



Biochar for Wastewater Treatment: An Integrative Review of Feedstocks, Engineering Strategies, Adsorption Mechanisms, and Future Perspectives

ST. Aisyah Humaerah and Sri Magfirah HS*

Environmental Science Study Program, Faculty of Mathematics and Natural Sciences, Universitas Negeri Makassar, Makassar, 90222, Indonesia

*Corresponding Author: srimagfirah@unm.ac.id

ARTICLE INFO

Article history:

Received 10 August 2026

Revised 22 September 2026

Accepted 10 October 2026

Available online 20 October 2026

E-ISSN: [2656-1492](https://doi.org/10.32734/jcnar.v8i2.26953)

How to cite:

ST Aisyah Humaerah and Sri Magfirah HS. Biochar for Wastewater Treatment: An Integrative Review of Feedstocks, Engineering Strategies, Adsorption Mechanisms, and Future Perspectives. Journal of Chemical Natural Resources. 2026. 8(2): 131-147.

ABSTRACT

The increasing volume and complexity of wastewater have driven the development of effective and sustainable treatment technologies. Biochar is a biomass-based adsorbent with considerable potential for wastewater treatment because its pore characteristics, surface area, functional groups, and mineral composition can be engineered according to target pollutants. This review aims to synthesize the relationships among biomass types, production conditions, activation and modification strategies, physicochemical characteristics, adsorption mechanisms, performance, and application readiness of biochar. Literature was searched through Scopus, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis, MDPI, and selected SINTA-indexed journals for 2021–2026. A total of 40 articles were selected based on relevance, credibility, and information completeness and analyzed using a descriptive-comparative approach. The synthesis indicates that biochar performance results from interactions among feedstock, production conditions, engineering strategies, pollutant properties, and operating conditions. Activation using H_3PO_4 , KOH, and NaOH and modification with bentonite, magnetic materials, metal oxides, and carbon-based materials can alter surface characteristics and pollutant affinity. However, increased surface area does not necessarily result in proportional improvements in adsorption performance, highlighting the need to integrate characterization and adsorption data for mechanistic interpretation. Key research gaps include testing standardization, regeneration and stability, validation using real wastewater and multicomponent systems, continuous-flow development and scale-up, and sustainability assessment through Life Cycle Assessment and techno-economic analysis. The review highlights the need for engineered biochar that simultaneously considers performance, stability, safety, process feasibility, and sustainability.

Keyword: Biochar, Wastewater Treatment, Adsorption, Biomass Feedstock, Engineered Biochar

ABSTRAK

Peningkatan volume dan kompleksitas air limbah mendorong pengembangan teknologi pengolahan yang efektif dan berkelanjutan. Biochar merupakan adsorben berbasis biomassa yang berpotensi digunakan dalam pengolahan air limbah karena karakteristik pori, luas permukaan, gugus fungsi, dan komposisi mineralnya dapat direkayasa sesuai target polutan. Review ini bertujuan mensintesis hubungan antara jenis biomassa, kondisi produksi, strategi aktivasi dan modifikasi, karakteristik fisikokimia, mekanisme adsorpsi, kinerja, dan kesiapan aplikasi biochar. Literatur ditelusuri melalui Scopus, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis, MDPI, dan beberapa jurnal terindeks SINTA untuk periode 2021–2026. Sebanyak 40 artikel dipilih berdasarkan relevansi, kredibilitas, dan kelengkapan informasi, kemudian dianalisis secara deskriptif-komparatif. Hasil sintesis menunjukkan bahwa kinerja biochar merupakan hasil interaksi antara *feedstock*, kondisi produksi, strategi *engineering*, sifat polutan, dan kondisi operasi. Aktivasi menggunakan H_3PO_4 , KOH, dan NaOH serta modifikasi dengan bentonit, material magnetik, oksida logam, dan material berbasis karbon dapat mengubah karakteristik permukaan dan afinitas terhadap polutan. Namun, peningkatan luas permukaan tidak selalu



This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International.
<https://doi.org/10.32734/jcnar.v8i2.26953>

menghasilkan peningkatan kinerja adsorpsi yang sebanding, sehingga interpretasi mekanisme memerlukan integrasi data karakterisasi dan adsorpsi. Kesenjangan penelitian meliputi standardisasi pengujian, regenerasi dan stabilitas, validasi menggunakan air limbah nyata dan sistem multikomponen, pengembangan sistem *continuous-flow* dan *scale-up*, serta evaluasi keberlanjutan melalui *Life Cycle Assessment* dan analisis tekno-ekonomi. Kajian ini menegaskan perlunya pengembangan *engineered biochar* yang mempertimbangkan kinerja, stabilitas, keamanan, kelayakan proses, dan keberlanjutan secara bersamaan.

Kata Kunci: Biochar, Pengolahan Air Limbah; Adsorpsi, Bahan Baku Biomassa, Biochar Hasil Rekayasa

1. Introduction

Access to clean water is fundamental to public health, ecosystem sustainability, and economic development. In line with the targets of Sustainable Development Goal 6 (SDG 6), the management of clean water and wastewater has become a global priority. However, population growth, urbanization, industrialization, and agricultural intensification have increased both the volume and complexity of wastewater. In addition to conventional pollutants, such as organic matter, suspended solids, and nutrients, wastewater may contain emerging contaminants, including antibiotics, pharmaceutical residues, pesticides, dyes, heavy metals, hormones, and persistent organic compounds. The diversity of these contaminants and their characteristics has driven the development of treatment technologies that are effective, economically feasible, and sustainable [1–4].

Various technologies have been developed to remove pollutants from wastewater, including coagulation–flocculation, biological processes, ion exchange, membrane filtration, advanced oxidation processes, and adsorption. Among these approaches, adsorption has been widely investigated because it is relatively simple, easy to operate, and applicable to various groups of contaminants. These advantages have encouraged the development of biomass-based adsorbents derived from renewable resources, which may contribute to more sustainable waste management [5–7].

Biochar is a biomass-based material that has been extensively investigated as an adsorbent for water and wastewater treatment. It is primarily produced through the thermochemical conversion of biomass under oxygen-limited conditions, particularly via pyrolysis, as well as through other thermochemical processes that yield carbon-based biomass materials. Feedstock types and production conditions play important roles in determining biochar characteristics, including pore structure, surface area, functional groups, surface charge, and mineral content, which subsequently influence its interactions with contaminants. The utilization of agricultural residues, forestry residues, and other biomass resources also provides opportunities to support waste-to-resource approaches and the circular economy [7–11]. Biochar and activated carbon are related carbon-based adsorbents, but they differ in their production routes. Activated carbon generally undergoes additional activation to develop its porous structure and is considered in this review as a comparative context. However, biochar produced without further engineering may not be suitable for all types of contaminants. Therefore, various engineering strategies have been developed to improve its properties and performance [4,12].

Biochar engineering strategies include physical and chemical activation, surface modification, functionalization, doping, composite formation, and the development of magnetic biochar. These strategies can alter the surface area, pore distribution, functional groups, surface charge, and chemical properties of the material. Such changes subsequently influence adsorption mechanisms, including pore filling, electrostatic interactions, ion exchange, surface complexation, π – π interactions, and precipitation. For biochar with catalytic properties, certain engineering strategies may also broaden pollutant removal mechanisms through oxidation or reduction processes. Various characterization techniques, including BET, SEM, FTIR, XRD, XPS, and TGA, are used to elucidate the relationships between material characteristics and removal mechanisms [13–17].

These developments have resulted in numerous review articles with diverse focuses; however, their coverage tends to remain segmented according to the objectives of the review, material types, or contaminant groups. Reviews focusing on biochar production primarily discuss feedstocks, thermochemical technologies, process conditions, and biochar characteristics [10,11,18,19]. Other reviews have focused on activation, modification, functionalization, magnetic materials, or metal- and heteroatom-doped biochar [14,15,20,21].

Meanwhile, several studies have emphasized specific contaminant groups, including heavy metals, organic contaminants, pharmaceuticals, and emerging contaminants [5,22–25]. More recent reviews have also begun to address regeneration, sustainability, wastewater applications, and challenges associated with real-world implementation [6,12,26].

Although various aspects of biochar have been extensively reviewed, differences in review focus, contaminant groups, material characteristics, and testing conditions mean that the relationships among feedstocks, engineering strategies, physicochemical characteristics, adsorption mechanisms, and treatment performance have not always been synthesized and compared consistently within a single perspective. Moreover, performance under batch and laboratory conditions does not necessarily reflect the behavior of biochar in real wastewater, multicomponent systems, continuous operation, and larger-scale applications. Regeneration, stability, leaching, clogging, testing standardization, economic feasibility, and scale-up also represent important considerations for the broader application of biochar [6,12,23,26]. Thus, the research gap underlying this review does not lie in the absence of studies addressing individual aspects of biochar, but rather in the need to synthesize and compare the interrelationships among these aspects, from feedstock selection to application readiness.

Based on this research gap, the novelty of this review lies in a cross-dimensional comparative synthesis that connects feedstocks and production conditions with engineering strategies, changes in physicochemical characteristics, adsorption mechanisms, and biochar performance in wastewater treatment. This synthesis is further linked to regeneration, stability, application in real wastewater, multicomponent systems, continuous-flow operation, scale-up, and sustainability to identify trade-offs among improved adsorption performance, material stability, regeneration requirements, leaching potential, cost, and application readiness. Therefore, this review aims to provide an integrated comparative synthesis of biomass feedstocks, production conditions, engineering strategies, physicochemical characteristics, adsorption mechanisms, performance, and application readiness of biochar for wastewater treatment, while identifying research gaps and future development directions.

2. Methods

This study is a literature review that aims to synthesize research developments on biochar as an adsorbent for wastewater treatment. The review was conducted through a literature synthesis to analyze the relationships among biomass types, biochar engineering strategies, physicochemical characteristics, adsorption mechanisms, applications for various pollutants, and future research directions.

2.1. Literature Search Strategy

The literature search was conducted using scientific databases and publication platforms, including Scopus, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis, MDPI, and selected national journals indexed in SINTA. The search focused on publications published between 2021 and 2026. A combination of search terms was used according to the scope of the review, including “*biochar*,” “*biochar adsorption*,” “*biochar activation*,” “*biochar modification*,” “*biochar characterization*,” “*biochar wastewater treatment*,” “*biochar heavy metals*,” “*biochar antibiotics*,” “*biochar dyes*,” “*biochar COD removal*,” and “*biochar bentonite*.” The search terms were used individually or combined using the Boolean operators AND and OR to identify literature relevant to the scope of the review.

2.2. Inclusion and Exclusion Criteria

The literature was screened based on predefined inclusion and exclusion criteria. The inclusion criteria were: (a) articles published between 2021 and 2026; (b) research articles or review articles; (c) studies addressing biochar in the context of water or wastewater treatment; (d) studies providing information on biomass feedstocks, production, activation or modification, characterization, applications, adsorption mechanisms, or research gaps; and (e) studies with accessible full texts. The exclusion criteria were: (a) articles published before 2021; (b) conference proceedings, books, book chapters, editorials, or other non-journal publications; (c) articles unrelated to biochar; (d) articles not relevant to water or wastewater treatment; (e) duplicate articles; and (f) articles that did not provide sufficient information for data extraction and synthesis.

2.3. Screening, Selection, and Article Justification

The literature selection process was conducted in several stages, including identification, screening, full-text assessment, and selection based on the predefined inclusion and exclusion criteria. A total of 65 articles

were identified through the established search strategy. The articles were then screened based on their titles and abstracts to assess their relevance to the scope of the review. Articles that were irrelevant or outside the defined scope were excluded from further consideration. The relevant articles were subsequently assessed through full-text examination to confirm their eligibility and the availability of information required for the synthesis. Following the selection process, 40 articles met the eligibility criteria and were selected as the primary sources for the literature synthesis. Thus, the final number of 40 articles resulted from a selection process based on relevance, scope, and information completeness rather than from an arbitrary number predetermined at the outset. The literature search and selection process are presented in Figure 1.

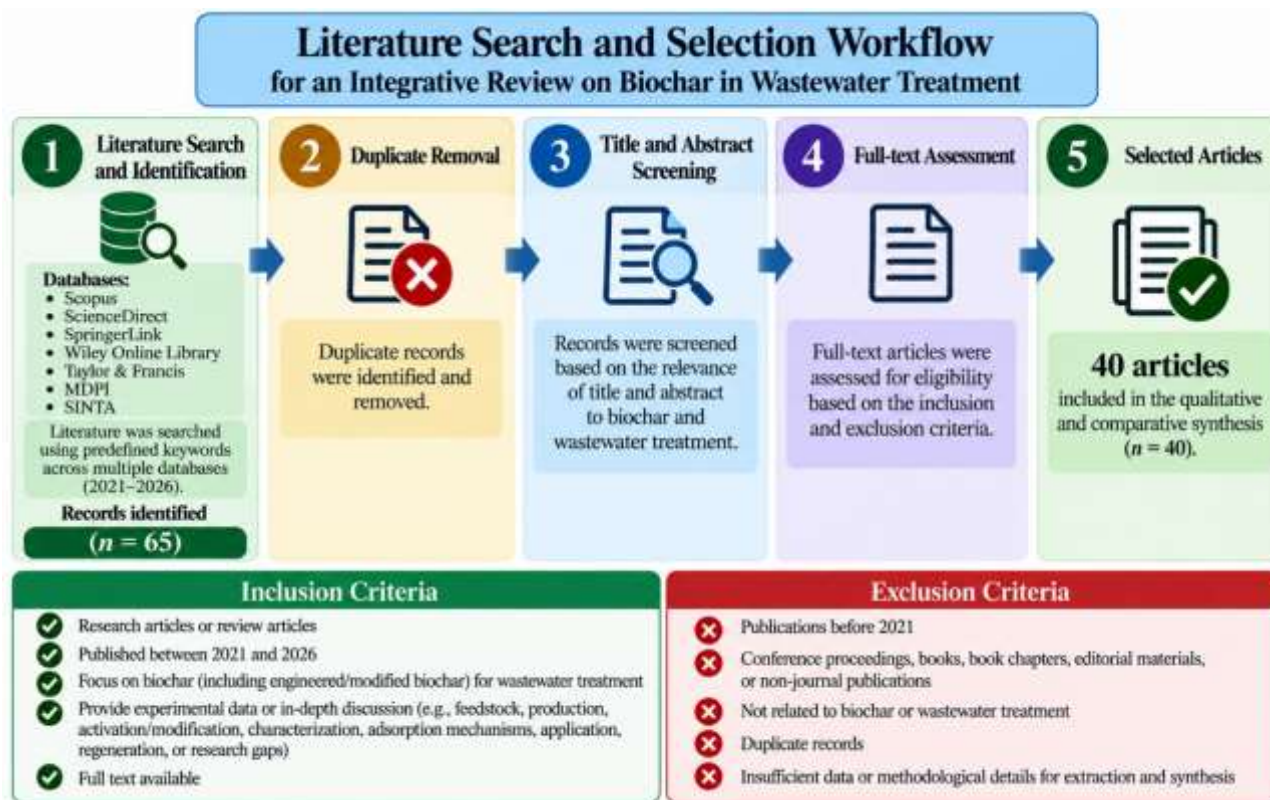


Figure 1. Literature Search and Selection Workflow for the Integrative Review of Biochar in Wastewater Treatment

2.4. Data Extraction and Synthesis

Data from the selected articles were extracted and analyzed using a descriptive-comparative approach based on key aspects, including biomass types, production conditions, activation and modification strategies, physicochemical characteristics, pollutant types, application conditions, adsorption performance, adsorption mechanisms, isotherm and kinetic models, and research gaps. Where available, quantitative data included removal efficiency, adsorption capacity, pH, adsorbent dosage, contact time, initial pollutant concentration, temperature, and regeneration conditions. The extracted data were then synthesized to identify research trends and relationships within the feedstock, process, property, performance framework, including the effects of engineering strategies on biochar characteristics and adsorption performance. The synthesis was also used to compare activation and modification approaches, identify research limitations, and formulate opportunities for further development of biochar for wastewater treatment applications. The findings were presented through synthesis tables, comparative analysis, and a Research Roadmap to illustrate research developments and future directions for biochar as a sustainable adsorbent in wastewater treatment.

3. Results and Discussion

The findings of the literature synthesis are organized into five interconnected dimensions: biomass feedstocks, biochar engineering strategies, physicochemical characterization, adsorption performance and behavior, and research gaps and future perspectives. This structure traces the relationship from feedstock selection and material development to adsorption performance and application readiness.

3.1. Biomass Feedstocks

Feedstock selection represents an initial step that determines the fundamental characteristics of biochar and subsequently influences its suitability as an adsorbent. Based on the synthesis of 40 articles, the feedstocks used included various agricultural residues, lignocellulosic biomass, and biomass with relatively high mineral contents. These differences are associated not only with biomass availability but also with variations in lignocellulosic composition, mineral/ash content, and initial functional groups that undergo transformation during thermochemical processing [10,11,18].

Table 1. Feedstock characteristics and their implications for biochar

Feedstock type	Key characteristics	Biochar characteristics relevant to adsorption	Implications for application	Source
Corn cobs	Lignocellulosic biomass and agricultural residue	Carbon structure, porosity, and functional groups can be developed through pyrolysis and activation	Potential for various environmental and adsorption applications following appropriate conditioning	[25]
Rice husk/rice straw	Lignocellulosic biomass with a substantial mineral/ash fraction	Carbon structure and surface characteristics are influenced by the initial composition and production conditions	Can be utilized as an adsorbent and wastewater treatment material	[11]
Wheat straw	Lignocellulosic biomass with a composition different from corn cobs	Differences in surface properties may result in varying affinities toward organic pollutants	Adsorption responses may be specific to the type of pollutant	[27]
Bagasse	Lignocellulosic agro-industrial residue	Pore characteristics and functional groups depend on pyrolysis conditions and engineering strategies	Potentially applicable as a carbon source for adsorbents	[10,18]
Bamboo	Lignocellulosic biomass	Carbon structure and pore characteristics are influenced by production conditions	Can be engineered for specific target pollutants	[10,18]
Sewage sludge	Contains organic and mineral/inorganic fractions	Mineral characteristics and pore structure may provide additional functionality after engineering	Potential for adsorption, but requires attention to safety and potential contaminant release	[28]
Alternative biomass	Highly variable composition	Biochar characteristics depend on feedstock composition and production conditions	Feedstock selection should be tailored to the target pollutant and application objectives	[11,18]

Differences in feedstock composition influence biomass transformation during pyrolysis and can result in biochar with distinct surface characteristics, pore structures, and functional groups. However, the effects of feedstock cannot be fully separated from production conditions, as temperature, residence time, and heating rate also determine the development of the carbon structure and the physicochemical properties of biochar [11,18]. Therefore, comparisons among feedstocks should consider the production conditions employed rather than biomass type alone.

The comparison of corn cob and wheat straw biochar reported by Beljin et al. [27] provides a relatively controlled example because both feedstocks were pyrolyzed at 700 °C. Corn cob biochar had a specific surface area of 111 m²/g, whereas wheat straw biochar had a specific surface area of 61 m²/g. Nevertheless, the two biochars exhibited different affinities toward PAH compounds. Corn cob biochar showed a higher affinity for fluorene, whereas wheat straw biochar exhibited a higher affinity for naphthalene and pyrene. These differences indicate that surface area alone cannot be used as the sole indicator of adsorption performance, as

pollutant affinity is also influenced by surface chemical characteristics and the compatibility between biochar surface interactions and the chemical properties of the pollutants.

These findings indicate that the contribution of feedstock operates through an interconnected chain of relationships. Biomass composition influences transformations during production, which in turn shape the carbon structure, porosity, mineral composition, and surface functional groups. These resulting characteristics determine the types of interactions that may occur with pollutants. Thus, the relationship between feedstock and adsorption performance is not direct but is mediated by biochar characteristics and pollutant properties.

This relationship is also evident in sewage-sludge biochar. Agoe et al. [28] reported that post-pyrolysis NaOH treatment increased the surface area from approximately 27.5 to 144.27 m²/g, accompanied by increased adsorption capacity toward methylene blue and Hg. These findings demonstrate that the initial characteristics of a feedstock can be further developed through engineering. Therefore, feedstock should not be regarded as an isolated factor but rather as the starting point for developing material characteristics suited to specific application targets.

Overall, the synthesis indicates that no single feedstock is universally optimal for all adsorption applications. Biomass composition determines the potential initial characteristics, production processes govern material transformation, biochar characteristics determine surface properties and pore structure, while pollutant properties and operating conditions determine interactions and adsorption performance. Therefore, feedstock selection should be based on the compatibility among feedstock composition, process conditions, biochar characteristics, pollutant properties, and application objectives rather than solely on biomass availability. This framework can be described as feedstock–process–property–pollutant matching, which provides an important basis for the development of engineered biochar for wastewater treatment applications.

3.2. Biochar Engineering Strategies: Activation and Modification

Activation and modification are engineering strategies used to tailor the physicochemical characteristics of biochar to target pollutants and application conditions. Activation is primarily employed to develop the pore structure and/or modify surface chemistry, whereas modification involves incorporating specific components or functionalities, such as minerals, magnetic materials, metal oxides, and carbon-based materials. Thus, biochar engineering is not solely aimed at increasing surface area or adsorption capacity but rather at developing a combination of material properties that is compatible with the expected interaction mechanisms with pollutants [7,13,18].

Table 2. Comparison of biochar activation strategies

Activation strategy	Main effect on biochar	Advantages	Limitations	Source
H ₃ PO ₄	Develops porosity and modifies surface chemistry	Can develop pore structure while influencing functional groups	Requires washing and may generate chemical residues	[29–31]
KOH	Promotes pore formation and increases surface area	Potential to produce highly porous structures	Chemical consumption and washing requirements	[7]
NaOH	Modifies the surface and improves pore accessibility	Can improve surface characteristics	Requires washing and residue control	[28]
HCl / HNO ₃	Alters functional groups and/or removes certain mineral components	Can tailor surface chemistry for specific targets	May alter the structure and generate chemical waste	[7]
Steam / CO ₂	Develops pores through physical activation	Does not require chemical impregnation	Requires energy and thermal process control	[7,18]

The synthesis indicates that activation can simultaneously alter multiple characteristics of biochar. For example, Ouyang et al. [29], reported that biochars derived from several biomass sources and activated with H₃PO₄ exhibited specific surface areas ranging from 571.0 to 1006.3 m²/g. Meanwhile, Agoe et al. [28] reported an increase in the surface area of sewage-sludge biochar from approximately 27.5 to 144.27 m²/g

following NaOH treatment. The differences in the magnitude of these changes indicate that the response to activation is determined not only by the type of activator but also by feedstock composition, pyrolysis conditions, and the initial characteristics of the biochar.

Furthermore, an increase in surface area does not necessarily result in a proportional improvement in adsorption performance. Marcelino et al [31] reported that oxidation of corn cob biochar using H_3PO_4 enhanced glyphosate adsorption even though the surface area of the oxidized material was not higher. This finding indicates that surface chemistry may act as a more relevant limiting or facilitating factor than surface area alone, particularly when adsorption involves specific interactions between surface functional groups and pollutant molecules. Therefore, changes in surface area should be interpreted together with information on functional groups, surface charge, and the chemical properties of the adsorbate.

This relationship also highlights the importance of distinguishing changes in material properties from evidence supporting specific adsorption mechanisms. An increase in BET surface area indicates the development of surface area and/or porosity but does not, by itself, demonstrate that enhanced adsorption occurs through pore filling. Similarly, changes in FTIR or XPS spectra may indicate alterations in surface chemistry but do not independently establish a specific type of interaction. Stronger mechanistic interpretation requires the integration of pre- and post-adsorption characterization with pH, pH_{pzc}, isotherm, kinetic, and adsorption performance data. This approach is important for distinguishing structural changes, changes in surface chemistry, and their respective contributions to adsorption performance.

In addition to activation, modification strategies are employed when the characteristics of pyrolysis- or activation-derived biochar do not fully meet the required functions. Modification can serve different purposes, such as introducing active sites, improving selectivity, facilitating adsorbent separation after treatment, or enhancing reusability.

Table 3. Comparison of biochar modification strategies

Modification strategy	Primary function	Common targets / applications	Limitations	Source
Biochar–bentonite / mineral composites	Introduce additional active sites and mineral functionalities	Metals and dissolved pollutants	Composite composition affects the contribution of each component	[32]
Magnetic biochar	Facilitate separation and modify surface functionality	Metals and organic compounds	Potential agglomeration and changes in porosity	[21,33]
Metal oxide-loaded biochar	Introduce reactive sites and/or specific affinity	Heavy metals and emerging contaminants	Potential leaching and synthesis complexity	[14,34]
GO / CNT and carbon-based materials	Enhance surface interactions and modify carbon structure	Organic compounds and emerging contaminants	Cost and material complexity	[13]
LDH / MOF / biopolymer	Introduce adsorption sites or selective functionalities	Anions, metals, and organic pollutants	Cost, stability, and production complexity	[35]

These modifications represent a shift from biochar as a relatively general-purpose adsorbent toward engineered biochar designed for specific functions. For example, Bai and Hong [32], showed that combining biochar with bentonite resulted in a higher Hg adsorption capacity than that of biochar and bentonite used individually under the same system conditions. This finding suggests that material integration can create or enhance interaction sites that are not optimally available in the individual components.

Beyond improving adsorption capacity, engineering can also target operational performance. Yan et al. [33] reported that the modified material retained approximately 93.8% of its adsorption performance after repeated use and regrinding. This finding indicates that the evaluation of engineered biochar should consider not only initial performance but also its stability and ability to retain functionality during repeated use. However, enhanced functionality through activation and modification is inevitably accompanied by trade-offs. Chemical

activation may increase chemical consumption, washing requirements, and residue management, whereas modification with minerals, metal oxides, or nanostructured materials may increase synthesis complexity and require evaluation of stability and leaching potential. Magnetic modification, on the other hand, can facilitate adsorbent separation but may also alter pore structure and surface properties. Therefore, increased adsorption capacity should not be the sole basis for selecting an engineering strategy.

Overall, the synthesis indicates that engineering strategies should be selected according to the material functions required for the target pollutant and application conditions. Activation can be directed toward developing porosity or tailoring surface chemistry, whereas modification can be used to introduce specific functions such as selectivity, separation, or reusability. Thus, the more appropriate relationship is not simply engineering $\rightarrow$ higher adsorption, but rather engineering $\rightarrow$ property/function $\rightarrow$ pollutant interaction $\rightarrow$ performance, while considering trade-offs involving chemical and energy requirements, process complexity, stability, leaching, regeneration, and cost.

3.3. Biochar Characterization

Characterization is an essential step for linking changes induced by pyrolysis, activation, and modification to the properties of biochar that determine its adsorption behavior. Based on the synthesis of 40 articles, no single characterization technique can adequately capture all relevant characteristics of biochar. Therefore, interpretation of structure–property–performance relationships should consider a combination of techniques covering textural properties, morphology, surface chemistry, structure, and mineral composition [7,12,13].

Table 4. Characterization techniques and their contributions to biochar evaluation

Characterization technique	Main information obtained	Contribution to adsorption interpretation	Limitation	Source
BET	Specific surface area and pore characteristics	Evaluates the development of porosity and accessibility of adsorption sites	High surface area does not necessarily result in high adsorption capacity	[7,12]
SEM	Surface morphology and structure	Observes changes in morphology and pore structure	Does not directly provide information on surface chemistry	[7,13]
FTIR	Surface functional groups	Identifies functional groups that may interact with adsorbates	Absorption bands may overlap	[7,12]
XPS	Surface composition and chemical states	Identifies elements and changes in chemical bonding at the surface	Relatively complex analysis and primarily represents the surface layer	[12,13]
XRD	Crystalline phases and mineral components	Identifies minerals and changes in crystalline structure	Less informative for highly amorphous carbon phases	[7]
EDS/EDX	Elemental composition and local distribution	Identifies elements present on the surface/material	Does not directly provide information on functional groups	[7,12]
Raman	Carbon structure and degree of structural order	Evaluates changes in carbon structure	Interpretation requires supporting parameters	[12]
TEM	High-resolution morphology and structure	Observes micro-/nanostructure and particle distribution	Sample preparation and interpretation are relatively complex	[12]
TGA	Thermal stability and decomposition	Evaluates thermal stability and changes in material components	Does not directly demonstrate adsorption mechanisms	[12]

Functionally, each characterization technique provides different but complementary information for elucidating the adsorption behavior of biochar. BET is primarily used to evaluate surface area and pore structure, whereas SEM and TEM provide information on surface morphology and structure. FTIR and XPS provide information on functional groups and surface chemistry, while XRD and EDS/EDX assist in identifying mineral phases and elemental composition. The *pHpzc* provides information on surface charge characteristics under specific pH conditions, whereas adsorption data are used to evaluate the actual performance of the material toward target pollutants. Therefore, characterization should not be viewed as a set of standalone measurements, but rather as a complementary body of evidence for linking material properties to adsorption behavior.

BET and SEM characterization primarily provide information on textural and morphological properties. BET is used to evaluate surface area and pore characteristics, whereas SEM reveals changes in surface morphology following pyrolysis, activation, or modification. However, surface area cannot be used as the sole indicator of adsorption performance. Marcelino et al. [31], for example, demonstrated that modification of corn cob biochar with H_3PO_4 enhanced glyphosate adsorption despite the absence of a corresponding increase in surface area. This finding indicates that surface chemical characteristics may be as important as textural properties in determining adsorption performance.

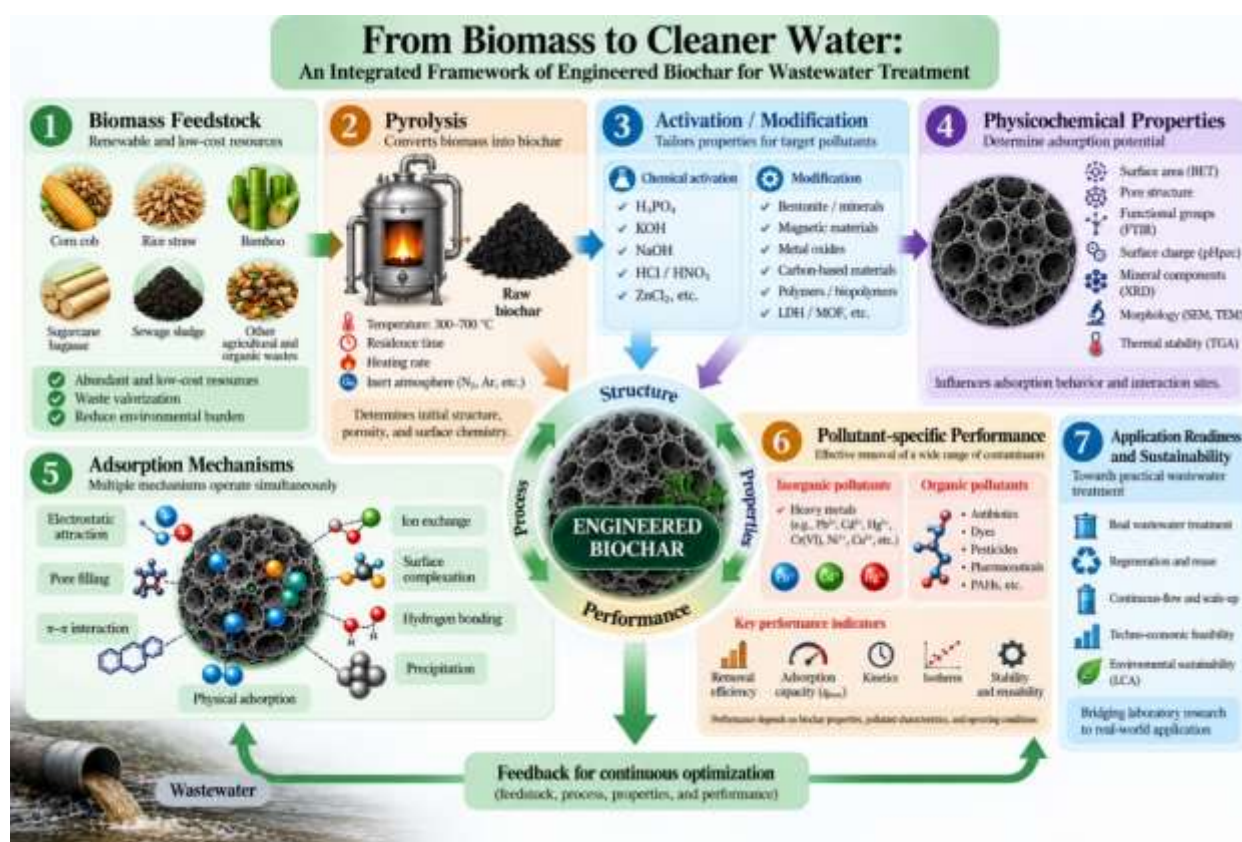


Figure 2. Conceptual framework linking biomass feedstock, pyrolysis, activation / modification, physicochemical properties, adsorption mechanisms, and pollutant-specific performance toward application readiness and sustainability.

Textural information should be further complemented by FTIR and XPS to evaluate functional groups and surface chemical states. Changes in oxygen-containing groups or other elements following activation and modification can be used to interpret potential interactions between biochar and adsorbates. Meanwhile, XRD and EDS/EDX provide additional information on mineral phases and elemental composition, particularly for biochar derived from feedstocks with high mineral contents or modified using inorganic materials [7,12].

Raman, TEM, and TGA provide complementary information on carbon structure, high-resolution morphology, and thermal stability, respectively. Their use becomes more relevant when the research aims to elucidate structural changes induced by engineering treatments or to evaluate material stability. However, the results obtained from these techniques still need to be interpreted together with other characterization results and adsorption data. Therefore, no single characterization parameter can independently demonstrate an adsorption mechanism. BET can indicate the development of surface area and pore structure, but it does not

demonstrate that adsorption occurs through pore filling. Similarly, changes in FTIR bands may indicate changes in functional groups but do not automatically establish a specific interaction mechanism. Stronger interpretation can be obtained when characterization results are integrated with pH, *pHpzc*, isotherm, and kinetic data, as well as changes in material characteristics before and after adsorption.

3.4. Adsorption Performance and Behavior of Engineered Biochar

The adsorption performance of biochar is influenced by the interactions among adsorbent characteristics, pollutant properties, and operating conditions. Based on the synthesis of the reviewed articles, the parameters most frequently affecting adsorption outcomes include pollutant type and concentration, pH, adsorbent dosage, contact time, temperature, and biochar surface characteristics. Therefore, adsorption capacity and removal efficiency should be interpreted within the context of the experimental conditions of each study and should not be used to establish performance rankings across studies when the testing conditions differ substantially.

Table 5. Comparison of adsorption performance and biochar system characteristics

Pollutant	Biochar / feedstock	Engineering	Performance parameter	Key conditions	Reported mechanism / model	Source
Pb ²⁺	Biomass-based biochar	Different pyrolysis temperatures	Removal of 43–72% for BC-350 and BC-450	pH 6.5; 60 min	PSO; surface interactions	[36]
Hg ²⁺	Millet straw biochar	Biochar–bentonite composite	<i>q</i> _{max} 6.541–11.722 mg/g	25 °C; pH 7; dosage 1 g/L	Langmuir	[32]
Pb ²⁺	Palm kernel shell biochar	H ₃ PO ₄ activation	<i>q</i> _{max} 0.1717 mg/g	pH 7; dosage 20 g/L; 180 min; 25 °C	Langmuir; PSO	[30]
Glyphosate	Corn cob biochar	H ₃ PO ₄ oxidation	Capacity increased from 0.58 to 1.49 mg/g	Equilibrium reached at approximately 60 min	Langmuir/Freundlich depending on material	[31]
CIP	Biochars from several biomass sources	H ₃ PO ₄ activation	Capacity of 50.9–120.6 mg/g in lake water	25 °C; lake-water matrix	Isotherm/kinetic models varied by material	[29]
Methylene blue	Sewage-sludge biochar	NaOH treatment	Capacity of approximately 9–35 mg/g	C ₀ 400 mg/L; dosage 500 mg; 200 rpm	PSO	[28]
Hg	Sewage-sludge biochar	NaOH treatment	Capacity of approximately 17–36 mg/g	C ₀ 400 mg/L; adsorbent dosage 500 mg; 200 rpm	PSO	[28]
CIP	Engineered biochar	Biochar engineering	Langmuir <i>q</i> _{max} 523.0 mg/g; <i>q</i> _{exp} 572.8 mg/g	25 °C; pH 6; C ₀ 30–120 mg/L; dosage 0.1 g/L; 6 h	Langmuir	[3]
PAHs	Corn cob vs. wheat	Pyrolysis at 700 °C	Log K _d 4.35–5.69 L/kg	C ₀ 0.05 mg/L; equilibrium ≤24 h	Freundlich	[27]

Pollutant	Biochar / feedstock	Engineering	Performance parameter	Key conditions	Reported mechanism / model	Source
	straw biochar					
Pb ²⁺ , Ni ²⁺ , Cu ²⁺	Corn cob; bagasse	Unmodified	Pb ²⁺ : 11.34/8.96; Ni ²⁺ : 15.71/15.46; Cu ²⁺ : 11.96/12.00 mg/kg	pH 6.5; 180 min	Langmuir/Freundlich; PSO	[37]
COD, TSS	Corn cob	Vertical-flow constructed wetland	COD: 80.8– 86.9%; TSS: 54–62%	Livestock wastewater; 6 months	Langmuir; adsorption and biological processes	[38]

Note: Adsorption capacities and removal efficiencies are reported as presented in the original studies and should not be directly compared across studies because experimental conditions, adsorbate concentration, adsorbent dose, pH, contact time, temperature, and wastewater matrices differ.

The comparison presented in Table 5 indicates that no single engineering strategy produces consistent performance across all pollutant groups. Biochar performance depends on the compatibility between material characteristics and pollutant properties, as well as the operating conditions employed. For heavy metals, for example, changes in production conditions can result in substantial differences in adsorption performance. Assirey and Altamimi [36] reported Pb²⁺ removal of approximately 43–72% for biochars produced under different conditions. Nguyen et al. [39] also demonstrated that pyrolysis temperature and residence time influenced the physicochemical properties of corn cob biochar and subsequently affected its adsorption capacity toward paraquat. These findings reinforce the relationship between production conditions, material characteristics, and adsorption performance, indicating that differences in performance cannot be attributed solely to feedstock type or the presence of an activating agent.

Material modification can produce more specific changes in performance toward target pollutants. Bai and Hong [32] reported that the $q_{\max}$ for Hg²⁺ increased from 6.541 mg/g for the initial biochar to 9.152 mg/g after modification and to 11.722 mg/g for the biochar–bentonite composite. This increase suggests that the addition of a mineral phase can alter surface characteristics and provide a different interaction environment for metal ions. However, these values should not be interpreted as evidence that biochar–bentonite composites are generally superior to all other types of biochar, because performance comparisons remain dependent on the adsorption conditions and system characteristics employed.

For organic pollutants, the relationship between material characteristics and adsorption performance also exhibits non-uniform patterns. Marcelino et al. [31] reported an increase in glyphosate adsorption capacity from approximately 0.58 to 1.49 mg/g after modification of corn cob biochar using H₃PO₄. This improvement was not solely associated with surface area, supporting the role of surface chemistry and adsorbent–adsorbate interactions. Zhang et al. [40] reported a tetracycline adsorption capacity of 184.62 mg/g for magnetically modified corn cob biochar, with the proposed mechanisms involving *pore filling*, π – π interactions, hydrogen bonding, and electrostatic interactions. The material also retained more than 91% of its adsorption performance after five regeneration cycles. These findings indicate that engineering can be directed not only toward increasing adsorption capacity but also toward maintaining material functionality during repeated use.

Large differences in adsorption capacity are also observed for ciprofloxacin. Ouyang et al. [29] reported capacities of 50.9–120.6 mg/g in lake water for biochars derived from several biomass types and activated with H₃PO₄, whereas Du et al. [3] reported a Langmuir $q_{\max}$ of 523.0 mg/g and an experimental adsorption

capacity of 572.8 mg/g for engineered biochar. The latter experiment was conducted at 25 °C, pH 6, an initial concentration of 30–120 mg/L, an adsorbent dosage of 0.1 g/L, and a contact time of 6 h. These differences should not be interpreted simply as differences in material quality because the two studies employed different feedstock characteristics, engineering strategies, pollutant concentrations, adsorbent dosages, and operating conditions. Therefore, adsorption capacity values are more appropriately used to illustrate the reported performance range and the influence of system conditions rather than to establish rankings among materials. As another example, Dechapanya and Khamwichit [30] reported a Pb^{2+} adsorption capacity of 0.1717 mg/g. This value cannot be directly compared with capacities reported in other studies because the feedstock, engineering strategy, pollutant concentration, adsorbent dosage, and operating conditions differed substantially. Such comparisons instead highlight the importance of experimental context when interpreting adsorption capacity.

Beyond batch systems, Gotore et al. [38] evaluated corn cob biochar in a vertical-flow constructed wetland for the treatment of swine wastewater. COD removal reached 80.8–86.9%, while TSS removal ranged from 54–62% under saturated and semi-saturated conditions. These findings indicate that biochar performance in integrated treatment systems is influenced not only by adsorption but also by operating conditions and biological processes.

Isotherm and Kinetics

Isotherm models are used to describe the relationship between adsorbate concentration and adsorption capacity under equilibrium conditions. Langmuir and Freundlich are among the models most frequently used in the reviewed articles. The Langmuir model assumes a maximum adsorption capacity on a relatively homogeneous surface, whereas the Freundlich model is generally more applicable to heterogeneous surfaces. However, the statistical fit of an isotherm model should not be used alone to establish an adsorption mechanism [7,24].

The same consideration applies to kinetic models. Pseudo-first-order (PFO) and pseudo-second-order (PSO) models are widely used to describe adsorption rates. Dechapanya and Khamwichit [30], for example, obtained a high PSO fit ($R^2 > 0.99$); however, this result alone is insufficient to conclude that the adsorption mechanism is definitively chemisorption. Mechanistic interpretation should be supported by surface characterization and other evidence of adsorbent–adsorbate interactions [7].

Adsorption Mechanisms

The literature synthesis indicates that adsorption by biochar generally involves more than one mechanism, with the contribution of each mechanism depending on biochar surface properties, pollutant characteristics, and solution conditions. *Pore filling* and hydrophobic interactions may contribute to the adsorption of organic compounds, whereas π – π interactions, *hydrogen bonding*, electrostatic interactions, *surface complexation*, and *ion exchange* may play roles in different systems [7,17].

Beljin et al. [27] reported PAH adsorption behavior consistent with contributions from *pore filling*, π – π stacking, and *hydrogen bonding*. In modified biochar or biochar containing mineral phases, *surface complexation* and *ion exchange* may become more relevant. Thus, adsorption mechanisms should be presented as interpretations supported by multiple complementary lines of evidence rather than determined solely from isotherm or kinetic models.

Overall, the synthesis indicates that adsorption performance results from interactions among biochar structure, surface chemistry, pollutant properties, and operating conditions. An increase in surface area or the use of a particular activating agent does not consistently result in improved performance across all pollutants. Therefore, biochar development should focus on matching material characteristics with target pollutants and evaluating performance under conditions that more closely represent real wastewater. In addition to initial adsorption capacity, regeneration, stability, leaching, the presence of competing species, and performance in multicomponent systems should be considered before an engineered biochar is regarded as having broader application readiness.

3.5. Research Gaps and Future Perspectives

The synthesis of 40 articles indicates that research on biochar for wastewater treatment has evolved from the utilization of diverse biomass feedstocks and optimization of production processes toward the development

of engineered biochar with surface characteristics tailored to target pollutants. However, comparability across studies remains limited due to variations in feedstocks, pyrolysis conditions, activation/modification strategies, characterization methods, and adsorption conditions. These variations highlight the need for more standardized and integrative evaluation approaches to establish clearer relationships within the feedstock–process–property–performance framework [11,18,35].

Table 6. Research gaps and future research directions

Research gap	Main issue	Research direction	Source
Standardization	Differences in production and testing conditions limit performance comparability	Standardize reporting of feedstock, pyrolysis conditions, characterization, and adsorption conditions	[6,11]
Sustainable activation	Chemical activation may increase chemical consumption, washing requirements, and residue management	Develop more environmentally friendly and resource-efficient activation strategies	[9,12]
Multicomponent systems	Most studies use single-solute solutions, resulting in limited representation of competition among pollutants	Evaluate pollutant mixtures and real wastewater matrices	[22,35]
Regeneration and stability	Data on repeated use and long-term changes in performance remain limited	Evaluate regeneration cycles, stability, and leaching potential	[12,35]
Real wastewater	Interfering components and complex matrices may alter adsorption performance	Validate biochar using actual wastewater with well-characterized properties	[6,35]
Continuous-flow and scale-up	Many studies remain based on laboratory-scale batch systems	Develop fixed-bed systems, breakthrough analysis, continuous operation, and pilot-scale applications	[22,26]
Sustainability	Adsorption performance is not always evaluated together with energy consumption, cost, process waste, and environmental impacts	Integrate Life Cycle Assessment (LCA), techno-economic analysis, and material life-cycle evaluation	[9,12]

One of the major research gaps is the limited comparability of data across studies. Differences in pH, initial concentration, adsorbent dosage, contact time, and solution matrix can result in different adsorption capacities or removal efficiencies even when similar types of biochar are used. Therefore, future studies should report experimental conditions more comprehensively and adopt parameters that enable more consistent comparisons across studies [6,22].

Another research gap concerns the transition from model systems to real-world application conditions. The use of single-solute solutions remains predominant, whereas actual wastewater contains various ions and compounds that may compete for adsorption sites. In addition, adsorbent performance after regeneration, the potential release of components from biochar, and stability during repeated use require more systematic evaluation [12,35]. Accordingly, initial adsorption capacity should not be considered the sole indicator of material performance.

At the application stage, research needs to move beyond batch adsorption toward continuous-flow and pilot-scale systems. Fixed-bed systems require evaluation of different parameters, including flow rate, bed depth, empty-bed contact time, breakthrough behavior, and regeneration. Such development is important for determining whether performance achieved at the laboratory scale can be maintained during continuous operation [26]. In addition to technical considerations, material sustainability should be incorporated into the evaluation. Feedstock selection, energy consumption during pyrolysis, chemical requirements for activation, washing requirements, post-use adsorbent management, production costs, and potential environmental impacts should be considered simultaneously. Life Cycle Assessment and techno-economic analysis can help

determine whether improvements in adsorption performance are commensurate with the process burdens required to achieve them [9,12].



Figure 3. Research roadmap for the development and application of engineered biochar in wastewater treatment, from laboratory studies to real-world implementation, incorporating technical, environmental, and economic considerations.

Based on this synthesis, the development of biochar for wastewater treatment should be directed toward an integrated development chain: Feedstock selection → pyrolysis → activation/modification → physicochemical properties → adsorption mechanism → performance → regeneration/stability → real wastewater → continuous-flow → scale-up → sustainability. This framework indicates that biochar development should not stop at improving adsorption capacity but should simultaneously consider performance, stability, safety, reproducibility, process feasibility, and environmental impacts. Such an integrative approach can provide a basis for accelerating the transition of engineered biochar from laboratory-scale studies toward more realistic wastewater treatment applications [9,35].

4. Conclusion

The synthesis of 40 articles indicates that biochar performance in wastewater treatment results from interactions among feedstock, production conditions, engineering strategies, physicochemical characteristics, pollutant properties, and operating conditions. Activation and modification can tailor the surface properties and pollutant affinity of biochar; however, increases in surface area do not necessarily result in proportional improvements in adsorption performance. Therefore, the feedstock–process–property–performance relationship needs to be understood integratively, and adsorption mechanisms cannot be established based solely on a single characterization parameter or adsorption model.

The comparative synthesis also reveals trade-offs between improved performance and process requirements, including chemical consumption, synthesis complexity, stability, regeneration, leaching potential, and cost. Major research gaps remain in the standardization of production and testing conditions, limited data on regeneration and long-term stability, validation using real wastewater and multicomponent systems, and the development of continuous-flow and scale-up applications.

The main contribution of this review is the integration of relationships among feedstock selection, engineering strategies, material properties, adsorption mechanisms, performance, and application readiness within a unified evaluation framework. Future research should validate engineered biochar using real wastewater matrices, evaluate repeated use and leaching, develop fixed-bed and continuous-flow systems, and integrate Life Cycle Assessment (LCA) and techno-economic analysis to assess technical, economic, and environmental feasibility.

5. Acknowledgments

The authors would like to express their sincere gratitude to all parties who provided support during the preparation of this article.

6. Conflict of Interest

The authors declare that there are no conflicts of interest related to the preparation of this article.

References

- [1] Bahago NA, Wyasu G, Ugboaja VC. Optimization of activated carbon preparation from corncob wastewater treatment. *Commun. Phys. Sci.* 2021;7(2):58–68.
- [2] Utama DK, Alfiana AF, Rizkita N, Lestari DI, Aminah S. Adsorption of tofu liquid waste using rice husk activated carbon. *Sci. Educ. Appl. J.* 2025;7(1):94–107.
- [3] Du K, Li J, Arsalan M, Wang W, Yang G. Preparation of high-efficient phosphoric acid modified biochar toward ciprofloxacin removal from wastewater. *Ind. Crop. Prod.* 2025;226:120649. doi:10.1016/j.indcrop.2025.120649.
- [4] Vandana TU, Tripathy BK, Mishra RK, Sharma A, Mohanty K. A review on waste biomass-derived biochar: production, characterisation, and advanced analytical techniques for pollutants assessment in water and wastewater. *Process Saf. Environ. Prot.* 2025;201:107505. doi:https://doi.org/10.1016/j.psep.2025.107505.
- [5] Nand S, Prakash P, Verma S, Mishra S, Patel A, Shukla S, et al. Biochar for mitigating pharmaceutical pollution in wastewater: a sustainable solution. *Sci. Total Environ.* 2025;966:178743. doi:10.1016/j.scitotenv.2025.178743.
- [6] Kampila T, Manyuchi MM, Stinner W, Mbohwa C. A critical assessment of potential to use sewage sludge derived biochar in wastewater treatment. *Carbon Trends.* 2026;23:100645. doi:10.1016/j.cartre.2026.100645.
- [7] Singh S, Khan NA, Shehata N, Singh J, Ramamurthy PC. Insight into biochar as sustainable biomass : production methods, characteristics, and environmental remediation. *J. Clean. Prod.* 2024;475:143645. doi:10.1016/j.jclepro.2024.143645.
- [8] Setiani V, Priastuti U, Yuniarta DP. Improvement of soil chemical properties using corn cob biochar (btj). *J. Presipitasi (Media Komun. dan Pengemb. Tek. Lingkungan).* 2021;18(1):1–9.
- [9] Li J, Sun W, Lichtfouse E, Maurer C, Liu H. Life cycle assessment of biochar for sustainable agricultural application: a review. *Sci. Total Environ.* 2024;951:175448. doi:10.1016/j.scitotenv.2024.175448.
- [10] Amalina F, Syukor A, Razak A, Krishnan S, Sulaiman H, Zularisam A., et al. Biochar production techniques utilizing biomass waste-derived materials and environmental applications – a review. *J. Hazard. Mater. Adv.* 2022;7:100134. doi:10.1016/j.hazadv.2022.100134.
- [11] Sharma T, Gbolahan I, Bhushan A, Joshi J, Shah K, Vuppaladadiyam AK, et al. Parametric influence of process conditions on thermochemical techniques for biochar production : a state-of-the-art review. *J. Energy Inst.* 2024;113:101559. doi:10.1016/j.joei.2024.101559.
- [12] Awasthi D, Raj P, Godara R. Biochar for sustainable applications: advances in characterization, activation, and life cycle assessment. *Biomass and Bioenergy.* 2026;213:109435. doi:10.1016/j.biombioe.2026.109435.
- [13] Chu M, Zhao J, Zou M, Xing W, Liu Y. Advances on biochar applications for organic wastewater treatment : material design, removal mechanisms, innovative machine learning and challenges. *Environ. Res.* 2025;286:122967. doi:10.1016/j.envres.2025.122967.
- [14] Hamid Y, Liu L, Usman M, Naidu R, Haris M, Lin Q, et al. Functionalized biochars: synthesis, characterization, and applications for removing trace elements from water. *J. Hazard. Mater.* 2022;437:129337. doi:10.1016/j.jhazmat.2022.129337.
- [15] Liu C, Zhang H. Modified biochar adsorbents (mbas) for heavy metal ions adsorption : a critical review. *J. Environ. Chem. Eng.* 2022;10(2):107393. doi:10.1016/j.jece.2022.107393.
- [16] Qu J, Shi J, Wang Y, Tong H, Zhu Y, Xu L, et al. Applications of functionalized magnetic biochar in environmental remediation: a review. *J. Hazard. Mater.* 2022;434:128841. doi:10.1016/j.jhazmat.2022.128841.
- [17] Zeghioud H, Fryda L, Djelal H, Assadi A, Kane A. A comprehensive review of biochar in removal of organic pollutants from wastewater: characterization, toxicity, activation/functionalization and influencing treatment factors. *J. Water Process Eng.* 2022;47:102801. doi:10.1016/j.jwpe.2022.102801.
- [18] Safarian S. Performance analysis of sustainable technologies for biochar production: a comprehensive review. *Energy Reports.* 2023;9:4574–93. doi:10.1016/j.egyr.2023.03.111.

- [19] Ghosh D, Anderson N, Han H. Comparative assessment of biochar reactor technologies for biomass conversion : design, performance, and application suitability. *J. Clean. Prod.* 2026;538:147269. doi:10.1016/j.jclepro.2025.147269.
- [20] Bao Z, Shi C, Tu W, Li L, Li Q. Recent developments in modification of biochar and its application in soil pollution control and ecoregulation. *Environ. Pollut.* 2022;313:120184. doi:10.1016/j.envpol.2022.120184.
- [21] Liu Y, Chen Y, Li Y, Chen L, Jiang H, Li H, et al. Fabrication , application , and mechanism of metal and heteroatom co-doped biochar composites (mhbc) for the removal of contaminants in water : a review. *J. Hazard. Mater.* 2022;431:128584. doi:10.1016/j.jhazmat.2022.128584.
- [22] Biswal BK, Balasubramanian R. Use of biochar as a low-cost adsorbent for removal of heavy metals from water and wastewater : a review. *J. Environ. Chem. Eng.* 2023;11(5):110986. doi:10.1016/j.jece.2023.110986.
- [23] Luo Z, Yao B, Yang X, Wang L, Xu Z, Yan X, et al. Novel insights into the adsorption of organic contaminants by biochar : a review. *Chemosphere.* 2022;287:132113. doi:10.1016/j.chemosphere.2021.132113.
- [24] Mei Y, Zhuang S, Wang J. Adsorption of heavy metals by biochar in aqueous solution : a review. *Sci. Total Environ.* 2025;968:178898. doi:10.1016/j.scitotenv.2025.178898.
- [25] Tripathi A, Ekanayake A, Kumar V, Vithanage M. Emerging contaminants in polluted waters : harnessing biochar ' s potential for effective treatment. *J. Environ. Manage.* 2025;373:123778. doi:10.1016/j.jenvman.2024.123778.
- [26] Alshehri MA, Pugazhendhi A. Biochar for wastewater treatment: addressing contaminants and enhancing sustainability: challenges and solutions. *J. Hazard. Mater. Adv.* 2024;16:100504. doi:10.1016/j.hazadv.2024.100504.
- [27] Beljin J, Isakovski MK, Agbaba J, Vujic M, Maletic S. Adsorptive behavior of corn cob and straw derived biochar for polycyclic aromatic hydrocarbon removal from aqueous systems. *Processes.* 2025;13:1521. doi:10.3390/pr13051521.
- [28] Agoe AK, Pouloupoulos SG, Sarbassov Y, Shah D. Investigation of sewage sludge – derived biochar for enhanced pollutant adsorption : effect of particle size and alkali treatment. *Energies.* 2024;17:4554. doi:10.3390/en17184554.
- [29] Ouyang J, Chen J, Chen W, Zhou L, Cai D, Ren C. H₃PO₄ activated biochars derived from different agricultural biomasses for the removal of ciprofloxacin from aqueous solution. *Particuology.* 2023;75:217–27. doi:10.1016/j.partic.2022.07.016.
- [30] Dechapanya W, Khamwichit A. Biosorption of aqueous pb (ii) by h₃po₄-activated biochar prepared from palm kernel shells (pks). *Heliyon.* 2023;9:e17250. doi:10.1016/j.heliyon.2023.e17250.
- [31] Marcelino NVA, Santos HVR Dos, Cuba RMF, Teran FJC. Effect of h₃po₄ oxidation of corn cob biochar on the adsorption of a commercial glyphosate formulation. *Desalin. Water Treat.* 2022;274:102–14. doi:10.5004/dwt.2022.28801.
- [32] Bai Y, Hong J. Preparation of a novel millet straw biochar-bentonite composite and its adsorption property of hg²⁺ in aqueous solution. *Materials (Basel).* 2021;14:1117. doi:10.3390/ma14051117.
- [33] Yan N, Hu B, Zheng Z, Lu H, Chen J, Zhang X, et al. Twice-milled magnetic biochar: a recyclable material for efficient removal of methylene blue from wastewater. *Bioresour. Technol.* 2023;372:128663. doi:10.1016/j.biortech.2023.128663.
- [34] Yu S, Zhang W, Dong X, Wang F, Yang W, Liu C, et al. A review on recent advances of biochar from agricultural and forestry wastes : preparation, modification and applications in wastewater treatment. *J. Environ. Chem. Eng.* 2024;12(1):111638. doi:10.1016/j.jece.2023.111638.
- [35] Qin Z, Yuan Y, Xu M, Wan C, Li M, Duan Y. The multifunctional applications and mechanisms of biochar in wastewater treatment : from adsorption to catalysis. *J. Environ. Manage.* 2026;405:129755. doi:10.1016/j.jenvman.2026.129755.
- [36] Assirey EA, Altamimi LR. Chemical analysis of corn cob-based biochar and its role as water decontaminants. *J. Taibah Univ. Sci.* 2021;15(1):111–21. doi:10.1080/16583655.2021.1876350.
- [37] Tehreem S, Yousra M, Alamer KH, Alsudays IM, Sarwar S, Kamal A, et al. Analysis of the role of various biochar in the remediation of heavy metals in contaminated water and its kinetics study. *J. Saudi Chem. Soc.* 2022;26(5):101518. doi:10.1016/j.jscs.2022.101518.
- [38] Gotore O, Rameshprabu R, Itayama T. Adsorption performances of corn cob-derived biochar in saturated and semi-saturated vertical-flow constructed wetlands for nutrient removal under erratic oxygen supply. *Environ. Chem. Ecotoxicol.* 2022;4:155–63. doi:10.1016/j.enceco.2022.05.001.
- [39] Nguyen CT, Tungtakanpoung D, Tra VT, Kajitvichyanukul P. Kinetic, isotherm and mechanism in

paraquat removal by adsorption process using corn cob biochar produced from different pyrolysis conditions. *Case Stud. Chem. Environ. Eng.* 2022;6:100248. doi:10.1016/j.cscee.2022.100248.

- [40] Zhang T, Li W, Luo J, Zhao M, Wang Y, Fan S. Magnetic mesoporous corncob biochar for tetracycline adsorption: 2d-ftir-cos analysis and quantitative mechanistic insight. *Colloids Surfaces A Physicochem. Eng. Asp.* 2025;723:137378. doi:10.1016/j.colsurfa.2025.137378.