Biochar-Based Environmental Carbon Materials for Water Pollution Control: Modification Methods, Mechanisms, and Environmental Impacts – A Comprehensive Review

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ABSTRACT

Water pollution from heavy metals, nutrients, dyes, pharmaceuticals, Per- and PolyFluoroAlkyl Substances (PFAS), and pesticides poses serious global challenges, as conventional treatments often fail to remove trace contaminants effectively and produce secondary waste. Biochar, produced by biomass pyrolysis, offers a sustainable environmental carbon material with tunable surface chemistry, porosity, and carbon sequestration potential, making it a promising low-cost alternative to activated carbon. However, pristine biochar requires modification to overcome low surface area, limited functional groups, and poor selectivity for emerging pollutants. This review examines modification methods, adsorption mechanisms (ion exchange, surface complexation, π-π interactions, hydrophobic partitioning), and environmental impacts, including ecotoxicity, leaching risks, and long-term stability. Key findings highlight biochar's versatility across fixed-bed systems, permeable reactive barriers, constructed wetlands, and decentralized treatment, with regeneration strategies enabling reusability. Current challenges include inconsistent preparation standards, limited real wastewater studies, aging mechanisms, performance-safety trade-offs, and scale-up barriers. Future directions emphasize green modifications, multifunctional composites, AI-optimized design, and Advanced Oxidation Processes (AOP) membrane integration for sustainable water management.

Keywords: Biochar, Water Pollution, Modification, Adsorption Mechanisms, Environmental Impacts, Regeneration

INTRODUCTION

Global Challenges in Water Pollution

Water pollution is now a major global challenge, driven by industrial discharge, mining, intensive agriculture, urban wastewater, and landfill leachate. Key contaminants include heavy metals (such as Pb, Cd, Hg), excess nutrients (nitrate, phosphate), synthetic dyes, pharmaceuticals and personal care products, pesticides, and persistent PFAS, many of which are toxic, bioaccumulative, and resistant to biodegradation[1]. These pollutants can cause carcinogenic, neurotoxic, and endocrine-disrupting effects in humans, and they damage aquatic ecosystems, reduce biodiversity, and threaten drinking water security[2]. Their occurrence at low concentrations, frequent co-contamination, and chemical diversity make monitoring and control very difficult on a global scale[3].

A research by C. S. Tshangana *et al (*2025*)* [4] noted that conventional water and wastewater treatment technologies, including coagulation-flocculation, sedimentation, activated sludge, advanced oxidation, granular activated carbon adsorption, and membrane filtration, often show limited removal of trace pharmaceuticals, dyes, pesticides, and especially short-chain PFAS. These processes can be energy-intensive, prone to fouling, and produce secondary wastes, such as spent sludge and brines, that require further management. Many small and medium-sized facilities in developing regions cannot afford advanced systems, leading to incomplete treatment and continuous pollutant release[5]. These limitations have motivated the development of biochar-based environmental carbon materials, which offer tunable surface chemistry and porosity for enhanced adsorption, but their performance, mechanisms, and environmental impacts must be critically assessed in the context of real water matrices[6].

Biochar as a Promising Environmental Carbon Material

Biochar is a carbon-rich environmental material produced by pyrolysis of biomass such as crop residues, wood wastes, and sewage sludge at about 300–800 °C in limited oxygen[6]. The process converts unstable organic matter into aromatic carbon structures with high stability and porous texture. This stabilizes part of the biogenic carbon that would normally return to the atmosphere as CO_2, so biochar can act as a long-term terrestrial carbon sink on centennial time scales[7]. When integrated into waste-to-energy or biorefinery systems, biochar production supports a circular economy by upgrading low-value wastes into value-added carbon materials for soil improvement and pollution control.

Biochar also shows promise as a low-cost adsorbent, and it is often compared with commercial activated carbon for water treatment. [8] indicated that activated carbon typically has higher and more consistent surface area and adsorption capacity, but its production is energy intensive and often relies on fossil or high-grade feedstocks, leading to higher cost and environmental footprint. In contrast, biochar can be produced locally from abundant biomass wastes with lower energy input, can sequester carbon, and can reach comparable sorption performance when properly engineered or activated[9]. These advantages make biochar a promising environmental carbon material, although its variable quality and lower capacity in some cases remain important challenges.

Necessity of Biochar Modification

Pristine biochar often has limited performance for water pollution control, so modification is usually necessary (Figure 1[10]). Many raw biochars made at low or moderate pyrolysis temperatures have relatively low surface area and simple pore structures, which restricts adsorption capacity, especially when contaminant concentrations are high[11]. In addition, unmodified biochar usually contains mainly oxygen-based functional groups and has fewer specific sites, such as nitrogen, sulfur, or metal-oxide groups, that can form strong complexes with target pollutants[12]. This weak surface chemistry limits its ability to bind diverse ions and polar organic molecules in complex water matrices.

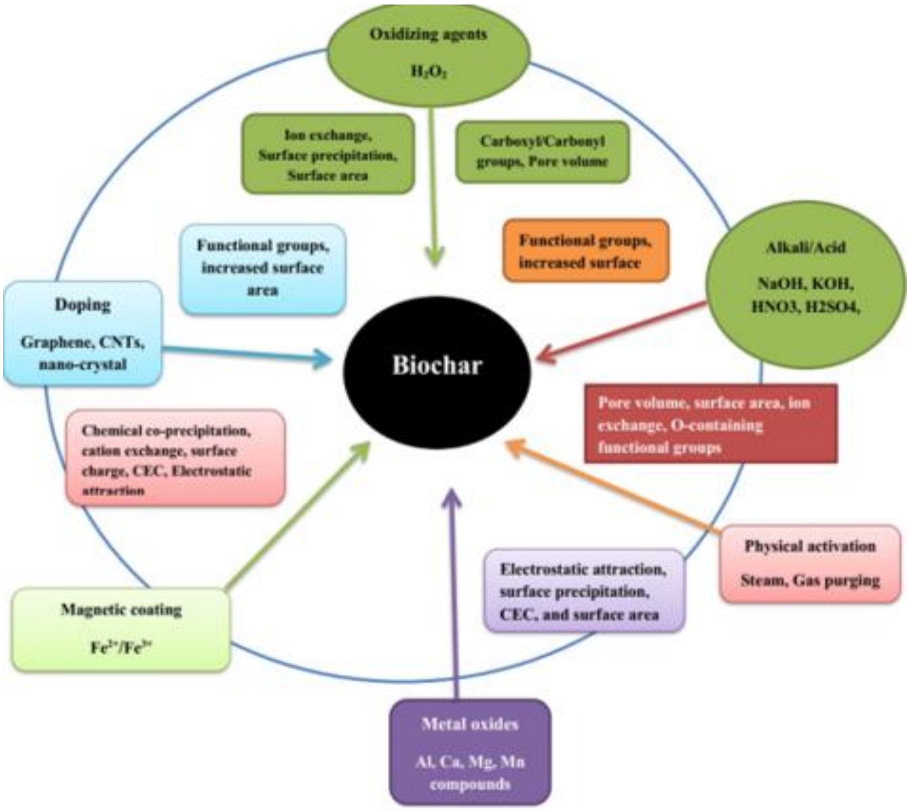


Figure 1: Biochar modification techniques (schematic diagram)[10].

Because of these intrinsic limits, pristine biochar often shows weak selectivity toward emerging contaminants such as pharmaceuticals, PFAS, dyes, and modern pesticides, particularly under competitive conditions where many solutes coexist[13]. Modified or engineered biochars, produced by activation or impregnation with acids, alkalis, metals, or functional polymers, can increase surface area, tune pore size, and introduce new functional groups to improve affinity and selectivity for target compounds[14].

These changes enhance mechanisms such as electrostatic attraction, surface complexation, π-π interactions, and hydrophobic partitioning, which are important for the selective removal of trace organic contaminants[10]. Therefore, developing modified biochar is essential to move from general sorbents to tailored materials suitable for advanced water treatment.

Scope and Objectives of This Review

This review will focus on biochar-based environmental carbon materials for water pollution control, with emphasis on how specific modification strategies change biochar structure and, in turn, adsorption mechanisms toward heavy metals, nutrients, dyes, pharmaceuticals, PFAS, and pesticides.

It will summarize recent work on physical, chemical, and compositing modification routes, and link these routes to changes in surface area, pore structure, and surface functional groups that govern sorption behavior in realistic water matrices. In addition, the review will discuss environmental impacts of modified biochar, including carbon sequestration potential, stability, leaching, and regeneration performance during water treatment.

Compared with previous reviews that mainly describe preparation methods and general applications of biochar for contaminant removal, this work will place special focus on the modification-structure–mechanism–environmental impact relationships for emerging contaminants.

It will critically compare pristine and engineered biochars against conventional sorbents, highlight knowledge gaps on selectivity, long-term performance, and field-scale behavior, and outline design principles for safer and more efficient biochar-based materials.

By integrating mechanistic understanding with environmental assessment, this review aims to help researchers and engineers develop biochar modification strategies that are both effective for advanced water treatment and consistent with sustainability goals.

Preparation and Physicochemical Properties of Biochar

Feedstock Sources

Biochar feedstock sources play a key role in determining the final properties of the material for water pollution control applications. Agricultural residues form one of the largest and most accessible groups of feedstocks. Common examples include rice husk, wheat straw, corn stover, peanut shells, sugarcane bagasse, and cotton stalks. Common biochar feedstocks include crop residues and other agricultural by-products, wood and forestry wastes, sewage sludge from municipalities, and various forms of animal manure (Figure 2)[13].

These materials are generated in huge quantities from global farming activities-for instance, rice production alone yields over 150 million tons of husk annually worldwide[15]. When pyrolyzed, agricultural residues typically produce biochar with moderate carbon content (40-60%), significant ash levels (10-30%), and inherent nutrients like potassium, phosphorus, and silica. Rice husk biochar stands out due to its high silica content (up to 20%), which gives natural abrasion resistance but can limit porosity unless processed further[16].

Wheat straw and corn stover yield more porous structures with better adsorption potential for organic pollutants. The main advantage of these feedstocks is their low cost and abundance in rural areas, making decentralized biochar production feasible, but seasonal availability and high moisture content often require pre-drying[16].

Figure 2: Pyrolysis of diverse biomass sources yields biochar[13].

Forestry wastes and wood processing by-products represent another major category, prized for producing high-quality biochar suitable for environmental carbon materials. Sources include sawdust, wood chips, bark, branches, logging residues, and mill wastes from timber processing. These lignocellulosic materials have high cellulose (40-50%) and lignin (20-30%) content, which during pyrolysis at 500-700°C forms highly stable aromatic carbon structures with low ash (1-10%) and excellent porosity development[4]. Surface areas can reach 300-500 m^2/g even without activation, far superior to many agricultural biochars. Pine wood and hardwood chips are particularly favored because they generate uniform particle sizes and minimal contaminants[17]. Forestry biochar excels in applications requiring long-term stability and high organic pollutant adsorption capacity, such as PFAS and pharmaceuticals removal from water. However, transportation costs from remote forest sites and slower decomposition kinetics during pyrolysis can increase production expenses compared to farm wastes[18].

Sludge, manure, and industrial biomass by-products provide opportunities for waste valorization but introduce more challenges. Sewage sludge and municipal biosolids contain organic matter mixed with pathogens, heavy metals, and pharmaceuticals, yet pyrolysis at >600°C effectively stabilizes these hazards while concentrating phosphorus for potential reuse[19]. Livestock manure (chicken, cow, pig) offers nutrient-rich biochar but high ash (30-50%) and variable metal content demand strict feedstock screening. Industrial by-products like paper mill sludge, palm oil empty fruit bunches, and biorefinery residues expand supply chains while supporting circular economy goals[20]. Proper selection and pretreatment ensure biochar safety and performance for water treatment.

Pyrolysis Technologies

Pyrolysis is the main thermal process to convert biomass feedstocks into biochar through heating in limited oxygen. Different pyrolysis technologies control biochar yield, carbon stability, porosity, and surface chemistry, which directly affect performance for water pollution control. Slow pyrolysis is the standard method for high-quality environmental biochar. It operates at moderate temperatures of 400-700°C with low heating rates (5-20°C/min) and long vapor residence times (30 min to several hours)[1]. This process favors solid char formation over liquids and gases, typically giving biochar yields of 25-35% from dry biomass. Fixed-bed reactors, rotary kilns, and screw auger systems are common at lab and industrial scales. Slow pyrolysis develops well-ordered aromatic carbon structures with moderate surface area (200-500 m^2/g) and stable functional groups, making the biochar suitable for long-term adsorption of heavy metals, dyes, and PFAS in water treatment[19]. The method also maximizes carbon sequestration potential since much of the biomass carbon stays in the solid phase.

Fast pyrolysis prioritizes liquid bio-oil production but yields biochar as a by-product. It uses very high heating rates (>100-1000°C/s), temperatures around 500-600°C, and short vapor residence times (0.5-5 s) to quickly release volatiles[7]. Biochar yield drops to 10-25%, but the rapid process creates highly porous char with surface areas often exceeding 400 m^2/g due to explosive volatile escape[9]. Fluidized bed reactors and ablative systems are typical. The resulting biochar has irregular pore structures and higher reactivity, which can benefit organic pollutant adsorption but may reduce stability in wet environments[6]. Fast pyrolysis suits integrated biorefineries where biochar supplements bio-oil and syngas streams, though additional activation is often needed for water treatment applications.

Hydrothermal carbonization (HTC) and microwave-assisted pyrolysis provide innovative alternatives for wet or challenging feedstocks. HTC processes biomass in hot pressurized water (180-250°C, 10-50 bar) without prior drying, yielding hydrochar (40-70%) with spherical morphology, high oxygen content, and good ion exchange capacity for nutrient and metal removal[20]. Microwave pyrolysis applies electromagnetic heating for ultra-fast, uniform pyrolysis (100-1000°C/s) that reduces energy use by 30-50% and processing time. It produces biochar with expanded micropores and enhanced surface functionality[4]. Both methods handle sludge, manure, and high-moisture wastes effectively, supporting circular economy goals, but face scale-up challenges, including pressure vessel costs for HTC and microwave penetration limits[2].

Key Physicochemical Properties

Surface area and pore structure control how well biochar adsorbs pollutants from water. Pristine biochar usually shows a moderate surface area that increases with higher pyrolysis temperature as volatiles escape and create internal voids[21]. Micropores give access for small molecules like pharmaceuticals and heavy metal ions, while larger mesopores work better for dyes and organic compounds with a bigger size[22]. The pore distribution depends on both feedstock type and processing conditions. Feedstocks rich in lignin, like wood, create more uniform pore networks compared to grassy materials. These structural features directly affect how fast and how much pollutant biochar can capture in real wastewater treatment[22]. Good pore connectivity also helps water flow through fixed-bed filters without quick clogging.

Elemental composition shows the degree of carbonization through Hydrogen-to-Carbon (H/C) and Oxygen-to-Carbon (O/C) ratios[23]. Lower ratios mean more stable aromatic carbon structures that resist decay over a long time. High carbon content with few hydrogen and oxygen atoms indicates graphitic domains formed during pyrolysis[22]. This aromaticity gives biochar its black color and chemical resistance, which is important for repeated use in water systems and carbon sequestration benefits. Aromatic rings also support π-π interactions with organic pollutants like pesticides and PFAS[20]. The stability reduces breakdown in wet environments and maintains adsorption sites during multiple regeneration cycles. Surface functional groups provide chemical binding sites for targeted pollutant removal. Oxygen groups like carboxyl, hydroxyl, and phenolic create a negative charge for cation exchange with heavy metals and nutrients[24].

These groups form at lower pyrolysis temperatures when more volatile matter remains. Higher temperatures reduce oxygen content but concentrate mineral ash that adds basic sites[16]. Nitrogen or sulfur doping during modification creates a specific affinity for certain contaminants. The balance between physical pores and chemical groups determines overall performance across diverse water pollutants[13]. Understanding these properties guides the selection of biochar type for specific treatment needs.

Structure-Property Relationships

Temperature and feedstock type strongly control biochar structure development during pyrolysis. Higher temperatures cause more complete carbonization as volatile compounds escape, leaving behind fused aromatic ring structures that form the stable carbon matrix. Feedstock composition plays an equal role - lignocellulosic materials like wood produce ordered graphitic domains because of high lignin content, while grassy agricultural residues create more disordered carbon with mineral inclusions[25]. Herbaceous feedstocks often trap ash components within the carbon framework during pyrolysis, which affects pore connectivity and surface reactivity. These differences mean wood-derived biochar typically shows better structural uniformity for adsorption applications, while agricultural biochar offers natural nutrient and mineral sites that enhance ion exchange[26]. The interaction between processing conditions and raw material determines final pore architecture and chemical stability, which guides material selection for specific water treatment needs[25].

Carbon matrix evolution follows clear stages as pyrolysis progresses from hemicellulose, cellulose, and lignin decomposition. Early stages release oxygen-rich volatiles and form aliphatic chains with many functional groups[27]. Intermediate temperatures reorganize these into fused aromatic clusters through dehydration and condensation reactions. Final high-temperature stage completes graphitization where polyaromatic sheets stack into turbostratic structures similar to graphene layers[22]. This evolution increases chemical resistance and reduces hydrophilic sites, changing biochar from reactive char to stable environmental carbon material. The matrix transformation directly controls pollutant binding mechanisms aliphatic phases favor hydrogen bonding with polar organics, while aromatic cores enable strong π-π stacking with aromatic contaminants like dyes and pharmaceuticals[27]. Feedstock minerals catalyze these carbonization pathways, creating unique matrix defects that become active adsorption sites.

These structure-property relationships create predictable performance patterns for water pollution control. Biochars with well-developed aromatic matrices excel at hydrophobic organic removal through partitioning and π-electron interactions, while those retaining oxygen functional groups show superior heavy metal complexation[28]. Pore structure evolution determines diffusion kinetics and capacity limits under competitive adsorption conditions typical of real wastewater[27]. Understanding these coupled effects allows targeted design of biochar variants, low-temperature agricultural biochar for nutrient recovery, and high-temperature wood biochar for recalcitrant organics[25]. The systematic structure-property mapping provides a foundation for engineering next-generation sorbents with optimized performance across diverse contaminant classes.

Removal Performance of Biochar-Based Materials for Water Pollutants

Heavy Metal Removal

Biochar-based materials exhibit effective Pb^{2+} removal from water via multiple mechanisms. Pristine biochar uses ion exchange, where Pb^{2+} cations replace calcium or magnesium ions on negatively charged surface sites. Oxygen functional groups, such as carboxyl and phenolic, form strong inner-sphere complexes that bind Pb even at low pH. According to (Alsadik et al., 2025),modified biochars with iron oxides or phosphate groups form stable Pb minerals such as pyromorphite ($Pb_5(PO_4)_3Cl$) that prevent metal release back to water. Rice husk biochar works well for Pb because natural silica helps precipitate lead silicate compounds. Wood biochar shows higher capacity due to a larger micropore volume that traps Pb hydrate clusters[29]. These materials work in industrial wastewater with high Pb levels from battery manufacturing and electroplating operations.

Cd^{2+} removal by biochar depends on surface precipitation and cation-π interactions. Biochar minerals like carbonate and phosphate react with Cd^{2+} to form insoluble $CdCO_3$ and $Cd_3(PO_4)_2$ that stay stable across a wide pH range[19]. Aromatic rings in high-temperature biochar create π-electron clouds that attract Cd^{2+} through non-electrostatic forces. Sewage sludge biochar excels for Cd because it retains phosphorus from the original waste that precipitates cadmium phosphate [20]. Competitive conditions with calcium ions reduce Cd uptake, so magnetic biochar separation helps concentrate adsorption sites. These properties make biochar effective for treating mine drainage and agricultural runoff contaminated with cadmium from phosphate fertilizers.

Cr(VI) needs reduction to Cr(III) before immobilization, and biochar does both steps. Biochar electron donor groups like phenolic and quinone reduce toxic Cr(VI) to less harmful Cr(III), then surface adsorption or precipitation occurs as $Cr(OH)_3$[4]. Acidic functional groups speed up electron transfer, while high-temperature biochar provides more persistent free radicals for reduction. Arsenic removal uses similar redox plus ligand exchange where as(V) oxyanions bind to iron or aluminum sites on modified biochar. Mercury removal combines sulfide precipitation and amalgamation on sulfur-doped biochar surfaces[2]. In mixed heavy metal solutions, biochar shows selectivity where Pb binds stronger than Cd due to higher complexation constants, but phosphate modification improves multi-metal performance.

Nutrient Removal

Biochar removes phosphate from water mainly through chemical precipitation and ligand exchange reactions on its mineral-rich surface[1]. Calcium, magnesium, iron, and aluminum compounds naturally present in biochar ash react with phosphate ions to form stable minerals such as hydroxyapatite, struvite, or metal phosphates that resist dissolution across wide pH ranges typical of wastewater (Figure 3)[30]. Low-temperature biochar retains more mineral content from feedstocks like bone meal, manure, or eggshell-amended biomass, creating abundant precipitation sites[31]. Surface functional groups like carboxyl and phenolic groups also contribute through direct complexation, especially in acidic conditions where phosphate exists as $H_2PO_4^-$. Modified biochars with lanthanum, zirconium, or magnesium loading create specific high-affinity sites that selectively bind phosphate even when competing anions like chloride or sulfate are present[1]. These materials work well in agricultural runoff, municipal wastewater, and industrial effluents, where phosphorus causes eutrophication problems. Phosphate-loaded biochar can later serve as a slow-release fertilizer after regeneration, supporting circular nutrient management.

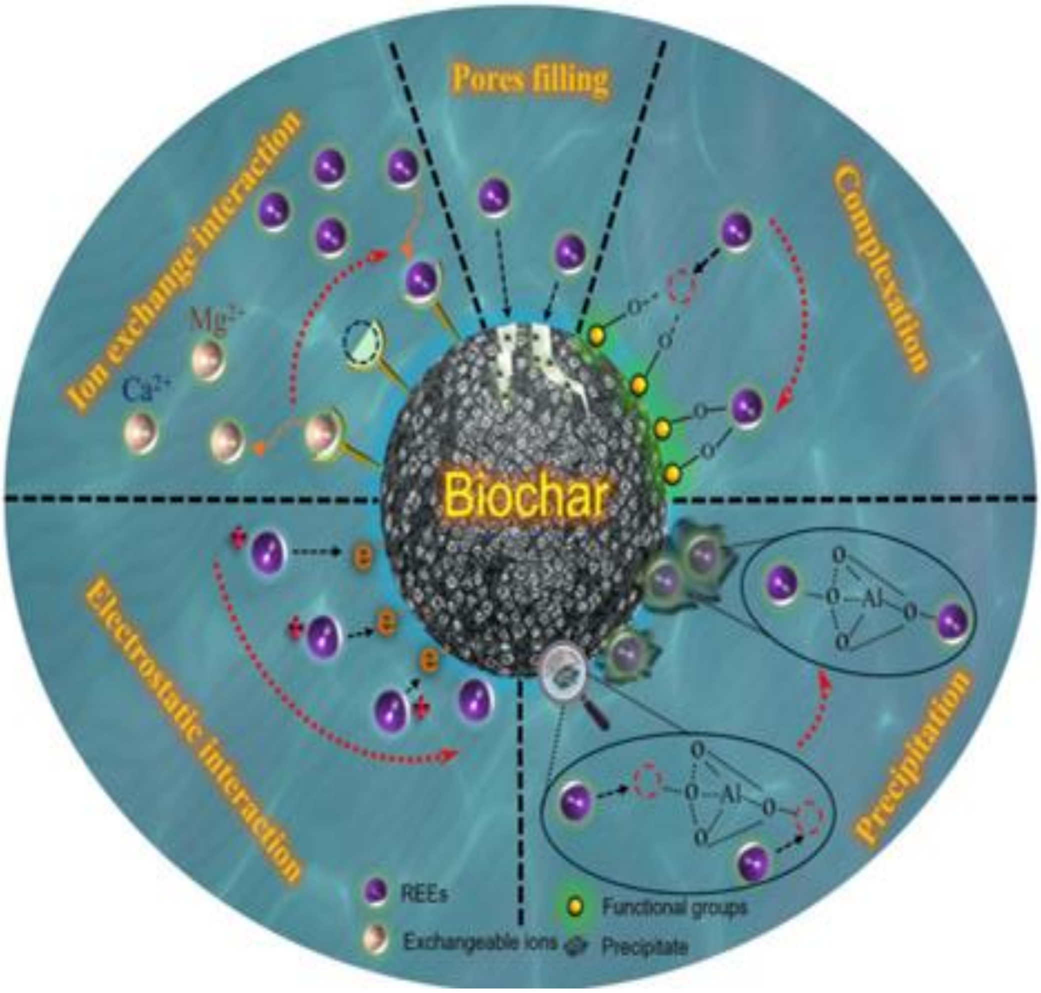


Figure 3. Mechanisms of rare earth element adsorption by biochar[30].

Ammonium removal by biochar occurs primarily through cation exchange and electrostatic attraction to negatively charged surfaces. Biochar developed from animal manure or sewage sludge naturally contains exchangeable cations like calcium, potassium, and magnesium that ammonium ions (NH_4^+) displace during adsorption[19]. Oxygen-containing functional groups deprotonate at neutral pH to create -COO^- and -O^- sites that strongly attract NH_4^+ through Coulombic forces. Pore entrapment further enhances capacity in microporous biochars derived from woody feedstocks[20]. Acidic modification with phosphoric acid or sulfur increases surface charge density and protonated sites that favor ammonium binding. In competition with other cations like K^+ or Na^+ common in wastewater, ammonium shows moderate preference due to its larger hydrated radius[19]. These properties make biochar effective for treating livestock wastewater, food processing effluents, and urban stormwater where high ammonium levels threaten aquatic life.

Nitrate removal presents greater challenge because nitrate (NO_3^-) experiences electrostatic repulsion from negatively charged biochar surfaces at typical water pH. Pristine biochar shows limited nitrate adsorption, relying mainly on weak hydrogen bonding or van der Waals forces with surface imperfections[4]. Anionic exchange capacity dramatically improves with basic modification using amines, quaternary ammonium groups, or layered double hydroxides that create positive charge sites. High-temperature biochar with graphitic domains sometimes adsorbs nitrate through π-electron interactions, though capacity remains lower than for phosphate or ammonium[2]. Biological augmentation with denitrifying bacteria on biochar biofilms offers a hybrid approach where physical adsorption concentrates nitrate for microbial reduction to harmless nitrogen gas. In multi-nutrient systems, phosphate and sulfate compete strongly with nitrate, so sequential treatment or tailored surface chemistry proves necessary[4]. Biochar thus addresses eutrophication by targeting all three major nutrients through complementary mechanisms.

Organic Pollutant Removal

Biochar removes dyes from water through several strong adsorption mechanisms that work together effectively. Aromatic rings in biochar create powerful π-π stacking interactions with dye molecules that also contain benzene rings, such as methylene blue, Congo red, and reactive brilliant red[1]. Hydrophobic partitioning becomes important for non-polar dyes, where pollutant molecules dissolve into biochar's non-polar carbon matrix rather than staying in water. Pore filling occurs when dye molecules physically enter biochar's internal pore structure, especially for larger textile dyes. Hydrogen bonding between dye functional groups and oxygen-containing sites on the biochar surface adds another binding force[32]. Low-temperature biochar works better for dyes because it retains more oxygen groups for hydrogen bonding, while high-temperature biochar provides more aromatic sites for π-π interactions. Surface area and pore volume play key roles, but chemical interactions usually control selectivity in wastewater containing mixed organic pollutants from textile factories and dye manufacturing[2].

Phenolic compounds bind to biochar through multiple pathways that make removal very efficient across different water conditions. Phenol, bisphenol A, and chlorophenols show strong affinity for graphitic carbon domains through π-π electron donor-acceptor interactions, where biochar acts as an electron acceptor[33]. Phenolic -OH groups form hydrogen bonds with carboxyl and carbonyl sites abundant on most biochars. Partitioning into hydrophobic regions works well for non-polar phenols, while electron-rich phenolic rings undergo partial electron transfer to biochar's persistent free radicals[2]. Acidic conditions favor phenol adsorption by protonating the biochar surface and reducing electrostatic repulsion. Iron oxide or manganese modifications create catalytic sites that partially oxidize phenols to less mobile quinones[19]. These mechanisms prove effective for industrial wastewater from petrochemical plants, resin production, and phenolic resin manufacturing, where phenolic compounds cause toxicity and odor problems.

Antibiotics, pharmaceuticals, and endocrine-disrupting compounds present special challenges due to their persistence and low environmental concentrations[34]. Tetracycline, sulfonamides, and carbamazepine adsorb through strong π-π interactions with biochar's aromatic structure, plus hydrogen bonding with multiple functional groups on drug molecules. Estrogenic compounds like 17β-estradiol and bisphenol A partition favorably into hydrophobic biochar regions while forming hydrogen bonds simultaneously. Pore structure controls access for larger antibiotic molecules, while surface functional groups determine affinity for polar pharmaceuticals. Persistent free radicals on the biochar surface sometimes initiate mild oxidation that transforms recalcitrant pharmaceuticals into less toxic forms[2]. In real wastewater containing complex mixtures, antibiotics compete less effectively than estrogens due to size exclusion effects. Modified biochars with β-cyclodextrin cavities or metal-organic frameworks create size-selective binding for specific pharmaceuticals. These properties make biochar particularly valuable for treating hospital wastewater, pharmaceutical manufacturing effluent, and municipal sewage impacted by personal care products[34].

Emerging Contaminants

Biochar removes PFAS from water mainly through hydrophobic partitioning and electrostatic interactions that work well together. PFAS molecules have long fluorinated carbon chains that strongly prefer the non-polar carbon matrix inside biochar pores rather than staying in water[1]. Long-chain PFAS like PFOA and PFOS show much better adsorption than short-chain types because their hydrophobic tails match biochar's graphitic domains perfectly[35]. Surface functional groups create a negative charge that attracts positively charged PFAS headgroups, especially at neutral pH, common in groundwater. High-temperature biochar works best because it has more aromatic carbon and fewer oxygen groups that could interfere with hydrophobic binding[1]. Modified biochar with chitosan or amines adds positive charge sites that improve short-chain PFAS capture through stronger electrostatic forces. These properties make biochar effective for treating contaminated groundwater near airports, military bases, and industrial sites where firefighting foams release PFAS over many years[35].

Microplastics removal by biochar depends on physical trapping and surface adhesion rather than chemical bonding. Biochar's hierarchical pore structure captures microplastic particles through size exclusion, especially effective for particles matching mesopore dimensions[19]. Surface roughness and functional groups create sticky sites where plastics adhere through van der Waals forces and hydrogen bonding. Biochar flakes naturally form filter cakes that physically block even nanoscale plastics during water flow[35]. Modified biochar with magnetic nanoparticles allows easy separation of captured microplastics from treated water. In wastewater treatment, biochar outperforms sand filters because its rough surface traps irregularly shaped plastic fragments better than smooth grains[20]. These mechanisms prove valuable for municipal wastewater plants and stormwater runoff, where laundry fibers, tire wear particles, and cosmetic microbeads create ongoing microplastic pollution.

Personal care products, including triclosan, parabens, and UV filters, present special removal challenges due to their diverse chemical structures and low environmental concentrations. Biochar removes these compounds through combined π-π stacking, hydrogen bonding, and hydrophobic partitioning that match each compound's specific properties[4]. Triclosan binds strongly to aromatic carbon domains through its phenolic rings, while parabens form hydrogen bonds with carboxyl groups on the biochar surface. UV blockers partition into hydrophobic regions due to their long alkyl chains. Pore structure controls access for larger molecules, while surface chemistry determines binding strength for polar functional groups[2]. In real wastewater containing detergents, fragrances, and pharmaceuticals, personal care products compete moderately with surfactants but show better affinity than simple alcohols[4]. Acid-washed biochar improves performance by increasing the positive surface charge that attracts anionic UV filters. These capabilities make biochar particularly useful for advanced wastewater treatment targeting trace emerging contaminants from consumer products.

Environmental Impacts and Risk Assessment

Ecotoxicological Impacts

Biochar can protect aquatic organisms by removing pollutants, but it can also create new risks, so ecotoxicological assessment is essential before large-scale use. Laboratory and mesocosm studies show that biochar particles added to streams or ponds can change the structure and function of benthic communities, for example, by altering invertebrate colonization, respiration, and community metabolism, even when dissolved contaminant levels decrease[36]. Fine biochar particles and biochar-derived dissolved organic matter can increase water turbidity, shift light penetration, and modify oxygen dynamics, which may stress algae, invertebrates, and fish larvae[37]. Some biochars contain polycyclic aromatic hydrocarbons, persistent free radicals, or residual metals from the feedstock, and these components can leach into water and cause sub-lethal toxicity such as oxidative stress, enzyme inhibition, and altered gene expression in aquatic organisms[38]. These findings show that biochar should not be assumed inert; its composition, particle size, and dose must be evaluated using standardized acute and chronic toxicity tests with representative aquatic species before field deployment[39].

When biochar is used to capture metals from contaminated water, the resulting metal-loaded biochar becomes a potential secondary source of toxicity if it is not handled properly. Under changing environmental conditions such as acidification, redox shifts, or organic ligand inputs, sorbed metals like cadmium, lead, and zinc can be remobilized from the biochar surface and released back into porewater or overlying water, where they are bioavailable to algae, invertebrates, and fish[38]. Studies on pyrolysis products from metal-rich feedstocks and metal-modified biochars show that high ash content and unstable mineral phases increase leaching risk, especially at low pH, while surface-bound polycyclic aromatic hydrocarbons in metal-doped biochars can add organic toxicity on top of metal toxicity[40]. In aquatic tests, eluates from some metal-loaded biochars reduce the survival and growth of model organisms such as Daphnia and zebrafish embryos, indicating the combined effects of dissolved metals and co-released organics[37]. These results suggest that long-term stability of metal complexes on biochar and leaching behavior under realistic water and sediment conditions are critical parameters for risk assessment.

Because of these possible impacts, recent reviews highlight the need for formal environmental risk assessment frameworks tailored to biochar and metal-loaded biochar used in water remediation. Recommended approaches include characterization of endogenous contaminants in the biochar (metals, PAHs, dioxin-like compounds), leaching tests across realistic pH and salinity ranges, and tiered ecotoxicity testing on multiple trophic levels, combined with life cycle assessment to capture upstream and downstream burdens[39]. Risk assessors also emphasize that biochar properties depend strongly on feedstock and pyrolysis conditions, so generic assumptions about safety are not appropriate and product-specific evaluation is required[41][42]. Field and mesocosm studies are particularly important to understand long-term fate of biochar particles, their possible transport as colloids, and their interaction with sediments and biota under fluctuating environmental conditions. According to Sawant et al.,[43]integrating these ecotoxicological and risk assessment steps into project design helps ensure that biochar-based technologies deliver net environmental benefits without creating new hidden risks in aquatic ecosystems.

Leaching Behavior

Metal release risks from biochar depend strongly on how metals bind to the carbon surface and how stable those bonds remain under changing water conditions. When biochar captures heavy metals like lead, cadmium, copper, and zinc from contaminated water, the metals initially attach through ion exchange, surface complexation with oxygen groups, and precipitation as phosphates or carbonates[1]. However, acidic conditions common in acid rain or industrial wastewater can protonate these binding sites and release metals back into solution. Biochars made from sewage sludge or manure carry inherent metals from the original waste that become concentrated during pyrolysis, creating a higher leaching potential compared to clean wood-derived biochar[44]. Low pyrolysis temperatures leave more volatile metals loosely bound on the surface, where they desorb easily during water contact[45]. High-ash-content biochars show increased risk because soluble mineral phases dissolve and carry metals with them. Standard leaching tests like SPLP and TCLP reveal that pH below 5.0 dramatically increases metal mobility while alkaline conditions promote reprecipitation[1]. These risks become most serious when metal-loaded biochar enters natural water bodies or when spent adsorbent requires disposal after water treatment.

Aging and weathering dramatically change biochar leaching behavior over time as environmental exposure alters surface chemistry and structure. Fresh biochar contains abundant oxygen functional groups that provide strong metal binding through complexation, but natural oxidation over months to years converts these to more stable mineral-like phases or covers surfaces with secondary minerals that trap metals more permanently[19]. Microbial colonization creates biofilms that both protect bound metals from release and sometimes produce organic acids that enhance desorption. Freeze-thaw cycles and wet-dry periods physically fracture biochar particles, exposing previously protected internal metal sites to leaching[20]. Sunlight exposure generates reactive oxygen species that degrade surface functional groups and mobilize sorbed contaminants. Long-term field studies show that while initial leaching peaks during first rainfall events after biochar application, metal release typically declines over time as biochar surfaces equilibrate with soil solution chemistry and form more crystalline metal phases[45]. However, DOC from decomposing organic matter can form soluble metal-organic complexes that increase leaching even from aged biochar.

Understanding these dynamic processes guides safe biochar management strategies for water treatment applications. Short-term batch tests underestimate long-term risks while accelerated aging protocols better predict field behavior[4]. Composite biochars combining high-surface-area carbon with mineral stabilizers show most promise for minimizing metal remobilization. Regeneration techniques that avoid harsh chemical stripping preserve binding capacity through multiple cycles[2]. Disposal planning must consider final pH environment and co-existing ions that influence metal speciation. Comprehensive leaching characterization across fresh, aged, and regenerated states provides essential data for regulatory approval and commercial deployment of biochar-based water remediation technologies[45].

Stability and Long-term Performance

Biochar structural aging occurs gradually when the material contacts water, dissolved oxygen, microbes, and changing chemistry in aquatic systems over months to years. Fresh biochar contains abundant oxygen functional groups like carboxyl and phenolic that provide strong initial pollutant binding sites through complexation and ion exchange, but natural oxidation processes slowly convert these reactive sites into more stable quinone and carbonyl structures or mineral-like coatings that reduce surface reactivity over time[1]. Physical weathering from water flow, freeze-thaw cycles, and particle collisions breaks larger biochar fragments into finer particles that expose previously protected internal surfaces while increasing overall specific surface area through fragmentation[5]. Microbial colonization creates biofilms that both physically protect the carbon matrix from further oxidation and produce organic acids that can slowly dissolve surface mineral phases[4]. Aromatic carbon rings that dominate high-temperature biochar resist biodegradation much better than aliphatic components remaining in low-temperature char, so materials pyrolyzed above certain thresholds maintain structural framework longer under continuous water exposure[1]. These aging processes change adsorption capacity from chemically-specific binding toward more general physical trapping and partitioning, which affects long-term performance for different pollutant classes in continuous flow treatment systems.

Oxidation in aquatic systems represents the primary chemical degradation pathway that determines biochar service life and carbon sequestration value. Dissolved oxygen slowly penetrates biochar pores and reacts with edge sites of aromatic graphene-like sheets, gradually adding oxygen-containing functional groups that increase hydrophilicity and water solubility of surface layers[4]. Sunlight-driven photochemical reactions generate reactive oxygen species including hydroxyl radicals and singlet oxygen that attack carbon-carbon bonds particularly at defect sites and pore entrances, creating additional oxidation products[2]. Redox-active metals like iron and manganese naturally present or added during modification can catalyze oxygen reduction reactions that accelerate biochar surface corrosion through Fenton-like mechanisms producing additional radicals[46]. pH fluctuations influence oxidation rates because acidic conditions protonate carbon surfaces and enhance electron transfer to dissolved oxygen while alkaline conditions form protective carbonate coatings[47]. Biochars with high graphitic domain content and low hydrogen-to-carbon ratios show slowest oxidation rates because their condensed aromatic structure lacks reactive edge sites for oxygen attack[46]. These oxidation dynamics directly impact long-term pollutant removal capacity since aged surfaces lose specific functional group interactions while gaining non-selective pore filling characteristics.

Long-term performance in water treatment depends on balancing initial high-capacity adsorption with gradual structural evolution that maintains functionality through multiple operational cycles. Laboratory aging studies using hydrogen peroxide or UV irradiation simulate years of natural exposure and show that properly pyrolyzed biochar retains over half its original capacity after accelerated aging equivalent to several field seasons[4]. Field deployments in wastewater lagoons, stormwater filters, and drinking water plants demonstrate that biochar columns maintain hydraulic performance without excessive clogging because aging fragmentation counteracts initial pore blocking by organics[2]. Carbon stability proves particularly important for regulatory approval since jurisdictions increasingly require verified sequestration alongside pollutant removal performance[46]. Composite biochars incorporating mineral stabilizers or clay minerals show enhanced resistance to both physical attrition and chemical oxidation compared to pure carbon materials. Regeneration strategies that avoid complete surface stripping preserve aged biochar's evolved mineral-organic hybrid structure that often performs better than fresh material for certain recalcitrant contaminants[45]. Comprehensive stability testing across fresh, aged, and regenerated states provides essential data for designing robust biochar-based water treatment systems with predictable decades-long service life.

Carbon Sequestration and Climate Co-Benefits

Biochar provides strong carbon sequestration benefits because its highly aromatic carbon structure resists decomposition for centuries when applied to land or used in water treatment systems. During pyrolysis, biomass loses volatile compounds as gases while concentrating stable aromatic carbon rings that mimic graphite structure, making the material much more recalcitrant than fresh organic matter that normally returns to atmosphere through respiration or combustion[1]. High-temperature pyrolysis creates more condensed polyaromatic sheets with fewer reactive edge sites, enhancing long-term persistence even under continuous water exposure or soil microbial activity. This stability converts recent photosynthetically fixed carbon that would normally cycle quickly back to CO_2 into a terrestrial carbon pool lasting hundreds of years[5]. Biochar from agricultural residues, forestry wastes, and municipal biomass represents circular carbon management by upgrading waste streams into climate mitigation materials. When biochar-treated water sludge or spent adsorbent gets land applied after use, the sequestered carbon continues providing soil benefits while maintaining atmospheric CO_2 removal[46]. International carbon accounting protocols recognize biochar persistence based on hydrogen-to-carbon ratios and pyrolysis temperature, providing verified carbon credits alongside water purification services.

Beyond direct sequestration, biochar application creates multiple climate co-benefits through greenhouse gas emission reductions in agricultural and waste management systems. Biochar-amended soils show reduced methane production from anaerobic microbial processes because the porous structure improves aeration and oxygen diffusion, which inhibits methanogenesis[42]. Nitrous oxide emissions drop substantially due to the adsorption of ammonium and the inhibition of denitrification pathways, particularly important in nitrogen-fertilized croplands and livestock operations[4]. Biochar catalyzes the formation of stable mineral-associated organic matter that protects additional soil carbon from decomposition. In water treatment contexts, biochar filters prevent organic carbon mineralization that would otherwise release CO_2 during conventional biological treatment[46]. Production side-streams like syngas and bio-oil can displace fossil fuels in industrial heating, creating additional displacement credits. These combined effects mean biochar systems deliver greater total climate mitigation than sequestration alone, with emission avoidance often exceeding direct carbon storage by significant margins across different deployment scenarios[48].

Lifecycle assessment confirms biochar's favorable climate profile when produced from sustainable biomass sources and applied appropriately. Waste biomass diverted from open burning or landfilling avoids direct CO_2, CH_4, and N_2O emissions while creating stable carbon products[19]. Energy recovery from pyrolysis gases reduces reliance on fossil energy carriers. Soil application enhances crop productivity, which sequesters more atmospheric CO_2 through increased plant growth[20]. Water treatment applications concentrate nutrients in biochar that return to agriculture as slow-release fertilizers, closing nutrient loops while preventing synthetic fertilizer production emissions[4]. Economic analyses show biochar systems become cost-competitive at moderate carbon prices due to revenue streams from water treatment, agricultural improvement, and verified carbon credits. Policy frameworks increasingly support biochar deployment through inclusion in national carbon removal strategies and agricultural subsidy programs that recognize dual environmental service delivery[2].

Regeneration, Reusability, and Practical Applications

Regeneration Methods

Thermal regeneration is the most traditional approach for restoring pollutant-saturated biochar, and it relies on heating the spent material to drive off sorbed organics or to oxidize them into gaseous products while trying to preserve the underlying carbon matrix[49]. In practice, biochar is usually regenerated at temperatures lower than initial pyrolysis to avoid excessive burn-off, so volatile organic contaminants desorb or decompose while the aromatic backbone remains largely intact. For heavy metal-loaded biochar, controlled thermal treatment in oxidizing or mildly reducing atmospheres can convert surface complexes into more stable mineral phases or release weakly bound species, but too aggressive conditions risk sintering, pore collapse, or metal volatilization[50]. Multi-metal modified biochars designed for mercury or arsenic capture, for example, often require carefully tuned isothermal regeneration in specific gas compositions to repair active sites without over-carbonizing the support[45]. Overall, thermal regeneration offers simple operation and broad applicability but can consume significant energy and gradually reduces surface area and functional groups with repeated cycles, which must be considered in life-cycle and economic assessments.

Chemical desorption methods use liquid reagents to strip adsorbed pollutants from biochar surfaces under milder conditions, aiming to preserve porosity and surface chemistry more effectively than high-temperature treatment[50]. Common regenerants include acids, bases, salts, and complexing agents that disrupt electrostatic interactions, ion exchange equilibria, and surface complexes, thereby releasing bound metals, nutrients, dyes, or pharmaceuticals back into solution where they can be concentrated and treated separately[51]. For metal-loaded biochars, acid washing can effectively desorb cations but may also dissolve mineral components and introduce new ions, whereas chelating agents can selectively mobilize target metals while leaving the carbon framework largely unchanged.

Organic pollutants held by hydrophobic partitioning and π-π interactions may respond better to organic solvents or surfactant-assisted washing that displace molecules from carbon domains[49].

Repeated chemical regeneration can gradually oxidize or hydrolyze surface functional groups and may generate secondary liquid waste that requires management, so process optimization must balance regeneration efficiency, biochar integrity, and downstream treatment of concentrated regenerant streams[52].

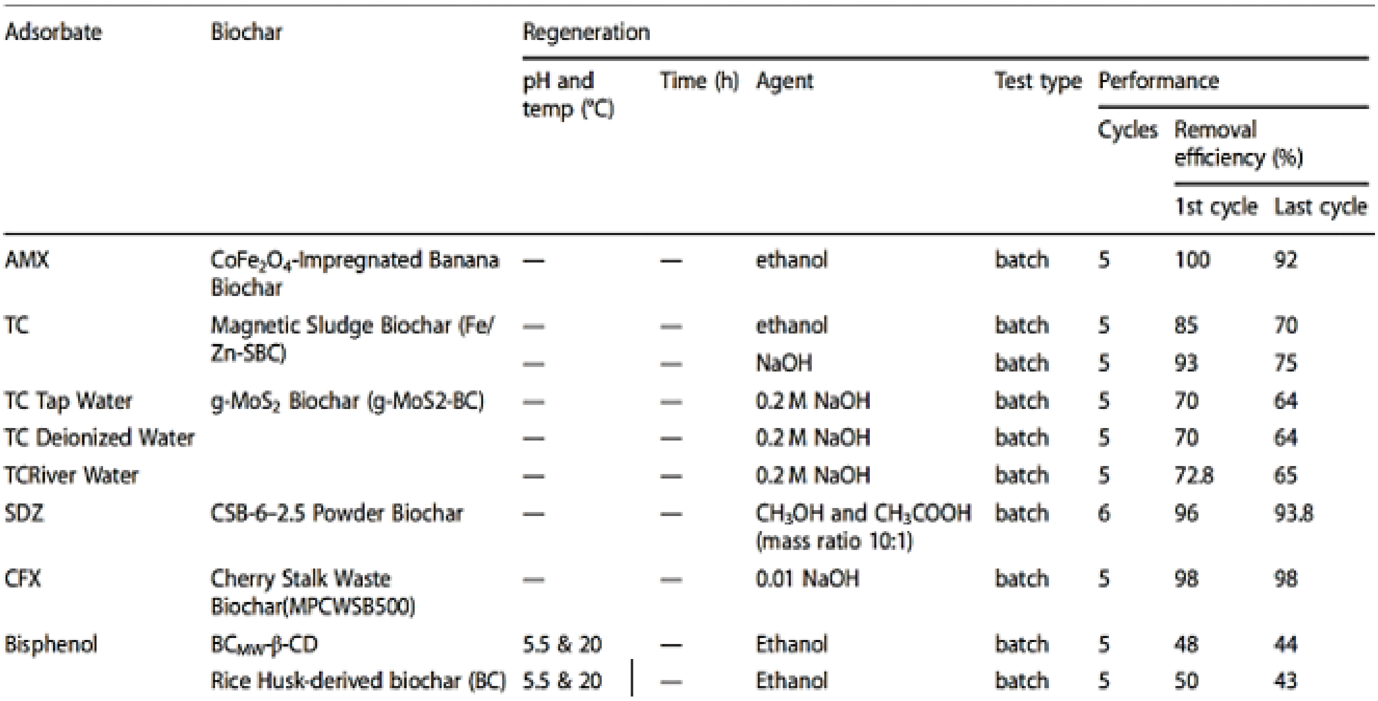
Electrochemical regeneration represents a more recent and flexible strategy that uses applied potentials to drive in situ oxidation or reduction of adsorbed contaminants directly on the biochar surface, often in simple electrolyte solutions[53]. In anodic modes, pollutant molecules are oxidized by electro-generated reactive oxygen species such as hydrogen peroxide and hydroxyl radicals, effectively “self-cleaning” the carbon surface without the need for high bulk temperatures[54].

Cathodic processes can reduce species like Cr(VI) to less harmful forms while simultaneously desorbing them, allowing recovery or further treatment in solution[55]. Because biochar is electrically conductive after suitable activation or compositing with metals, it can function as both an adsorbent and electrode, enabling integrated adsorption–regeneration systems where cycles proceed with limited structural damage and relatively low energy input compared with furnace regeneration. Reactor design, electrolyte composition, and potential control are crucial to avoid excessive carbon corrosion or pore blockage by oxidation byproducts[56]. Emerging work on electrochemically active biochar composites, originally developed for energy storage electrodes, shows that tailored surface functionalities and graphitic domains can improve both adsorption and electrochemical regeneration performance, suggesting promising routes for long-lived, regenerable biochar adsorbents in practical water treatment[55].

Reusability Performance

Reusability performance of biochar-based adsorbents depends on how well adsorption capacity is maintained over repeated adsorption-regeneration cycles in realistic water treatment conditions. With each cycle, some active sites become irreversibly occupied by strongly bound pollutants, co-precipitated minerals, or natural organic matter, which gradually reduces the number of available sorption sites for new contaminants[2]. Pore blockage by retained organics and fine particulates further limits access to internal surface area, especially in micropores that contribute strongly to adsorption of small molecules[57].

Changes in surface chemistry during regeneration, such as loss of oxygen-containing functional groups or partial oxidation of aromatic domains, also alter the balance between electrostatic attraction, complexation, and hydrophobic interactions, leading to progressive changes in both capacity and selectivity for different contaminants[6]. Table 1 presents biochar reusability data for various antibiotics[58]. These mechanisms explain why even biochars with high initial adsorption capacity can show measurable efficiency decay over multiple reuse cycles if regeneration is not carefully optimized.



Adsorbate	Biochar	Regeneration						
		pH and temp (°C)	Time (h)	Agent	Test type	Performance		
						Cycles	Removal efficiency (%)	
							1st cycle	Last cycle
AMX	$CoFe_2O_4$-Impregnated Banana Biochar	—	—	ethanol	batch	5	100	92
TC	Magnetic Sludge Biochar (Fe/Zn-SBC)	—	—	ethanol	batch	5	85	70
		—	—	NaOH	batch	5	93	75
TC Tap Water	g-MoS_2 Biochar (g-MoS2-BC)	—	—	0.2 M NaOH	batch	5	70	64
TC Deionized Water		—	—	0.2 M NaOH	batch	5	70	64
TCRiver Water		—	—	0.2 M NaOH	batch	5	72.8	65
SDZ	CSB-6–2.5 Powder Biochar	—	—	CH_3OH and CH_3COOH (mass ratio 10:1)	batch	6	96	93.8
CFX	Cherry Stalk Waste Biochar(MPCWSB500)	—	—	0.01 NaOH	batch	5	98	98
Bisphenol	BC_{MW}-β-CD	5.5 & 20	—	Ethanol	batch	5	48	44
	Rice Husk-derived biochar (BC)	5.5 & 20	—	Ethanol	batch	5	50	43

Table 1: Reusability of biochar for adsorbing antibiotics from wastewater via chemical regeneration. Rephrase this to avoid plagiarism[58].

Different regeneration methods cause different patterns of adsorption efficiency decay, and the rate of decline depends strongly on pollutant type and biochar modification strategy. Thermal regeneration may effectively remove sorbed organics but can also burn off part of the carbon matrix and collapse delicate pore structures, which reduces surface area and damages specific active sites that were created during initial activation[58]. Chemical desorption using acids, bases, or chelating agents can release metals, dyes, or pharmaceuticals, but repeated exposure can leach mineral components, change surface charge, and introduce new ions that compete with target pollutants in later cycles. For some dye- and antibiotic-loaded biochars, alkaline desorption regenerates capacity relatively well because it reverses electrostatic and hydrogen-bond interactions without severe structural damage, whereas very strong acids or oxidants tend to degrade pore walls and functional groups[59]. Studies on biochars derived from leaves, agricultural residues, and engineered composites consistently report that micropore blockage, partial loss of functional groups, and structural rearrangement are key reasons for gradual reduction in adsorption efficiency after several regeneration cycles[9].

Engineered biochars and composite materials are being designed specifically to improve reusability by stabilizing surface structure and minimizing efficiency loss across many adsorption-desorption cycles[6]. Strategies include introducing robust mineral phases, heteroatom doping, and hierarchical pore structures that maintain access to active sites even when some pores become partially fouled[60]. Some studies show that moderate adsorption capacity combined with excellent structural robustness and gentle regeneration protocols can give better long-term performance than very high initial capacity with rapid decay, highlighting that reusability is as important as single-cycle uptake[51]. Life-cycle and techno-economic assessments increasingly evaluate adsorbents on the basis of cumulative removal over many cycles rather than first-cycle performance, emphasizing the value of materials that maintain stable adsorption efficiencies under repeated use. Overall, understanding adsorption efficiency decay mechanisms and integrating this knowledge into material design, regeneration scheme selection, and operational conditions is essential for deploying biochar-based adsorbents as practical, long-lived components of water treatment systems[2].

Engineering Applications

Fixed-bed systems represent the most straightforward engineering approach for deploying biochar as a water treatment adsorbent because they adapt proven granular media filtration concepts to biochar's unique adsorption properties[61]. Biochar granules, pellets, or extruded particles pack into columns where contaminated water flows downward or upward through the bed, allowing extended contact time between pollutants and adsorption sites throughout the carbon matrix[62]. Design considerations focus on balancing hydraulic loading rates with breakthrough time, where slow flows maximize removal of recalcitrant contaminants like PFAS and pharmaceuticals while faster rates suit higher-throughput applications targeting nutrients or dyes. Biochar's irregular particle shapes and broad size distribution require careful grading to prevent excessive headloss buildup from fines migration, and periodic backwashing maintains hydraulic capacity[63]. Pelletized biochar from coconut husk or rice straw works particularly well because uniform density prevents channeling and ensures even pollutant distribution across the bed cross-section. Pilot studies demonstrate that biochar fixed beds achieve multi-barrier treatment by sequentially removing suspended solids, organics, metals, and micropollutants through physical straining, biodegradation in biofilms, and chemical adsorption[57]. These systems scale easily from household point-of-use filters to municipal treatment plants, with regeneration or replacement intervals determined by effluent monitoring.

Permeable reactive barriers (PRBs) integrate biochar as an in situ reactive zone that passively treats groundwater plumes flowing through buried trenches or walls, offering cost-effective remediation for contaminated aquifers. Biochar PRBs target dissolved organics, metals, and nutrients through adsorption while zero-valent iron or other reactive fills handle redox-sensitive contaminants like chlorinated hydrocarbons[63]. The barrier's high porosity maintains natural groundwater flow without pumping, and biochar's affinity for hydrophobic compounds like PFAS complements reactive minerals that precipitate metals. Design emphasizes hydraulic conductivity matching aquifer conditions to prevent preferential flow paths around the barrier, with biochar particle size and packing density optimized to balance reaction time and permeability[64]. Field deployments show biochar PRBs create redox gradients that support microbial degradation alongside abiotic adsorption, extending overall barrier longevity. Monitoring wells upgradient, within, and downgradient track plume capture and treatment efficiency, guiding maintenance such as partial excavation and biochar replenishment when saturation occurs[65]. These passive systems prove particularly valuable for long-term management of legacy contamination at industrial sites and landfills where active pumping proves prohibitively expensive.

Constructed wetlands and decentralized treatment systems leverage biochar's multifunctional properties to enhance biological and physical processes in low-tech, distributed water management. In horizontal subsurface flow wetlands, biochar substrate replaces gravel to provide adsorption sites for nutrients and organics while supporting plant roots and microbial biofilms that drive anaerobic degradation[66]. Biochar improves oxygen transfer from plant roots and maintains aerobic microsites that promote nitrification alongside denitrification in stratified zones. For decentralized rural applications, biochar-packed household filters treat surface water, rainwater, or groundwater by removing pathogens through size exclusion and disinfection byproducts through carbon adsorption[67]. Modular biochar cartridge systems enable community-scale treatment where local biomass feedstocks support self-reliance and reduce transport costs. Integration with solar disinfection or membrane prefiltration creates robust multibarrier trains suitable for remote settings lacking electricity or skilled operators. Long-term performance benefits from biochar's slow organic matter accumulation that maintains hydraulic conductivity while gradual regeneration through plant root activity extends service intervals[68]. These nature-based engineering solutions scale from individual households to small communities while delivering multiple ecosystem services, including water purification, biomass utilization, and habitat creation.

Current Challenges and Research Gaps

Current biochar research for water treatment still suffers from inconsistent preparation standards and poor comparability between studies, which limits the transfer of laboratory results to engineering design and regulation[69]. Many papers use different feedstocks, pyrolysis temperatures, activation methods, and post-treatments without reporting full process details such as heating rate, gas atmosphere, residence time, and cooling conditions, so it is difficult to reproduce materials or link performance to specific production parameters in a systematic way[41]. Even when similar biomasses are used, laboratory furnaces, pilot kilns, and field cookstoves produce biochars with very different pore structures, mineral phases, and surface chemistries because of scale and operation differences. Standard protocols for characterizing key parameters such as surface area, pore size distribution, elemental ratios, ash composition, and leachable impurities are not uniformly applied, and different laboratories rely on different analytical methods and reporting formats[41]. These issues create large uncertainty when comparing adsorption capacities, kinetic parameters, and regeneration behavior across studies, and they also slow the development of regulatory standards for safe use of biochar in contact with drinking water and aquatic environments.

Another major gap is the limited number of studies that test biochar in real or complex wastewaters rather than idealized single-solute solutions, which can strongly overestimate practical performance. Real waste streams from industry, agriculture, and municipalities contain competing ions, natural organic matter, surfactants, colloids, and fluctuating pH and redox conditions that all influence adsorption and breakthrough behavior in ways not captured by simple batch experiments with pure chemicals[41]. Pilot- and field-scale studies that expose biochar to realistic hydraulic loads, temperature variations, and long-term contamination patterns remain relatively rare, and many of those focus on one contaminant class without monitoring mixed pollutant fate[70]. There is also a scarcity of long-duration column tests and mesocosm trials that evaluate how biochar performs over months or years of operation, including fouling, clogging, and regeneration needs under real operating constraints[70]. As a result, design guidelines for fixed-bed reactors, permeable reactive barriers, or constructed wetlands using biochar still rely heavily on extrapolation from short-term laboratory data, which introduces risk when scaling to full-scale water treatment systems.

Understanding of aging mechanisms for biochar in aquatic and soil–water interfaces is improving but remains incomplete, particularly regarding how physical, chemical, and biological weathering jointly affect long-term sorption and stability[69]. Accelerated aging studies show that cycles of wetting-drying, freezing-thawing, ultraviolet exposure, and microbial colonization can modify surface functional groups, block pores with secondary minerals or organic coatings, and change dissolved organic matter release, all of which alter pollutant binding behavior over time[71]. Detailed work using spectroscopy and micro-scale imaging indicates that oxidation increases oxygen-to-carbon ratios and introduces humic-like components in biochar-derived dissolved organic matter, which can either enhance or reduce metal and organic contaminant immobilization depending on conditions[72]. However, most aging experiments are still relatively short compared with expected service lifetimes in real water infrastructures, and they often focus on single aging factors in isolation rather than realistic combinations[73]. Nano- and modified biochars introduce additional uncertainties because their smaller size and higher reactivity may accelerate structural changes and potential release of colloidal particles, which is not yet well quantified under repeated treatment cycles[74].

Finally, there are important trade-offs between maximizing contaminant removal performance and ensuring environmental safety, as well as significant barriers to scale-up and commercialization of biochar-based water technologies[41]. Strongly modified biochars that incorporate metals, nanoparticles, or persistent functional coatings often show superior adsorption capacities for specific pollutants, but they may introduce new ecotoxicological risks through metal leaching, polycyclic aromatic hydrocarbon residues, or reactive surface species, especially as materials age[72]. Comprehensive risk assessment frameworks that integrate leaching behavior, aging effects, and ecotoxicity with life-cycle greenhouse gas and energy accounting are still emerging and are not yet routinely applied in technology evaluation[42]. On the commercialization side, challenges include ensuring consistent quality in large-scale production, integrating biochar reactors into existing treatment plants, securing financing for decentralized systems, and developing clear certification and monitoring protocols that satisfy regulators and carbon markets at the same time[69]. Addressing these combined technical, environmental, and economic gaps will require coordinated interdisciplinary research, harmonized standards, and more field-scale demonstration projects that explicitly link performance, safety, and cost in real operating environments[71].

Future Perspectives

Future biochar development will focus on green and low-cost modification methods that use waste-derived reagents and mild processing to create high-performance materials without expensive or hazardous chemicals. Researchers are exploring natural agents like plant extracts, fruit peels, eggshells, and agricultural wastes to introduce functional groups through simple hydrothermal or ball-milling processes instead of harsh acid/alkali activation[75]. These approaches avoid secondary pollution while maintaining or improving adsorption selectivity for specific contaminants[76]. Biochar-based multifunctional materials will combine adsorption, catalysis, and antimicrobial properties in single composites by incorporating plant-derived polyphenols, metal oxides from industrial wastes, or microbial enzymes during pyrolysis. Integration with advanced oxidation processes will use biochar as both catalyst support and adsorbent to degrade recalcitrant organics like PFAS and pharmaceuticals before final polishing, while biochar membranes and hybrid nanofiltration systems will target emerging micropollutants with reduced fouling[77]. AI-assisted material design will accelerate optimization by predicting optimal feedstock-pyrolysis-modification combinations through machine learning models trained on large datasets of biochar properties and performance[78]. These tools will enable rapid screening of thousands of synthesis conditions to maximize target pollutant removal while minimizing environmental impacts.

Biochar will play a central role in sustainable water management by enabling decentralized, low-energy treatment systems that treat source water, stormwater, and wastewater while recovering nutrients and sequestering carbon[79]. Household biochar filters using locally produced material will provide safe drinking water in rural areas without electricity or chemical supplies, while community-scale constructed wetlands with biochar substrates will remove nutrients and metals from agricultural runoff before reaching natural waters[80]. Large-scale wastewater plants will adopt biochar reactors as cost-effective pre-treatment to reduce organic load before biological stages, extending membrane life in downstream advanced treatment. Carbon credit programs will incentivize biochar use by valuing its dual benefits of water purification and atmospheric CO_2 removal, creating new revenue streams for treatment facilities[81]. Policy frameworks must support standardized biochar quality certification, life-cycle assessment guidelines, and demonstration projects that validate performance across different water matrices and climates. Research priorities include field validation of hybrid systems, economic modeling of full-scale deployment, and international standards for biochar in drinking water contact applications[79]. Successful commercialization will depend on collaboration between material scientists, water engineers, policymakers, and local communities to deliver biochar solutions that are technically robust, economically viable, and culturally appropriate for global water challenges[82].

CONCLUSION

Biochar-based environmental carbon materials show strong potential to remove a wide range of water pollutants, including heavy metals, nutrients, dyes, pharmaceuticals, PFAS, pesticides, and other emerging contaminants, mainly through adsorption, ion exchange, surface complexation, and redox processes. Their performance depends strongly on feedstock type, pyrolysis conditions, and modification strategy, which together control surface area, pore structure, elemental composition, functional groups, and long-term stability in aquatic environments. Modified biochars can reach high removal efficiency and better selectivity, but they also raise new questions about ecotoxicological effects, leaching of co-contaminants, and aging behavior of metal- and pollutant-loaded materials during storage, reuse, and disposal. For practice, this means that biochar design and application must consider not only initial adsorption capacity but also regeneration feasibility, reusability under realistic water matrices, environmental safety, and compatibility with existing treatment units such as fixed-bed filters, permeable reactive barriers, constructed wetlands, and decentralized systems. Future work should move from simplified batch tests toward long-term pilot and full-scale studies, use harmonized characterization and reporting standards, and integrate life-cycle assessment, carbon sequestration accounting, and formal risk assessment. With careful control of production, modification, and deployment, biochar can become an important part of sustainable water management, linking pollutant removal, waste valorization, and climate mitigation in both centralized and decentralized treatment strategies.

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