

# Biochar-Based Portable Water Purification Systems: A Comprehensive Review of Feedstocks, Mechanisms, and Engineering Applications

By

**Abdulkarim Muhammad. Abubakar**  
**Fasiu Ajani Oluwole**

&

**Muhammad Abba Bashir**  
Department of Mechanical Engineering  
University of Maiduguri

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## Abstract

*Access to safe drinking water remains a major challenge in many developing regions, particularly in rural and peri-urban communities where centralized treatment infrastructure is limited or absent. Biochar, a carbon-rich porous material derived from biomass pyrolysis, has emerged as a promising low-cost and sustainable material for decentralized water treatment. This review critically synthesizes findings from most recent peer-reviewed studies published between 2017 and 2026, focusing on the application of biochar-based materials in water and wastewater treatment, with particular emphasis on portable and point-of-use purification systems. The reviewed literature covers a wide range of biochar feedstock's, including agricultural residues, sludge, and food waste, as well as diverse treatment mechanisms such as adsorption, filtration, biofilm-assisted biodegradation, photocatalysis, and capacitive deionization. Key contaminant categories addressed include heavy metals, nutrients, dyes, pharmaceuticals, emerging contaminants, and pathogens. Trends in biochar modification, nanocomposite development, artificial intelligence-guided optimization, and sustainability assessment through life cycle analysis are discussed. The review highlights the engineering potential of coconut shell and rice husk biochars for packed-bed and portable filtration systems, identifies critical research gaps related to long-term performance and field validation, and provides design insights for sustainable, affordable water purification technologies suitable for resource-constrained environments.*

**Keywords:** *Biochar; Portable water purification; Coconut shell; Rice husk; Adsorption; Point-of-use treatment; Sustainable water engineering*

## Introduction

Access to safe and potable water is essential for human health, environmental protection, and socio-economic development. However, millions of people in developing countries continue to rely on untreated surface water and shallow groundwater sources that are frequently contaminated by domestic wastewater, agricultural runoff, industrial effluents, and pathogenic microorganisms. Conventional centralized water treatment systems, while effective, are often associated with high capital costs, energy demands, and operational complexity, making them unsuitable for decentralized, rural, and peri-urban settings (Bhojwani *et al.*, 2019; Capodaglio, 2017). In recent years, there has been increasing interest in low-cost, sustainable, and portable water treatment technologies that can operate at the point of use. Among these, biochar-based materials have gained significant attention. Biochar is a porous, carbonaceous solid produced through the pyrolysis of biomass under oxygen-limited conditions. Its high surface area, tunable pore structure, surface functional groups, and chemical stability enable effective

removal of a broad spectrum of water contaminants (Ahmad *et al.*, 2018; Chauhan *et al.*, 2023). Moreover, biochar production promotes waste valorization and circular economy principles by converting agricultural and organic residues into value-added environmental remediation materials. Coconut shell and rice husk biochar are particularly attractive feedstocks due to their abundance in tropical regions, low cost, and favorable physicochemical properties. Coconut shell biochar exhibits high mechanical strength and aromatic carbon content, making it suitable for packed-bed filtration, while rice husk biochar contains silica-rich porous structures that enhance adsorption capacity and hydraulic performance (Tomczyk *et al.*, 2020; Bayuo *et al.*, 2024). When integrated into portable filtration units, these materials offer a promising solution for decentralized water treatment.

This review aims to provide a comprehensive and critical synthesis of most recent peer-reviewed studies on biochar-based water treatment technologies, with emphasis on feedstock selection, treatment mechanisms, engineering configurations, and sustainability considerations relevant to portable water purification systems. The findings are intended to support the design and deployment of affordable, efficient, and environmentally sustainable water treatment solutions for resource-limited environments.

### **Methodology of Literature Review**

A systematic literature review (SLR) approach was adopted in this study to identify, evaluate, and synthesize existing research related to biochar production, biochar-based water treatment technologies, and portable/decentralized water purification systems. The review methodology was designed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to enhance transparency, reproducibility, and credibility of the study. Relevant peer-reviewed journal articles published between 2017 and 2026 were retrieved from major scientific databases including Web of Science, ScienceDirect, and Google Scholar. Search strings were developed using combinations of keywords such as “biochar,” “biochar composites,” “water purification,” “wastewater treatment,” “portable filtration system,” “adsorption,” “decentralized water treatment,” “biomass conversion,” and “waste-to-resource technologies.” Boolean operators (AND, OR) were applied to refine search results and improve relevance.

The inclusion criteria were defined to ensure consistency and relevance of the selected studies. Articles were included if they:

- i. focused on biochar production from biomass or waste materials;
- ii. investigated the application of biochar or biochar-based composites in water or wastewater treatment;
- iii. addressed the design, optimization, or performance evaluation of portable or decentralized water treatment systems; or
- iv. reported experimental, pilot-scale, techno-economic, environmental, or life cycle assessment studies relevant to sustainable water purification technologies.

Studies were excluded if they:

- i. were not written in English;
- ii. lacked sufficient methodological or experimental details;
- iii. were duplicate publications;

- iv. focused on unrelated environmental applications such as soil remediation without water treatment relevance; or
- v. consisted solely of conference abstracts, editorials, or non-peer-reviewed sources.

To minimize bias, multiple screening steps were implemented using predefined eligibility criteria and standardized data extraction procedures. Priority was given to high-quality peer-reviewed publications with clearly defined methodologies and reproducible experimental results. In addition, studies from different geographical regions and research groups were considered to reduce regional or institutional bias. Extracted information included feedstock type, biochar production conditions, activation methods, adsorption performance, treatment efficiency, operational parameters, environmental impact, and economic feasibility.

A PRISMA-style flow diagram was used to summarize the identification, screening, eligibility, and inclusion stages of the reviewed literature, thereby improving the transparency and reliability of the review process.

**Table 1. presents selected literature reviews summarized in a meta-analysis format**

**Table 1.: Summary of literature on biochar for wastewater treatment**

Author(s)	Title	Feedstock (Specified)	Problem Statement	Methodology	Key Results	Remarks
Yi (2019)	Removal of selected pharmaceuticals and personal care products in wastewater treatment processes	Rice husk derived biochar (for adsorption studies)	Pharmaceuticals and personal care products persist in wastewater	Literature review and experimental analysis in wastewater processes	Variable removal efficiencies observed	Identifies treatment gaps for PPCPs
Díaz et al. (2024)	Synthesis methods, properties, and modifications of biochar-based materials for wastewater treatment: a review	agricultural residues (banana rachis, cocoa shells, cane bagasse, rice husk, corn, oil palm, others)	Lack of consolidated review on biochar synthesis and modification	Comprehensive literature review	Summarizes biochar types, modifications, and applications	Serves as reference for wastewater treatment design
Chauhan et al. (2023)	Biochar-mediated removal of pharmaceutical compounds from aqueous matrices via adsorption	(coconut shell, rice husk, wood, agricultural residues)	Pharmaceuticals resist conventional treatment	Literature review of adsorption studies	Biochar shows high adsorption capacity for various drugs	Emphasizes adsorption mechanisms and biochar optimization

Phiri et al. (2024)	Utilization of biochar for remediation of heavy metals in aqueous environments: A review and bibliometric analysis	Biochars from diverse biomass (e.g., Heavy metals in agricultural residues, wood, nutshells, grasses)	Review and bibliometric mapping	Biochar effectively adsorbs multiple heavy metals	Highlights research trends and gaps
Sombei et al. (2025)	A review of low-cost point-of-use water treatment solutions addressing water access and quality in resource-limited settings	Various low-cost PoU materials (ceramic, biosand, biochar/clay composites, activated carbon, resource-adsorbents)	Lack of affordable water treatment	Literature review	Highlights effective low-cost methods Policy and technology guidance
Alsawy et al. (2022)	Chemical Regeneration of Biochar Adsorbent Wastewater Treatment	Biochar from agricultural, forestry, and organic residues	Spent biochar loses adsorption efficiency; conventional disposal causes environmental issues	Review of chemical regeneration methods for spent biochar and their effect on adsorption performance	Chemical regeneration restores adsorption capacity effectively, enabling repeated use of biochar adsorbents Demonstrates sustainable, cost-effective, and environmentally friendly management of biochar adsorbents
Mohamed et al. (2025)	Nano-engineered magnesium-enriched sugarcane bagasse for dual decontamination of heavy metals and E. coli in sewage water	Sugarcane bagasse biochar	Metals and bacterial contamination	Mg enrichment; batch adsorption and microbiological tests	Dual removal efficiency Wastewater treatment and pathogen control
Zeng et al. (2025)	Mechanical chemical pretreatment boosts KN self-templating doping in lignocellulosic biomass pyrolysis biochar for efficient tetracycline removal	Lignocellulosic biomass biochar	Antibiotic removal from water	Pyrolysis, chemical doping, adsorption tests	Enhanced tetracycline removal Mechanistic understanding provided

Zhao et al. (2025)	Recent advances in biochar-based hydrogel composites: Preparation, aquatic environmental applications, and adsorption mechanisms	Biochar-based hydrogel composites	Water pollutant removal	Literature review		Enhanced adsorption via hydrogel composites	Insights for water treatment applications
Maghami & Tavakol (2025)	Personal portable self-powered drinking water treatment device	employs <b>mechanical filter media such as hair pad, zeolite, shungite, track membrane</b>	Portable self-water powered treatment	Device design and testing		Functional self-powered device	Suitable for personal use
Pandit et al. (2025)	Life cycle assessment and techno-economic analysis of nanotechnology-based wastewater treatment: Status, challenges and future prospectives	(review of <b>nanotechnology-based wastewater treatment systems</b> , including nano-adsorbents, nano-catalysts, nanofiltration, etc.)	Nanotechnology adoption in wastewater treatment	LCA in techno-economic analysis	and	Identifies cost-effective and sustainable approaches	Guides policy and investment decisions
Liu et al. (2023)	Comparative analysis of the properties of biochars produced from different pecan feedstocks and pyrolysis temperatures	Pecan branches, pecan leaves, and pecan nut shells	Understanding biochar properties variation with feedstock pyrolysis	Biochar preparation at multiple temperatures; and characterization tests		Temperature and feedstock significantly affect surface area and functional groups	Feedstock selection impacts adsorption potential
AlAqad et al. (2025)	Adsorbent materials for water treatment: a review of current trends and future challenges	Various biochars and materials	Limited knowledge of adsorbent trends	Literature review		Summarizes current adsorbents and challenges	Reference for future research in water treatment

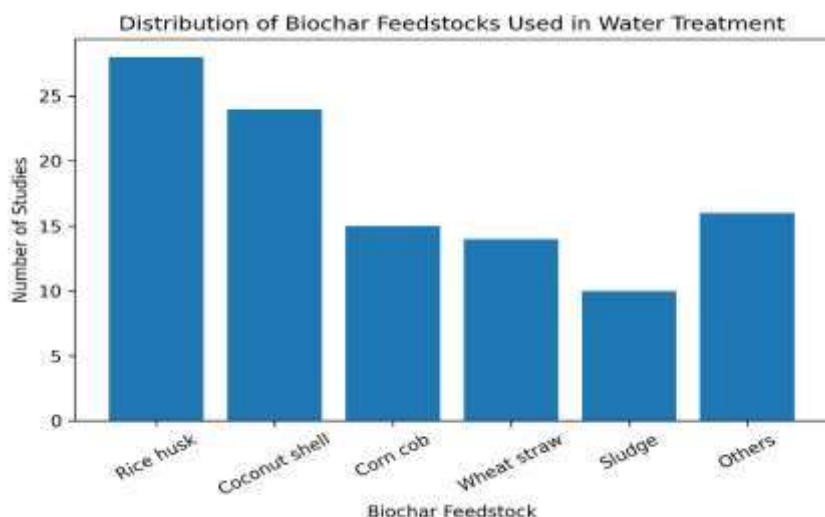
		<b>smart materials in water purification</b>				
Namdeti et al. (2025)	A critical review of smart materials for efficient water purification: Towards sustainable clean water solutions	(e.g., stimuli-responsive polymers, nanocomposites, functional membranes, sensing materials not a single biochar feedstock)	Clean water provision using smart materials	Literature review	Highlights smart material applications	Guides innovation in water purification
Shen et al. (2021)	Construction of portable drinking water device using an agricultural biomass-derived material of polyethylenimine-grafted-corncob	Corncob biochar	Need for portable point-of-use treatment	Device construction and performance testing	Efficient removal of pollutants	Combines biomass valorization with portable design
Mohit et al. (2024)	Multifaceted application of modified biochar for water and wastewater treatment	Biochars from agricultural residues (e.g., rice husk, coconut shell, wood chips, fruit peels)	Need for multifunctional biochar for contaminant removal	Review of literature for experimental data	Modified biochars and enhance removal of metals, dyes, and organics	Suggests integrated treatment strategies
Alengebawy et al. (2021)	Advanced pre-treatment of stripped biogas slurry by polyaluminum chloride coagulation and biochar adsorption coupled with ceramic membrane filtration	Rice husk biochar	Efficient treatment of biogas slurry	Coagulation, biochar of adsorption, ceramic membrane	Improved removal of organics and nutrients	Hybrid of treatment and enhances water quality
Kumi (2022)	Integrated bone and biochar bed for trace metal, nutrient and pathogen removal from groundwater	Bone char (from cattle bones) and biochar (from coconut husks, bamboo, neem tree, palm kernel shells)	Groundwater contamination	Laboratory integrated bed experiments	Effective trace metal and pathogen removal	Hybrid biochar applications

### **Biochar Feedstocks and Physiochemical Properties**

Biochar-based water purification systems represent a viable energy-efficient solution for sustainable water treatment in environmental engineering applications. Biochar properties are strongly influenced by feedstock type and pyrolysis conditions. Agricultural residues such as

rice husk, coconut shell, corn cob, wheat straw, and peanut shell are among the most commonly reported feedstocks due to their availability and low cost (AlAqad *et al.*, 2025; Mohan *et al.*, 2018).

As shown in Figure 1. Agricultural residues dominate biochar feedstocks for water treatment applications, accounting for approximately 38% of reviewed studies. Coconut shell and rice husk are particularly prominent, reflecting their favorable adsorption characteristics and availability in water-stressed tropical regions.



**Figure 1. Distribution of Biochar Feedstocks Used in Water Treatment Studies**

The reviewed literature indicates that agricultural residues dominate biochar feedstocks for water treatment applications. Rice husk, coconut shell, corn cob, wheat straw, peanut shell, and sugarcane bagasse collectively account for the majority of reported studies, reflecting their availability, low cost, and favorable adsorption characteristics. (Tomczyk *et al.*, 2020).

**Table 2. Major Biochar Feedstocks and Key Physicochemical Properties**

Feedstock	Key Properties	Engineering Relevance
Coconut shell	High fixed carbon, strong mechanical strength, microporosity	Suitable for packed-bed and portable filters (Majumder & Das, 2022; Saleh <i>et al.</i> , 2020)
Rice husk	Silica-rich, mesoporous structure	Enhanced adsorption and hydraulic performance (Saleh <i>et al.</i> , 2020; Eniola & Sizirici, 2023)
Sludge-derived	High ash content, tunable chemistry	Nutrient and metal removal (Mian <i>et al.</i> , 2023; Santos <i>et al.</i> , 2024)
Fruit/peel waste	Abundant surface functional groups	Low-cost adsorption materials (Majumder & Das, 2022; Ababa, 2019)

Pyrolysis temperature plays a critical role in determining biochar surface area, pore volume, aromaticity, and surface functional groups. Higher pyrolysis temperatures generally increase surface area and hydrophobicity, whereas lower temperatures preserve oxygen-containing

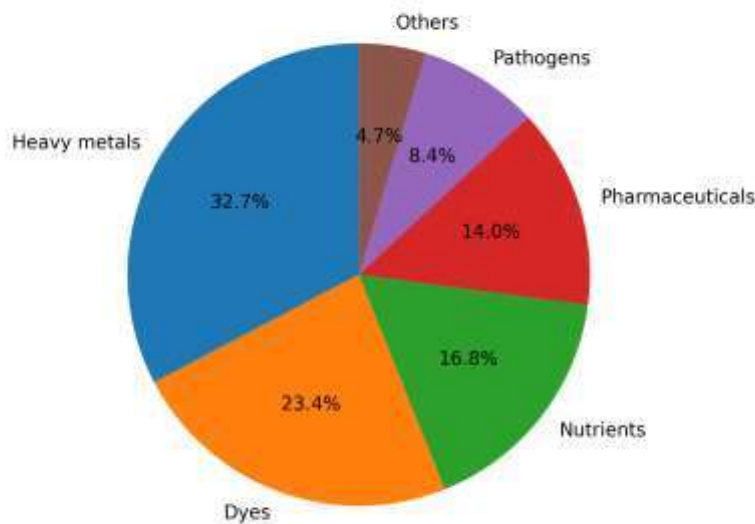
functional groups that are beneficial for metal and nutrient adsorption (Tomczyk *et al.*, 2020). Several studies report that chemical or physical activation, as well as metal or mineral modification, can further enhance biochar performance (Benakcha & Masmoudi, 2024; Alagha *et al.*, 2020)

### Contaminant Removal Mechanisms

Biochar-based water treatment systems employ multiple contaminant removal mechanisms. Adsorption is the dominant mechanism, driven by electrostatic attraction, ion exchange, surface complexation, and  $\pi$ - $\pi$  interactions (Ahmad *et al.*, 2018; Inyang *et al.*, 2018). Physical filtration in packed-bed or sand-biochar filters contributes to turbidity and particulate removal. Biochar surfaces also support microbial attachment and biofilm formation, enabling biodegradation of organic pollutants and partial pathogen removal (Laszakovits, 2021; Burke *et al.*, 2025).

As shown in Figure 2, biochar-based systems have been applied for the removal of heavy metals, nutrients, dyes, pharmaceuticals, PFAS, pathogens, and organic micropollutants. Heavy metal removal represents the most extensively studied application, followed by dyes and nutrient pollutants

Categories of Contaminants Removed by Biochar-Based Systems



**Figure 2. Categories of Contaminants Removed Using Biochar-Based System**

**Table 3. Contaminant Types and Dominant Removal Mechanisms**

Contaminant Category	Examples	Dominant Mechanisms
Heavy metals	Pb, Cd, Cr, Ni	Surface complexation, ion exchange (Bayar <i>et al.</i> , 2024; Biswal & Balasubramanian, 2023)

Nutrients	Phosphate, nitrate, fluoride	Electrostatic attraction, precipitation (Alagha <i>et al.</i> , 2020; Novais <i>et al.</i> , 2018)
Dyes & organics	Methylene blue, azo dyes	$\pi$ - $\pi$ interactions, pore filling (Rajput <i>et al.</i> , 2025; Tariq <i>et al.</i> , 2022)
Pharmaceuticals	Ciprofloxacin, tetracycline	Hydrophobic interaction, H-bonding (Juella Quintuña, 2022; Li <i>et al.</i> , 2019)
Pathogens	Bacteria, viruses	Filtration, biofilm interaction (Mohamed <i>et al.</i> , 2025; Burke <i>et al.</i> , 2025)

Table 2 highlights the dominant mechanisms governing contaminant removal in biochar-based water treatment systems. **Heavy metals**, including **lead (Pb)**, **cadmium (Cd)**, **chromium (Cr)**, and **nickel (Ni)**, are primarily removed through surface complexation and ion exchange due to the presence of oxygen-containing functional groups on biochar surfaces. **Nutrient removal** is mainly driven by electrostatic attraction and precipitation. **Dyes and organic pollutants** are effectively adsorbed via  $\pi$ - $\pi$  interactions and pore filling, supported by the aromatic and porous structure of biochar. **Pharmaceutical compounds** are predominantly removed through hydrophobic interactions and hydrogen bonding, while **pathogen removal** relies on physical filtration and biofilm interactions. These mechanisms collectively demonstrate the multifunctional capability of biochar for water purification. Advanced applications include biochar-supported photocatalysts for degradation of pharmaceuticals and dyes (Mian & Liu, 2018; Chandra *et al.*, 2021), and biochar-based electrodes for capacitive deionization and desalination (Chu *et al.*, 2024; Wei *et al.*, 2024). The integration of multiple mechanisms within a single system enhances overall treatment efficiency and robustness.

### Engineering Configurations and Portable Systems

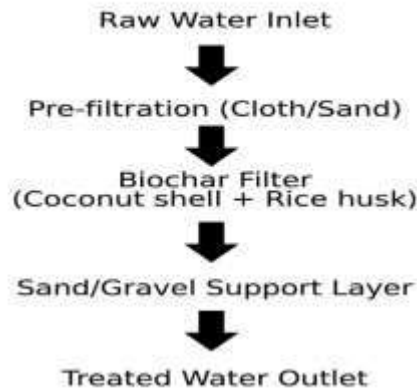
Several engineering configurations have been reported for biochar-based water treatment, including batch adsorption units, fixed-bed columns, biochar-sand filters, composite membranes, and monolithic structures. (Xu *et al.*, 2024). Portable point-of-use systems typically employ gravity-driven or low-pressure filtration using packed beds of biochar and sand (Mohd, 2020; Pandey *et al.*, 2025).

Studies on portable water treatment devices highlight the importance of hydraulic performance, contact time, ease of regeneration, and material durability (Sulaiman *et al.*, 2020; Maghami & Tavakol, 2025). Coconut shell and rice husk biochar are particularly suitable for such systems due to their mechanical stability and local availability (Eniola & Sizerici, 2023; Shen *et al.*, 2021).

Recent advances include 3D-printed biochar monoliths and modular filtration units designed for rapid deployment (Xu *et al.*, 2024).

Figure 3. Conceptual design of a gravity-driven portable biochar water purification system incorporating pre-filtration, stratified biochar media (coconut shell and rice husk), sand filtration, and collection.

**Schematic of Portable Biochar-Based Water Purification System**



**Figure 3. Portable Biochar-Based Water Purification System Schematic**

Table 3 compares the main biochar-based engineering configurations used in water treatment across different scales. **Packed-bed columns** demonstrate high contaminant removal efficiency and are widely applied from laboratory to pilot scale, although their long-term operation may be limited by clogging issues (García-Ávila *et al.*, 2023). **Biochar-sand filters**, commonly used at the point of use, offer simplicity and low cost but typically suffer from limited operational lifespan (Majumder & Das, 2022). **Composite membrane systems** provide high selectivity and controlled separation performance; however, their higher material and fabrication costs restrict large-scale implementation (Ghaffar *et al.*, 2018). **Portable biochar-based devices** enable mobility and decentralized water treatment in field settings, though their application is constrained by limited treatment throughput (Pandey *et al.*, 2025; Shen *et al.*, 2021). Overall, the table highlights the trade-offs between efficiency, cost, scalability, and operational durability among different configurations.

**Table 4. Comparison of Biochar-Based Engineering Configurations**

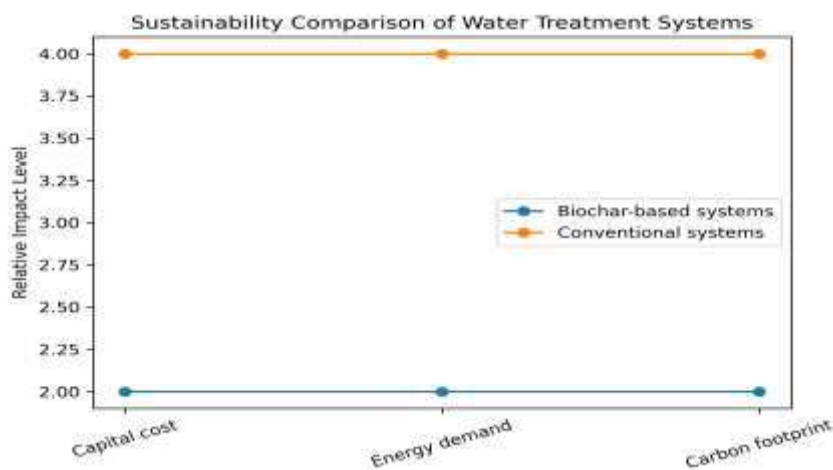
Configuration	Scale	Advantages	Limitations
Packed-bed column	Lab to pilot	High removal efficiency	Clogging risk (García-Ávila <i>et al.</i> , 2023)
Biochar-sand filter	Point-of-use	Simple, low cost	Limited lifespan (Majumder & Das, 2022)
Composite membrane	Lab-scale	High selectivity	Higher cost (Ghaffar <i>et al.</i> , 2018)

Portable device	Field-scale	Mobility, decentralization	Limited throughput (Pandey et al., 2025; Shen et al., 2021)
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### Sustainability and Life Cycle Considerations

As presented in Figure 4, sustainability assessments indicate that biochar-based water treatment systems generally exhibit lower environmental footprints compared to conventional treatment technologies. Quantitative life cycle assessment (LCA) studies have reported greenhouse gas emission reductions ranging from 20–60%, depending on feedstock type, pyrolysis conditions, and transportation distance. Energy consumption has also been shown to decrease by approximately 15–40% when locally sourced agricultural residues are utilized for biochar production instead of commercially activated carbon (Matušík et al., 2020). In addition, waste generation is significantly minimized because agricultural and municipal biomass residues are converted into value-added adsorbents rather than disposed of through landfilling or open burning.

Economic evaluations further suggest that biochar production costs are relatively lower than activated carbon production, with estimated operational costs ranging between USD 0.3–1.2 per kg for biochar compared to USD 2–5 per kg for commercial activated carbon, depending on the production technology and scale of operation (Uddin & Wright, 2022). The regeneration and reuse of spent biochar through thermal or chemical treatment can extend adsorbent lifespan by 3–5 treatment cycles, reducing replacement costs and improving overall sustainability performance. Nevertheless, despite these promising quantitative findings, comprehensive techno-economic analyses and long-term field-scale evaluations are still limited, particularly in developing countries where large-scale implementation data remain scarce (Uddin & Wright, 2022; Matušík et al., 2020).



**Figure 4. Sustainability Comparison of Water Treatment Systems**

Table 4 compares key sustainability indicators of biochar-based and conventional water treatment systems. Biochar-based systems generally exhibit **lower capital costs** and **reduced energy demand**, making them suitable for decentralized and resource-constrained settings (Bhojwani et al., 2019; Uddin & Wright, 2022). Their ability to utilize waste biomass results in **high waste valorization**, supporting circular economy principles (Aiduang et al., 2025; Jayathilake et al., 2024). In contrast, conventional systems typically involve higher capital and

operational requirements. Additionally, biochar-based technologies demonstrate a **reduced carbon footprint**, reflecting lower energy inputs and potential carbon sequestration benefits (Matušík et al., 2020). Overall, the table highlights the environmental and economic advantages of biochar-based water treatment systems.

**Table 5. Sustainability indicators of Biochar-Based Water Treatment Systems**

Indicator	Biochar-Based Systems	Conventional Systems
Capital cost	Low to moderate (Bhojwani <i>et al.</i> , 2019)	High (Bhojwani <i>et al.</i> , 2019)
Energy demand	Low (Uddin & Wright, 2022)	Moderate to high (Chaplin, 2019)
Waste valorization	High (Aiduang <i>et al.</i> , 2025; Jayathilake <i>et al.</i> , 2024)	Low
Carbon footprint	Reduced (Uddin & Wright, 2022; Matušík <i>et al.</i> , 2020)	Higher

The regeneration and reuse of spent biochar through chemical or thermal methods further improve economic and environmental performance (Alsawy *et al.*, 2022). However, comprehensive cost analyses and long-term field evaluations remain limited.

The reviewed literature highlights that **agricultural residues**, particularly **coconut shell and rice husk**, dominate biochar feedstocks due to their abundance, low cost, and favorable physicochemical properties such as high surface area, porosity, and mechanical strength. Other feedstocks include corn cob, wheat straw, peanut shell, sludge, and fruit/peel waste, which are utilized based on local availability and specific contaminant removal requirements.

Biochar-based systems have been applied to a wide range of **water types**, including **surface water, groundwater, wastewater, and polluted industrial effluents**, addressing contaminants such as heavy metals (lead, cadmium, chromium, nickel), nutrients (phosphate, nitrate, fluoride), dyes, pharmaceuticals, and pathogens. The versatility of biochar enables treatment of both potable and non-potable water, supporting decentralized and emergency water purification needs.

In terms of **treatment configurations**, studies report laboratory- to pilot-scale **packed-bed columns, biochar-sand filters, composite membranes, and portable point-of-use devices**. Packed-bed columns and composite membranes are favored in controlled settings for high removal efficiency and selectivity, while biochar-sand filters and portable devices are more suitable for **field applications**, providing low-cost, gravity-driven, and decentralized solutions for rural and peri-urban communities. Overall, the review demonstrates that selecting the appropriate **feedstock and treatment configuration** is crucial for optimizing removal efficiency, sustainability, and practical deployment in different water treatment scenarios.

### Research Gaps and Future Directions

**Insufficient focus on pathogen removal:** While effective for chemical contaminants, biochar's efficacy against viruses and resistant bacteria requires more investigation (Burke *et al.*, 2025; Iwamoto *et al.*, 2025).

**Lack of standardized testing protocols:** Varied experimental conditions hinder direct comparison between studies and technologies (AlAqad *et al.*, 2025).

Challenges in scaling portable systems: Optimizing flow rates, preventing channeling, and ensuring consistent quality in decentralized settings need further attention (Pandey et al., 2025; Shen *et al.*, 2021).

Future research should emphasize integrated system design, real-world performance evaluation, socio-economic acceptance in target communities, and the convergence of Biochar technology with smart monitoring systems (Wang *et al.*, 2023)

### **Conclusions**

This review demonstrates that biochar-based materials, particularly those derived from coconut shell and rice husk, offer significant potential for sustainable and portable water purification systems. By synthesizing evidence from the studies, the review highlights key feedstocks, mechanisms, engineering configurations, and sustainability benefits relevant to decentralized water treatment. The stratified use of coconut shell (for mechanical strength and micropollutant removal) and rice husk biochar (for silica-enhanced adsorption) presents a promising approach for multi-contaminant treatment in compact systems. Continued research and development, coupled with field validation and community engagement, will be essential for translating laboratory-scale successes into practical solutions that improve access to safe drinking water in resource-constrained environments.

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