

Life-cycle sustainability of biochar, magnetic biochar and emerging bio-based adsorbents for microplastic removal from freshwater

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ABSTRACT

Microplastics are persistent contaminants increasingly detected across freshwater systems. While adsorption is a promising remediation approach, high removal efficiency alone does not indicate overall sustainability. The holistic economic and environmental performance of an adsorbent depends heavily on raw-material sourcing, synthesis energy, chemical modification, separation, regeneration cycles, and end-of-life management. This review critically evaluates the life-cycle sustainability of waste-biomass-derived biochar, magnetic biochar, and emerging bio-based materials investigated for microplastic remediation. Recent studies show that biochar-based systems achieve exceptional microplastic retention under real-water conditions; jujube-waste biochars and woodchip-derived sand columns have demonstrated >99% to complete removal of nylon and polyethylene particles. Similarly, rice-husk and corncob magnetic biochars exhibit up to 99.96% and 97% removal efficiency, respectively. However, chemical and magnetic modifications introduce secondary environmental burdens via metal precursors, chemical activating agents, solvent usage, high energy consumption, and risks of nanoparticle leaching. While independent life-cycle studies suggest waste-derived biochars offer clear environmental advantages over conventional coal-based activated carbons, microplastic-specific cradle-to-grave life-cycle assessments remain limited. Consequently, no single adsorbent can currently be classified as universally sustainable. Pristine biochar holds substantial intrinsic sustainability potential, whereas magnetic biochar provides clear engineering advantages where rapid magnetic recovery and reuse are required. Finally, this review proposes an integrated evaluation framework combining life-cycle assessment (LCA), life-cycle costing (LCC), ecotoxicity parameters, microplastic mass balances, and end-of-life safety metrics to scale up sustainable freshwater remediation.

Keywords: Microplastics; freshwater remediation; biochar; magnetic biochar; bio-based adsorbents; life-cycle assessment; life-cycle costing; regeneration; ecotoxicity; sustainable remediation

INTRODUCTION

Microplastic pollution has become an important environmental issue because plastic particles are persistent, mobile and capable of interacting with natural organic matter, metals, microorganisms and other contaminants. Although marine systems have historically received most scientific attention, freshwater environments are increasingly recognized as important reservoirs and transport pathways. Rivers receive plastic inputs from wastewater, stormwater, textile fibres, road runoff, agricultural activities and fragmentation of larger plastic debris. Lakes and ponds can act as long-term accumulation zones, while groundwater can transport particles through porous media, fractures and recharge pathways.

Conventional water-treatment processes can remove a considerable fraction of larger microplastics through coagulation, sedimentation, flotation, filtration and membrane separation. However, small microplastics and nanoplastics are more difficult to recover, and many conventional processes transfer rather than destroy the plastic. The search for low-cost polishing materials has therefore stimulated interest in adsorption and adsorption-assisted filtration. (Ali et al., 2023; Verma et al., 2024)

A major difficulty in evaluating this field is that laboratory studies commonly report percentage removal or adsorption capacity under simplified conditions. These parameters provide information about technical performance but do not describe the complete environmental or economic burden. A material can display an exceptionally high adsorption capacity while requiring expensive chemicals, high-temperature processing, extensive washing or difficult regeneration. Conversely, a material with a lower capacity may be more sustainable if it is manufactured from locally available waste biomass and can be reused many times in a simple fixed-bed system. (Hsieh et al., 2022; Ahmad et al., 2023)

The central question addressed in this review is therefore not simply which adsorbent removes the highest percentage of microplastics, but which material has the greatest potential to remove microplastics with the lowest combined environmental and economic burden over its complete life cycle.

A major finding of the literature search is that the number of experimental microplastic-adsorption papers is substantially greater than the number of studies that perform a complete cradle-to-grave life-cycle assessment and life-cycle cost analysis for the same adsorbent. Consequently, some sustainability evidence is indirect: recent life-cycle studies of biochar or activated carbon used for other water contaminants are used to evaluate production-stage burdens of the same material classes. Such evidence is explicitly treated as supporting evidence rather than as a direct measurement of the life-cycle impact of microplastic removal (Ali et al., 2023; Verma et al., 2024; Das et al., 2024).

ADSORPTION – AN EFFICIENT ATTRACTIVE METHOD FOR MICROPLASTIC REMOVAL

Adsorption-based treatment can capture microplastics through a combination of surface attachment and physical retention. Depending on the adsorbent and water chemistry, relevant interactions include hydrophobic attraction, electrostatic attraction, hydrogen bonding, van der Waals interactions, π - π interactions, surface complexation, pore or void entrapment, straining and mechanical interception. These mechanisms differ from conventional molecular adsorption of dissolved contaminants because microplastics are relatively large particulate objects. (Ali et al., 2023; Ji et al., 2024; Mota et al., 2025; Song et al., 2026)

A recent review of biochar-based microplastic remediation emphasizes that adsorption depends on biochar surface chemistry, pore structure, surface area, aromaticity and charge, as well as microplastic polymer type, particle size, pH, ionic strength and dissolved organic matter. Consequently, high BET surface area alone cannot be used as a reliable predictor of microplastic-removal performance.

BIOCHAR AS A SUSTAINABLE ADSORBENT

Feedstock and production advantages

Biochar is a carbon-rich material produced by thermochemical conversion of biomass under oxygen-limited conditions. Potential feedstocks include rice husk, sugarcane bagasse, corncob, sawdust, wood residues, agricultural straw, algae and other biomass wastes. The principal sustainability advantage is the possibility of converting a low-value or problematic waste stream into a functional treatment material.

Recent reviews identify biochar as one of the most promising sustainable materials for microplastic and nanoplastic remediation because its surface chemistry can be modified while its feedstock can be obtained from renewable or waste resources. However, biochar quality depends strongly on feedstock composition and pyrolysis conditions. Contaminated biomass may introduce metals or organic contaminants into the final product, and severe pyrolysis can increase energy consumption (Mishra et al., 2023; Li et al., 2024; Mota et al., 2025). Abdoul Magid and co-workers investigated the adsorption of polystyrene nanoplastics on corncob biochar produced at different pyrolysis temperatures. Increasing the pyrolysis temperature increased surface area, hydrophobicity and aromaticity, while oxidation increased oxygen-containing surface groups. Pore filling, hydrophobic interactions and hydrogen bonding were identified as important mechanisms. Increasing pH generally reduced adsorption under the investigated conditions. The study demonstrates that pyrolysis temperature should be optimized rather than maximized, because excessive thermal severity can increase production energy without providing a proportional environmental benefit (Abdoul Magid et al., 2021).

Hsieh and co-workers incorporated a thin layer of biochar into sand filtration columns. Among the tested materials, woodchip-derived biochar provided particularly strong microplastic retention. A 1 wt% woodchip-biochar layer achieved complete removal under the investigated real river-water and sewage-water conditions. The system could also be regenerated and reused. This study is highly relevant to sustainability because it demonstrates that biochar does not necessarily need to be dispersed as a free powder. Integrating a small amount of waste-derived biochar into an existing filtration bed may reduce adsorbent consumption and simplify recovery (Hsieh et al., 2022).

Ahmad and co-workers evaluated jujube-waste-derived biochars in fixed-bed columns for simultaneous removal of microplastics and heavy metals. More than 99% removal of the investigated nylon and polyethylene microplastics was reported under the experimental conditions. The higher-temperature biochar demonstrated substantially greater microplastic retention than sand. The study is important because it uses an agricultural waste feedstock and a continuous-flow configuration, both of which are closer to practical treatment than conventional batch experiments (Ahmad et al., 2023).

MAGNETIC BIOCHAR

Magnetic biochar is produced by incorporating a magnetic phase, commonly iron oxide, into biochar. The principal engineering advantage is that the adsorbent can be recovered from water using an external magnetic field. This can reduce the need for secondary filtration or centrifugation and may facilitate regeneration and reuse. (Shahzad et al., 2025; Shakoor et al., 2026)

The sustainability benefit of magnetization is therefore indirect. Magnetization does not necessarily increase adsorption capacity, and it introduces additional raw materials, synthesis steps, washing requirements and potential risks associated with metal or nanoparticle release. Magnetic biochar should therefore be considered more sustainable than ordinary biochar only when the benefits of improved recovery and reuse compensate for the environmental and economic burden of magnetic modification.

Wu and co-workers prepared magnetic biochar from rice husk and reported up to 99.96% microplastic removal under the investigated conditions. The authors proposed electrostatic attraction, surface complexation, hydrogen bonding and π - π interactions as contributing mechanisms. Following thermal regeneration at approximately 500 °C, the material retained about 90% of its adsorption performance after four uses. The study demonstrates the attractive combination of agricultural-waste utilization, high removal and reuse. However, the thermal regeneration requirement must be included in any life-cycle analysis (Wu et al., 2023).

Li and co-workers investigated pristine and environmentally aged polyamide microplastics using magnetic biochar derived from corncob. Removal of aged polyamide was approximately 97% under the reported conditions and was substantially higher than removal of pristine particles. Aging increased surface roughness and changed surface chemistry, thereby increasing interactions with the biochar. This result is important because environmental microplastics are normally weathered rather than pristine laboratory particles (Li et al., 2023).

Parashar and Hait developed CTAB-modified magnetic biochar using iron chloride and a cationic surfactant. The material achieved approximately 98% removal under favorable synthetic-water conditions and approximately 96.3% and 94.1% removal from two investigated sewage-treatment effluents. The reported adsorption capacity was 247.52 mg g⁻¹ and useful performance was retained for three reuse cycles. The real-effluent results strengthen the practical significance of the material. At the same time, the use of CTAB and iron salts demonstrates why the sustainability of a modified adsorbent cannot be inferred from the biomass feedstock alone (Parashar and Hait, 2024).

ACTIVATED CARBON

Activated carbon is a mature water-treatment adsorbent with established manufacturing and regeneration technologies. Its high surface area and extensive industrial experience make it an important benchmark for evaluating newer bio-based materials. However, activation can require substantial thermal energy and chemical inputs. The sustainability of activated carbon depends strongly on the precursor. Waste-derived activated carbon can have a substantially different environmental profile from coal-derived or fossil-based activated carbon. (Jaria et al., 2022; Vilén et al., 2022)

Jaria and co-workers reviewed the economic and environmental aspects of waste-based activated carbons and showed that precursor price, activation method, energy demand and regeneration strongly affect economic and environmental performance. A separate comparative life-cycle assessment of activated carbon produced from different raw materials found that electricity production and direct process emissions were major contributors to environmental impact, while coal-derived activated carbon showed particularly high impacts across several categories. (Jaria et al., 2022; Shaheen et al., 2022; Vilén et al., 2022)

CHITOSAN AND CELLULOSE-BASED ADSORBENTS

Natural polymers such as chitosan, chitin and cellulose are attractive because they are renewable, potentially biodegradable and rich in functional groups capable of interacting with microplastics. Chitosan contains amino and hydroxyl groups, while cellulose provides hydroxyl-rich surfaces and can be engineered into membranes, aerogels, sponges and fibres. (Ullah et al., 2025; Xu et al., 2023; Zhuang et al., 2022)

Chitosan-based materials can have good adsorption performance but may suffer from limited mechanical strength and stability, particularly under acidic conditions. Cross-linking and composite formation can improve mechanical stability but add chemicals and processing steps. Cellulose-based aerogels and sponges can provide highly porous structures, but nanocellulose production may itself require considerable mechanical or chemical energy. (Ullah et al., 2025; Zhuang et al., 2022)

Xu and co-workers developed a chitosan/bacterial-cellulose sponge that combined mechanical resilience with microplastic adsorption. Another recent study developed a biodegradable chitin-cellulose nanofibre sponge and reported removal efficiencies of approximately 75–93% for different functionalized polystyrene particles while retaining substantial performance after regeneration. These studies demonstrate the potential of natural polymers, but their life-cycle advantages require confirmation through standardized LCA and cost analysis. (Xu et al., 2023; Chitin-cellulose sponge study (2025))

GRAPHENE-BASED MATERIALS AND METAL–ORGANIC FRAMEWORKS

Graphene oxide, graphene-like carbons, carbon nanotubes and metal–organic frameworks can provide high surface areas and tunable surface chemistry. Strong interactions such as π - π attraction and hydrophobic interaction can produce high microplastic adsorption capacities. For example, graphene-like carbon/layered-double-oxide materials have demonstrated high removal of polystyrene particles,

while graphene oxide/cellulose aerogels have reported capacities exceeding 200 mg g⁻¹ in laboratory studies. (Liu et al., 2024; Ali et al., 2023; Das et al., 2024)

Despite high laboratory performance, these materials currently have weaker evidence for low whole-life environmental burden. Their synthesis can require high-purity precursors, multiple reaction steps, solvents, specialized ligands, metal salts and energy-intensive purification. Their fine particle size can also make recovery difficult. Therefore, high adsorption capacity should not be interpreted as proof of sustainability. (Ali et al., 2023; Song et al., 2026)

COMPARATIVE ASSESSMENT OF ADSORBENT CLASSES

The table should be interpreted as a qualitative synthesis rather than a numerical ranking. The experimental studies use different microplastic polymers, particle sizes, concentrations, water matrices, adsorbent doses and analytical methods. Direct comparison of reported adsorption capacities is therefore not scientifically valid without normalization. (Verma et al., 2024; Mota et al., 2025; Chandravanshi et al., 2026)

Table 1: Comparative assessment of adsorbent classes

Material	Technical evidence	Feedstock/production	Recovery	Main environmental concern	Overall sustainability potential
Waste-biomass biochar	Strong; >90% and >99% reported in several systems	Waste biomass; comparatively simple	Requires filtration/immobilization	Leaching, PAHs, fine particles	Very high
Magnetic biochar	Very strong; up to 99.96% in selected studies	Biochar + Fe modification	Magnetic recovery	Fe/nanoparticle release; modification energy	Very high potential
Waste-derived activated carbon	Strong and technologically mature	Activation can be energy/chemical intensive	Established regeneration	Activation energy and chemicals	High
Chitosan/cellulose	Moderate to strong	Renewable biopolymers	Depends on structure	Mechanical stability and modification	High potential
Graphene-based materials	Very strong laboratory evidence	Complex synthesis	Often difficult	Embodied energy and persistence	Moderate currently
MOFs	Very strong laboratory evidence	Metal/ligand-intensive	Difficult for fine powders	Metal/ligand release and cost	Moderate to low currently

Is Adsorption Capacity Alone a Sustainability Metric

Adsorption capacity, usually expressed as milligrams of microplastic removed per gram of adsorbent, is a useful material-performance parameter but does not capture the environmental burden of producing, transporting, regenerating and disposing of the adsorbent. For example, a metal–organic framework or graphene-based composite may show a higher theoretical capacity than a simple agricultural-waste biochar, but its synthesis may require substantially more energy and expensive reagents. (Jaria et al., 2022; Shaheen et al., 2022; Vilén et al., 2022; Norberto et al., 2023)

The appropriate sustainability comparison should therefore normalize environmental and economic impacts to a common service. A suitable functional unit is the treatment of one cubic metre of freshwater to achieve a defined reduction in microplastic mass. A second useful functional unit is the removal of one gram of microplastic. (Shaheen et al., 2022; Li et al., 2024)

Environmental burden per gram of MP removed = Total life-cycle environmental impact / Mass of MP removed

Cost per gram of MP removed = Total life-cycle cost / Mass of MP removed

ENVIRONMENTAL RISKS ASSOCIATED WITH BIOCHAR AND MAGNETIC BIOCHAR

Metal and nanoparticle release

Magnetic biochar commonly contains iron oxides such as Fe_3O_4 . Incomplete magnetic recovery, acidic conditions or repeated regeneration may promote iron release. Fine magnetic particles may also escape into treated water. Such releases should be measured rather than assumed to be negligible. (Shahzad et al., 2025; Shakoor et al., 2026)

Leaching of metals and organic contaminants

The feedstock determines the chemical quality of biochar. Contaminated biomass may transfer metals into the biochar, while high-temperature pyrolysis can produce or concentrate polycyclic aromatic hydrocarbons. Recent reviews therefore emphasize leaching and ecotoxicity as important considerations in biochar-based microplastic treatment. (Li et al., 2024; Mishra et al., 2023; Shakoor et al., 2026)

Secondary microplastic pollution

Adsorption transfers microplastics from water to the adsorbent. It does not automatically destroy the plastic. If a spent adsorbent is regenerated, transported or disposed of improperly, the captured microplastics may be released again. Consequently, the treatment process must be evaluated using a complete microplastic mass balance. (Mota et al., 2025; Shakoor et al., 2026)

Life-Cycle Assessment Framework

A complete life-cycle assessment (Fig.1) should follow the principles of ISO 14040 and ISO 14044. For microplastic adsorbents, the preferred boundary is cradle-to-grave or cradle-to-cradle. The analysis should begin with biomass or precursor production and include transportation, drying, pyrolysis, activation or magnetic modification, washing, treatment, adsorbent recovery, regeneration, reuse and final disposal (ISO, 2006a; ISO, 2006b; Vilén et al., 2022).

The proposed life-cycle sequence is:

- Feedstock collection and transport.
- Drying and pretreatment.
- Pyrolysis or adsorbent synthesis.
- Chemical activation or magnetic modification.
- Washing and drying.
- Transport to the treatment facility.
- Freshwater treatment and energy use.
- Adsorbent and microplastic recovery.
- Regeneration and repeated use.
- Management or destruction of captured microplastics.
- Final disposal of unrecoverable adsorbent.

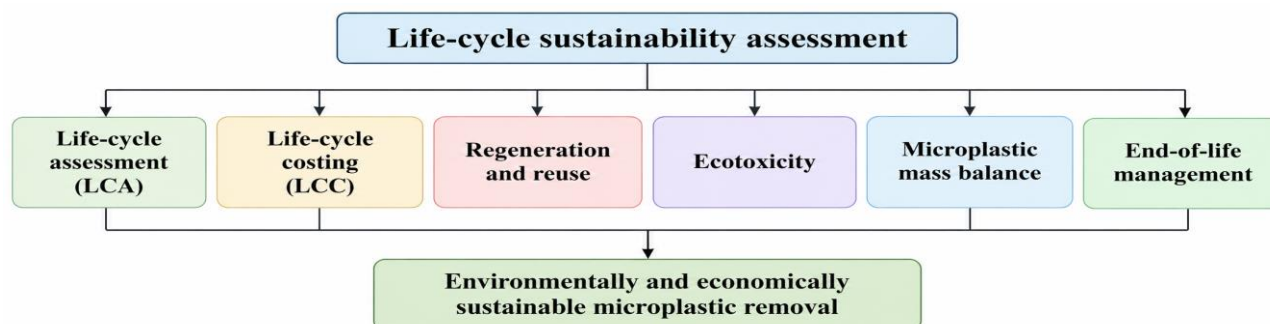


Figure 1: Framework for life-cycle sustainability assessment of adsorbents for microplastic removal.

Recommended impact categories

The assessment should include climate-change impact, cumulative energy demand, water consumption, resource depletion, freshwater ecotoxicity, human toxicity, eutrophication, acidification and particulate emissions. For magnetic materials, metal release and nanoparticle-related impacts require particular attention. (Li et al., 2024; Norberto et al., 2023; Vilén et al., 2022)

Life-Cycle Cost Assessment

Life-cycle costing should include capital expenditure, operating expenditure, adsorbent production, transportation, energy, regeneration, replacement and final disposal. A material should not be described as low-cost merely because its biomass feedstock is inexpensive. The cost of producing a functional adsorbent can be dominated by drying, pyrolysis, activation, chemical modification or magnetic synthesis. (Jaria et al., 2022; Shaheen et al., 2022; Norberto et al., 2023)

$$\text{Total life-cycle cost} = \text{CAPEX} + \text{OPEX} + \text{regeneration cost} + \text{replacement cost} + \text{disposal cost}$$

Where CAPEX = Capital Expenditure (the initial investment required to set up the treatment system) and OPEX = Operating Expenditure (the recurring cost of operating the treatment system)

$$\text{Cost per gram of MP removed} = \text{Total life-cycle cost} / \text{Total verified MP mass removed}$$

The second equation is particularly useful because it prevents an adsorbent with excellent adsorption capacity but poor regeneration or high synthesis cost from appearing artificially economical.

REGENERATION FEASIBILITY

Regeneration is one of the most important variables determining the sustainability of an adsorbent. If a material is used only once, its production burden is assigned to a single treatment cycle. If it can be reused ten or twenty times with modest loss of capacity, the production burden is distributed over a much larger amount of treated water. (Wu et al., 2023; Li et al., 2023; Parashar and Hait, 2024; Chitin-cellulose sponge study (2025))

Regeneration studies should report the number of cycles, adsorption capacity after each cycle, energy consumed, adsorbent mass loss, metal leaching and microplastic release. Thermal regeneration may have the additional advantage of destroying captured plastic, but this must be demonstrated through mass balance and chemical analysis rather than inferred from a reduction in particle count (Wu et al., 2023; Parashar and Hait, 2024; Chitin-cellulose sponge study (2025)).

$$\text{Regeneration retention (\%)} = (q_n/q_0) \times 100$$

Where q_0 = initial adsorption capacity of the fresh adsorbent (mg/g or particles/g)

q_n = adsorption capacity after the n^{th} regeneration cycle

ECOTOXICITY EVALUATION

Environmental safety should be evaluated for fresh, spent and regenerated adsorbent. Fresh adsorbent tests indicate inherent toxicity; spent adsorbent tests reveal the effects of accumulated microplastics and co-contaminants; regenerated adsorbent tests identify changes caused by repeated treatment. (Shakoor et al., 2026; Ullah et al., 2025; Chitin-cellulose sponge study (2025))

Chemical characterization should include dissolved and total iron, other potentially toxic metals, polycyclic aromatic hydrocarbons, dissolved organic carbon and released fine particles. Biological tests should ideally include freshwater algae, Daphnia and fish, with sediment organisms included where particle accumulation is likely. The biodegradable chitin-cellulose sponge study is notable because it included biological compatibility and biodegradation assessment rather than assuming that a natural polymer is automatically safe. (Li et al., 2024; Shakoor et al., 2026)

IMPORTANCE OF REAL FRESHWATER CONDITIONS

Many adsorption experiments use deionized or ultrapure water, whereas rivers and lakes contain calcium, magnesium, sodium, chloride, sulfate, bicarbonate, natural organic matter, suspended solids, microorganisms and algae. These constituents can compete for adsorption sites, alter electrostatic interactions and promote or inhibit microplastic aggregation. (Ji et al., 2024; Mota et al., 2025; Song et al., 2026)

Real-water validation should therefore be performed using representative river water, lake water, pond water and groundwater. The effects of pH, ionic strength, dissolved organic carbon, turbidity and competing contaminants should be measured. Continuous-flow experiments

are particularly important because hydraulic conditions can differ substantially from those in batch reactors. (Hsieh et al., 2022; Ahmad et al., 2023; Chandravanshi et al., 2026)

IMPORTANCE OF MICROPLASTIC AGING

Environmental microplastics are typically weathered by ultraviolet radiation, mechanical abrasion, oxidation and biofilm formation. Aging changes surface roughness, crystallinity, charge and oxygen-containing functional groups. The study of magnetic corncob biochar and aged polyamide demonstrates that aged particles may interact more strongly with biochar than pristine particles. (Li et al., 2023; Ji et al., 2024)

Future sustainability assessments should therefore include pristine and aged PE, PP, PS, PET and PA rather than relying only on commercially available pristine microspheres. (Li et al., 2023; Mota et al., 2025)

OVERALL EVIDENCE FOR THE MOST SUSTAINABLE ADSORBENT

The current literature does not provide sufficient direct evidence to declare a universally optimal adsorbent on a complete cradle-to-grave basis. The strongest evidence instead supports a distinction between intrinsic material sustainability and engineering recoverability. (Mota et al., 2025; Shakoor et al., 2026; Chandravanshi et al., 2026)

Waste-biomass-derived biochar has the strongest intrinsic sustainability case because it can use low-value biomass, requires comparatively simple processing, has demonstrated high microplastic removal and can potentially be integrated into existing filtration systems. Independent life-cycle studies of waste-derived biochar also indicate lower energy demand, greenhouse-gas emissions and production cost than some conventional activated-carbon routes under the studied conditions. (Hsieh et al., 2022; Ahmad et al., 2023; Shaheen et al., 2022; Li et al., 2024)

Magnetic biochar has the strongest engineering case when adsorbent recovery is essential. Recent studies have reported very high microplastic removal, including up to 99.96% for rice-husk magnetic biochar, approximately 97% removal of aged polyamide using magnetic corncob biochar, and approximately 94–96% removal from real sewage effluents using modified magnetic biochar. Nevertheless, the additional burden of iron precursors, synthesis, washing, regeneration and potential nanoparticle release must be included before concluding that magnetic biochar has a lower total life-cycle burden than pristine biochar. (Wu et al., 2023; Li et al., 2023; Parashar and Hait, 2024; Shahzad et al., 2025)

PROPOSED DECISION FRAMEWORK FOR SUSTAINABLE SCALE-UP

A scientifically defensible comparison should evaluate each adsorbent using six interconnected modules: technical performance, life-cycle environmental impact, ecotoxicity, regeneration, economics and end-of-life safety. (Shakoor et al., 2026; Vilén et al., 2022; Shaheen et al., 2022)

- Technical performance: removal efficiency, adsorption capacity, breakthrough time and complete microplastic mass balance.
- Environmental assessment: greenhouse-gas emissions, energy demand, water consumption, resource depletion and ecotoxicity.
- Ecotoxicity: iron and metal leaching, PAHs, fine-particle release and biological effects on algae, *Daphnia* and fish.
- Regeneration: number of cycles, retained capacity, energy consumption, adsorbent loss and microplastic release.
- Economics: capital cost, operating cost, energy, adsorbent replacement, regeneration and disposal.
- End-of-life: safe recovery or destruction of captured microplastics and controlled disposal of unrecoverable adsorbent.

Rather than assigning an arbitrary overall score, a Pareto analysis is recommended. An adsorbent is considered preferable when no competing material simultaneously provides lower environmental burden, lower cost, higher microplastic removal, greater regeneration and lower toxicity. This approach avoids hiding important trade-offs behind a single numerical sustainability score.

RECOMMENDED EXPERIMENTAL BENCHMARK

For future comparative research, all candidate adsorbents should be evaluated under a common experimental protocol. The same real freshwater should be used, together with a mixed population of environmentally aged PE, PP, PS, PET and PA particles. Batch screening should be followed by fixed-bed or continuous-flow experiments. At least five to ten regeneration cycles should be investigated, and complete mass balances should be performed for microplastics and metals. (Chandravanshi et al., 2026; Shakoor et al., 2026)

The preferred functional unit is the removal of one gram of microplastic from one cubic metre of real freshwater. Environmental results should be reported as kilograms of CO₂-equivalent per gram of microplastic removed, megajoules per gram of microplastic removed, litres of water consumed per gram removed and rupees per gram removed. This would allow a meaningful comparison among biochar, magnetic biochar, activated carbon and biodegradable polymer adsorbents.

CONCLUSIONS

The present review demonstrates that adsorption-based technologies have considerable potential for freshwater microplastic remediation. Biochar, magnetic biochar, activated carbon, chitosan, cellulose and advanced carbon materials have demonstrated significant microplastic removal under laboratory and pilot-scale conditions. However, reported removal efficiencies cannot be directly compared because microplastic type, particle size, concentration, water matrix, adsorbent dose and analytical methods vary among studies (Wu et al., 2023; Li et al., 2023; Parashar and Hait, 2024; Ullah et al., 2025).

Waste-biomass-derived biochar shows strong potential for reducing intrinsic environmental and economic burdens because it utilizes renewable or waste feedstocks, requires comparatively simple processing, can be integrated with filtration systems and has demonstrated high removal performance. Magnetic biochar offers an important engineering advantage where rapid adsorbent recovery and reuse are required, although the environmental burden associated with iron incorporation, chemical processing and regeneration must be considered.

Activated carbon remains an important benchmark owing to its technological maturity and established regeneration infrastructure, although activation may increase energy and chemical requirements. Chitosan and cellulose-based materials offer renewable and biodegradable characteristics, while graphene-based materials and metal-organic frameworks require further evidence regarding their whole-life environmental and economic burdens (Mota et al., 2025; Shakoor et al., 2026).

The major research gap is the absence of standardized, real-water, continuous-flow and cradle-to-grave comparisons of competing adsorbents. Future assessments should integrate life-cycle assessment, life-cycle costing, ecotoxicity, regeneration, complete microplastic mass balance and safe end-of-life management. Thus, sustainability should be evaluated based on the environmental and economic burden per unit mass of microplastic removed rather than removal efficiency alone. Direct microplastic-specific life-cycle evidence remains insufficient to establish any adsorbent as universally sustainable (Shaheen et al., 2022; Vilén et al., 2022; Li et al., 2024).

CONFLICT OF INTEREST

The authors have declared that no conflict of interest exists.

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