendliness, and functional groups. The nanostructure properties and surface groups are major contributors to the surface areas. According to Panahi et al. [17], high-temperature biochar (~750°C) exhibits a larger surface area, enhanced pore filling, reduced carbonyl group content, and an impressive removal efficiency of approximately 99% within four minutes, outperforming PS nanoparticles. The mesoporous biochar with a high surface area, porosity, and structural capacity demonstrated reusability up to 5 cycles with a maximum adsorption capacity of 45 mg g-1, while CTAB-modified rice straw biochar was used to remove polystyrene microplastics [21]. Surface modification by the alkyl groups facilitated surface activity, which resulted in a high removal efficiency of 99.56% in the experiment [21]. The adsorption capacity of biochar can be greatly influenced by surface modification and pyrolysis temperature. The subsequent oxidation treatment with HNO_3/H_2SO_4 at 900°C increases the oxygen-containing groups and specific surface area of corncob biochar, which favors hydrogen bonding interactions to improve PS MPs/NPs removal [22]. The characteristics of biochar are maintained well and possess high reusability during the decomposition procedure. Fe-BC composite has been demonstrated to possess great applications in removing polystyrene microplastics, while it can be reused up to three times [23-24]. According to Shi et al. [25], a removal capacity of approximately 95.2% of nanoplastics was reported using magnetic biochar made at 500 °C.

Adsorption properties of biochar on micro/nanoplastics are influenced by pyrolysis temperature, surface functionalities, hydrophobicity, or modification. High-temperature biochar shows favourable properties to create interlocking mechanisms like π-π interaction, hydrogen bonding, electrostatic forces, or aggregation. With the increasing diversity in micro and nanoplastics composition, improvement in the properties of biochar for efficient removal technology becomes essential. However, direct comparison across studies remains challenging due to significant variations in experimental conditions, including differences in polymer type, particle size, water chemistry, and adsorption metrics. As a result, reported removal efficiencies may not accurately reflect intrinsic material performance. Furthermore, many studies emphasize high removal efficiency without adequately addressing energy input, material stability, or environmental trade-offs. This limits the ability to identify truly optimal biochar systems for scalable applications.

3. Results

Biochar mechanisms for micro/nanoplastics removal

The adsorption of micro/nanoplastics onto biochar occurs primarily through five mechanisms: pore filling, electrostatic interaction, surface complexation, hydrophobic interaction, and π–π stacking (Fig. 1). Pore filling enables the physical entrapment of plastic particles within biochar's porous structure. Electrostatic attraction arises from charge differences between biochar and the typically negative surface of plastic particles. Surface complexation occurs when oxygen-containing functional groups on biochar form coordination bonds with plastics or surface metals. Hydrophobic interactions facilitate aggregation between the hydrophobic surfaces of biochar and plastics, especially at higher pyrolysis temperatures that increase surface hydrophobicity. Finally, π–π stacking results from interactions between aromatic rings in biochar and those in polymer backbones, enhanced by high-temperature pyrolysis that promotes biochar aromaticity and electron-rich domains. These complementary mechanisms collectively contribute to the high adsorption efficiency observed in various studies (summarized in Table 1).

These mechanisms are discussed below.

1) Pore filling: nano/microplastics are difficult to remove due to their small particle size. In comparison, biochar is porous, and the particles are physically enclosed, resulting in the saturation of pores and eventually adsorbing micro/nanoplastics [21].

2) Electrostatic interaction: Adsorbents are electrostatically based, and this forms a nucleation point, which leads to the eventual formation of crystals to remove the pollutant. In the case of micro/nanoplastics, adsorbents with a positive surface charge are more suitable to achieve optimal adsorption efficiency due to the overall negative surface charge of the micro/nanoplastics [20, 26]. Nevertheless, electrostatic attraction may be reduced in high-ionic-strength conditions as the counterions can neutralize the biochar surface charge [10]. During high-temperature pyrolysis, the polarity of biochar decreases, which increases its hydrophobicity and enhances MP/NP adsorption. Electrostatic forces also play a role in adsorbing micro/nanoplastics by physical interception, including pore filling and filtration.

3) Surface complexation: The surface of the adsorbent can also have various oxygen-based functional groups and thus forms complexes with plastic micro/nanoparticles. The addition of metals to adsorbents or micro/nanoplastics could improve metal complex formation [27].

4) Hydrophobic contact: Nano/Microplastics can be hydrophobic, which allows hydrophobic adsorbents to form aggregates and capture the hydrophobic micro/nanoparticles of plastic [27]. According to the study of Omorogie & Helmreich, [28], they noted that the migration of MPs/NPs in the water is a growing concern across the world since it has been associated with serious ecological degradation. Also, Dong et al. [12] noted that pollutants that are more hydrophobic are easier to eliminate by biochar because they have a more pronounced attraction to the hydrophobic surface of this material. The higher the pyrolysis temperature, the more functional polar groups on the biochar surface, and thus, the biochar is hydrophobic. The hydrophobic interactions are some of the most predominant forces that determine the adsorption of MP/NP onto biochar, with other mechanisms involved.

5) π–π EDA stacking: High aromatization intensity, association between aromatic ring micro/nanoplastics, and acidic functional groups (such as C–O or O–C=O bonds) can serve as an electron-transfer site between micro/nanoplastics and adsorbents to facilitate π-π stacking interactions [29]. In pyrolysis processes, charge differences between aromatic cycles result in areas rich or depleted in electrons for biochar. Valence interactions and π-π bonding are crucial processes for highly aromatic micro/nanoplastics adsorption with a benzene ring [30]. During pyrolysis processes, charge differences between aromatic cycles result in areas rich or depleted in electrons for biochar. At lower and high pyrolysis temperatures (<500°C), biochar acts as an electron acceptor due to its polar groups. At higher pyrolysis temperatures (>500°C), biochar acts as an electron donor because of its free electrons. Higher biochar ordering occurs with increased pyrolysis temperatures. These promote biochar-micro/nanoplastic interactions due to improved biochar ordering [31]. π-π bonding and Valence interactions are crucial in highly aromatic micro/nanoplastics adsorption with a benzene ring [30].

Table 1. Literature review of recent development of biochar adsorbents for micro/nanoplastics removal until 2025.

Biochar Adsorbents	**Pyrolysis**	**Post-Modification**	**MP/NP Type**	**MP/NP Size / Shape**	**Removal Performance**	**Mechanism of Removal**	**Ref.**
Coconut Shell + Palm Kernel Shell	600 °C	—	Amine-modified PS (A100)	100 nm, amorphous	46.71 mgg^{-1}	Electrostatic binding	[32]
Coffee waste	Treated with $(NH_4)H_2PO_4$	—	PS	~6 µm spheres	4.78–4.85 mgg^{-1}	Hydrophobic interaction	[28]
Corncob biochar	500 °C	Magnetization (iron)	PS (pristine & aged)	27–307 µm	1145–1737 mgg^{-1}	Electrostatic attraction	[33]
	500 - 900 °C	Oxidation with 5% H_2SO_4 / HNO_3	PS (Polystyrene)	~50 nm	15.22–23.98 mgg^{-1}	π–π EDA and electrostatic attraction	[22]
	500 °C	—	PS	50 nm	74.40–126.37 mgg^{-1}	Surface area and π–π stacking drive adsorption.	[21]
Fe/Mg-layered double oxides	—	—	PS	100 nm	57.9 mgg^{-1}	Electrostatic attraction, π-π stacking	[34]
Filamentous algae	400–600 °C, ± $Fe(NO_3)_3$	Magnetization (iron)	PS	1 µm spheres	176.99–215.58 mgg^{-1}	Surface area	[35]
Iron-modified biochar	—	Iron impregnation ($FeCl_3$) + thermal treatment	PS	100 nm	1626.3 mgg^{-1}	Electrostatic attraction, hydrophobic π–π interactions, complexation	[24]
Jujube Leaf Waste	300 and 700 °C	—	PE and NY	≤10 µm pellets	≥98% removal	Surface area and hydrophobic sites	[36]
London plane bark	500 °C	—	Oxidized PS	3 µm	24.01–34.29 mgg^{-1}	Hydrogen bonding and electrostatics.	[37]
Magnetic biochar	—	Magnetization (iron)	Carboxylate-modified PS	(0.02 -2.00)	87%	Electrostatics attraction	[38]
	—	Magnetization (iron)	PS	1 µm	>98% removal	Electrostatic attraction.	[13]
	—	Magnetization (iron oxide)	PS	3 µm	68.57 mgg^{-1}	Electrostatic interactions	[39]

Table 1 (continued)

Magnetic corncob biochar	—	—	PVC	0.05–10 μm	92-94%	Hydrophobic interactions.	[40]
Magnetic pinewood	300 - 700 °C	magnetic modification using Fe_3O_4	PS	100 nm	57.09 mgg^{-1}	π–π interactions, hydrophobic interactions, and electrostatic attraction	[25]
Magnetic Rice straw	24.85°C	Magnetic modification (Fe_3O_4) + CTAB surfactant	PS	100 nm	54.07 mgg^{-1}	Electrostatic attraction, hydrophobic interactions, and π–π stacking	[41]
MgAl-layered double oxide (LDO) biochar	30–50 °C	—	PS	<10 μm	360 mgg^{-1}	Hydrophobic and π–π interactions.	[42]
Polygonum amphibium L.	450 - 550 °C	—	PS	50 nm	68–89 mgg^{-1}	π–π stacking	[43]
Rice straw biochar	500 °C	—	PS	30–80 nm	99.96%	π–π interactions and hydrophobic effects.	[44]
	300–900 °C	Magnetization + Zeolite (ZSM-5) or CTAB	Carboxylate-modified PS	1 μm spheres	247.52 mgg^{-1}	Electrostatic attraction	[45]
Walnut Shell	700 °C	—	Sulfonate-modified PS	50 nm	0.25–19.23 mgg^{-1}	Hydrophobic interaction	[46]
Water treatment sludge	800 °C	Magnetization with $MgCl_2$	PS	3–5000 nm spheres	53.27–73.60 mgg^{-1}	Hydrogen bonding.	[47]
Woodchip & Lignin, Cellulose	400–700 °C	—	Carboxylate-modified PS	~98 ± 9 nm	23 mgg^{-1}	Hydrophobic interaction and hydrogen bonding	[48]

(L.): nylon: NY, polystyrene: PS, and polyvinyl chloride: PVC

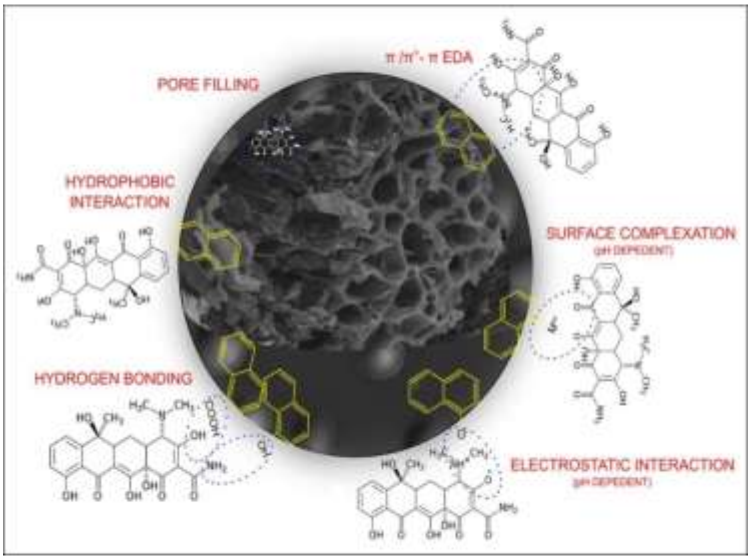

Figure 1. Mechanisms of biochar for Micro/Nanoplastic adsorption (adapted with permission from Elsevier).

3.1. Comparative mechanistic insight and critical evaluation

Although numerous studies report high removal efficiencies of biochar for micro- and nanoplastics (MNPs), a critical comparison of the underlying mechanisms reveals substantial variability governed by feedstock type, pyrolysis conditions, surface modification, and environmental factors. High-temperature biochars (>700 °C) are consistently associated with enhanced adsorption performance, primarily attributed to increased aromaticity, surface area, and hydrophobicity, which favor π–π interactions and hydrophobic aggregation [21,22]. In contrast, chemically modified biochars, particularly those functionalized with metals or oxidizing agents, tend to promote electrostatic attraction and surface complexation due to the introduction of charged or oxygen-containing functional groups [24,34]. These distinctions highlight that adsorption is not governed by a single dominant mechanism but rather by a complex interplay of physicochemical interactions that vary with material design.

However, a major limitation in the current body of literature lies in the predominance of simplified experimental conditions. Most studies employ single-type polymers (commonly polystyrene) in deionized water systems, which do not adequately represent the chemical complexity of natural or wastewater matrices. Under realistic conditions, factors such as ionic strength, pH fluctuations, and the presence of natural organic matter (NOM) can significantly alter adsorption behavior. For example, elevated ionic strength can screen electrostatic interactions, thereby reducing adsorption efficiency, while NOM may compete for active sites or form surface coatings that hinder direct contact between biochar and MNPs [10]. These effects are rarely quantified systematically, leading to potential overestimation of adsorption performance.

Furthermore, inconsistencies in reported adsorption capacities, ranging from negligible values to over 1000 mg g^{-1}, underscore the lack of standardized experimental protocols and normalization criteria across studies. Without normalization based on parameters such as surface area, particle size, and solution chemistry, direct comparison between studies remains challenging and may obscure true performance trends.

Another critical consideration is the trade-off between adsorption efficiency and sustainability. While high pyrolysis temperatures enhance hydrophobicity and adsorption capacity, they also increase energy consumption and carbon footprint. Similarly, chemical modifications (e.g., CTAB functionalization or acid oxidation) improve adsorption performance but may introduce environmental risks, including secondary pollution and chemical residues, if not properly managed. These trade-offs are often overlooked in performance-driven studies. Therefore, advancing biochar-based MNP removal requires standardized experimental frameworks and quantitative mechanistic studies under environmentally relevant conditions, supported by integrated techno-economic and life cycle assessments.

░ 4. Challenges in biochar-based adsorption removal of micro/nanoplastics from Water

Despite the promising adsorption performance of biochar for micro- and nanoplastics (MNPs), its practical implementation remains constrained by environmental complexity, material variability, and scalability limitations. Reported efficiencies are highly dependent on controlled laboratory conditions, including pH, ionic strength, and particle size distribution, which do not adequately reflect real-world water matrices. Furthermore, most studies focus on short-term batch experiments, with limited attention to long-term stability, regeneration efficiency, and economic feasibility. This gap raises concerns regarding the reliability and transferability of laboratory-scale findings to practical applications. A critical limitation across existing studies is the lack of standardized experimental protocols, making direct comparison between biochar systems difficult. Variations in feedstock, pyrolysis conditions, and testing environments result in inconsistent adsorption performance, complicating the identification of optimal material design strategies. Consequently, while biochar demonstrates significant potential, the mechanistic understanding and practical deployment of these systems remain underdeveloped.

4.1. Environmental Risks and Stability of Adsorbents

The environmental safety of biochar-based adsorbents is an important yet often overlooked consideration. Structural degradation during use or regeneration may result in the release of fine particles or leaching of embedded metals, leading to secondary contamination. This concern is particularly relevant for modified biochars, where chemical treatments or metal impregnation introduce additional risks.

Moreover, the synthesis of advanced adsorbents, including biochar composites, carbon nanotubes, and metal-organic frameworks, often involves energy-intensive processes or toxic reagents. While these modifications enhance adsorption performance, they may compromise environmental sustainability if not properly managed. Therefore, a balance between adsorption efficiency and environmental safety must be established through comprehensive risk assessment.

4.2. Adsorbent Design and Structural Optimization

The development of efficient and scalable biochar adsorbents requires precise control over structural and surface properties. High surface area, hierarchical porosity, and functional group density are critical parameters influencing adsorption performance. While reducing particle size and increasing porosity can enhance adsorption capacity, such modifications may also reduce mechanical stability and complicate separation processes.

In addition, most studies emphasize material synthesis without adequately linking structural properties to performance under realistic environmental conditions. Although computational approaches such as molecular dynamics simulations offer potential for predicting interactions between biochar and MNPs, their application remains limited. Future research should integrate experimental and modeling approaches to establish structure–performance relationships and guide rational adsorbent design.

4.3. Integration with Complementary Technologies

Adsorption alone may be insufficient for efficient MNP removal in complex water systems, particularly under conditions of high pollutant load or competing species. Integrating biochar adsorption with complementary techniques, such as membrane filtration, magnetic separation, or coagulation, offers a promising pathway to enhance overall treatment efficiency. Among these, magnetic biochar systems have demonstrated particular potential due to their ease of recovery and reusability. However, the performance of such hybrid systems is rarely evaluated under continuous-flow or large-scale conditions. As a result, their practical applicability remains uncertain, highlighting the need for pilot-scale validation and process optimization.

4.4. Regeneration and Reusability

Regeneration and reuse are critical for the economic and environmental viability of biochar-based adsorption systems. However, current studies provide limited data on long-term reusability, with most investigations restricted to a few adsorption–desorption cycles. Thermal and chemical regeneration methods are commonly employed, yet these approaches may alter biochar structure, reduce adsorption capacity, or increase operational costs.

Importantly, the trade-off between regeneration efficiency and structural stability is insufficiently addressed in the literature. Without robust regeneration strategies, the large-scale application of biochar remains economically and environmentally unsustainable. Therefore, the development of low-energy and structurally preserving regeneration techniques is essential.

4.5. Post-degradation and integration with other techniques

The management of spent biochar and adsorbed micro- and nanoplastics (MNPs) remains a critical challenge in achieving complete and sustainable remediation. While adsorption effectively concentrates MNPs onto biochar surfaces, it does not eliminate the pollutants, necessitating further treatment of saturated adsorbents.

Advanced degradation methods, including photocatalysis, electrocatalysis, and thermal conversion, have been increasingly explored as complementary strategies. For instance, Sun et al. [42] demonstrated that biochar integrated with MgAl-layered double oxides enables simultaneous adsorption and photocatalytic degradation of polystyrene nanoplastics, achieving degradation efficiencies exceeding 90% under UV irradiation. Similarly, Jiao et al. [39] reported that electrocatalytic treatment using Fe-modified lignin-based magnetic biochar facilitates the breakdown of microplastics into shorter-chain hydrocarbons and oxygenated intermediates, indicating potential for chemical valorization. Thermal treatment approaches also show promise. Wang et al. [13] reported that re-pyrolysis of microplastic-loaded biochar can regenerate the adsorbent while converting plastic residues into carbon-rich materials, supporting circular resource utilization. These studies highlight the feasibility of integrating adsorption with degradation processes to address both removal and disposal challenges. However, despite these promising findings, most studies remain limited to laboratory-scale investigations under controlled conditions. The long-term stability, energy requirements, and scalability of these integrated systems are rarely evaluated. Moreover, the potential formation of secondary by-products during degradation processes is not sufficiently addressed, raising concerns regarding environmental safety.

Therefore, future work should focus on developing integrated adsorption–degradation systems that are energy-efficient, scalable, and environmentally benign, supported by comprehensive evaluation under realistic water treatment conditions. Despite these advances, the lack of systematic comparison between degradation pathways and insufficient assessment of by-product toxicity remain key limitations that must be addressed before large-scale implementation.

5. Knowledge Gaps and Research Directions

Despite significant progress in the development of biochar-based adsorbents for micro- and nanoplastics (MNPs) removal, several critical gaps hinder their practical application and scientific advancement.

First, the current understanding of adsorption processes remains largely empirical, with limited development of predictive models. Most studies rely on simplified isotherm models (e.g., Langmuir or Freundlich), which fail to capture the complexity of MNP–biochar interactions under dynamic environmental conditions. The absence of robust modeling frameworks restricts the ability to predict adsorption performance across varying feedstocks, surface chemistries, and water matrices. The integration of advanced computational approaches, including machine learning and molecular simulations, is therefore essential to enable data-driven optimization of biochar systems.

Second, a major limitation lies in the lack of validation under realistic environmental conditions. Most reported studies are conducted using single-type polymers (predominantly polystyrene) in controlled laboratory settings, which do not reflect the heterogeneity of natural water systems. Factors such as aging of plastics, presence of natural organic matter, and competing ions can significantly reduce adsorption efficiency. The absence of pilot-scale or field-scale studies represents a critical barrier to the translation of laboratory findings into practical water treatment applications.

Third, the mechanistic understanding of MNP adsorption remains largely qualitative. While interactions such as electrostatic attraction, hydrophobic effects, and π–π stacking are frequently reported, their relative contributions under varying environmental conditions are not quantitatively established. This limitation is further compounded by inconsistencies in characterization techniques and experimental methodologies, hindering the development of a unified mechanistic framework.

Finally, sustainability considerations remain insufficiently addressed. Limited studies evaluate long-term adsorbent stability, regeneration efficiency, and life cycle environmental impacts. In particular, the energy demands of high-temperature pyrolysis and the potential environmental risks associated with chemical modification are rarely assessed in a systematic manner. Without integrating techno-economic analysis and life cycle assessment, the scalability and environmental viability of biochar-based systems remain uncertain.

Addressing these gaps requires a multidisciplinary approach that integrates experimental research, modeling, and system-level evaluation. Future studies should prioritize standardized methodologies, real-world validation, and sustainability assessment to facilitate the transition of biochar technologies from laboratory research to practical water treatment solutions.

6. Conclusion

Micro- and nanoplastics (MNPs) represent a significant and growing environmental challenge due to their persistence, widespread distribution, and potential risks to ecosystems and human health. This review demonstrates that biochar is a promising and sustainable adsorbent for MNP removal, owing to its high surface area, tunable surface chemistry, and cost-effective production from biomass waste. The adsorption of MNPs onto biochar is governed by multiple interacting mechanisms, including hydrophobic interactions, electrostatic attraction, pore filling, surface complexation, and π–π interactions. The effectiveness of these mechanisms is strongly influenced by biochar properties such as feedstock type, pyrolysis temperature, and surface modification, as well as environmental conditions. Among the materials reviewed, iron-modified and corncob-derived biochars consistently show high removal efficiencies.

Despite these advances, several critical limitations remain, particularly the lack of standardized methodologies, insufficient understanding under realistic environmental conditions, and limited data on long-term stability and scalability. These challenges highlight the gap between laboratory-scale performance and practical application.

Overall, while biochar-based systems offer strong potential for mitigating MNP pollution, their successful implementation will depend on overcoming these limitations and translating experimental findings into robust, real-world water treatment solutions.

6.1. Future Research Directions

1) Standardization frameworks: Establish internationally accepted testing protocols and reporting standards to enable cross-study comparability and meta-analysis.

2) Energy-efficient biochar engineering: Develop low-temperature or catalytic pyrolysis strategies and green modification routes to reduce environmental footprint.

3) Pilot- and field-scale validation: Transition from batch experiments to continuous-flow and real wastewater systems to evaluate operational feasibility.

4) Advanced regeneration strategies: Design low-energy, structurally preserving regeneration methods and quantify performance over extended cycles.

5) Integrated process design: Engineer hybrid systems (e.g., adsorption–membrane, adsorption–photocatalysis) with optimized process synergy rather than simple coupling.

6) Data-driven material optimization: Apply machine learning and multiscale modeling to predict structure–performance relationships and guide rational biochar design.

Declarations

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Competing Interests Statement

Authors have declared no competing interests.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

Peter Mafimisebi: Writing – review, editing, original draft, Akinbobola Ogundiran Writing – review & editing, Saeed Muhammad: Writing – review & editing, Niniola Olateju: Writing – review & editing.

Informed Consent

Not applicable for this study.

Availability of Data and Material

This review article synthesizes data from previously published studies, and no new primary data were generated. All data supporting the findings are derived from the literature cited in the references. Figures are used with permission from their respective sources. For access to the original data, please refer to the cited publications.

Institutional Review Board Statement

Not applicable for this study.

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