



WASTE-DERIVED MATERIALS FOR WATER PURIFICATION – A REVIEW

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ABSTRACT :

Rapid growth in municipal, agricultural and industrial waste generation has created a dual environmental challenge: waste streams require safe management while water resources require increasingly effective and affordable purification. Waste-derived materials offer a circular pathway in which discarded biomass, food residues, agricultural by-products, industrial wastes, sewage-derived solids and selected plastic wastes are transformed into adsorbents, catalysts, filtration media, ion-exchange materials and multifunctional composites. This review examines recent advances in the synthesis and utilization of waste-derived materials for water purification, with emphasis on material preparation, surface engineering, pollutant-removal mechanisms, regeneration, recovery, environmental safety and scale-up.

The review covers agricultural residues, food wastes, forestry biomass, animal-derived wastes, sewage sludge, industrial solid wastes such as fly ash, red mud and slags, and emerging plastic-waste-derived carbon materials. Conversion routes including drying, grinding, carbonization, pyrolysis, hydrothermal carbonization, physical activation, chemical activation, functionalization, mineralization, magnetic modification and composite fabrication are discussed. Their applications for heavy metals, dyes, phenols, pharmaceuticals, nutrients, pesticides, PFAS and other emerging contaminants are evaluated. Adsorption remains the dominant mechanism, but ion exchange, surface complexation, electrostatic attraction, precipitation, redox reactions, photocatalysis and catalytic oxidation increasingly contribute to multifunctional treatment.

Recent literature demonstrates that waste-derived biochars and activated carbons can achieve high removal of several contaminant classes, while modified materials can improve selectivity, regeneration and separation. However, laboratory adsorption capacity alone is not sufficient evidence of sustainability. Feedstock variability, chemical activation, leaching of inorganic constituents, regeneration energy, secondary waste, competing ions, real-water performance and end-of-life management must be considered. Field-scale studies remain comparatively limited, and recent literature explicitly identifies scale-up and realistic water matrices as important knowledge gaps.

The review proposes a circular-material framework linking waste selection, synthesis, characterization, treatment performance, regeneration, resource recovery and lifecycle assessment. Future progress is expected from hybrid biochar–mineral composites, magnetic materials, waste-derived catalysts, membrane and filtration integration, machine-learning-assisted material optimization, continuous-flow systems and standardized lifecycle and techno-economic reporting. Properly designed, waste-derived purification media can simultaneously reduce waste burdens and improve water quality, but commercialization requires evidence beyond batch experiments and a full assessment of environmental safety.

Keywords: waste-derived materials; water purification; biochar; activated carbon; agricultural waste; industrial waste; adsorption; circular economy; wastewater treatment; sustainable materials; resource recovery.

1. Introduction

Water pollution and solid-waste accumulation are traditionally treated as separate environmental problems. Water treatment requires materials, chemicals and energy, while waste management requires collection, stabilization, disposal or conversion. Waste-derived purification materials connect these two challenges by using waste as a feedstock for materials that remove contaminants from water. The approach is attractive because it can reduce dependence on virgin activated carbon or synthetic sorbents while creating value from residues that might otherwise be burnt, landfilled or left to decompose. The concept is especially relevant for agricultural and food-processing regions where large quantities of rice husk, coconut shell, sugarcane bagasse, fruit peels, sawdust, crop residues, bones and eggshells are continuously generated. Reviews of agricultural waste-derived biochar emphasize its availability, relatively low cost and potential for wastewater remediation.

Industrial wastes provide a second major feedstock family. Fly ash, red mud, blast-furnace slag, steel slag and industrial sludge contain silica, aluminosilicates, iron oxides, calcium-bearing phases and other components that can provide adsorption or catalytic functionality.

Biochar has become one of the most studied waste-derived materials. It can be produced from agricultural, forestry and other biomass residues by

thermochemical conversion. Recent reviews describe its applications for heavy metals, nutrients, dyes, phenols, pharmaceuticals, microplastics and other contaminants and increasingly consider modification, machine learning and process integration. The term 'waste-derived material' should nevertheless be used carefully. A waste is not automatically a safe material. Feedstocks may contain metals, salts, pathogens, persistent organic compounds or ash-forming minerals. Chemical activation may introduce hazardous residues, while poorly controlled pyrolysis can produce undesirable compounds. A sustainable material must therefore satisfy both performance and safety criteria. This review examines the complete pathway from waste feedstock to purification material. The central premise is that the success of waste-derived materials should be measured not only by adsorption capacity but by the net environmental value delivered across the material lifecycle. [1, 2, 3, 5, 13]

2. Review Scope and Methodology

This review was developed as a critical narrative synthesis of recent peer-reviewed literature, prioritizing research and review articles from approximately 2023–2026. Literature searches focused on combinations of waste-derived materials, agricultural waste, industrial waste, biochar, activated carbon, adsorbent, water purification, wastewater treatment, heavy metals, dyes, pharmaceuticals, nutrients, PFAS, microplastics, regeneration, circular economy, lifecycle assessment and scale-up.

Evidence was organized around seven questions: (1) which waste streams can be converted into purification materials; (2) how synthesis controls material properties; (3) what mechanisms govern pollutant removal; (4) which contaminants can be targeted; (5) how materials perform in real water and continuous systems; (6) how regeneration and spent-material management influence sustainability; and (7) what barriers must be addressed before commercial deployment.

Reported removal efficiencies and adsorption capacities are not treated as directly comparable unless experimental conditions are similar. Differences in pH, ionic strength, initial concentration, adsorbent dose, particle size, contact time, temperature, water matrix and analytical methods can substantially change apparent performance.

3. Classification of Waste Feedstocks

Feedstock family	Examples	Potential material products	Key advantages	Main concern
Agricultural residues	Rice husk, straw, bagasse, corn residues	Biochar, activated carbon, silica-carbon composites	Abundant, renewable	Seasonal variability
Food waste	Fruit peels, shells, bones, eggshells	Biochar, hydroxyapatite, Ca-rich sorbents	High availability	Biodegradation and contamination
Forestry residues	Sawdust, bark, wood chips	Carbon adsorbents, activated carbon	Carbon-rich structure	Competition with other uses
Animal residues	Bone, feathers, shells	Hydroxyapatite, N-rich carbon, CaCO ₃ sorbents	Functional mineral phases	Pathogen and odor control
Sewage-derived solids	Sludge, biosolids	Ash, biochar, mineral-carbon composites	Large waste stream	Metals and persistent contaminants
Industrial solids	Fly ash, red mud, slag	Mineral sorbents, geopolymer media	Reactive minerals	Leaching/toxicity
Plastic waste	PE, PP, PET and mixed plastics	Activated carbon, carbon catalysts	Large persistent waste stream	Energy and emission control
Other residues	Paper, textile fibers, spent biomass	Carbon, cellulose/chitosan media	Potential local feedstocks	Variable composition

4. Synthesis Routes for Waste-Derived Materials

The synthesis of waste-derived materials may be accomplished by adopting any one of the following routes. [1,2,3,6,11,13]

4.1 Physical preparation

The simplest route is washing, drying, grinding and sieving the waste to produce a natural adsorbent. Such materials retain cellulose, lignin, proteins, mineral ash and native functional groups. Physical preparation has low chemical demand but may provide limited surface area and inconsistent performance.

4.2 Carbonization and pyrolysis

Pyrolysis thermally decomposes biomass under limited oxygen, producing biochar, gases and condensable products. Temperature strongly affects surface area, aromaticity, ash content, pore structure and functional groups. Higher temperatures often increase aromatic carbon and surface area but can reduce oxygen-containing groups that participate in complexation.

4.3 Hydrothermal carbonization

Hydrothermal carbonization converts wet biomass under elevated temperature and pressure, reducing the need for energy-intensive drying. Hydrochars often differ from conventional pyrochars in surface chemistry and oxygen-containing functionality, making process selection important for the target contaminant.

4.4 Physical activation

Steam or carbon dioxide activation can enlarge pores and increase accessible surface area. It avoids some chemical residues but may require high temperature and careful control to prevent excessive burn-off.

4.5 Chemical activation

KOH, H₃PO₄, ZnCl₂ and other activating agents can create high surface area and tailored pore structures. Chemical activation can substantially improve adsorption, but washing, chemical recovery, corrosion and residual ions must be incorporated into lifecycle assessment.

4.6 Functionalization

Functionalization introduces specific chemical groups or phases. Amine groups can enhance binding of acidic species, sulfur-containing groups can interact with certain metals, and metal oxides can provide sites for anions or redox reactions.

4.7 Mineralization and composite formation

Waste-derived carbon can be combined with iron oxides, zeolites, hydroxyapatite, silica, alumina or polymers to create multifunctional composites. Recent research on biochar–zeolite composites emphasizes combining carbon surface chemistry with ion exchange, porosity and magnetic or catalytic functionality.

5. Characterization and Structure–Function Relationships

Material characterization should connect measured properties to purification performance. Surface area alone is insufficient because a high-area material may have poor affinity for the target contaminant. The best studies combine several methods. For example, a material intended for metal removal should be characterized before and after adsorption to determine whether ion exchange, surface complexation or precipitation occurred. This post-treatment characterization is essential for mechanistic claims.

6. Adsorption Mechanisms

Adsorption is the dominant application of waste-derived materials because carbonaceous and mineral surfaces can provide large numbers of reactive sites. The apparent removal of a contaminant may arise from several simultaneous processes. [1, 3, 5, 11]

6.1 Physical adsorption

Van der Waals interactions and pore filling can capture organic molecules. Micropores are particularly important for small molecules, whereas mesopores improve diffusion and accessibility.

6.2 Electrostatic attraction

Surface charge and contaminant ionization strongly influence adsorption. Solution pH can therefore reverse adsorption behavior by changing both surface charge and pollutant speciation.

6.3 Ion exchange

Mineral phases and oxygen-containing groups can exchange counter-ions with dissolved contaminants. This mechanism is particularly relevant to ammonium, some metal ions and selected anions.

6.4 Surface complexation

Metal ions can bind to oxygen-, nitrogen- or sulfur-containing functional groups. Complexation may provide stronger and more selective retention than nonspecific adsorption.

6.5 Precipitation

Calcium-, phosphate- and iron-rich waste-derived materials can promote precipitation of sparingly soluble contaminants. Bone-derived hydroxyapatite is a representative example for some metal ions.

6.6 Redox transformation

Iron-containing materials can participate in electron transfer, while carbon materials may act as electron shuttles. These functions can convert contaminants rather than merely transfer them to a solid.

7. Agricultural Waste-Derived Biochar

Agricultural residues are among the most accessible precursors for waste-derived carbon. Rice husk, rice straw, wheat straw, corn residues, sugarcane bagasse, coconut shell, peanut shell, fruit pits and other residues have been investigated. Rice husk, for example, can provide a silica-rich framework, while coconut shells can yield carbon with favorable pore structures. Bagasse and straw contain cellulose, hemicellulose and lignin that decompose differently during thermal conversion. Recent reviews report strong performance of biochar for metals and organic contaminants, but performance depends strongly on preparation and modification. [1, 4, 3, 14]

8. Food Waste-Derived Materials

Food waste offers chemically diverse precursors. Fruit peels can provide lignocellulosic carbon and oxygenated groups; eggshells provide calcium carbonate; bones provide calcium phosphate and hydroxyapatite; and chitin-rich residues can be converted into nitrogen-containing sorbents. The advantage of food-waste valorization is the combination of waste reduction and material production. However, food waste may contain salts, fats and biodegradable fractions that complicate processing. Pretreatment and controlled drying are therefore important. Natural food residues can also function directly as biosorbents or coagulants. The agricultural wastes are used as natural adsorbents or coagulants for dye removal and its modification can increase removal efficiency. [6, 12]

9. Animal-Derived and Mineral-Rich Waste Materials

Bone-derived materials can contain hydroxyapatite, which provides calcium and phosphate sites for metal immobilization. Eggshells and shell wastes are rich in calcium carbonate and can contribute to precipitation and pH buffering. These materials can be especially useful for metals because removal may occur through ion exchange, surface complexation and mineral precipitation. Their relatively low cost is attractive, but hygienic processing and mineral consistency must be controlled. The use of mineral-rich waste should also consider dissolution. If treatment changes pH or ionic strength substantially, the material may release calcium, phosphate or other constituents. Water-quality improvement should therefore be evaluated as a net outcome rather than based solely on target-contaminant removal. [1, 6]

10. Industrial Waste-Derived Adsorbents

Industrial residues offer a broad range of mineral chemistries. Fly ash contains aluminosilicate and calcium phases; red mud contains iron and aluminum oxides; blast-furnace slag is rich in calcium and silica; steel slag contains calcium, iron and magnesium phases; and industrial sludge can contain reactive mineral and carbon fractions. The major difference from biomass-derived materials is the importance of leaching. A material may remove lead or phosphate while releasing arsenic, chromium, aluminum or soluble salts. Therefore, leaching tests under realistic water chemistry should be mandatory before environmental deployment. [2]

11. Sewage Sludge and Biosolid-Derived Materials

Sewage sludge contains organic carbon and mineral nutrients, making it a potentially valuable feedstock for carbonaceous and mineral adsorbents. Pyrolysis can reduce organic volatility and concentrate mineral components. However, sludge can contain heavy metals, PFAS, pharmaceuticals, pathogens and other persistent chemicals. Pyrolysis does not automatically eliminate all contaminants; some compounds may volatilize, transform or become concentrated in the solid or ash. For this reason, sludge-derived adsorbents require stringent feedstock characterization, emissions control, leaching tests and end-of-life assessment. Their use may be more appropriate in controlled industrial treatment systems than in applications where spent adsorbent is dispersed into the environment. [2]

12. Plastic-Waste-Derived Activated Carbon

Plastic waste is increasingly being investigated as a carbon precursor. Thermochemical conversion and activation can transform selected plastics into porous carbon materials. A 2025 Journal of Environmental Management review describes plastic-waste-derived activated carbon as a circular-economy approach that turns persistent plastic pollution into a potential water-remediation material. The concept is attractive but requires careful emissions

management because plastic feedstocks can generate hazardous gases or condensates depending on polymer composition and additives. Mixed plastic streams are particularly challenging. PET, polyethylene and polypropylene may require different conversion conditions. The final carbon must be tested for residual catalysts, metals, aromatic compounds and leachable additives. Material safety should be demonstrated before water-contact use. [7]

13. Waste-Derived Materials for Heavy-Metal Removal

Heavy metals are among the most widely studied targets because adsorption and mineral precipitation can provide strong removal. Lead, cadmium, chromium, arsenic, nickel, copper, zinc and mercury have all been investigated with waste-derived materials. [8]

Pollutant	Promising waste-derived materials	Dominant mechanisms
Pb(II)	Biochar, hydroxyapatite, eggshell, iron composites	Complexation, ion exchange, precipitation
Cd(II)	Crop biochar, bone, mineral-carbon composites	Complexation, ion exchange
Cr(VI)	Iron-modified biochar, carbon composites	Reduction + adsorption
As(V)/As(III)	Iron-rich biochar, red mud, slag-derived media	Ligand exchange, adsorption
Cu(II)	Lignocellulosic biochar, activated carbon	Complexation, electrostatic attraction
Ni(II)	Biochar, ash/mineral composites	Ion exchange, complexation

14. Pharmaceuticals, Pesticides and Emerging Contaminants

Pharmaceuticals and pesticides are more challenging than many dyes because they occur at lower concentrations and may be chemically diverse. Adsorption performance depends on ionization, hydrophobicity, molecular size and functional groups. A treatment material that promotes partial transformation should be evaluated for toxicity and persistence of the products rather than only parent-compound removal. [7]

15. Hybrid and Composite Waste-Derived Materials

Pristine waste materials often have limitations in capacity, selectivity, kinetics or mechanical strength. Composite formation addresses these limitations by combining complementary functions. [7,9]

Composite	Functional combination	Potential advantage
Biochar–Fe oxide	Carbon adsorption + iron reactivity	Metal/anion removal, magnetic separation
Biochar–zeolite	Carbon + ion exchange	Broader contaminant range
Biochar–hydroxyapatite	Carbon + phosphate mineral	Heavy-metal immobilization
Biochar–TiO ₂	Adsorption + photocatalysis	Capture and degradation
Biochar–graphene-like carbon	Porosity + conductivity	Electrochemical/catalytic treatment
Geopolymer–carbon	Mineral structure + carbon sites	Fixed-bed stability

16. Real-Water Performance

Synthetic laboratory water often overestimates performance because it lacks competing ions and dissolved organic matter. In real wastewater, calcium, magnesium, bicarbonate, chloride, sulfate and natural organic matter can compete for sites or block pores. Therefore, validation should proceed from synthetic single-solute tests to multi-solute solutions, then real wastewater or groundwater. Where possible, field pilots should operate across seasonal conditions. The literature increasingly recognizes this issue. Recent reviews call for more realistic field-scale evaluation and standardized performance reporting. [5, 10, 11]

17. Environmental Safety and Leaching

The environmental safety of a purification material is as important as its adsorption capacity. Waste-derived materials may release metals, soluble salts, carbonaceous compounds or residual activating chemicals. Safety testing should use actual water chemistry where possible. Materials that pass simple distilled-water leaching tests may behave differently in saline or acidic industrial waters. [5, 10, 11]

18. Machine Learning-Assisted Material Design

Machine learning can accelerate material optimization by linking synthesis variables to adsorption performance. Inputs may include feedstock composition, pyrolysis temperature, residence time, activation method, surface area, pore volume, pH and functional-group descriptors. Outputs can include adsorption capacity, selectivity and regeneration performance. Recent biochar research explicitly identifies machine learning as a tool for optimizing production and functionality. However, ML models require standardized datasets. Literature data often differ in experimental conditions

and reporting quality. A model trained on incompatible datasets may produce misleading conclusions. Future research should build open benchmark datasets with standardized metadata. Physics-informed and interpretable models are particularly promising because they can connect predicted performance with adsorption mechanisms rather than treating material composition as an opaque input. [3]

19. Key Challenges to Commercialization

- Feedstock variability can produce inconsistent material quality.
- Activation and modification can increase cost and environmental burden.
- Laboratory adsorption capacities are often not representative of real-water performance.
- Many studies use single-solute batch systems rather than continuous treatment.
- Spent-material management is frequently underreported.
- Leaching and ecotoxicity assessments are not consistently included.
- Few studies combine lifecycle assessment with techno-economic analysis.
- Regeneration stability and multi-cycle performance require stronger evidence.
- Regulatory acceptance of waste-derived water-contact materials may require contaminant-specific certification.
- Standardized reporting is needed for meaningful comparison across studies.

20. Conclusions

A genuinely sustainable waste-derived purification material must therefore close several loops simultaneously: waste must become a useful feedstock; contaminants must be removed without generating unacceptable secondary waste; the material should be regenerable or safely managed; and the complete process should deliver a measurable lifecycle benefit. Future research should prioritize continuous-flow validation, standardized testing, safe multifunctional composites, low-energy synthesis, machine-learning-assisted design and integrated lifecycle assessment. With these improvements, waste-derived materials can move from laboratory demonstrations toward reliable circular water-treatment technologies.

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