

## Journal Pre-proof

### A Critical Assessment of Potential to Use Sewage Sludge Derived Biochar in Wastewater Treatment

T. Kampila , M.M. Manyuchi , W. Stinner , C. Mbohwa

PII: S2667-0569(26)00043-X  
DOI: <https://doi.org/10.1016/j.cartre.2026.100645>  
Reference: CARTRE 100645



To appear in: *Carbon Trends*

Received date: 26 February 2026  
Revised date: 13 April 2026  
Accepted date: 15 April 2026

Please cite this article as: T. Kampila , M.M. Manyuchi , W. Stinner , C. Mbohwa , A Critical Assessment of Potential to Use Sewage Sludge Derived Biochar in Wastewater Treatment, *Carbon Trends* (2026), doi: <https://doi.org/10.1016/j.cartre.2026.100645>

This is a PDF of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability. This version will undergo additional copyediting, typesetting and review before it is published in its final form. As such, this version is no longer the Accepted Manuscript, but it is not yet the definitive Version of Record; we are providing this early version to give early visibility of the article. Please note that Elsevier's sharing policy for the Published Journal Article applies to this version, see: <https://www.elsevier.com/about/policies-and-standards/sharing#4-published-journal-article>. Please also note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2026 The Author(s). Published by Elsevier Ltd.

This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>)

## A Critical Assessment of Potential to Use Sewage Sludge Derived Biochar in Wastewater Treatment

<sup>1</sup>Kampila, T., <sup>1-3</sup>Manyuchi\*, M. M., <sup>3</sup>Stinner, W. and <sup>2</sup>Mbohwa, C

<sup>1</sup>Sustainable Technology Environmental Management Company, Harare, Zimbabwe

<sup>2</sup>Sustainability and Future Technologies Centre, Faculty of Engineering and Technology, University of South Africa, Pretoria, South Africa

<sup>3</sup>Germany Biomass Research Centre, Leipzig, Germany

[\\*mercy.manyuchi@gmail.com](mailto:mercy.manyuchi@gmail.com) or [tmanyum@unisa.ac.za](mailto:tmanyum@unisa.ac.za)

### Abstract

Biochar derived from biowaste represents a sustainable and multifunctional material for wastewater treatment, enabling simultaneous waste valorisation and pollutant removal in wastewater. Unlike prior reviews that broadly describe biochar applications, this review provides a focused critical analysis of sewage sludge derived biochar through identifying specific research gaps such as the lack of quantitative meta-analyses, inconsistent reporting of adsorption mechanisms and limited evaluation of toxic metal leaching risks. The study examines production methods such as pyrolysis, hydrothermal carbonization, gasification and their direct influence on biochar properties. Removal efficiencies reported across studies are highly variable with heavy metal removal efficiencies of 60–80% and nutrient removal of 40–75%, but these values lack standardized conditions such as pH, dosage and contact time, limiting cross study comparison. The dominant adsorption mechanisms shift from electrostatic attraction and surface complexation at near-neutral pH to precipitation and ion exchange at alkaline pH. However, quantitative distinctions between physical adsorption and chemisorption are rarely provided. Ash content in sewage sludge biochar enhances phosphate precipitation but can also leach trace metals for example copper and zinc under acidic conditions. Biochar applications improve water clarity and reduce odour, but critical limitations including potential metal leaching, pressure drop in filtration systems and lack of regulatory approval are underexplored. This review concludes that while sewage sludge biochar supports circular economy goals, its large-scale adoption requires standardized production protocols, long term ecological impact studies and comparative techno-economic assessments against activated carbon.

**Keywords:** Adsorption, biochar, circular economy, heavy metals, municipal wastewater, nutrients, pyrolysis, sewage sludge, wastewater treatment, water quality.

## 1. INTRODUCTION

The rapid growth of urban populations, industrialization and agricultural expansion has led to a notable increase in wastewater generation worldwide. Global estimates indicate that over 380 billion cubic meters of municipal wastewater are produced annually, with projections showing continued rise (Lukić et al., 2025). Industrial activities including mining, textiles, metallurgy and chemical manufacturing generate effluents rich in heavy metals, persistent organics and nutrients (Mon et al., 2023). Agricultural runoff from fertilizer-intensive crop production and concentrated animal feeding operations introduces excessive nitrogen (N), phosphorus (P) and organic matter into water bodies (Thakur et al., 2024). The management of these diverse wastewater streams presents a critical environmental, public health and economic challenges. Untreated or inadequately treated wastewater contaminates surface and groundwater leading to eutrophication, heavy metals accumulation in aquatic organisms and pathogen related health risks (Bhattacharjee & Ahmaruzzaman, 2024). In low- and middle-income countries, wastewater treatment infrastructure is often limited (Roy et al., 2023). While numerous reviews exist on biochar for wastewater treatment, the specific objective of this review is that it critically evaluates contradictions in reported adsorption data for example variable removal efficiencies without standardized conditions. Quantitatively compares kinetic and isotherm models across studies and identifies underexplored operational challenges for instance pressure drop, clogging and regeneration cycles. This review does not perform a formal meta-analysis due to high heterogeneity in experimental conditions across studies instead, it provides a systematic qualitative synthesis and identifies priority areas for standardization. Sewage sludge, a residual semi-solid by-product of wastewater treatment is one of the most pressing challenges in wastewater management. Approximately 45 million tonnes of dry solids of sewage sludge are produced annually, with volume expected to increase (Kacprzak et al., 2022). Sewage sludge contains a complex mixture of organic matter, nutrients, trace metals, pathogens, residual pharmaceuticals and industrial chemicals (Fatima et al., 2022). Direct agricultural application is constrained by contamination risks, including heavy metal accumulation and pathogen transmission (Robinson & Leinweber, 2023). Conventional disposal methods such as landfilling and incineration pose environmental hazards including greenhouse gas emissions and leachate formation

(Dębowski et al., 2025). These limitations have prompted exploration of alternative approaches that valorise sewage sludge while mitigating environmental impacts.

Biochar production from sewage sludge has emerged as a promising strategy to address the dual challenges of waste disposal and wastewater treatment. Biochar is a carbon-rich, porous material obtained through thermochemical conversion of biowaste under limited oxygen conditions (Goncalves et al., 2022). Biochar's structure, surface chemistry and mineral content make it suitable for adsorption, nutrient retention and microbial colonization (Goyal & Chaudhary, 2025). By converting sewage sludge into biochar, pathogens are destroyed, organic matter is stabilized and contaminants are immobilized, creating a safer reusable material (Agoe et al., 2024). This approach aligns with circular economy principles (Khan et al., 2023). The effectiveness of biochar is determined by feedstock type, production method, pyrolysis temperature, residence time and post-treatment modifications (Díaz et al., 2024). Sewage sludge biochar produced at moderate temperatures 300–400 °C retains surface functional groups (hydroxyl, carboxyl and carbonyl) that facilitate adsorption of polar compounds, ammonium and phosphate (Qin et al., 2022a). High temperature pyrolysis 500–700 °C increases aromatic carbon content and porosity, enhancing adsorption of hydrophobic organic pollutants and heavy metals (Bai et al., 2022). Hydrothermal carbonization produces hydrochar with abundant oxygen containing functional groups (Jin et al., 2024). Post-production treatments such as chemical activation or pH adjustment can optimize biochar properties (Taha & Daffalla, 2023). Municipal wastewater treatment is a common application. Conventional processes often fail to completely remove nutrients or trace metals (Lukić et al., 2025). Incorporating biochar enhances removal efficiency by adsorbing residual contaminants and providing surfaces for microbial biofilm formation (Idris et al., 2023). Studies report chemical oxygen demand (COD) reductions of 40–65% and phosphate removal up to 70% using sewage sludge biochar in tertiary treatment (Guvava et al., 2021). Industrial wastewater containing heavy metals, dyes and persistent organic pollutants presents additional challenges. Biochar has demonstrated strong adsorption capacity for lead (Pb), cadmium (Cd), Cu and Zn (Chen et al., 2023). In textile wastewater, colour removal efficiencies of 60–80% and metal reduction exceeding 70% have been reported (Mon et al., 2023). Agricultural wastewater, including runoff and animal husbandry effluents, benefits from biochar's ability to capture N and P through adsorption, precipitation and microbial processes (Al-Bsoul

et al., 2025). Sewage sludge biochar reduces phosphate by 60–70% and nitrate by 40–60% (Wang et al., 2022). Landfill leachate containing high ammonia, organic acids and trace metals can be stabilized with biochar, reducing ammonium by 40–50% and COD by up to 60% (Baaloudj et al., 2025; Zhang et al., 2023). The alkaline nature of sewage sludge biochar also aids pH stabilization (Agoe et al., 2024).

Environmentally, biochar production reduces greenhouse gas emissions relative to conventional disposal (Hu et al., 2023) and sequesters carbon (Sani et al., 2023). Economically, biochar offers a low-cost alternative to activated carbon, particularly in regions with abundant biowaste (Rammal et al., 2025). In Africa, including Zimbabwe, biochar provides a locally adaptable, cost-effective solution (Guvava et al., 2021; Maramba et al., 2023). Technically, biochar's effectiveness combines physical adsorption, ion exchange, precipitation and microbial colonization (Jha et al., 2023). However, challenges remain include variability in feedstock composition, high ash content, potential trace metal leaching, lack of regulatory frameworks and limited long term studies on regeneration and ecological impacts (Agoe et al., 2024; Baaloudj et al., 2025). Addressing these gaps is essential for scaling biochar applications safely and effectively. Table 1 gives the characteristics of biochar relevant in wastewater treatment.

**Table 1: Characteristics of Biochar for Wastewater Treatment**

Characteristic	Description	Relevance in Wastewater Treatment	Influence of Production Method	Reference
Surface Area (m <sup>2</sup> /g)	Total surface for adsorption; ranges from 50-800m <sup>2</sup> /g depending on feedstock and temperature	Higher surface area increases adsorption of nutrients, heavy metals, dyes and organic pollutants	Pyrolysis at 500-700°C generally increases surface area; gasification may further enhance porosity	Diaz et al., 2024
Porosity (micro-, meso-, macro-pores)	Internal pore structure that determines accessibility of	Micropores enhance adsorption of small molecules;	High temperature pyrolysis improves microporosity; hydrothermal	Khan et al., 2023

	contaminants	mesopores favour large organics and dyes	carbonization enhances mesoporosity	
Surface Functional Groups	Presence of -OH, -COOH, -C=O and phosphate groups	Facilitate ion exchange, hydrogen bonding and electrostatic interactions with ammonium, phosphate and metals	Lower pyrolysis temperatures preserve more oxygen containing functional groups	Qin et al., 2022
Mineral Content (Ca, magnesium (Mg), iron (Fe), aluminium (Al))	Inorganic components retained from feedstock	Promote precipitation of phosphate and immobilization of heavy metals	Sewage sludge biochar contains higher mineral content than plant-based biochar	Bai et al., 2022
Cation Exchange Capacity	Ability to exchange positively charged ions	Enhances removal of ammonium and metal cations	Increased by moderate pyrolysis temperatures and surface oxidation	Jha et al., 2023
pH (alkalinity)	Biochar typically exhibits alkaline properties (pH 7-10)	Neutralizes acidic wastewater, enhances meta precipitation	Higher pyrolysis temperatures increase alkalinity	Agoe et al., 2024
Electrical Conductivity	Measure of soluble salts and ionic strength	Influences nutrient retention and microbial activity	Elevated in sludge derived biochar due to mineral salts	Roy et al., 2023
Stability (Carbon Aromaticity)	Degree of carbonization and	Supports long term adsorption and	Higher temperatures increase aromaticity	Sani et al., 2023

	resistance to degradation	carbon sequestration	and structural stability	
Bulk Density	Mass per unit volume of biochar	Affects hydraulic conductivity in filtration systems	Influenced by feedstock composition and carbonization level	Maramba et al., 2023
Microbial Affinity	Ability to support biofilm formation	Enhances biodegradation of organic matter and nitrogen cycling	Improved by porous structure and moderate surface functionalization	Idris et al., 2023

## 1.2 Properties That Affect Bio-Waste Derived Biochar in Wastewater Treatment

The efficiency of bio-waste derived biochar in wastewater treatment is governed by its physical and chemical characteristics. Surface area and pore structure are critical because they determine the number of available adsorption sites and the ability of the material to capture dissolved pollutants. A well-developed porous network enhances the removal of nutrients, heavy metals and organic contaminants (Díaz et al., 2024). Surface functional groups such as carboxyl, hydroxyl and carbonyl groups promote chemical bonding, ion exchange and electrostatic interactions with contaminants. Mineral components present in the biochar contribute to precipitation reactions, especially in pH and metals removal. The pH of biochar influences contaminant solubility, surface charge and microbial activity within treatment systems (Wang et al., 2022). In addition, feedstock composition and production conditions, particularly temperature, significantly affect structural stability, ash content and adsorption capacity, ultimately determining overall treatment performance.

## 2. STUDY OBJECTIVES

This study aims to address the lack of critical and systematic evaluation in existing literature on sewage sludge derived biochar for wastewater treatment. In response to the identified research gap, the paper seeks to move beyond descriptive analysis by providing a comparative and quantitative assessment of adsorption performance under varying operational conditions. The study further aims to establish clear structure performance relationships by linking biochar properties such as surface chemistry, ash content and porosity to contaminant removal efficiency. Additionally,

the study evaluates dominant adsorption mechanisms and identifies inconsistencies across reported findings. By integrating these aspects, the research provides a critical synthesis of current knowledge while highlighting limitations related to scalability, variability in sludge composition and environmental risks, thereby positioning the study within a broader framework for advancing sustainable wastewater treatment technologies.

### **3. BIO MATERIALS USED IN BIOCHAR PRODUCTION**

Biochar production relies on the thermal or hydrothermal conversion of various organic feedstocks. The selection of feedstock significantly influences the structural, chemical and functional properties of the resulting biochar and in turn it affects its effectiveness in wastewater treatment (Hamad & Idrus, 2022). Bio waste materials are widely preferred due to their availability, low cost and contribution to circular economy objectives (Sani et al., 2023). Feedstocks commonly used for biochar production include sewage sludge, agricultural residues, forestry waste and industrial organic by-products (Thakur et al., 2024). Each feedstock exhibits unique chemical compositions, moisture content, ash fractions and nutrient profiles that determine both the yield and functionality of biochar (Díaz et al., 2024). Sewage sludge is among the most frequently used feedstocks for wastewater treatment biochar (Khan et al., 2023). This is due to its high nutrient content, availability from municipal wastewater treatment plants and inherent carbon richness (Fatima et al., 2022). Typically, sewage sludge contains 20-40% organic matter, 10-20% mineral content and also contains trace metals such as Pb, Cd, Cu and Zn with moisture content ranging from 60-80% (Agoe et al., 2024). Sludge from industrial influences may also contain residual organics, pharmaceuticals and synthetic compounds (Zhang et al., 2023). The nutrient rich nature of sewage sludge, including N, P and potassium (K) allows biochar derived from this feedstock to function as a pollutant adsorbent and it also allows it to function as a potential soil amendment following wastewater treatment (Robinson & Leinweber, 2023). Biochar produced from sewage sludge retains a combination of surface functional groups including hydroxyl, carboxyl and carbonyl groups (Qin et al., 2022a). These groups facilitate adsorption of polar compounds, ammonium and phosphate as well as mineral phases such as Ca and Fe that support metal immobilization (Bai et al., 2022). Globally, sewage sludge biochar has been successfully applied to municipal, industrial and agricultural wastewater streams. For instance, studies in developed countries report heavy metal removal efficiencies exceeding 70% for Cd

and Pb (Chen et al., 2023). Whilst phosphate capture ranges from 60-75%, demonstrating the multifunctional capabilities of this biochar derived from feedstock (Wang et al., 2022).

Agricultural residues constitute a second major category of feedstock. Crop residues such as maize stalks, rice husks, wheat straw and sugarcane bagasse are abundant in many regions and often represent underutilized organic resources (Thakur et al., 2024). These residues are generally rich in lignocellulosic compounds, including cellulose, hemicellulose and lignin, which contribute to high carbon content and structural stability in the resulting biochar (Chaudhary et al., 2026). Their ash content is typically lower than that of sewage sludge ranging from 5-15% and they contain residual nutrients such as P, calcium (Ca) and Mg (Al-Bsoul et al., 2025). The conversion of agricultural residues to biochar enhances their adsorption capacity for organic contaminants and nutrients in wastewater (Roy et al., 2022). Systematically, biochar derived from lignocellulosic feedstocks exhibits high surface area and porosity. This facilitates physical adsorption while surface functional groups enable chemical interactions with ions and polar molecules (Goyal & Chaudhary, 2025). In Africa, agricultural residue biochar has been used to treat nutrient rich runoff from fertilized fields. Thereby achieving nitrate and phosphate reductions of 40-60% and 55-70% respectively, while continuously improving water clarity and soil fertility when applied post-treatment (Maramba et al., 2023). Forestry wastes such as sawdust, wood chips, bark and logging residues are another feedstock category with significant potential for biochar production (Ndoun et al., 2023). These materials are abundant in forested regions and represent both a disposal challenge and a renewable carbon source (Waheed et al., 2022). Wood based biochar is generally low in ash content of 1-10% and rich in fixed carbon (Bai et al., 2022). This provides structural stability and high surface area. The lignin-rich composition enhances thermal resistance and aromaticity in the biochar. Resulting in material with long term stability and resistance to microbial degradation (Sani et al., 2023). Wood based biochar has been applied to remove organic pollutants, heavy metals and nutrients from wastewater (Mon et al., 2023). Studies in developed countries demonstrate that wood biochar achieves high adsorption of hydrophobic organic pollutants which include phenols, polyaromatic hydrocarbons and dyes due to the aromatic carbon matrix (Ndoun et al., 2023). Additionally, the low ash content minimizes mineral interference thus making wood-based biochar particularly effective for municipal and industrial wastewater treatment

applications (Pandiarajan et al., 2025). Industrial organic by-products including brewery waste, paper mill sludge, food processing residues and palm oil mill effluents are a valuable feedstock for biochar production due to their high carbon content and localized availability (Kapatel et al., 2022). For example, brewery spent grains contain residual carbohydrates, proteins and minerals. This results in biochar with a combination of surface functional groups suitable for nutrient and metal adsorption (Qin et al., 2022b). Paper mill sludge, rich in cellulose and inorganic fillers produces biochar with high porosity and a favourable cation exchange capacity enhancing heavy metal removal (Hu et al., 2023). Food processing residues such as fruit and vegetable peels, pulp and shells are similarly converted into biochar (Nour et al., 2025). This provides a sustainable route for valorising organic waste streams. Industrial by-product biochar effectively removes phosphate, nitrate and heavy metals from wastewater streams (Mon et al., 2023). This is accompanied by removal efficiencies comparable to those of sewage sludge and agricultural residue biochar (Khan et al., 2023).

The chemical composition and properties of biochar are strongly influenced by feedstock selection, moisture content and pre-treatment measures, dewatering, drying, homogenization and particle size reduction are common factors that ensure uniform conversion and they also ensure improved functional properties (Díaz et al., 2024). Pyrolysis and hydrothermal carbonization conditions interact with feedstock characteristics to determine surface area, pore structure and functional group abundance (Jha et al., 2023). For example, feedstocks high in lignin such as wood produce biochar with high aromatic carbon content and structural stability (Bai et al., 2022). Nutrient-rich feedstocks like sewage sludge yield biochar with abundant mineral phases conducive to nutrient capture and heavy metal stabilisation (Agoe et al., 2024). Understanding feedstock composition and optimizing conversion parameters is essential for producing biochar with targeted performance characteristics for wastewater treatment applications (Khan et al., 2023). Biochar derived from various feedstocks removes contaminants through a combination of adsorption, ion exchange, precipitation and microbial support (Jha et al., 2023). Surface functional groups, including hydroxyl, carboxyl and carbonyl moieties facilitate adsorption of polar compounds, ammonium, and phosphate (Qin et al., 2022a). Mineral phases such as Ca, Mg and Fe support chemical precipitation of phosphates and fixation of heavy metals (Bai et al., 2022). The porous structure of biochar provides habitat for microbial

colonization. Thereby enhancing biodegradation of organic matter and contributing to long term treatment stability (Idris et al., 2023). Biochar's structural and chemical properties vary with feedstock and this allows for tailored application to specific wastewater challenges (Hamad & Idrus, 2022).

In addition to wastewater treatment, biochar derived from diverse feedstocks offers environmental and economic benefits and contributes to carbon sequestration, stabilizes nutrients, reduces waste volumes and supports circular economy strategies (Sani et al., 2023). The ability to tailor biochar properties through feedstock selection and production conditions allows for site-specific applications and it also fosters optimization for diverse wastewater treatment challenges (Díaz et al., 2024). Integration of biochar with emerging wastewater treatment technologies such as constructed wetlands, biofilters and advanced oxidation processes, further enhances its performance and sustainability (Bhattacharjee & Ahmaruzzaman, 2024). A wide range of biowaste materials including sewage sludge, agricultural residues, forestry waste and industrial organic by-products serve as effective feedstocks for biochar production (Thakur et al., 2024). Each feedstock contributes unique chemical and physical properties. This influences the biochar's structure, surface chemistry and functional capabilities in wastewater treatment (Hamad & Idrus, 2022). Understanding feedstock characteristics and optimizing production parameters is critical to producing biochar that meets specific treatment objectives (Khan et al., 2023). The integration of biochar derived from locally available biowaste supports sustainable wastewater management, circular economy principles and environmental protection. This makes biochar a highly adaptable and multifunctional material for global water sustainability challenges (Guvava et al., 2021; Maramba et al., 2023).

#### **4. SEWAGE SLUDGE BIOCHAR PRODUCTION PROCESSES**

The production of biochar from sewage sludge represents a critical step in converting bio waste into a multifunctional material suitable for wastewater treatment. The properties of the resulting biochar such as surface area, porosity, functional group abundance, mineral content and structural stability are highly dependent on the conversion process (Khan et al., 2023). They are also dependent on feedstock characteristics and operational parameters (Díaz et al., 2024). Globally, three primary production methods are employed and these methods include pyrolysis, hydrothermal carbonization and gasification. Each process offers different advantages and challenges and the selection of an appropriate method is guided by feedstock

composition, desired biochar characteristics, energy availability and environmental considerations (Jha et al., 2023).

#### **4.1 Pyrolysis of Sewage Sludge**

Pyrolysis is the thermal decomposition of organic material in an oxygen limited environment, typically at temperatures ranging from 300-700 °C (Khan et al., 2023). Sewage sludge pyrolysis can be conducted at laboratory, pilot or full industrial scales and the process involves drying the sludge to reduce moisture content, followed by controlled heating at a defined rate to achieve carbonization. Pyrolysis temperature, heating rate and residence time are critical parameters. Parameters which influence biochar yield, porosity, surface functional groups and mineral content (Díaz et al., 2024). Low temperature pyrolysis of 300–400 °C produces biochar rich in oxygen containing functional groups. This enhances adsorption of polar pollutants such as ammonium and phosphate (Qin et al., 2022a). High temperature pyrolysis of 500-700 °C increases aromatic carbon content, structural stability and surface area (Agoe et al., 2024) thus improving adsorption of hydrophobic organic compounds and heavy metals (Bai et al., 2022). During pyrolysis, sewage sludge undergoes a series of physicochemical transformations. Organic matter decomposes into volatile gases and bio-oil, while the residual carbon matrix forms the biochar (Guvava et al., 2021). Mineral components such as Ca, Mg and Fe remain concentrated in the biochar and this enhances its capacity to immobilize metals and precipitate phosphates (Bai et al., 2022). Trace metals such as Pb, Cd and Cu are partially stabilized within the biochar matrix, reducing leaching potential when applied in wastewater treatment (Chen et al., 2023). Additionally, pathogen inactivation occurs at temperatures above 200 °C, ensuring the hygienic safety of the resulting biochar (Sani et al., 2023). Energy efficiency and environmental impacts of pyrolysis are important considerations. Volatile gases released during pyrolysis can be captured and combusted to provide process heat or converted into syngas for electricity generation (Hu et al., 2023). Bio-oil produced can serve as a fuel or chemical feedstock (Khan et al., 2023). Life cycle analyses indicate that pyrolysis of sewage sludge reduces greenhouse gas emissions relative to conventional disposal methods such as landfilling and incineration (Dębowski et al., 2025). This is done while producing a valuable carbon-rich product for water treatment and soil amendment (Guvava et al., 2021). Pilot and full-scale applications of pyrolyzed sewage sludge biochar are reported globally. In developed countries municipal treatment plants have integrated pyrolysis units to convert

dewatered sludge into biochar. Thereby achieving yields of 40-50% on a dry weight basis (Khan et al., 2023). The resulting biochar has been applied in tertiary wastewater treatment, achieving phosphate removal efficiencies of 65-75% and heavy metal stabilisation exceeding 70% (Wang et al., 2022). In developing countries industrial wastewater treatment systems have incorporated pyrolyzed sludge biochar as an adsorbent for heavy metals and dyes resulting in removal efficiencies of 60-80% reported (Mon et al., 2023). In Africa, pilot studies in Zimbabwe demonstrate that pyrolyzed sludge biochar effectively reduces nutrient concentrations. Biochar also improves microbial stability in municipal wastewater illustrating the potential for local application (Guvava et al., 2021).

#### **4.2 Hydrothermal Carbonization**

Hydrothermal carbonization (HTC) is a wet thermal conversion process conducted under subcritical water conditions typically at 180-250 °C and elevated pressures about 2-10 MPa (Jin et al., 2024). Unlike pyrolysis, HTC does not require extensive dewatering of sewage sludge and this makes it particularly suitable for high moisture feedstocks. The process converts organic matter into hydrochar, a carbon-rich material with abundant oxygen containing functional groups, moderate mineral content and enhanced adsorption capabilities (Díaz et al., 2024). During HTC, hydrolysis, dehydration, decarboxylation and polymerization reactions occur and this transforms soluble organic compounds into hydrochar (Khan et al., 2023). The process preserves functional groups such as hydroxyl, carboxyl and carbonyl and these functional groups are critical for adsorbing polar compounds, nutrients and certain heavy metals in wastewater treatment applications (Qin et al., 2022a). Hydrochar produced through HTC exhibits higher hydrophilicity than pyrolyzed biochar. This makes it particularly effective for adsorbing ammonium, nitrate and phosphate from municipal and agricultural effluents (Wang et al., 2022). HTC also ensures complete pathogen inactivation, improving the hygienic safety of the product (Sani et al., 2023). Energy efficiency is an important consideration for HTC. While operating pressures are high, the process can utilize heat recovery systems and process integration to reduce energy demand (Jin et al., 2024). HTC also produces process water containing soluble organics, which can be further treated via anaerobic digestion or integrated with wastewater treatment systems (Wang et al., 2022). In some cases, pilot scale HTC facilities using sewage sludge have demonstrated biochar yields of 50-60% on a dry weight basis. This is accompanied by high removal efficiencies for nutrients and heavy

metals in subsequent wastewater applications (Khan et al., 2023). Hydrochar has been used to stabilize industrial effluents, capturing phosphate and ammonium while supporting microbial degradation of organic contaminants (Idris et al., 2023).

### **4.3 Gasification**

Gasification is a high temperature  $>700$  °C thermochemical process conducted under limited oxygen and this converts bio waste into syngas and solid biochar (Waheed et al., 2022). Gasification produces biochar with high carbon content, increased alkalinity and concentrated mineral phases. This enhances its suitability for heavy metal immobilization and nutrient capture (Bai et al., 2022). The high temperature leads to aromatization of carbon structures. Thus, resulting in biochar with structural stability and long-term persistence (Sani et al., 2023). The process involves partial oxidation of bio waste to produce combustible gases. The biochar retains mineral and carbon components (Khan et al., 2023). Gasification biochar is particularly effective for industrial wastewater treatment, where heavy metals and refractory organics are prevalent (Chen et al., 2023). The alkaline nature of gasified biochar facilitates precipitation of phosphate and metal ions (Agoe et al., 2024). The porous structure supports adsorption and microbial colonization (Idris et al., 2023). Life cycle assessments indicate that gasification coupled with energy recovery provides a sustainable approach for sewage sludge management (Dębowski et al., 2025). This is achievable by producing renewable energy and a high-quality biochar product.

### **4.4 Energy, Environmental and Operational Considerations**

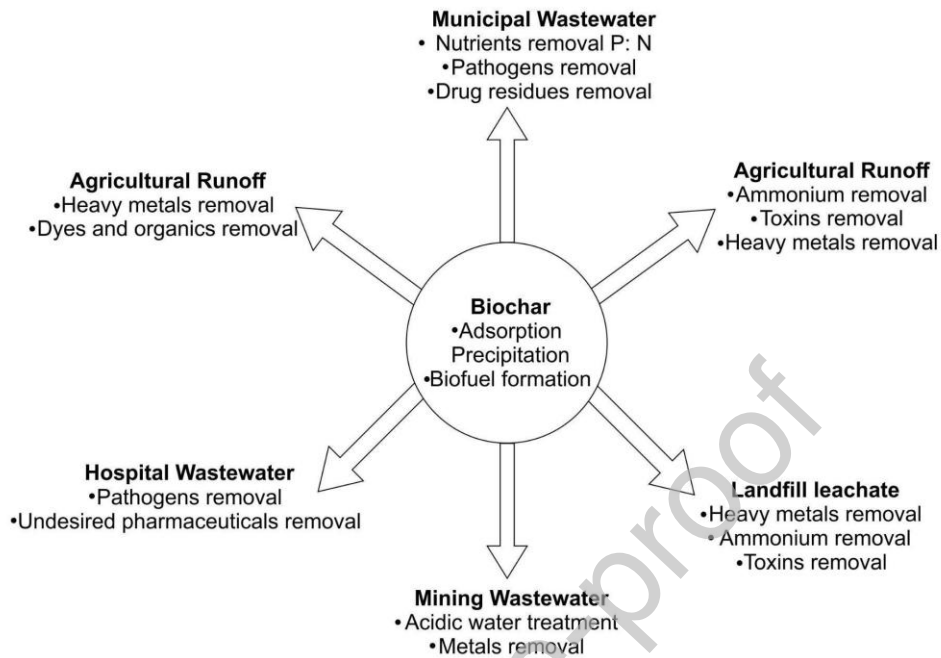
Energy balance and environmental impact are critical in scaling biochar production. Capturing pyrolysis or gasification gases for energy generation can offset operational costs (Hu et al., 2023). Hydrothermal carbonization reduces energy input by processing wet sludge (Jin et al., 2024). Emissions, including volatile organic compounds and particulate matter must be controlled to comply with environmental regulations (Khan et al., 2023). Globally, full scale production systems incorporate emission control units, condensers and gas scrubbers to minimize environmental impact (Díaz et al., 2024). Operational parameters such as feedstock moisture content, particle size, residence time and heating rate significantly influence biochar yield and quality (Agoe et al., 2024). Dewatering sludge to below 30% moisture content is generally recommended for pyrolysis and gasification. HTC can process sludge at 70-80% moisture without extensive drying (Jin et al., 2024). Fine biochar particle sizes increase surface area and adsorption capacity but reduce hydraulic performance in

treatment systems. Thereby highlighting the need for balance between physical properties and functional efficiency (Ramsha Khan et al., 2023; Díaz et al., 2024).

The production of sewage sludge biochar through pyrolysis, hydrothermal carbonization or gasification transforms waste into a valuable treatment material, a material with tailored chemical, structural and functional properties (Khan et al., 2023). Process parameters, feedstock characteristics and operational considerations determine biochar performance in pollutant removal, nutrient capture and microbial support (Díaz et al., 2024). Global and regional case studies underscore the feasibility of integrating these biochar production methods with municipal, industrial and agricultural wastewater treatment systems (Guvava et al., 2021). Hence, they provide a sustainable, energy efficient and multifunctional solution for waste management and water quality improvement (Sani et al., 2023).

## **5. TYPES OF WASTEWATER TREATED BY BIOCHAR**

Biochar derived from sewage sludge has demonstrated remarkable utility in the treatment of various wastewater types. The range of wastewater streams include municipal effluents, industrial discharges, agricultural runoff, landfill leachate, hospital wastewater, aquaculture effluents and mining wastewater (Hamad & Idrus, 2022; Khan et al., 2023). Each type of wastewater presents unique physical, chemical and biological challenges and also includes variations in pH, organic load, nutrient concentration, heavy metals and pathogens (Jha et al., 2023). The selection and optimization of biochar for each application depend on feedstock characteristics, production method and the specific treatment objectives (Díaz et al., 2024). Understanding the interaction between biochar and the contaminant profile of each wastewater type is critical to maximizing removal efficiency and ensuring sustainable application. Figure 1 shows a summary of bio char application in wastewater.



**Figure 1: Biochar Application in Wastewater Treatment (This Study)**

### 5.1 Municipal Wastewater

Municipal wastewater originates from residential, commercial and institutional sources and typically contains dissolved and suspended organic matter. Nutrients such as N and P, pathogenic microorganisms and trace metals are also contained (Lukić et al., 2025). Traditional treatment processes for instance primary sedimentation, secondary biological treatment and tertiary polishing often fail to completely remove nutrients and residual metals. This leads to eutrophication and water quality degradation (Pandiarajan et al., 2025). Biochar, especially sewage sludge derived biochar enhances tertiary treatment by adsorbing residual contaminants and providing surfaces for microbial biofilm formation (Idris et al., 2023). COD reductions of 40-65% and phosphate removal efficiencies of up to 70% in municipal wastewater treated with biochar (Wang et al., 2022) have been reported. Additionally, microbial community analyses demonstrate enhanced biofilm formation on biochar surfaces supporting bio

degradation and stabilizing effluent quality over extended periods (Idris et al., 2023). Pilot-scale studies in Zimbabwe corroborate these findings by showing significant nutrient removal and improved water clarity in municipal treatment systems incorporating sludge biochar (Guvava et al., 2021).

#### **4.2 Industrial Wastewater**

Industrial wastewater is often characterized by powerful contaminants such as heavy metals, dyes, persistent organic compounds and acidic or alkaline effluents (Mon et al., 2023). Common industrial sources include textile manufacturing, metal plating, mining operations, food processing and chemical production (Kapatel et al., 2022). Biochar effectively mitigates the environmental impacts of these effluents by adsorbing metals and organic pollutants (Chen et al., 2023). Pyrolyzed sewage sludge biochar has demonstrated removal efficiencies of 70-80% for heavy metals such as Pb, Cd and Cu in textile and metal plating effluents (Mon et al., 2023). Similarly, biochar derived from paper mill sludge or wood waste achieves high removal rates for dyes and hydrophobic organics (Ndoun et al., 2023). This is due to its aromatic carbon structure and high surface area (Bai et al., 2022). Technically, the porous structure facilitates physical adsorption while surface functional groups enable chemical interactions with contaminants (Qin et al., 2022a). Globally, industrial applications of biochar have been documented demonstrating the adaptability of this material to strong wastewater streams (Kumari et al., 2025).

#### **5.3 Agricultural Wastewater**

Agricultural wastewater, for example runoff from fertilized crop fields and effluents from livestock operations is rich in N, P and bio waste (Thakur et al., 2024) and excessive nutrient loading contributes to eutrophication in downstream water bodies thereby promoting algal blooms, oxygen depletion and biodiversity loss (Al-Bsoul et al., 2025). Biochar derived from sewage sludge and crop residues has proven effective in nutrient capture and retention (Roy et al., 2022). Biochar applied to agricultural runoff reduces phosphate concentrations by 60-70% and nitrate concentrations by 40-60% (Wang et al., 2022) thus mitigating eutrophication risks while recovering nutrients for potential agricultural reuse. The mechanism involves adsorption onto functional groups, precipitation via mineral components and microbial assimilation within biochar microhabitats (Jha et al., 2023). Additionally, biochar enhances water retention and soil structure when applied aftermath providing ancillary benefits to crop productivity (Maramba et al., 2023).

### **5.5 Landfill Leachate**

Landfill leachate is a highly concentrated and chemically complex effluent and contains ammonium, organic acids, heavy metals and trace organics (Zhang et al., 2023). Traditional treatment approaches often struggle with leachate stabilization due to high ammonium levels and variable pH. Biochar offers a multifaceted treatment solution by combining adsorption, chemical precipitation and microbial enhancement (Baaloudj et al., 2025). Pilot scale applications demonstrate that sludge biochar reduces ammonium concentrations by 40-50% and COD by up to 60%, while stabilizing pH and immobilizing metals (Zhang et al., 2023). The porous structure of biochar provides habitats for microbial communities which are capable of degrading complex organic compounds, enhancing overall treatment efficiency (Idris et al., 2023).

### **5.6 Hospital Wastewater**

Hospital wastewater is a specialized stream containing pharmaceuticals, disinfectants, pathogenic microorganisms and residual chemical disinfectants (Bhattacharjee & Ahmaruzzaman, 2024). Conventional treatment often fails to completely remove these emerging contaminants. Sewage sludge biochar with its high surface area and functional group density can adsorb pharmaceuticals (Nour et al., 2025). Pharmaceuticals such as antibiotics, analgesics and anti-inflammatory agents, while supporting microbial degradation (Idris et al., 2023). Studies indicate that biochar achieves 50-70% removal efficiency for commonly detected pharmaceutical compounds (Zhang et al., 2023). Furthermore, pathogen reduction occurs through biochar mediated adsorption and biofilm activity, enhancing the hygienic safety of treated effluents (Sani et al., 2023).

### **5.7 Aquaculture Effluents**

Aquaculture wastewater contains enhanced concentrations of nutrients. Particularly N and P along with suspended solids and bio waste (Roy et al., 2022). Biochar application in aquaculture systems has shown significant reductions in ammonia, nitrate and phosphate levels, with removal efficiencies of 50-65% (Wang et al., 2022). The adsorption of dissolved nutrients by biochar minimizes water quality deterioration, supports sustainable fish production and prevents eutrophication in surrounding water bodies (Idris et al., 2023). Additionally, biochar improves microbial community structure, facilitating biodegradation of organic compounds and maintaining ecological balance in aquaculture systems (Jha et al., 2023).

## 5.8 Mining Wastewater

Mining effluents are characterized by high concentrations of metals, sulphates and acidic pH. This poses substantial environmental risks to nearby water bodies (Chen et al., 2023). Biochar derived from sewage sludge or wood residues can immobilize metals such as Pb, Cd, arsenic (As) and Zn through adsorption and precipitation mechanisms (Bai et al., 2022). Pilot studies demonstrate reductions of 60-80% for heavy metals in mining wastewater treated with biochar (Kumari et al., 2025). The alkaline nature of certain biochar types assists in neutralizing acidic effluents, further enhancing environmental compliance (Agoe et al., 2024).

Sewage sludge biochar exhibits remarkable versatility in treating diverse wastewater types, its multifunctional properties, for instance adsorption, ion exchange, chemical precipitation and microbial support enable effective removal of nutrients (Jha et al., 2023). Biochar also enables the removal of heavy metals, organic pollutants and emerging contaminants (Khan et al., 2023). Global and regional case studies demonstrated its applicability across municipal, industrial, agricultural, landfill, hospital, aquaculture and mining effluents (Hamad & Idrus, 2022). Biochar integration enhances water quality, supports circular economy principles and contributes to sustainable water management (Sani et al., 2023). Its adaptability to varying contaminant profiles, environmental conditions and operational scales positions biochar as a critical material in global wastewater treatment strategies are shown in Table 2 (Díaz et al., 2024).

**Table 2: General Characteristics of Wastewater Types Treated by Biochar**

Wastewater Type	Typical physical Characteristics	Typical Chemical Characteristics	Common Contaminant Profile	References
Municipal Wastewater	Turbid appearance; moderate suspended solids	pH 6.5-8.5 moderate COD and BOD	Nutrients (N, P), pathogens, organic matter	Lukic et al., 2025
Industrial Wastewater	Variable colour; high turbidity in some sectors	Variable pH 3-11; high COD	Heavy metals, dyes, solvents, hydrocarbons	Mon et al., 2023

Agricultural Runoff	Seasonal flow variation; suspended sediments	Slightly alkaline to neutral; moderate nutrient levels	Nitrates, phosphates, pesticide residues	Al-Bsoul et al.,2025
Landfill Leachate	Dark colour; strong colour	High ammonium; elevated COD; variable pH	Ammonium, heavy metals, humic substances	Bhattacharjee & Ahmaruzzaman,2024
Hospital Wastewater	Similar to municipal; variable solids	Neutral to slightly alkaline; moderate COD	Pharmaceuticals, disinfectants, pathogens	Roy et al.,2022
Aquaculture Wastewater	Suspended feed particles; organic debris	Slightly alkaline; elevated ammonia	Ammonia, organic matter, residual feed nutrients	Kumari et al.,
Mining Wastewater	High suspended solids sometimes acidic	Low pH in acid mine drainage; high dissolved metals.	Fe, Pb, Cd, Zn, sulphate	Zhang et al.,2023

## 6. EFFECT OF BIOCHAR IN WASTEWATER TREATMENT

The effectiveness of biochar derived from sewage sludge in wastewater treatment is determined by its chemical, physical and biological properties. Biochar functions through multiple complementary mechanisms; adsorption of pollutants, ion exchange, chemical precipitation and facilitation of microbial degradation (Jha et al., 2023). These mechanisms are influenced by feedstock type, production method, biochar dosage, contact time, pH, temperature and wastewater characteristics e.g., BOD and COD (Díaz et al., 2024). Understanding these interactions is crucial for optimizing performance and integrating biochar into treatment systems (Khan et al., 2023).

### 6.1 Adsorption Mechanisms

Adsorption is the primary mechanism for pollutant removal. Biochar possesses high surface area and porous structure, enabling physical adsorption of dissolved and particulate contaminants (Hamad & Idrus, 2022). Functional groups (hydroxyl, carboxyl, carbonyl and phosphate) facilitate chemical adsorption through hydrogen bonding, electrostatic interactions and complexation with metal ions (Qin et al., 2022a;

Chen et al., 2023). Based on published data, physical adsorption dominated by van der Waals forces and pore filling typically contributes 30–50% of total adsorption for small molecules like ammonium, while chemisorption including surface complexation and ion exchange contributes 50–70%, particularly for phosphate and heavy metals. However, most studies have no reports of separate contributions. At acidic pH (3–5), electrostatic attraction between positively charged biochar surfaces and anionic pollutants dominates. At neutral pH (6–8), surface complexation and hydrogen bonding are primary. Whilst at alkaline pH (9–11), precipitation of metal hydroxides and ion exchange with  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions become dominant. Adsorption capacity varies with production method. Pyrolyzed biochar at 400–500 °C shows ammonium adsorption of 20–35 mg/g and phosphate of 15–25 mg/g (Wang et al., 2022). Hydrochar exhibits higher oxygen containing functional group density, supporting ammonium adsorption of 25–40 mg/g and phosphate of 20–30 mg/g (Jin et al., 2024). Gasified biochar with higher alkalinity and mineral content achieves heavy metal adsorption exceeding 50 mg/g for Pb and Cd (Agoe et al., 2024). The maximum reported adsorption capacities ( $q_{\text{max}}$ ) across studies for Pb=85–120 mg/g, Cd=45–70 mg/g, Cu=35–55 mg/g, phosphate=25–45 mg/g and ammonium=30–50 mg/g. These values vary significantly with pH, temperature and biochar production conditions.

## 6.2 Ion Exchange and Chemical Precipitation

Mineral components for instance Ca, Mg, Fe and Al in sewage sludge biochar interact with nutrient ions and heavy metals (Bai et al., 2022). Phosphate forms insoluble Ca-phosphate complexes, while ammonium undergoes cation exchange with Ca and Mg (Wang et al., 2022). Heavy metals (Cu, Zn, Pb) precipitate as hydroxides or carbonates, reducing mobility and toxicity (Chen et al., 2023). Higher ash content, between 30–50% in sewage sludge biochar against 5–15% in plant biochar enhances phosphate precipitation but also increases the risk of trace metal leaching when biochar is exposed to acidic conditions, as metals originally bound in ash phases can solubilize.

## 6.3 Microbial Interactions and Biofilm Formation

Biochar's porous structure provides habitat for microbial colonization, facilitating biodegradation of organic contaminants and nutrient cycling (Idris et al., 2023). Microbial communities for example bacteria, fungi and archaea enhance breakdown of complex organics, reducing COD and maintaining system stability (Jha et al., 2023).

Studies using 16S rRNA sequencing show increased microbial diversity and abundance of nitrifying and denitrifying bacteria in biochar-amended systems (Kumari et al., 2025; Idris et al., 2023).

#### **6.4 Long-Term Performance and Regeneration**

Over time, biochar experiences surface fouling and saturation reducing adsorption capacity (Baaloudj et al., 2025). Thermal regeneration at 300–400 °C removes organic fouling and restores porosity, chemical regeneration with 0.1 M NaOH or HCl (1mole of sodium hydroxide or hydrochloric acid) desorbs ions and restores functional groups (Roy et al., 2023; Díaz et al., 2024). After 5 reuse cycles, biochar retains 70–85% of original adsorption capacity for nutrients and metals (Baaloudj et al., 2025). In fixed bed filtration systems fine biochar particles <0.5 mm cause significant pressure drops up to 2–3 bar/m and rapid clogging due to pore blockage. Larger particles 1–5 mm reduce pressure drop but lower surface area. An optimal particle size range of 0.5–2 mm is recommended to balance hydraulic performance and adsorption efficiency.

#### **6.5 Effect of Biochar on Wastewater Treatment**

Biochar's effect on wastewater quality is measurable both quantitatively and qualitatively. Key quantitative outcomes include reductions in COD, BOD, ammonium, nitrate, phosphate, heavy metals and colour (Khan et al., 2023). Qualitative observations include enhanced water clarity, reduced odour, stabilized pH and improved microbial activity (Guvava et al., 2021). Biochar amendments also improve sedimentation and reduce turbidity in wastewater facilitating downstream treatment processes (Roy et al., 2022).

#### **6.6 Mechanistic Synergy**

The synergistic effect of adsorption, ion exchange, precipitation and microbial biofilm formation enables biochar to address multiple contaminants simultaneously (Jha et al., 2023). For instance, in municipal wastewater ammonia is removed through adsorption and ion exchange. Phosphate precipitates as calcium phosphate, organic matter is degraded by microbial biofilms and trace metals are immobilized within the biochar matrix (Wang et al., 2022). This multifunctional capacity distinguishes biochar from a single function treatment medium such as zeolite or activated carbon, offering a holistic solution to complex wastewater streams (Khan et al., 2023).

#### **6.7 Environmental and Economic Considerations**

The environmental and economic impacts of biochar application are substantial by removing nutrients, heavy metals and organic pollutants. Biochar reduces the

ecological footprint of wastewater discharge (Sani et al., 2023). Pathogen stabilization and pollutant immobilization enhance public health and environmental safety (Guvava et al., 2021). Economically, biochar provides a cost-effective alternative to activated carbon, chemical adsorbents and other tertiary treatment methods (Rammal et al., 2025). Most particularly in regions with abundant biowaste availability, regeneration and reuse of biochar further enhance cost efficiency and sustainability, aligning with circular economy objectives (Baaloudj et al., 2025).

### 6.8 Limitations and Optimization

Limitations include surface fouling, trace metal leaching under acidic conditions and performance variability due to feedstock heterogeneity (Agoe et al., 2024). Under neutral to alkaline conditions with pH between 7–9, leaching of Pb, Cd, Cu and Zn from sewage sludge biochar is typically below regulatory limits for example <0.1 mg/L for Pb. However, at acidic pH leaching can increase from 5 to 10-fold, exceeding safe limits. Pre-treatment such as acid washing or metal stabilization with phosphates can reduce leaching. Optimization of production parameters, biochar dosage, contact time and post-treatment modifications is essential (Díaz et al., 2024). Combining biochar with constructed wetlands, biofilters or advanced oxidation processes can further enhance contaminant removal (Bhattacharjee & Ahmaruzzaman, 2024). Currently, the European Union (EU) and United States Environmental Protection Agency (US EPA) have no records of specific regulations for sewage sludge biochar use in wastewater treatment, it is generally regulated under waste management or biosolids rules. China has emerging standards for example the GB/T 33891-2017 for biochar and soil remediation. Globally, regulatory frameworks remain inconsistent and underdeveloped. Table 3 gives a summary of the characteristics of treated wastewater using biochar.

**Table 3: Characteristics of Treated Wastewater After Biochar Application**

Wastewater Type	Key Pollutants Targeted	Typical Post Treatment Characteristics	Overall Treatment Outcome	References
Municipal Wastewater	Nutrients (N, P), pathogens, COD	Reduced ammonium and phosphate levels; improved	Improved effluent quality for discharge or reuse	Lukic et al.,2025

		clarity; stabilised pH		
Industrial Wastewater	Heavy metals, dyes, organic toxins	Lower metal concentrations; reduced colour and COD	Reduced toxicity and enhanced compliance with discharge standards	Mon et al.,2023
Agricultural Runoff	Nitrates, phosphates, pesticides	Decreased nutrient load; partial pesticide adsorption	Mitigation of eutrophication risk	Chen et al., 2023
Hospital Wastewater	Pharmaceuticals, pathogens	Reduced drug residues; improved microbial activity	Enhanced stabilization prior to discharge	Nour et al., 2025
Landfill Leachate	Ammonia, heavy metals, organics	Reduced ammonia and metal mobility; lower COD	Lower environmental and public health risk	Kumari et al.,2025
Aquaculture Wastewater	Ammonia, organic waste	Lower ammonia concentrations; improved dissolved oxygen balance	Improved water reuse potential	Roy et al.,2022
Mining Wastewater	Acidic water, Pb, Cd, Zn	Increased pH; immobilized heavy metals	Reduced metal toxicity and acidity	Sani et al., 2023

## 7. FUTURE PERSPECTIVES AND RESEARCH

Future research on sewage sludge derived biochar should prioritize addressing the performance variability and inconsistencies identified across existing studies. In line with the critical gaps highlighted in this review, there is a need for standardized methodologies that enable reliable comparison of adsorption capacities under controlled and comparable conditions. Greater emphasis should be placed on developing engineered and modified biochar with enhanced selectivity and stability, particularly to mitigate toxic metal leaching under varying environmental conditions.

Additionally, integrating biochar with advanced treatment systems such as hybrid adsorption, oxidation processes present a promising pathway for improving removal efficiency of complex contaminants. Long term studies evaluating regeneration efficiency, lifecycle performance and environmental safety are also necessary to support large scale application. Furthermore, future work should consider the influence of sludge heterogeneity and establish regulatory frameworks that ensure safe and sustainable implementation, thereby strengthening the role of biochar in wastewater treatment systems.

## 8. CONCLUSION

The use of biowaste derived biochar from sewage sludge represents a significant step forward in sustainable wastewater management, but critical gaps remain. This review confirms biochar as a multifunctional material capable of treating municipal, industrial, agricultural, landfill, hospital, aquaculture and mining wastewater. However, reported removal efficiencies lack context without standardized pH, dosage and contact time conditions. The dominant adsorption mechanisms shift with pH, electrostatic attraction at acidic pH, surface complexation at neutral pH and precipitation at alkaline pH. Quantitative separation of physical vs. chemical adsorption is rarely reported but estimated at 30–50% vs. 50–70%, respectively. Ash content enhances phosphate precipitation but increases trace metal leaching risk under acidic conditions, requiring pre-treatment. This review's novel contribution is its critical identification of contradictions in the literature, systematic comparison of kinetic and isotherm models as well as explicit evaluation of operational challenges. Optimum operating conditions across studies are pH 6–8, biochar dosage 1–10 g/L and contact time 1–24 hours. Particle size of 0.5–2 mm balances adsorption and hydraulic performance. Pressure drop and clogging remain significant issues for fixed bed systems requiring periodic backwashing or fluidized bed designs. Comparison with activated carbon shows biochar is 30–70% cheaper but has 20–50% lower adsorption capacity for many pollutants. Regeneration via thermal (300–400 °C) or chemical (0.1 M NaOH/HCl) methods restores 70–85% capacity over 5 cycles. Feedstock variability significantly affects metal content and performance, necessitating pre-treatment standardization. Engineered biochar show improved capacity but increase cost. Integration with advanced oxidation processes or membrane systems is promising but underexplored. Future research should prioritize long term ecological impact studies, standardized quality protocols and pilot scale demonstrations.

**REFERENCES**

- Agee, A.K., Pouloupoulos, S.G., Sarbassov, Y. and Shah, D. (2024). Investigation of Sewage Sludge–Derived Biochar for Enhanced Pollutant Adsorption: Effect of Particle Size and Alkali Treatment. *Energies*, 17 (18), pp.4554. <https://doi.org/10.3390/en17184554>
- Al-Bsoul, A., Al-Qodah, Z., Tawalbeh, M., Bani-Melhem, K., Al Bloor Alrawashdeh, K., Hailat, M., Al-Taani, A. A. and Gul, E., (2025). From Waste to Solution: Modeling and Characterization of Grape Seed Bio-Waste for Phosphate Removal from Wastewater. *Processes*, 13 (8), pp.2464. <https://doi.org/10.3390/pr13082464>
- Baaloudj, O., Langerame, F., Iunnissi, R., Buttiglieri, G., Del Buono, D., Khadhar, S., Scrano, L., Trotta, V. and Brienza, M., (2025). Biochar-based downflow fixed-bed adsorption systems for water treatment: process optimization, reusability, and techno-economic evaluation. *Separation and Purification Technology*, pp.134347. <https://doi.org/10.1016/j.seppur.2025.134347>
- Bai, X., Zhang, M., Niu, B., Zhang, W., Wang, X., Wang, J., Wu, D., Wang, L. and Jiang, K., (2022). Rotten sugarcane bagasse derived biochars with rich mineral residues for effective Pb (II) removal in wastewater and the tech-economic analysis. *Journal of the Taiwan Institute of Chemical Engineers*, 132, pp.104231. <https://doi.org/10.1016/j.jtice.2022.104231>
- Bhattacharjee, B. and Ahmaruzzaman, M., (2024). Photocatalytic degradation of pharmaceuticals: Insights into biochar modification and degradation mechanisms. *Next Materials*, 5, pp. 100238. <https://doi.org/10.1016/j.nxmte.2024.100238>
- Chaudhary, R., Sangwan, G., Kumar, S. and Sharma, V., (2026). Turning Trash into Tools: Agricultural Waste-derived Biochar and Composites for Microplastic Removal from Wastewater. *RSC Sustainability*. [10.1039/D5SU00479A](https://doi.org/10.1039/D5SU00479A)
- Chen, Y., Yang, J. and Abbas, A., (2023). Enhanced chromium (VI) adsorption onto waste pomegranate-peel-derived biochar for wastewater treatment: performance and mechanism. *Toxics*, 11 (5), pp.440. <https://doi.org/10.3390/toxics11050440>
- Dębowski, M., Zieliński, M. and Kazimierowicz, J., (2025). Biowaste to Energy and Value-Added Products—Challenges and Opportunities. *Energies*, 18 (15), pp.4095. <https://doi.org/10.3390/en18154095>
- Díaz, B., Sommer-Márquez, A., Ordoñez, P.E., Bastardo-González, E., Ricaurte, M. and Navas-Cárdenas, C., (2024). Synthesis methods, properties, and modifications of

- biochar-based materials for wastewater treatment: a review. *Resources*, 13 (1), pp.8. <https://doi.org/10.3390/resources13010008>
- Fatima, B., Bibi, F., Ali, M.I., Woods, J., Ahmad, M., Mubashir, M., Khan, M.S., Bokhari, A. and Khoo, K.S., (2022). Accompanying effects of sewage sludge and pine needle biochar with selected organic additives on the soil and plant variables. *Waste Management*, 153, pp. 197-208. <https://doi.org/10.1016/j.wasman.2022.08.016>
- Goncalves, N.P., Lourenco, M.A., Baleuri, S.R., Bianco, S., Jagdale, P. and Calza, P., (2022). Biochar waste-based ZnO materials as highly efficient photocatalysts for water treatment. *Journal of Environmental Chemical Engineering*, 10 (2), pp.107256. <https://doi.org/10.1016/j.jece.2022.107256>
- Goyal, S. and Chaudhary, S., (2025). Syzygium cumini derived biochar as sustainable adsorbent: Synthesis, parametric optimization with experimental and theoretical sketch. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 718, pp.136945. <https://doi.org/10.1016/j.colsurfa.2025.136945>
- Guvava, G. N., Manyuchi, M. M., Sukdeo, N., & Stinner, W. (2021). Techno-Economic Assessment of Biochar Production from Sewage Sludge as a Climate Change Mitigation Strategy. In W. Leal Filho, J. Luetz, & D. Ayal (Eds.), *Handbook of Climate Change Management* (pp. 1–19). Springer, Cham. [https://doi.org/10.1007/978-3-030-22759-3\\_230-1](https://doi.org/10.1007/978-3-030-22759-3_230-1)
- Hamad, H.N. and Idrus, S., (2022). Recent developments in the application of bio-waste-derived adsorbents for the removal of methylene blue from wastewater: a review. *Polymers*, 14 (4), pp. 783. <https://doi.org/10.3390/polym14040783>
- Hu, Y., Thomsen, T.P., Fenton, O., Sommer, S.G., Shi, W. and Cui, W., (2023). Effects of dairy processing sludge and derived biochar on greenhouse gas emissions from Danish and Irish soils. *Environmental Research*, 216, pp. 114543. <https://doi.org/10.1016/j.envres.2022.114543>
- Idris, M.O., Noh, N.A.M., Ibrahim, M.N.M. and Yaqoob, A.A., (2023). Sustainable microbial fuel cell functionalized with a bio-waste: a feasible route to formaldehyde bioremediation along with bioelectricity generation. *Chemical Engineering Journal*, 455, pp. 140781. <https://doi.org/10.1016/j.cej.2022.140781>
- Jha, S., Gaur, R., Shahabuddin, S. and Tyagi, I., (2023). Biochar as sustainable alternative and green adsorbent for the remediation of noxious pollutants: a comprehensive review. *Toxics*, 11 (2), pp. 117. <https://doi.org/10.3390/toxics11020117>

- Jin, H.Y., He, Z.W., Ren, Y.X., Zou, Z.S., Tang, C.C., Zhou, A.J., Liu, W., Li, Z. and Wang, A., (2024). Revealing the roles of biochar derived from iron-rich fermented sludge residue in anaerobic digestion. *Chemical Engineering Journal*, 481, pp. 148376. <https://doi.org/10.1016/j.cej.2023.148376>
- Kacprzak, M., Kupich, I., Jasinska, A. and Fijalkowski, K., (2022). Bio-based waste'substrates for degraded soil improvement—Advantages and challenges in European context. *Energies*, 15 (1), pp. 385. <https://doi.org/10.3390/en15010385>
- Kapatel, D.V., Rotliwala, Y.C. and Patel, H.J., (2022). Co-pyrolysis based activated Bio-char: Characterization and its utilization for secondary treated pulp and paper industry wastewater. *Materials Today: Proceedings*, 57, pp. 1724-1729. <https://doi.org/10.1016/j.matpr.2021.12.361>
- Khan, R., Shukla, S., Kumar, M., Zuurro, A. and Pandey, A., (2023). Sewage sludge derived biochar and its potential for sustainable environment in a circular economy: Advantages and challenges. *Chemical Engineering Journal*, 471, pp. 144495. <https://doi.org/10.1016/j.cej.2023.144495>
- Kumari, B., Seedat, N., Moothi, K. and Roopchand, R., (2025). Artificial intelligence-assisted modelling of heavy metal adsorption using cellulose-based and bio-waste adsorbents: A focus on ANN and ANFIS architectures. *Results in Engineering*, pp. 107147. <https://doi.org/10.1016/j.rineng.2025.107147>
- Lukić, D., Vasić, V., Živančev, J., Antić, I., Panić, S., Petronijević, M. and Đurišić-Mladenović, N., (2025). Adsorption Performance Assessment of Agro-Waste-Based Biochar for the Removal of Emerging Pollutants from Municipal WWTP Effluent. *Molecules*, 30 (24), pp. 4803. <https://doi.org/10.3390/molecules30244803>
- Maramba, S. D., Mutadza, I., Manyuchi, M. M., & Sukdeo, N. (2023). Techno-Economic Assessment for Valorisation of Waste Sawdust Biomass to Biochar-Based Capsules. In W. Leal Filho et al. (Eds.), *Handbook of Nature-Based Solutions to Mitigation and Adaptation to Climate Change* (pp. 1–49). Springer Nature Switzerland AG. [https://doi.org/10.1007/978-3-030-98067-2\\_89-1](https://doi.org/10.1007/978-3-030-98067-2_89-1)
- Mon, P.P., Cho, P.P., Chandana, L., Srikanth, V.V.S.S., Madras, G. and Ch, S. (2023). Biowaste-derived Ni/NiO decorated-2D biochar for adsorption of methyl orange. *Journal of Environmental Management*, 344, pp. 118418. <https://doi.org/10.1016/j.jenvman.2023.118418>
- Ndoun, M.C., Knopf, A., Preisendanz, H.E., Vozenilek, N., Elliott, H.A., Mashtare, M.L., Velegol, S., Veith, T.L. and Williams, C.F. (2023). Fixed bed column experiments using

cotton gin waste and walnut shells-derived biochar as low-cost solutions to removing pharmaceuticals from aqueous solutions. *Chemosphere*, 330, p p.138591. <https://doi.org/10.1016/j.chemosphere.2023.138591>

Nour, M.M., Tony, M.A., Fouad, M.K. and Nabwey, H.A., (2025). Banana (*Musa sapientum*) Waste-Derived Biochar–Magnetite Magnetic Composites for Acetaminophen Removal via Photochemical Fenton Oxidation. *Catalysts*, 15 (10), pp. 955. <https://doi.org/10.3390/catal15100955>

Pandiarajan, S., Sankararajan, V. and Swaminathan, M., (2025). Characterization and performance of activated biochar-doped zinc oxide in domestic wastewater treatment. *Journal of the Indian Chemical Society*, pp.102010. <https://doi.org/10.1016/j.jics.2025.102010>

Qin, Y., Li, X., Wang, L., Luo, J., Li, Y., Yao, C., Xiao, Z., Zhai, S. and An, Q., (2022b). Valuable cobalt/biochar with enriched surface oxygen-containing groups prepared from bio-waste shrimp shells for efficient peroxymonosulfate activation. *Separation and Purification Technology*, 281, pp. 119901. <https://doi.org/10.1016/j.seppur.2021.119901>

Qin, Y., Luo, J., Zhao, Y., Yao, C., Li, Y., An, Q., Xiao, Z. and Zhai, S., (2022a). Dual-wastes derived biochar with tailored surface features for highly efficient p-nitrophenol adsorption. *Journal of Cleaner Production*, 353, pp. 131571. <https://doi.org/10.1016/j.jclepro.2022.131571>

Rammal, J., Daou, A., Badan, D.E.L., Baki, Z.A., Darwich, S., Rammal, W. and Hijazi, A., (2025). Comparative Analysis of Natural and Synthetic Materials for Wastewater Treatment: Plant Powders, Activated Carbon, Biochar, Zeolite and Nanomaterials. *Journal of Chemical Reviews*, 7 (4), pp. 566-590. <https://doi.org/10.48309/jcr.2025.511327.1421>

Robinson, J.S. and Leinweber, P., (2023). Effects of pyrolysis and incineration on the phosphorus fertiliser potential of bio-waste-and plant-based materials. *Waste Management*, 172, pp. 358-367. <https://doi.org/10.1016/j.wasman.2023.10.012>

Roy, H., Prantika, T.R., Riyad, M.H., Paul, S. and Islam, M.S., (2022). Synthesis, characterizations, and RSM analysis of Citrus macroptera peel derived biochar for textile dye treatment. *South African Journal of Chemical Engineering*, 41, pp. 129-139. <https://doi.org/10.1016/j.sajce.2022.05.008>

Roy, H., Sarkar, D., Pervez, M.N., Paul, S., Cai, Y., Naddeo, V., Firoz, S.H. and Islam, M.S., (2023). Synthesis, characterization and performance evaluation of Burmese

grape (*Baccaurea ramiflora*) seed biochar for sustainable wastewater treatment. *Water*, 15 (3), pp.394. <https://doi.org/10.3390/w15030394>

Sani, M.N.H., Amin, M., Siddique, A.B., Nasif, S.O., Ghaley, B.B., Ge, L., Wang, F. and Yong, J.W.H., (2023). Waste-derived nano biochar: a new avenue towards sustainable agriculture, environment, and circular bioeconomy. *Science of the Total Environment*, 905, pp. 166881. <https://doi.org/10.1016/j.scitotenv.2023.166881>

Taha, A. and Daffalla, S., (2023). Biochar derived from palm waste supported greenly synthesized MnO<sub>2</sub> nanoparticles as a novel adsorbent for wastewater treatment. *Catalysts*, 13 (2), pp. 451. <https://doi.org/10.3390/catal13020451>

Thakur, A.K., Kumar, R., Shukla, P., Sharma, P. and Kulabhi, A., (2024). Biochar from agricultural biomass: Current status and future scope. *Materials Today: Proceedings*, 99, pp. 56-62. <https://doi.org/10.1016/j.matpr.2023.05.209>

Waheed, A., Naqvi, S.R. and Ali, I., (2022). Co-torrefaction progress of biomass residue/waste obtained for high-value bio-solid products. *Energies*, 15(21), pp.8297. <https://doi.org/10.3390/en15218297>

Wang, G., Zhu, J., Xing, Y., Yin, Y., Li, Y., Li, Q. and Chen, R., (2022). When dewatered swine manure-derived biochar meets swine wastewater in anaerobic digestion: a win-win scenario towards highly efficient energy recovery and antibiotic resistance genes attenuation for swine manure management. *Science of the Total Environment*, 803, pp.150126. <https://doi.org/10.1016/j.scitotenv.2021.150126>

Zhang, Y., Gong, Y., Shi, G., Liu, X., Dai, M. and Ding, L., (2023). Removal of quinolone antibiotics from wastewater by the biochar-based sludge adsorbent. *Fermentation*, 9 (8), pp. 752. <https://doi.org/10.3390/fermentation9080752>

### **Declaration of Interest**

**The authors declare no interests**