AIMS Bioengineering

AIMS Bioengineering, 13(1): 62–95.
DOI: 10.3934/bioeng.2026004
Received: 15 December 2025
Revised: 17 January 2026
Accepted: 10 February 2026
Published: 24 February 2026

https://www.aimspress.com/journal/Bioengineering

Review

Black gold - biochar: transforming agro-based biomasses into sustainable environmental solutions

Ayesha Mulla[1], Riddhi Chakraborty[1], Gaurav Rai[1], Bhawna Kandwal[1], Twisampati Das[1], Shrikant Hulkane[1], Ibrahim M. Banat[2,*], Sanket J. Joshi[3] and Surekha K. Satpute[1,*]

[1] Department of Microbiology, Savitribai Phule Pune University, Pune, Maharashtra, India
[2] School of Biomedical Sciences, Ulster University, Coleraine, Northern Ireland, UK
[3] Amity Institute of Microbial Technology, Amity University Rajasthan, Jaipur, Rajasthan, India

* **Correspondence:** Email: drsurekhasatpute@gmail.com; im.banat@ulster.ac.uk; Tel: +9102025622139; +442870123062.

Abstract: The escalating waste generated from agriculture, forestry, aquatic, and industrial sectors poses significant challenges, including environmental pollution, increased greenhouse gas emissions, and depletion of valuable resources. In response to these pressing issues, biochar has emerged as a renewable and sustainable biotechnological approach. Biochar, known as the Black Gold, is derived from the pyrolysis of various organic waste materials, reducing waste and creating a useful product for protecting the environment. Agriculture, forestry waste, food and fiber processing residues, and grassland biomass are the main sources for biochar production. Lignocellulosic materials with low moisture content are the preferred feedstock for biochar production. Biochar has diverse applications in carbon sequestration, soil remediation, and water and air purification, including toxic heavy metals (HMs) removal (e.g., chromium, arsenic, and lead). Biochar applications vary depending on the composition of the feedstocks used in the pyrolysis process. Chemically modified pristine biochar exhibits enhanced adsorption capacities for HMs, making it particularly effective for soil and water decontamination applications. This review highlights the important roles of biochar material for sustainable environmental applications, particularly in HMs removal from contaminated water systems. Innovations in biochar technologies are beneficial bioengineering activities to address the intertwined challenges of waste management toward environmental sustainability.

Keywords: agri-residues; biochar; black gold; lignocellulosic biomass; metals sequestration; decontamination

1. Introduction

The industrial revolution brought a notable change in the socio-economic conditions across the globe, and the accompanying scientific and technological advancements accelerated lifestyle quality for people worldwide. Unfortunately, this has also resulted in global warming, soil pollution, resource depletion, water scarcity, and an increase in environmental pollution and food shortages [1]. Water quality is generally diminishing due to the steady release of various organic and inorganic pollutants, including dyes, surfactants, and hazardous metals [2]. In addition, untreated wastewater discharge adds to the increased risk to public health due to the contamination of both surface and underground water bodies [3]. Wastewater management, therefore, has become an important communal and ecological task worldwide. In recent years, various agricultural industries have started transforming biomass waste into biochar, reducing the amount of waste released into the environment. This biochar is now widely used for improving soil quality, treating wastewater, and many other purposes.

Increased industrialization and urbanization activities have resulted in huge volumes of solid waste generation, which include urban, industrial, agricultural, biomedical, and radioactive wastes. India generates around 350 million tons of agricultural waste annually. In 2020–2021, the country produced 160,038.9 tons of solid waste each day, with 50% being treated, 18.4% landfilled, and 31.7% remaining unaccounted for [4,5]. Agricultural waste in India is rapidly increasing at an average annual rate of 5%–10%, causing significant environmental harm. On a global scale, China is the leading producer of agricultural waste with at least 1300 million tons [6], followed by Russia with 630–650 million tons [7], the United States of America with about 350 million tons [8], and Brazilian agro-industries generating close to 291 million tons [9]. The European Union contributes with 700 million tons, and the United Kingdom generates more than 10 million tons, all totaling to around 2.5 billion tons of agricultural waste per year, globally [10]. When these wastes are burned, they contribute to the overall pollution of soil, air, and water bodies [11]. Fruit waste and peels also contribute significantly to agricultural waste, and although disposal methods generate leachate and can release substantial fuel energy, burning these residues produces large quantities of greenhouse gases, pollutants, and airborne particles, which calls for sustainable management technologies for these wastes [12,13]. Post-harvest agricultural production generates large quantities of waste, including rice, wheat, and corn straw left unused in fields. Many local farmers burn this waste openly, creating smoke that significantly harms both human health and the environment. Limited awareness among farmers of the economic potential of recycling this waste further contributes to the challenges faced. Most agricultural waste comprises lignocellulosic materials, primarily cellulose, hemicellulose, and lignin [14–16]. Proper management of this waste can reduce environmental pollution and transform it into valuable products such as biochar.

Biochar is a carbon-rich, porous material produced through the conversion of biomass under limited or no oxygen supply, typically at temperatures between 350 and 700 °C. The term is derived from the Greek “bios” (life) and “char” (charcoal). It can be generated from a wide range of organic waste using various thermochemical processes, including pyrolysis, torrefaction, flash carbonization, gasification, and direct combustion. However, pyrolysis is the most widely employed because it can be optimized to maximize specific products (gas, oil, or char). Pyrolysis involves heating biomass in an oxygen-deficient environment (at 250–900 °C), producing solid biochar along with bio-oil and syngas as by-products, with process parameters including temperature, heating rate, residence time, and pressure governing product distribution and yield; lower temperatures and longer residence times generally favor higher biochar yields, converting approximately half of the biomass carbon into relatively stable char [17–20]. The physicochemical properties of the resulting biochar are strongly dependent on both feedstock composition and pyrolysis conditions, which together determine surface area (SA), porosity, ash content, pH, cation-exchange capacity (CEC), elemental carbon content, and nutrient availability [18–20]. These properties govern biochar's functional performance, including high adsorption capacity, enhanced water-holding ability, improved nutrient retention, soil pH amelioration, and stimulation of microbial activity. Its derivation from abundant lignocellulosic agro-industrial residues, combined with reusability and cost-effectiveness, makes biochar an environmentally sustainable material suitable for direct application or incorporation into composite formulations across diverse agricultural and environmental applications [21–23].

This review article describes the different sources/feedstock materials that are routinely used in the production of biochar, emphasizing their classification and the processes employed in its production. We also summarize the different physical, chemical, and biological methods applied for the modifications of biochar to highlight its efficiency in different applications. The review also outlines the hazardous effects of heavy metal (HM) accumulation on human health, along with their respective permissible exposure limits, particularly of aluminum (Al), arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), and iron (Fe). We also discuss the diverse applications of biochar, with particular emphasis on sequestering HMs along with other contaminants, relevant interactions, and removal using biochar. In conclusion, this review article sheds light on biochar feedstocks, production techniques, modifications, and diverse applications, with particular emphasis on HM sequestering from wastewater.

An extensive literature survey was carried out using varied online platforms, viz the National Center for Biotechnology Information (NCBI), Google Scholar, ScienceDirect, Web of Science, Directory of Open Access Journals (DOAJ), PubMed, and Journal Storage (JSTOR). Several review articles, research articles, short communications, reports, and case studies were consulted to compile the data in the form of illustrative tables and figures. The keywords, namely agri-residues, biochar, carbon footprint, waste management, metals sequestration, modifications, health, sewage, pretreatments, HMs, pyrolysis, classification of feedstock, and characterization, were used to design an outline of this article. Thorough data mining was performed from the peer-reviewed articles published in the American Chemical Society (ACS), Elsevier, Multidisciplinary Digital Publishing Institute (MDPI), Oxford University Press (OUP), Frontiers, Wiley, Taylor & Francis, SAGE Publications, ScienceDirect, Springer Nature, Royal Society of Chemistry (RSC), Bentham Science Publishers, BioMed Central, and Hindwai. Illustrations presented in the article were created meticulously using BioRender software (licensed, Professional Science Figure creator, BioRender, Toronto, ON, Canada). The data was systematically tabulated. The chemical structures denoting the functional groups on biochar (pristine and modified) were redrawn using the ChemSketch software (free, online version, Advanced Chemistry Development Inc., Toronto, Ontario, Canada). Overall, the literature published in the last two and a half decades is presented in the manuscript.

2. Feedstock for biochar production

The production of biochar is a sustainable process that does not require any harmful chemicals and basically converts any carbon-rich bio-waste into the eco-friendly "green adsorbent". The raw materials for production include agricultural and forestry waste, food and fiber processing residues, and biomass from grasslands; all of which are abundant and easy to collect. Biochar can broadly be classified according to the raw materials used.

The type of biomass feedstock plays a decisive role in determining the physicochemical characteristics of the biochar produced. Agricultural residues such as rice husk, wheat straw, bagasse, coconut shells, and other crop wastes are widely used feedstocks [24] due to their high lignocellulosic content, typically comprising cellulose (35%–50%), hemicellulose (15%–40%), and lignin (15%–25%) [25]. This composition strongly influences biochar yield, porosity, surface area (SA), and stability. Forestry residues, including bark, sawdust, wood chips, and shavings, are rich in lignocellulosic biomass [26], resulting in biochars with higher fixed carbon content and energy value, though their complex cell wall structure can make thermal decomposition more difficult. In contrast, aquatic biomass such as algae, fish scales, and shells contains higher proportions of proteins, carbohydrates, and lipids with minimal lignin, enabling easier conversion and producing nutrient-rich biochars, albeit with limitations related to collection costs [27]. Industrial residues from food, textiles, pulp, and paper industries, particularly cellulose-rich materials like wastepaper, peels, and fibers, also serve as valuable feedstocks, yielding porous biochar with variable surface charge and adsorption properties [28]. The differences in cellulose, hemicellulose, lignin, and protein content across feedstocks directly govern biochar structure, surface chemistry, and functional performance [29,30].

Finally, ash content and mineral phases play a critical role in biochar's performance. Elevated ash content, usually produced at pyrolysis temperatures exceeding 600 °C, enhances the alkalinity of biochar (pH 9–11) and facilitates the precipitation of metals as hydroxides or carbonates. In addition, mineral phases such as carbonates, oxides, silicates, and phosphates contribute reactive sites that enable long-term immobilization of HMs [31]. The various sources and the overall processes of pyrolysis, in addition to a detailed classification of biochar's raw materials based on their origin, are illustrated in Figure 1.

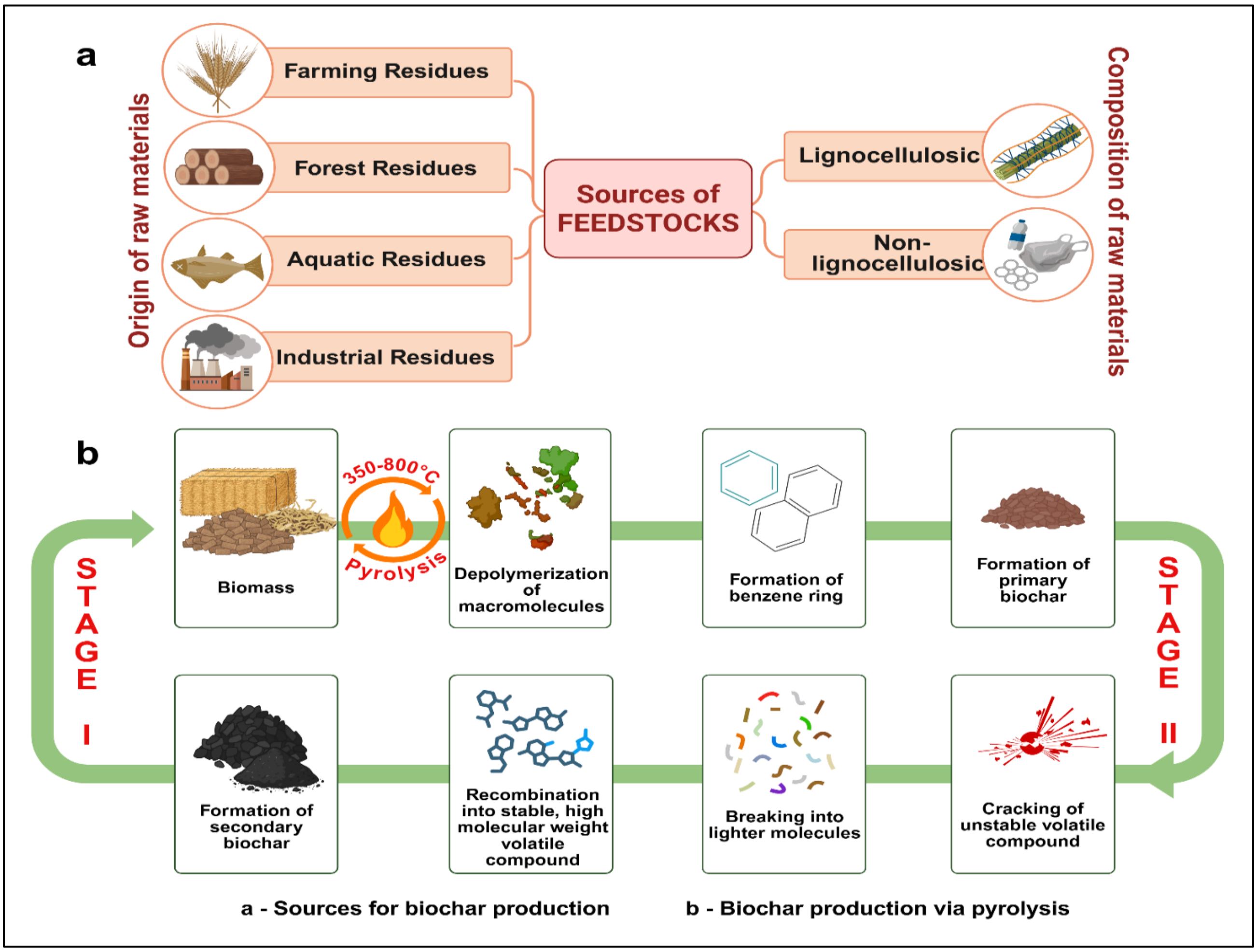

Figure 1. Sources of feedstock and pyrolysis process for biochar production. a) The sources of feedstock can be classified based on their origin (left side) and composition (right side). Farming, agriculture, and forestry residues are rich in lignocellulose, aquatic residues are richer in chitin and other proteins, and industrial residues contain a variety of constituents. b) The pyrolysis process of biochar production is essentially a two-step process resulting in the formation of primary and secondary biochar.

The primary conversion mechanism involves the synthesis and clustering of benzene rings to produce an aromatic polycyclic biochar structure, typically occurring at moderate temperatures between 350 °C and 550 °C. Furthermore, as temperatures increase to intensify biochar aroma, the process initiates secondary conversion mechanisms where unstable volatile molecules undergo cracking to produce additional secondary char and pyrolysis gases [32].

3. Pristine versus modified biochar

The properties that govern the function of biochar are listed in Figure 2. Pristine biochar often faces limitations in its effectiveness, particularly in pollutant removal from water, compared to activated carbon. Its low specific SA, pore volume, and limited surface functionality result in reduced adsorption capacity.

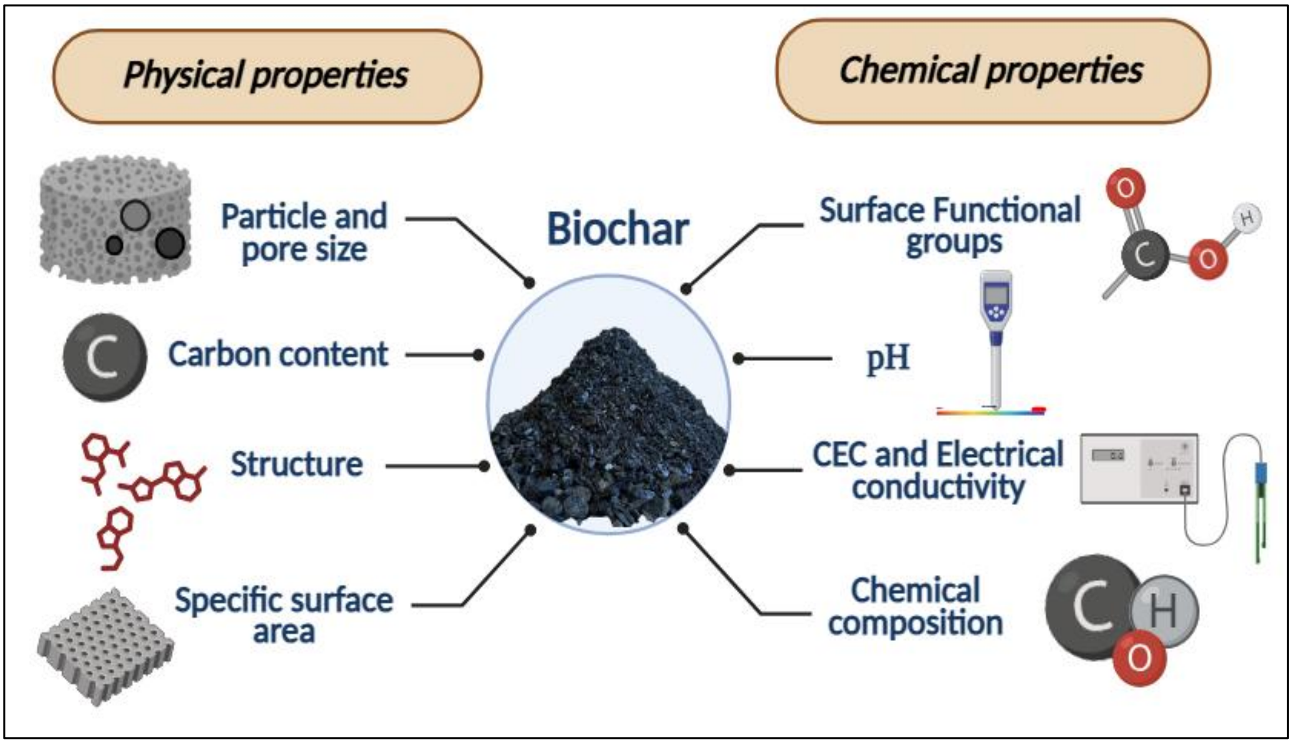

Figure 2. Physico-chemical properties of biochar. Important physicochemical characteristics of biochar include the size of pores, structure, and total surface area per unit volume, among others. The carbon content determines it effectivity as a fertilizer, while surface functional groups, pH, cation exchange capacity (CEC), electrical conductivity, and overall chemical composition affect its efficiency as a heavy metal sequestering agent.

Additionally, its stability under conditions like high temperature, pressure, or extreme pH can hinder some of its applications. While unmodified biochar has limited efficiency, activation techniques can enhance its surface functional groups, significantly improving its reactivity and ability to target certain contaminants [33]. Such modifications can be carried out using physical, chemical, or biological methods. Physical and chemical activation methods generally offer several advantages over biological processes, thus presenting a promising approach for sustainable and eco-friendly applications across diverse sectors, such as water purification, agriculture, and waste management. The surface of biochar possesses various aromatic functional groups, which are either alkaline in nature, such as pyridine, pyridone, and pyrrole, or acidic, such as carboxyl (-COOH), carbonyl (C=O), phenol, and ether groups. The functionality of pristine biochar can be enhanced via the addition of functional groups, as shown in Figure 3. The alterations in the chemical groups facilitate better interactions between the biochar and other molecules. In summary, different chemical, physical, and biological modifications are helpful in enhancing the efficiency of biochar for a broad range of applications. Different physical parameters and pyrolysis processes affecting biochar production, with their advantages and limitations, are listed in Table 1. Different modifications of biochar, their impact on properties, and respective applications are shown in Table 2.

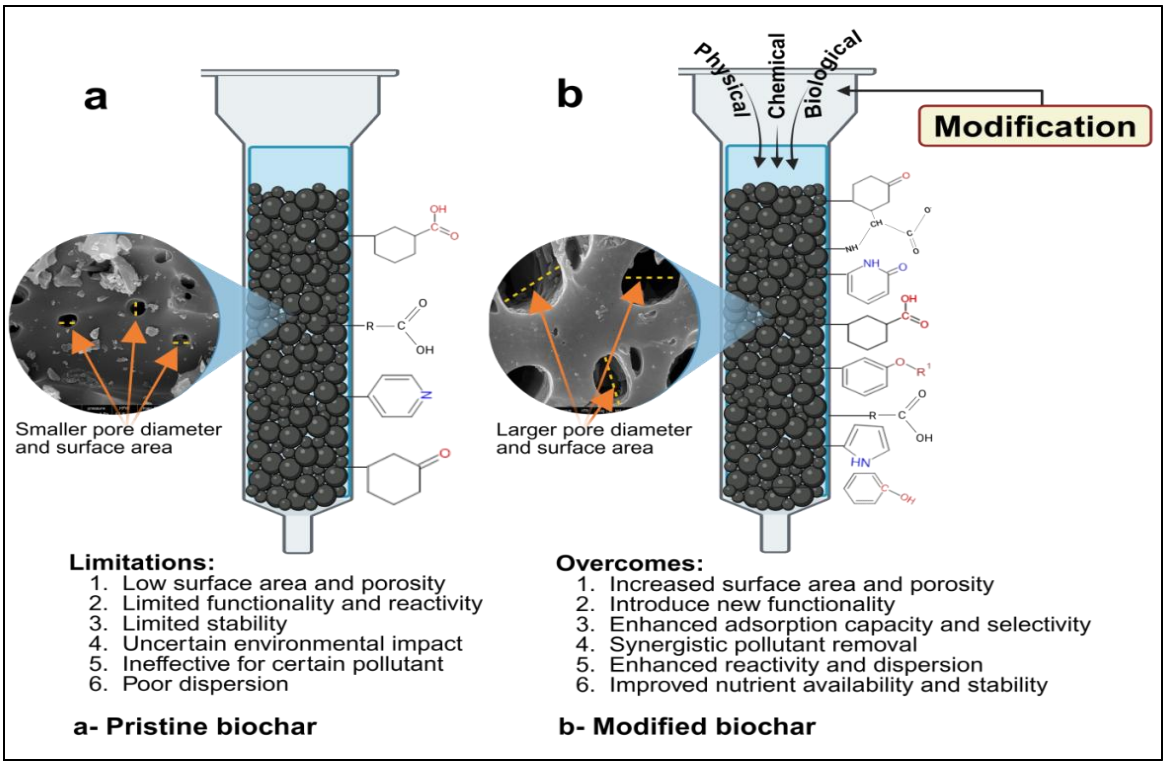

Figure 3. Addressing the limitations of pristine biochar through various modifications. The biochar produced by the process of pyrolysis that has not undergone further treatments is called pristine biochar. a) This pristine biochar, while quite efficient, has some limitations with respect to pore size, stability, functionality, and effect on the environment. b) Modifications of biochar: physical, chemical, and biological treatments, which confer additional functional groups, contributing to better stability and efficiency in various applications, especially heavy metal (HM) and contaminant sequestration. The biochar is represented as packed in a column, to demonstrate its use as a filter.

Table 1. Different physical parameters and pyrolysis processes used in biochar production, along with their advantages and limitations.

Types of pyrolysis and biochar (%)	Temp. (ºC)	Residence time	Heating (ºC/s)	Advantages	Limitations	Ref.
Slow (30–65)	300–650	30 min to days	0.1–1.0	Most effective, high biochar yield	Long process	[34]
Intermediate (25)	450–550	10–30 s	10–1000	Bio-oil, biochar, gases	Less biochar	[35]
Fast (12)	450–600	0.5–2 s	10–1000	High functionality, shorter residence time	Low surface area, less biochar	[36]
Flash (10–15)	800–1000	<0.5 s	>1000	Shorter residence time	High pressure	[37]
Vacuum	300–700	<1 s	0.1–1	Porous biochar, short residence time	-	[38]
Microwave-assisted (≈30)	400–800	<30 s	0.5–2	Uniform rapid heating	Difficult to control temperature	[39–41]
Hydrothermal carbonization (40–70)	180–350	5 min to 12 h	0.1–0.2	No pre-drying	High energy consumption	[38,42]
Torrefaction (75)	450–550	<2 h	-	High hydrophobicity, storability, and durability	Produced biomass is not suitable	[43,44]
Gasification (10)	>800	10–20 s	1–0.8	High syngas yield, short residence time	Low yield, gas emission	[45,46]

Table 2. Modifications of pristine biochar along with their proposed applications.

Type of modifications	Sources of biochar	Activating agents	Result after modifications	Applications	Ref.
Chemical	Sewage-sludge	$C_3H_6N_6$-modification	The maximum adsorption capacity of SSB increased from 64.20 to 126.75 mg/g.	Adsorption of Cd^{2+} ions from polluted water.	[47]
	MMbiochar	Fe impregnation	The SA of MMbiochar was substantially higher (378.08 $m^2\ g^{-1}$), offering more active sites compared to the unmodified biochar.	Effective removal of As (V) from contaminated water for sustainable environmental remediation.	[48]
	AMR	KOH and $ZnCl_2$	AC@KOH and AC@$ZnCl_2$ showed notable specific SAs of 1130 m^2/g and 797 m^2/g, respectively, and pore volumes of 0.568 cm^3/g and 0.476 cm^3/g.	Micro- and mesoporous carbon materials show great potential for applications in adsorption and catalysis.	[49]
	Corn stalks	Acidic amino acid	The adsorption capacities of PASP-biochar for Cd (II) and Pb (II) were 44.2 mg/g and 126.1 mg/g, respectively, significantly outperforming pristine biochar by factors of 3.78 and 2.70.	Used for HM adsorption, it effectively reduced Cd and Pb accumulation in wheat by lowering their translocation factors.	[50]
	Walnut shell	H_3PO_4	Specific SA increased from 117 m^2/g to 737 m^2/g.	Removal of methylene blue pigment.	[51]
Physical	Paper sludge	Ball-milling (Fe-MSDbiochar)	Fe-MSDbiochar effectively activated PDS, achieving 96.4% TC removal with adsorption contributing up to 80.7%.	Removal of TC from wastewater.	[52]
	CSC and OC	Microwave	Biochar produced through microwave gasification features a more developed pore structure compared to electric heating gasification.	Effective adsorption of DBF onto AC.	[53]
	Wheat straw	Steam	Ni-modified biochar exhibits an optimized pore structure, oxygen-rich functional groups, and excellent catalytic efficiency.	Optimize hydrogen production via steam reforming of biomass waste.	[54]
	Carbo lignis pulveratus	Ball-milling	Ball-milled biochar demonstrated superior adsorption performance compared to chemically modified biochar.	Removal of methylene blue from wastewater.	[55]
	Pine sawdust	Ball milled with 3-MPTS	3-MPTS enhanced pore enlargement in biochars, while ball milling increased their SA and introduced oxygen-containing functional groups, aiding in –SH group loading.	The synthesis of -SH-modified biochar with high efficiency for MeHg adsorption.	[56]

Continued on next page

Type of modifications	Sources of Biochar	Activating agents	Result after modifications	Applications	Ref.
Biological	Date palm leaves	Compost and vermicompost	Lowering biochar pH from 8.1 to 7.2 enhanced substrate-induced respirations when combined with vermicompost and improved microbial evenness and diversity.	Applied in arid regions to improve the fertility of the soil.	[57]
	Grass fibers	Elemental S and chitin	Biochars with high acid-buffering capacity showed a reduction in their buffering capacity and only a moderate pH drop. Microbial activation of biochar was enhanced by adding mineral fertilizer or chitin.	Bulk material for horticultural substrates.	[58]
	Corn stalk and fruit remains	Earthworm	The earthworm-modified biochar demonstrated increased functional groups (-OH, -NH, C-H, C=C, and C=O), elemental composition (SiO_2 and $CaCO_3$), pore size, and chemo-heterotrophy functions, while its specific SA decreased significantly.	Earthworm-modified biochar offers insights into future ecological restoration efforts.	[59]
	Reed	*Phanerochaete chrysosporium* U.S.A. NDM3-2 (fungus)	Biologically pretreated biochar shows enhanced catalytic performance at 750 °C, with a toluene conversion rate of 62.7%, compared to 33.7% for untreated biochar. This is attributed to its higher specific SA, greater mesoporous proportion, and increased alkali/alkaline earth metal content.	Toluene conversion as a tar model compound for sustainable environmental remediation.	[60]
	Various sources	Microbial-modified	Enhances soil quality by immobilizing and transforming contaminants and altering the soil's physical, chemical, and biochemical properties.	Aims to clean contaminated soil by removing salt and HMs.	[61]

*Note: SSB, sewage-sludge biochar; MM biochar, De-oiled Mentha waste; AMR, antibiotic mycelial residues; AC@KOH and AC@$ZnCl_2$, activated biochar with KOH and $ZnCl_2$; CSC, corn straw char; OC, oak char; DBF, dibenzofuran; AC, coconut-shell activated carbon; 3-MPTS, 3-trimethoxysilylpropanethiol; MeHg, methylmercury; Fe-MSD biochar, ball-milling iron-rich sludge biochar; TC, tetracycline; (-), data not found.

Recent research has raised concerns that engineered biochars, especially those enhanced with metals or nanoparticles (NPs), may unintentionally release these modifying agents into the environment. For instance, Phiri et al. [33] noted that nano zero-valent iron (nZVI) is widely regarded as a powerful adsorbent for HMs. Yet, its small particle size and tendency to oxidize or clump together limit its effectiveness when used alone. To address these drawbacks, nZVI is often incorporated into biochar, which provides a more stable matrix and improves adsorption efficiency in water treatments. While this composite approach shows considerable promise, it also carries the risk of iron ion leaching, which could pose ecological and human health challenges. Similarly, Zhao et al. [56] observed that thiol-modified biochars produced through ball milling may release sulfur groups under certain aqueous conditions, potentially leading to secondary contamination.

The long-term stability of engineered biochars is still not fully understood. Phiri et al. [33] pointed out that differences in feedstock and pyrolysis conditions make it difficult to predict how biochar will perform over extended periods, especially since most existing studies are short-term and concentrated in specific regions. In contrast, Chen et al. [62] offered rare long-term evidence through an 11-year field trial, which showed that repeated biochar applications consistently improved wheat yields and strengthened crop resilience to adverse weather. Their findings revealed that continuous biochar addition boosted wheat production by 7.9% compared with conventional straw incorporation, underscoring its potential role in sustainable agriculture under changing climate conditions.

Engineered biochars can inadvertently introduce new contaminants. Nosratabad et al. [63] warned that nanomaterial-modified biochars, while improving adsorption, may pose ecotoxicological risks if NPs detach or aggregate in soils and waters. Additionally, another work demonstrated that oak-based biochar used for Cr(VI) removal altered Cr isotope fractionation, suggesting possible secondary geochemical effects [64]. Doubts about biochar's economic viability and long-term sustainability remain key challenges to its large-scale implementation. In a systematic review, Campion et al. [65] highlighted that although biochar delivers clear agronomic and climate benefits, scaling up production is not without challenges. Large-scale deployment requires careful consideration of energy demands, reliable feedstock supply, and market competitiveness, all of which can limit its practicality despite its environmental promise.

4. Applications of biochar in water and wastewater treatment

Biochar, with its high carbon content compared to commercial activated carbon, is a versatile and eco-friendly material derived from biomass through thermochemical processes. Biomass type and pyrolysis temperature influence the properties of biochar and its effective preparation for environmental applications [66]. Porosity, SA, and hydrophobicity allow the removal of organic pollutants, while a low-temperature biochar, rich in oxygen-containing functional groups, is better suited for inorganic pollutants. The pH and residence time also affect the quality of biochar. Table 3 elucidates the roles of biochar under different treatment conditions. The following sections detail specific applications.

Table 3. Various roles of biochar preparations under different treatment conditions.

Application	Biomass	Temperature (°C)	Modified/ activation	Role of biochar	Ref.
Soil amendment	Rice straw	650	-	Elevated soil pH, SOC, microbial biomass P, and alkaline phosphatase activity influence soil phosphorus availability.	[67]
	Orange peel	450	-	1% OPB enhances maize growth and yield under salinity, boosting urease (55.4%), alkaline phosphatase (47.4%), and acid phosphatase (37.8%) activities in saline soil.	[68]
	Maize straw	350–550	-	Biochar addition boosts topsoil organic carbon (OC) by enhancing aggregation, and residue amendments increase the particulate organic matter (POM) to mineral-associated organic matter (MAOM) ratio.	[69]
Catalyst	Pine wood	400	$NaHCO_3$/air	A Pd catalyst on hierarchically porous carbon enables rapid formic acid dehydrogenation with a TOF of 156 h^{-1}.	[70]
	CC and PE	500	Ni/Co	The combined effect of CC and PE increases the gaseous yield by up to 19.40 wt%. Similarly, Ni and Co modifications enhance gaseous yield and hydrogen selectivity by approximately 2.5 times during pyrolysis.	[71]
	Corncob	650	CoNPs	Co@biochar-650 achieves a lignin liquefaction degree of 79.7% and a monophenol yield of 19.1 wt%, outperforming the supported Co/biochar-650 catalyst, which yielded only 15.4 wt%.	[72]
Carbon sequestering	Woodchips	400	-	Mixes with over 15% biochar double CO_2 uptake, while the 10% mix shows a 24% drop in thermal conductivity. Specific heat rises by up to 42% with higher biochar content.	[73]
	Crop residues	-	-	The potential carbon emission reductions from biochar production to utilization are estimated at approximately 780 Tg CO_2-eq per year under CPS and 680 Tg CO_2-eq per year under DPS.	[74]
	Lignocellulose-based	300–500	-	The aromatic backbone reduces the microbial metabolic quotient by 47%, promoting carbon storage in biomass and aiding in sequestration, while labile carbon has the opposite effect.	[75]

Continued on next page

Application	Biomass	Temperature (°C)	Modified/ activation	Role of biochar	Ref.
Microbial enhancer and crop improvement	Wheat	-	-	Biochar increases rice yield, enhancing leaf area by 25.3% under 1% salinity and 45.9% under 3% salinity. It also raises nitrogen content in leaves by 28.6% at 1 g/kg soil salinity. Additionally, biochar reduces N_2O emissions by shifting microbial communities, reducing *Actinobacteria* and increasing *Firmicutes*.	[76]
	Maize straw	400	-	Biochar boosts wheat yields by 7.9%, improves carbon storage and soil health, reduces heat stress, and enhances yields with higher rainfall.	[62]
	Rice husk	-	Vermicompost	Enhances moisture, infrared reflectance, and water use efficiency at 9.2%, 20.8%, and 13.6%, respectively, (due to enhanced carbon and water retention in soil aggregates).	[77]
Construction industry	Rice straw	900	C_2H_5OH/H_2O and H_2O_2 bleaching	3D biochar has the highest SA (524 m²/g) and maximum adsorption capacity (149.266 mg/g) for 10–60 mg/L MB. Its adsorption capacity is greater in neutral (142.870 mg/g) and alkaline (131.075 mg/g) conditions compared to acidic conditions (69.867 mg/g).	[78]
	Woody yard waste	400	Calcium hydroxide and bacteria	MICP generates carbonates that fill biochar pores, lowering surface charge density. It achieves 10% biochar substitution, balancing hydration products and doubling Aft (ettringite) content. MICP-modified biochar accelerates early cement hydration and enhances compatibility by incorporating carbonates and hydration products.	[79]
	Rice straw	500	-	Adding 3.0% biochar reduces hydraulic conductivity to 7.75×10^{-9} cm/s and porosity to 43.12%. The biochar–cement composite also effectively treats Pb^{2+} -contaminated soil, with leaching concentration dropping as biochar content increases.	[80]
Water and wastewater treatment	Spent mushroom	300–700	-	SMC biochar removes 97.43% of HMs at 500 °C pyrolysis and maintains 85% efficiency after five cycles, with a cost of RM 1000/t.	[81]
	Tea residue	500	Ferromagnetic N self-doped	At an initial NaCl concentration of 20 g/L, pH 3.8, and 2 V, 2 g of FNTB removes 99.97% of TCH at 100 mg/L and 78.86% of TOC.	[82]
	Coconut shell	-	Magnetic nano-Fe_3O_4 modified (chemical co-precipitation)	The COD of PW decreases from 387 to 37 mg/L in 10 min of low-speed mixing with magnetic nano-Fe_3O_4-modified coconut shell biochar.	[83]

SOC, soil organic carbon; OC, organic carbon; SOM, soil organic matter; POM, particulate organic matter; MAOM, mineral-associated organic matter; CC, corn cob; PE, plastic; CoNPs, cobalt nanoparticles; CPS, centralized production scenario; DPS, decentralized production scenario; IR, infiltration rate; WUE, water use efficiency; TCH, tetracycline hydrochloride; FNTB, ferromagnetic-modified N self-doped tea residue biochar; TOC, total organic carbon; PW, oilfield produced water.

Population growth and industrial activities have led to the significant release of wastewater containing harmful pollutants, such as dyes and HMs (Figure 4). These substances are non-biodegradable and harm the environment even in lower quantities (1 mg/L). Methods, like coagulation, reverse osmosis, ion exchange, membrane filtration, and biosorption, are used to remove these pollutants. Biological materials adsorb pollutants, and one million liters of water treatment costs 10–200 USD [84], making it a cost-effective and efficient method. While traditional adsorbents using activated carbon and zeolites are effective, their high production costs have driven the search for cheaper alternatives with better pollutant removal capabilities. Biochar has high carbon content, a porous structure, large SA, and functional groups, making it effective for wastewater treatment. Biochar removes pollutants through adsorption, electrostatic attraction, ion exchange, and pore binding. Engineered biochar can further enhance pollutant removal based on the specific contaminants involved.

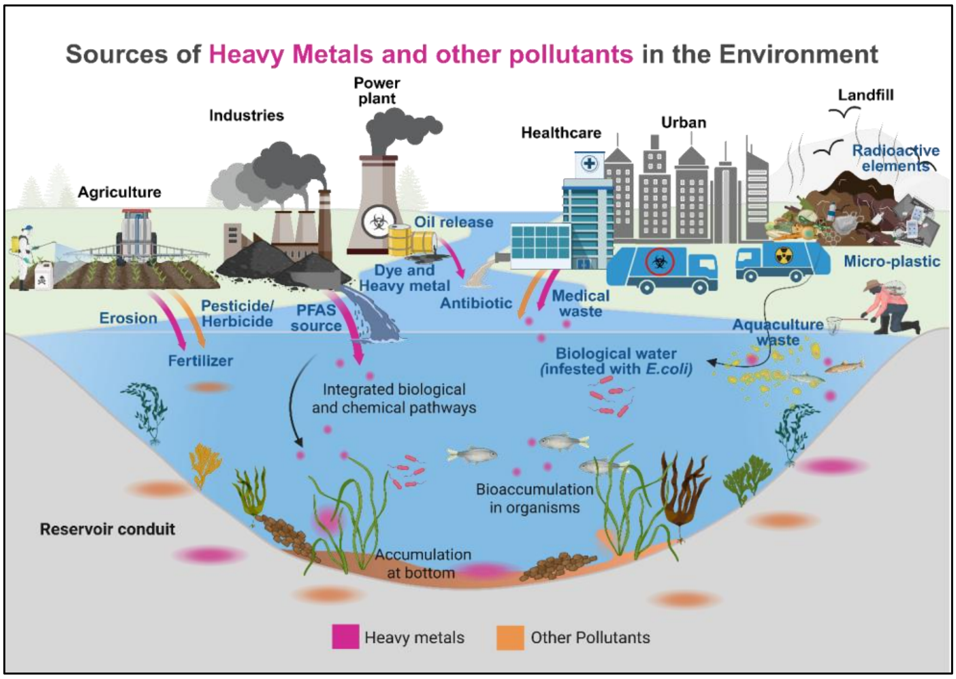

Figure 4. Sources of heavy metals (HMs) and other contaminants in the environment. Different sectors of human urbanization, such as agriculture, industries, and power plants, along with healthcare establishments, urban settlements, and landfills, release HMs and other pollutants into the environment, especially water. These pollutants accumulate not only at the bottom of the water bodies but also inside aquatic organisms, causing HM toxicity.

Recent surveys have reported that biochar has the ability to adsorb a wide range of contaminants from wastewater, including both organic and inorganic pollutants. Studies have demonstrated that biochar derived from sludge serves as an economical and recyclable adsorbent for the removal of antibacterial drugs [85]. Similarly, biochar produced from the unutilized parts of medicinal and aromatic plants plays a crucial role in wastewater purification, offering a sustainable approach to mitigating environmental pollution [86]. Table 4 summarizes the removal of different organic pollutants and both inorganic metals and metalloid contaminants from water via sorption. The ability of biochar to adsorb pollutants in water is based on the chemical composition of the contaminants and the type of biochar used.

Table 4. The removal of different suspended contaminants from water using biochar via the sorption process.

Contaminants (adsorbates)	Biochar source (adsorbent)	Pyrolysis temperature (ºC)	Adsorption capacity (mg/g)/removal efficiency (%)	Ref.
I. Organic (pollutants)				
Phenanthrene	Soybean stalk	700	99.5%	[87]
Chlortetracycline	Passion fruit peel	600	81%	[88]
Sulfamethazine	*Sicyos angulatus*	700	46%–95%	[89]
Methylene blue	Mangosteen peel	800	80%	[90,91]
Estrone	Litchi	650	4.18 mg/g	[92]
Bisphenol A	Cow manure	700	98%	[93]
Bisphenol A	Spruce	1200	77.4 mg/g	[94]
Tetracycline	Bamboo	500	95.75%	[95]
	Coffee grounds	250	96%	[96]
	Municipal sludge	800	86%	[97]
II. Inorganic (metal and metalloids)				
Cu^{2+}	Rice husk	500–600	37.5 mg/g	[65,98]
Pb^{2+}			433.9 mg/g	
Zn^{2+}			34.3 mg/g	
Cd^{2+}	Mangosteen peel	800	80%	[90,91]
Cr^{6+}	Oak	700	99%	[64]
Cr^{6+}	Passion fruit peel	600	97%	[88]
Cr^{6+}	Walnut shell	900	~65%	[99]
Pb^{2+}			~83%	
Cd^{2+}	Wheat straw	650–700	100%	[100]
Cu^{2+}			100%	
Zn^{2+}			100%	
Pb^{2+}	Anaerobic digested sludge	600	99%	[101]
Cu^{2+}			98%	
Ni^{2+}			26%	
Cd^{2+}			57%	
Mn^{2+}	Spent mushroom compost	300–700	7.665 mg/g	[81]
Pb^{2+}			17.34 mg/g	
Fe^{3+}			32.18 mg/g	
Cu^{2+}			49.83 mg/g	

For instance, activated biochar (AB) and catalytic biochar (CB) produced from sugarcane waste at 600 °C through a second-generation ethanol production process significantly remove methylene blue (85.8%–99.3%) and 17 β-stradiol (37.6%–76.7%) [102], whereas *Dillenia indica*–derived biochar has great antibiotic removal capacity, exhibiting maximum adsorption capacity for ciprofloxacin, chloroquine, tetracycline, amoxicillin, and ampicillin at 91.0, 99.0, 94.0, 7.0, and 5.0 $mg \cdot g^{-1}$, respectively, from wastewater [103]. Spent mushroom compost biochar removes 97.43% of HMs [81].

HM pollution requires immediate attention due to the ecological hazard it imposes on the environment [104]. Permissible limits of HMs as prescribed by the World Health Organization (WHO, 2017) [105] are listed below in Table 5.

Table 5. Permissible limits of heavy metals (World Health Organization 2022) (in mg/L) and their effects on human health [106–110].

HMs	Sources	Permissible limits (mg/L)	Mechanism of toxicity	Human health hazards
Cd (II)	Cadmium-containing products, phosphate fertilizer, PVC products, paint industry electroplating	0.003	Acts as a carcinogen	Neurodegenerative disorders, breast cancer, prostate cancer, demineralization of bones, diabetes, lung fibrosis, kidney damage, dyspnea, and weight loss.
Pb (II)	Electroplating, mining, fossil fuel burning, acid batteries, oxide synthesis for paint, and pigments	0.01	Production of ROS, depletion of antioxidants, cellular dysfunction, and apoptosis	Suspected carcinogen, loss of appetite, anemia, muscle and joint pains, diminished IQ, sterility, kidney problems, high blood pressure, hemolytic anemia, CV diseases, lung and bladder cancer.
As (III)	Smelting, agricultural pesticides, industrial waste	0.01	Indirect induction of ROS, upregulating inflammatory mediators (COX-2), and cardiovascular dysfunction	Arsenicosis, hypertension, CV disease risk, carotid atherosclerosis and diabetes mellitus, lung cancer, carcinogenesis, liver tumors, skin and gastrointestinal effects.
Cr (VI)	Petroleum refining, textile, and tannery industry	0.05	Produces ROS species, inhibition of DNA repair, and antioxidant defense	Suspected human carcinogen, producing lung tumors, and allergic dermatitis.
Hg (II)	Mining industries	0.006	Disrupts cellular function, disrupts protein and enzyme function, and ROS generation	Neurological damage, corrosive to skin, eyes, and muscle membrane, dermatitis, anorexia, kidney damage, and severe muscle pain.

Continued on next page

HMs	Sources	Permissible limits (mg/L)	Mechanism of toxicity	Human health hazards
Cu (II)	Electroplating, mining, and agriculture	2	Disrupting cellular and metabolic processes	Cirrhosis, Wilson's disease; long-term exposure causes irritation of the nose, mouth, eyes, headaches, stomachaches, dizziness, and diarrhea.
Zn (II)	Electroplating	3	Improper protein synthesis and elevated zinc levels hinder copper absorption	Causes short-term illness called "metal fume fever", vomiting, stomach cramps, headaches, and restlessness.
Ni (II)	Chemical, food processing industries, forest fires, incineration of waste, combustion of coal, petroleum refining, PCB manufacturing	0.07	Induces oxidative stress, inflammation, and epigenetic changes	Allergic contact dermatitis, oral hypersensitivity and risk of gingival hyperplasia, oral cancer, skin cancer, lung cancer, asthma, bronchitis, reproductive toxicity, carcinogenesis.
Fe (III)	Mining, fossil fuel combustion, steel manufacturing, and chemical production	2	Free radical formation (destructive)	Carcinogenesis, physical, muscular, and neurological degenerative processes (Parkinson's and Alzheimer's).

*Note: HMs, Heavy metals; ROS, reactive oxygen species; PVC, polyvinyl chloride; PCBs, polychlorinated biphenyls; CVSs, cardiovascular issues; IQ: intelligence quotient

Due to their tendency to accumulate in multiple organs (refer to Figure 5), it becomes essential to remove HMs from wastewater. Adsorption is a highly effective method for HM removal from aquatic environments [111]. The elimination of HM ions by biochar is mentioned in Table 4. As with organic contaminants, the removal of toxic substances by biochar depends on the type of HM and adsorbent used. Biochars synthesized from different biomass materials under varied conditions are capable of removing varied pollutants from wastewater. For example, spent mushroom composite-derived biochar produced at 300, 500, and 700 °C shows variable ability of adsorption of Cu^{2+}, Mn^{2+}, and Pb^{2+}, with the highest removal occurring with the 500 °C product for Cu^{2+} (2.573 mg/g), Mn^{2+} (1.522 mg/g), and Pb^{2+} (2.491 mg/g) [81].

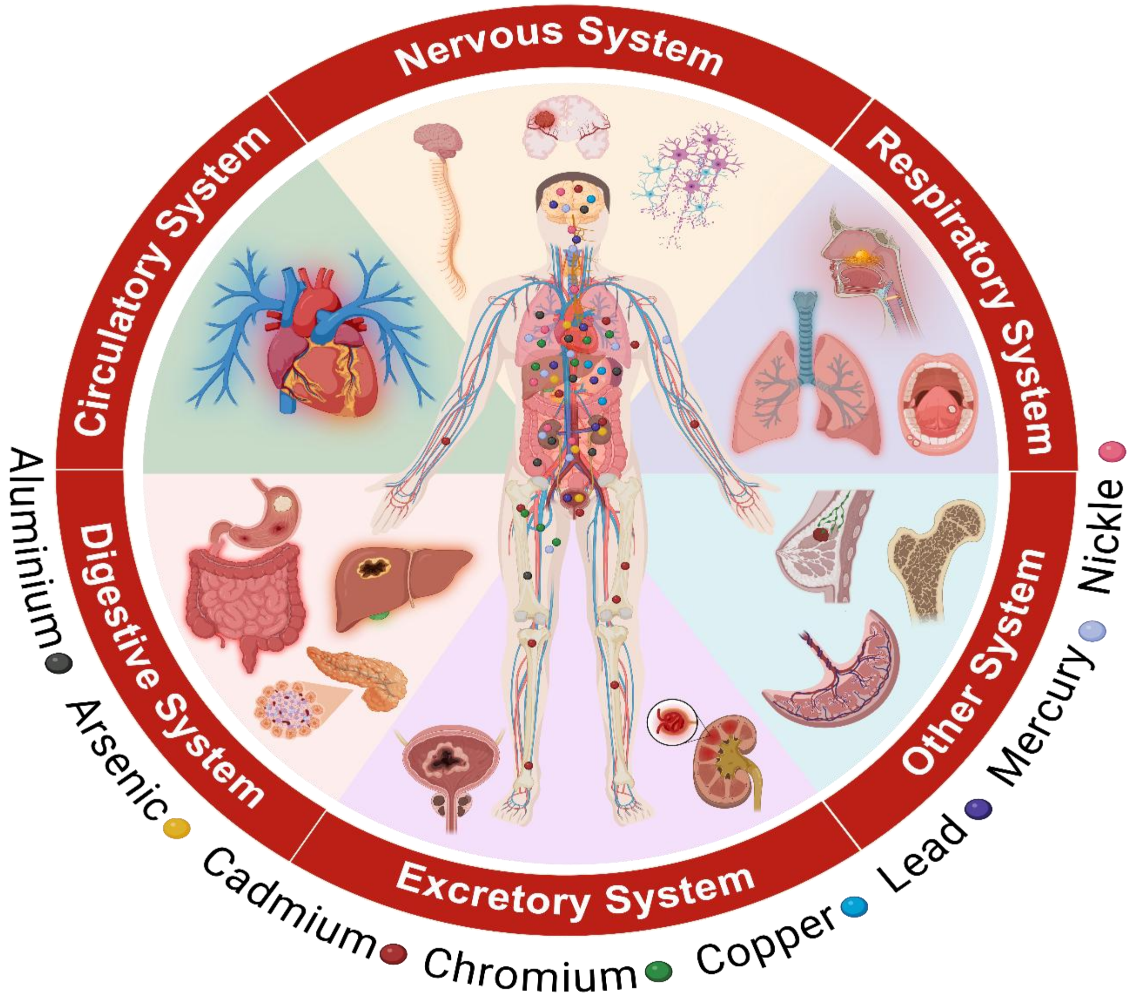

Figure 5. Deposition of heavy metals in different parts of body.

Magnetically modified water hyacinth biochar-alginate capsules generated at pyrolysis temperatures exceeding 500 °C provide a highly effective method for removing Cd^{2+} from wastewater, exhibiting a maximum sorption capacity of 45.8 $mg \cdot g^{-1}$ and adhering to pseudo first-order kinetics and the Langmuir isotherm model [112]. However, removal efficiencies of HMs depend on both the feedstock used and the metals targeted [113]. Along with HMs and organic contaminants, a systematic review concluded that sludge-derived biochar is capable of completely removing ammonium via monolayer chemisorptions [114], signifying that highly competitive biosorption exists when biochar is used as an adsorbent for HM and organic contaminant removal in the presence of ammonium. Besides adsorption, biochar can stimulate microbes, hence increasing the rate of organic waste removal. Arrebola et al. [115] reported that using fruitwood-derived biochar significantly increased the proportion of archaea in the microbial community, attributing this to the biochar's ability to mitigate ammonia and acid stress, thereby promoting greater microbial activity. Magnetic modification of biochar facilitates the recycling and reuse of biochar, especially when used for environmental remediation. For instance, Nyamunda et al. [116] demonstrated that the magnetic characteristics of biochar made from corn stalks were notably improved by incorporating a combination of $ZnCl_2$ and $FeCl_3$. Although initial studies indicated that, during batch trials, biochar effectively removes specific contaminants, untreated drinking water resources often contain multiple pollutants, which can result in competitive adsorption and outcomes that differ from laboratory findings. Additionally, flow dynamics in practical applications may impact biochar's adsorption performance. Therefore, further laboratory investigations are needed to simulate real practical treatment conditions and assess biochar's effectiveness in impurity removal in a case-by-case situation.

Optimal HM removal is highly dependent on the solution pH, which directly modulates surface charge and metal speciation [47,48,81]. For Cd^{2+} and Pb^{2+}, the highest adsorption capacities typically occur at an optimal pH between 5.0 and 6.0 [47,50,81]. Conversely, As^{3+} removal is maximized at a slightly alkaline pH of 7.5 [48,68]. Adsorbent dosage also significantly impacts performance, with optimal ratios often falling between 0.5 and 2.5 g/L [47,48,50,81]. For Hg^{2+}, lower dosages of approximately 40 mg/L have been effectively utilized [56]. Most adsorption processes are endothermic, meaning higher temperatures, often tested between 293 and 313 K, enhance capacities by increasing reaction spontaneity [47,60]. Furthermore, while initial uptake is often rapid, achieving equilibrium for complex metals like Pb or As requires extended contact times of up to 24 h [47,48,81].

The presence of competitive ions and dissolved organic matter (DOM) further modulates removal efficiency in aqueous environments [50]. High concentrations of cations like Na^{+} and Ca^{2+} (exceeding 12.5–25 mg/L) can inhibit HM uptake by competing for active sites or forming hydrated shells that block access to the biochar surface [50,81]. In multi-metal systems, Pb^{2+} often shows the highest affinity, while manganese (Mn) exhibits lower competitiveness for available binding sites [81]. Interestingly, low levels of DOM, such as humic or fulvic acids at 10 mg/L, can effectively improve removal rates by providing additional functional groups like -COOH and -OH for metal complexation [50]. However, the efficiency of these interactions is ultimately limited by the biochar's properties, such as its specific SA and the density of its active functional groups, which are determined by the feedstock and pyrolysis temperature used during its preparation [67,81].

While batch experiments provide foundational data, they possess significant limitations when applied to real-world environmental systems [80]. Most studies are laboratory-based, using homogenized materials that do not account for the non-homogeneous nature of real matrices like field soil or cementitious composites [73,80]. Real systems involve fluctuating conditions, such as varying flow rates, seasonal temperature shifts, and complex ionic backgrounds, which short-term batch trials oversimplify [62,74]. Furthermore, batch tests rarely assess long-term stability and durability [80]. Over time, biochar-based adsorbents may suffer from metal particle agglomeration (sintering) or coking, where filamentous carbon blocks pores and reduces catalytic activity in continuous systems [54,60]. Additionally, the high carbon-to-nitrogen ratio of biochar can lead to slow decomposition in actual ecosystems, a factor often ignored in brief lab assessments [62,74]. Finally, batch studies focus on removal efficiency but frequently neglect the management of spent adsorbents, which are classified as hazardous solid waste once saturated with HMs, presenting a significant logistical and environmental challenge for large-scale practical engineering projects [81].

Heavy metal removal from soil is inherently more complex than from aqueous systems due to a non-homogeneous matrix that restricts pollutant diffusion and alters removal dynamics [61,62,74]. While aqueous removal relies primarily on direct adsorption at optimized pH levels, soil remediation is heavily influenced by mineralogy, where soil-borne carbonates and silica facilitate chemical precipitation into stable forms like lead silicate [48,80]. The pH buffering capacity of soil, driven by inorganic carbon, often resists the shifts required for immobilization, necessitating biological treatments like elemental sulfur addition to stimulate sulfuric acid production [57,88]. Furthermore, microbial agents and macrofauna like earthworms actively transform metals through biomineralization and biological reduction, pathways absent in simple wastewater systems [59,61]. Finally, aging effects lead to long-term surface oxidation of amendments, increasing functional group density for complexation, though high carbon-to-nitrogen ratios may cause slower decomposition in real ecosystems [57,59,61].

Beyond these interactions, physical factors like bulk density and porosity are critical, as biochar application reduces soil compaction to improve aeration and water-holding capacity [61,62]. Capillary action and hydraulic conductivity further modulate the movement and leaching of toxic salt ions away from the rhizosphere [61]. Chemical indicators such as CEC and the C:P ratio serve as vital predictors for nutrient dynamics and microbial phosphorus limitation [61,67]. Biological health is characterized by the activity of soil enzymes like urease and phosphatase, which facilitate nutrient cycling alongside keystone microbial taxa [59,61,67,68]. These communities often shift from oligotrophs to copiotrophs in response to amended organic carbon, altering the long-term stability of particulate and mineral-associated organic matter [67,69]. Collectively, these factors restore physiological functions against abiotic stresses like osmotic imbalance and ionic toxicity [61,68].

5. Interaction of biochar for the removal of heavy metals

Biochar presents a sustainable solution for sequestering toxic HMs from contaminated environments. The removal of HMs using biochar involves a complex mechanism of diverse physicochemical interactions. These primarily involve leveraging biochar’s unique porous structure and rich surface chemistry. Key processes include surface adsorption, electrostatic interactions, redox reactions, ion exchange, pore filling, precipitation, non-covalent forces [particularly between molecules containing aromatic rings (π-π interactions)], complexation, and hydrophobic interactions.

5.1. Electrostatic interactions (EA)

For the most effective potential adsorption, electrostatic interactions play a key role in the formation of ionic bonds, which are influenced by several factors, including the point of zero charge (PZC), pH, and the ionic valence radii of HMs. EA refers to the interaction between oppositely charged adsorbates and adsorbent surfaces, which typically exhibits greater strength compared to physical adsorption [117]. A study by Zhang et al. [117] showed that, typically, in an aqueous environment, some elements like Cr, As, and antimony exist as anionic species, which get repelled by the similarly charged pristine form of biochar, limiting its effectiveness in adsorbing them. In order to overcome the issue, biochar is frequently modified to enhance its adsorption performance for these metals. For instance, biochar derived from the invasive plant *Mimosa pigra* underwent modification through metal impregnation with aluminum chloride ($AlCl_3$), followed by pyrolysis at 500 °C. This process resulted in the formation of aluminum oxide (Al_2O_3) and hydroxide $Al(OH)_3$ NPs on the biochar surface, which significantly increased its pore volume and shifted its pH of PZC from 6.00 to as high as 7.80. This modification created a positively charged surface that facilitates electrostatic attraction and chemisorption through the formation of $AlPO_4$ precipitates. Consequently, the sequestration of phosphate improved: the 2 M Al-modified biochar achieved a maximum adsorption capacity of 70.6 mg/g, whereas the unmodified biochar reached only 5.1 mg/g [118]. Other types of modifications include the use of cationic surfactant [119].

In contrast, Rani et al. [120] synthesized a carboxylate-functionalized biochar (BCKA) by chemically modifying leached rice straw biochar, which introduced a negative charge density to it. As a result, the modified biochar exhibited a maximum adsorption capacity of 261 mg/g for the cationic dye methylene blue (MB), compared to the pristine biochar's lower capacity. The enhanced adsorption was primarily attributed to the electrostatic attraction between the negatively charged carboxylate groups on the biochar and the positively charged MB molecules [120]. Biochar surfaces carry pH-dependent charges derived from oxygen and nitrogen functional groups. Negative charges attract metal cations, while positive charges facilitate anion exchange. For specific metals like Cd^{2+}, electrostatic forces are dominant, accounting for approximately 90% of the total adsorption capacity. This interaction is highly sensitive to the medium's pH [121].

5.2. Complexation

The HM adsorption onto biochar is significantly improved by surface complexation, a process reliant on the material's high oxygen-containing functional groups (e.g., -OH, -COOH, -CHO). These groups act as active sites, chemically bonding with HM ions. The success of this complexation, and thus the adsorption performance, depends heavily on the specific nature and density of these functional groups. The formation of stable complexes between these sites and metal ions is key to enhancing biochar's capacity for removing diverse HMs [122]. A study published in the Journal of Environmental Management examined the effectiveness of sepiolite-modified rice husk biochar in immobilizing HMs such as Pb^{2+}, Cd^{2+}, and Cr^{2+} in contaminated soils [123]. The modification process introduced additional oxygen-containing functional groups to the biochar, enhancing its capacity to immobilize these HMs through complexation mechanisms. The modified biochar increased adsorption sites, which facilitated the binding of HMs, thereby reducing their bioavailability and potential toxicity in the soil. This study highlights substantial improvement in adsorption capacity achieved through biochar modification via complexation interactions. HMs are sequestered via inner-sphere complexes formed with oxygen-containing functional groups like -COOH, -OH, and phenolic groups [124]. These groups act as ligands, creating stable chemical bonds [121]. This mechanism is significant for Pb^{2+}, contributing to nearly half of its total adsorption and ensuring tighter, less reversible binding [121,124].

5.3. Ion exchange (IE)

The IE represents a mechanism where ions are swapped between the negatively charged surface sites on the biochar and positively charged HMs ions from the surrounding solution. This exchange is primarily driven by coulombic forces between these charged species. Compared to other adsorption mechanisms, ion exchange is generally considered non-selective and offers a lower overall capacity for binding metals. It specifically involves the replacement of mobile cations, initially present on the biochar surface, such as K^+, Mg^{2+}, $Na^{2+,}$ and Ca^{2+}, with incoming metal ions. The efficiency of this process is significantly dependent on the chemical nature of the biochar's surface [125,126]. For instance, Wu et al. [127] reported that modified coconut shell biochar with Mg drastically enhanced its capacity to adsorb Pb^{2+} and Cd^{2+} from wastewater, increasing it 20-fold and 30-fold, respectively. This significant improvement was primarily attributed to substantially increased ion exchange and mineral precipitation capacity due to increased free -COOH and -OH moieties on the surface. These two mechanisms dominated the overall process for the Mg-modified biochar. Ion exchange involves the replacement of exchangeable ions on the biochar's surface, such as sodium or calcium, with HM cations [121]. This is considered a crucial mechanism for achieving solid binding, as evidenced by low desorption rates [124]. Cation exchange capacity (CEC) is a primary indicator of biochar's effectiveness in utilizing this specific pathway [121,124].

Ion exchange and surface complexation represent different pathways. Ion exchange occurs when biochar releases Ca^{2+} or K^+ that are replaced by HMs, a fast and reversible process, whereas surface complexation involves the formation of stronger inner sphere or outer sphere complexes between metals and functional groups, often covalent or coordination bonds [128,129]. Some functional groups act as electron donors or acceptors, imparting basic and acidic properties on biochar surfaces, which may promote a hydrophobic and hydrophilic environment, affecting HM removal as the CEC may diminish when functional groups are lost [130], leading to the development of aromatic carbon structures. Nevertheless, metals such as Cr(VI), Pb(II), and Cd(II) can still be removed if sufficient oxygen-containing groups (phenolic acids and -COOH groups) are retained [131].

5.4. Precipitation

The formation of insoluble compounds by metal ions directly onto the adsorbent's surface is known as surface precipitation. Key factors influencing this mechanism are the pH of the system and the solubility of the specific metal ions present. Biochars possessing high surface concentrations of phosphate and carbonate ions are more likely to facilitate surface precipitation. This tendency is linked to the inherent chemical nature of certain biochars (for instance, derived from sludge), which promotes the attachment of water molecules to the surface, consequently aiding precipitate formation [132]. For instance, the magnetic coconut shell biochar (MCSB) exhibited a maximum adsorption capacity for Cu^{2+} of 371.50 mg/g. Quantitative analysis of the adsorption process revealed that both chemical precipitation and ion exchange were significant contributors because of the incorporation of -COOH, -OH, C=O, and iron oxide groups. Furthermore, metal-π complexation involving the magnetic biochar structure also played a role in enhancing the overall copper uptake [133]. Sequestration occurs when HMs react with minerals like carbonates, silicates, and oxides to form insoluble solid precipitates [121,124]. Engineered biochars, such as those modified with hydroxyapatite or metal oxides, enhance this process by providing mineral-rich sites [124]. These stable mineral forms effectively immobilize metals within the biochar's structure, preventing their re-release into the environment [121,124].

5.5. Adsorption

Significant environmental organic contaminants include categories like dyes, pesticides, antibiotics, plasticizers, polycyclic aromatic hydrocarbons (PAHs), and phenols. Biochar can adsorb these compounds through several key mechanisms, including filling of pores, surface interactions, hydrophobic partitioning, electrostatic attraction, and hydrogen bonds. The physical entrapment of organic substances within biochar's pores, known as pore-filling, is a key adsorption mechanism. The extent of this adsorption is closely related to the micropores' surfaces [134]. Producing biochar at higher pyrolysis temperatures generally increases its carbonization degree, total SA, and micropore development. These enhanced structural properties lead to improved adsorption capacities. Consistent with this, the large SA and pore volume typical of carbon materials are known for boosting organic pollutant uptake via pore-filling [135]. Additionally, π–π electron donor–acceptor (EDA) interactions contribute significantly to adsorption, especially for organic pollutants with aromatic rings. These interactions occur between the biochar's graphitic surfaces (π-electrons donors) and the pollutant's aromatic components (π-electron acceptors), resulting in strong adsorption [63].

Other important mechanisms include hydrophobic interactions, where non-polar organic compounds are sequestered by non-polar regions of the biochar used in the water system. Hydrogen bonding and electrostatic forces also facilitate the removal of organic pollutants. For example, studies using sulfur-doped biochar from tapioca peel showed effective removal of dyes malachite green (30.2 mg/g) and rhodamine B (33.1 mg/g), with a combination of electrostatic attraction, surface complexation, and hydrogen bonding identified as the dominant removal mechanism [136]. Adsorption involves the binding of HMs onto biochar surfaces through oxygen-containing functional groups such as –OH and –C=O, a process driven by SA and porosity and often reversible depending on pH and ionic strength. In contrast, mineral precipitation occurs when metals react with mineral phases present in biochar ash (e.g., Ca, Mg, K, and P carbonates or phosphates), forming insoluble compounds that provide more stable immobilization [128,129]. Physical adsorption utilizes biochar's highly porous structure, including micropores, mesopores, and macropores, to trap metal ions. These pores function as a highway and reservoir for the rapid transport of particles [137]. A larger specific surface area typically enhances this process, providing more physical sites for metals to settle and adhere to the biochar [121]. Significant pieces of information can be retrieved from the following articles [121,124,137].

6. Conclusions and future prospects

A vast proportion of carbon-rich agricultural solid waste can be handled effectively and sustainably by converting it into beneficial materials such as biochar. The carbon-sequestering ability of biochar can be utilized to increase carbon credit allocations, where one ton of carbon dioxide equivalent equals one carbon credit. Hence, investing in biochar production plants can help to achieve climate goals through utilization in carbon trading. Among the different sources of biomass utilized in biochar preparations, the use of lignocellulosic-based biomass appears to be the preferred source of feedstock due to its low moisture content. Chemical, physical, and biological pretreatments of biochar can improve its properties, including surface activities, pore structures, surface functional groups, structural integrity, uniformity, and adsorption capacity. Slow pyrolysis remains the best production method due to higher biochar yield, while rapid vacuum pyrolysis is very effective in producing porous biochar, although with an oxidation-sensitive surface. Characterizations through analytical techniques are sufficient to get an idea about the structural integrity, ignitability, and surface activity of biochar. Biochar can be further activated to enhance its physicochemical properties (physical, chemical, or biological) for sustainable and eco-friendly applications in water purification, agriculture, and waste management. For biochar-mediated removal of HMs from contaminated water, a thorough understanding of the various adsorption mechanisms is necessary. Knowledge of these processes allows for the strategic manipulation of adsorbent or solution properties, which can enhance the overall adsorption performance, leading to high removal efficiencies. Standardization protocols enable better comparability of results across studies and facilitate the identification of key factors influencing biochar performance. To date, biomass from agricultural and forestry residues has been widely utilized as a feedstock for producing biochar. Given the increasing amount of industrial waste, such as that originating from the textile and cosmetic industries, studies must be conducted on the efficiency of biochar from these sources. This will reinforce the concept of a circular economy where waste materials can have a new purpose and be recycled, thus making the whole process sustainable.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgments

Funding: Financial support from Savitribai Phule Pune University is acknowledged. Surekha K. Satpute also expresses gratitude towards Anusandhan National Research Foundation (ANRF), New Delhi ANRF/PAIR/2025/000015/PAIR-B.

Conflict of interest

The authors declare no conflict of interest.

Author contributions

Ayesha Mulla, Riddhi Chakraborty, Gaurav Rai, Bhawna Khandwal, Twisampati Das, Shrikant Hulkane were involved in writing the preliminary original draft and visualization. Ibrahim M. Banat, Sanket Joshi, and Surekha K. Satpute carried out formal analysis and writing–original draft, visualization, and editing of the original draft. Construction of images: Images were created using a licensed copy of 'BioRender software' (Professional Science Figure creator, BioRender, Toronto, Ontario, Canada) purchased by the Department of Microbiology, Savitribai Phule Pune University, Pune, Maharashtra, India.

References

1. Kumar A and Bhattacharya T (2021) Biochar: a sustainable solution. *Environ Dev Sustain* 23: 6642–6680. https://doi.org/10.1007/s10668-020-00970-0
2. Aribam B, Alam W, Thokchom B (2021) Water, arsenic, and climate change, In: Binota Thokchom B, Qiu PP, Singh P, et al., *Water Conservation in the Era of Global Climate Change*, Netherlands: Elsevier, 167–190. https://doi.org/10.1016/B978-0-12-820200-5.00003-8
3. Bhatti HN, Nasir AW, Hanif MA (2010) Efficacy of *Daucus carota* L. waste biomass for the removal of chromium from aqueous solutions. *Desalination* 253: 78–87. https://doi.org/10.1016/j.desal.2009.11.029
4. Central Pollution Control Board (2021) Annual report on solid waste management (2020–21). Central Pollution Control Board, Delhi. Available from: https://cpcb.nic.in/uploads/MSW/MSW_AnnualReport_2020-21.pdf.
5. Bansod HS and Deshmukh P (2023) Biomedical waste management and its importance: a systematic review. *Cureus* 15: e34589. https://doi.org/10.7759/cureus.34589

6. Lee KT, Chen WH, Sarles P, et al. (2022) Recover energy and materials from agricultural waste via thermochemical conversion. *One Earth* 5: 1200–1204. https://doi.org/10.1016/j.oneear.2022.10.010
7. Agapkin AM, Makhotina IA, Ibragimova NA, et al. (2022). The problem of agricultural waste and ways to solve it. *IOP Conf Ser: Earth Environ Sci* 981: 022009. https://doi.org/10.1088/1755-1315/981/2/022009
8. Agricultural Waste Market Overview (2026). Available from: https://www.industryresearch.biz/market-reports/agricultural-waste-market-112685.
9. Siqueira MU, Contin B, Fernandes PRB, et al. (2022) Brazilian agro-industrial wastes as potential textile and other raw materials: a sustainable approach. *Mater Circ Econ* 4: 9. https://doi.org/10.1007/s42824-021-00050-2
10. Agricultural Waste Facts (2026). (Published 10th April 2024 by Mark Hall. Last modified 12th November 2025). Available from: https://www.businesswaste.co.uk/waste-facts/agricultural-waste-facts/.
11. Debnath B, Haldar D, Purkait MK (2021) A critical review on synthesis and applications of crystalline cellulose derived from agricultural wastes and forest residues. *Carbohydr Polym* 273: 118537. https://doi.org/10.1016/j.carbpol.2021.118537
12. Schiopu AM and Gavrilescu M (2010) Options for the treatment and management of municipal landfill leachate: common and specific issues. *Clean Soil Air Water* 38: 1101–1110. https://doi.org/10.1002/clen.200900184
13. Li S, Chen G (2020) Agricultural waste-derived superabsorbent hydrogels: Preparation, performance, and socioeconomic impacts. *J Clean Prod* 251: 119669. https://doi.org/10.1016/j.jclepro.2019.119669
14. Mussatto SI, Ballesteros LF, Martins S, et al. (2012) Use of agro-industrial wastes in solid-state fermentation processes, In: Show KY and Guo XX, *Industrial Waste,* Croatia: InTech, 121. https://doi.org/10.5772/36310
15. Shehrawat PS and Sindhu N (2015) Agricultural waste utilization for healthy environment and sustainable lifestyle. *Ann Agric Biol Res* 20: 110–114. Available from: http://www2.agrosym.rs.ba/agrosym/agrosym_2012/dokumenti/3_zast_zivotne/16_OA_Shehrawat.pdf.
16. Romruen O, Karbowiak T, Tongdeesoontorn W, et al. (2022) Extraction and characterization of cellulose from agricultural by-products of Chiang Rai Province, Thailand. *Polymers* 14: 1830. https://doi.org/10.3390/polym14091830
17. Sánchez ME, Lindao E, Margaleff D, et al. (2009) Pyrolysis of agricultural residues from rape and sunflowers: production and characterization of bio-fuels and biochar soil management. *J Anal Appl Pyrol* 85: 142–144. https://doi.org/10.1016/j.jaap.2008.11.001
18. Jiang SF, Sheng GP, Jiang H (2019) Advances in characterization methods of biomass pyrolysis products. *ACS Sustain Chem Eng* 7: 12639–12655. https://doi.org/10.1021/acssuschemeng.9b00868
19. Ippolito JA, Cui L, Kammann C, et al. (2020) Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. *Biochar* 2: 421–438. https://doi.org/10.1007/s42773-020-00067-x

20. Al-Rumaihi A, Shahbaz M, McKay G, et al. (2022) A review of pyrolysis technologies and feedstock: a blending approach for plastic and biomass towards optimum biochar yield. *Renew Sustain Energy Rev* 167: 112715. https://doi.org/10.1016/j.rser.2022.112715
21. Praveen S, Jegan J, Bhagavathi Pushpa T, et al. (2022) Biochar for removal of dyes in contaminated water: an overview. *Biochar* 4: 10. https://doi.org/10.1007/s42773-022-00131-8
22. Li S, Harris S, Anandhi A, et al. (2019) Predicting biochar properties and functions based on feedstock and pyrolysis temperature: a review and data syntheses. *J Clean Prod* 215: 890–902. https://doi.org/10.1016/j.jclepro.2019.01.106
23. Foong SY, Cheong KY, Kong SH, et al. (2023) Recent progress in the production and application of biochar and its composite in environmental biodegradation. *Bioresour Technol* 387: 129592. https://doi.org/10.1016/j.biortech.2023.129592
24. Jha S, Gaur R, Shahabuddin S, et al. (2023) Biochar as sustainable alternative and green adsorbent for the remediation of noxious pollutants: a comprehensive review. *Toxics* 11: 117. https://doi.org/10.3390/toxics11020117
25. Patil PD and Yadav GD (2019) Exploring the untapped potential of solar pretreatment for deconstruction of recalcitrant Kraft lignin in fungal biotransformation. *Clean Technol Environ Policy* 21: 579–590. https://doi.org/10.1007/s10098-018-1656-6
26. Badgujar KC and Bhanage BM (2018) Dedicated and waste feedstocks for biorefinery: an approach to develop a sustainable society, In: Bhaskar T, Pandey A, Venkata Mohan S, et al., *Waste biorefinery,* Netherlands: Elsevier, 3–38. https://doi.org/10.1016/B978-0-444-63992-9.00001-X
27. Gabhane JW, Bhange VP, Patil PD, et al. (2020) Recent trends in biochar production methods and its application as a soil health conditioner: a review. *SN Appl Sci* 2: 1–21. https://doi.org/10.1007/s42452-020-3121-5
28. Amalina F, Abd Razak AS, Krishnan S, et al. (2022) Water hyacinth (Eichhornia crassipes) for organic contaminants removal in water–a review. *J Hazard Mater Adv* 7: 100092. https://doi.org/10.1016/j.hazadv.2022.100092
29. Liu X, Zu X, Liu Y, et al. (2018a) Conversion of waste water hyacinth into high-value chemicals by iron (III) chloride under mild conditions. *BioResources* 13: 2293–2303. https://doi.org/10.15376/biores.13.2.2293-2303
30. Singh JK, Chaurasia B, Dubey A, et al. (2020) Biological characterization and instrumental analytical comparison of two biorefining pretreatments for water hyacinth (Eichhornia crassipes) biomass hydrolysis. *Sustainability* 13: 245. https://doi.org/10.3390/su13010245
31. Lehmann J and Joseph S (2009) Biochar for environmental management: an introduction, *Biochar for environmental management*, London: Routledge, 1–13. https://doi.org/10.4324/9780203762264
32. Kavan Kumar V and Panwar NL (2024) Pyrolysis technologies for biochar production in waste management: a review. *Clean Energy* 8: 61–78. https://doi.org/10.1093/ce/zkae036
33. Phiri Z, Moja NT, Nkambule TT, et al. (2024) Utilization of biochar for remediation of heavy metals in aqueous environments: a review and bibliometric analysis. *Heliyon* 10: e25785. https://doi.org/10.1016/j.heliyon.2024.e25785
34. Elkhalifa S, Mackey HR, Al-Ansari T, et al. (2022) Pyrolysis of biosolids to produce biochars: a review. *Sustainability* 14: 9626. https://doi.org/10.3390/su14159626

35. Daful AG and Chandraratne MR (2020) Biochar production from biomass waste-derived material, In: Hashmi S and Choudhury IA, *Encyclopedia of Renewable and Sustainable Materials,* Netherlands: Elsevier, 370–378. https://doi.org/10.1016/B978-0-12-803581-8.11249-4
36. Tomczyk A, Sokołowska Z, Boguta P (2020) Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Rev Environ Sci Biotechnol* 19: 191–215. https://doi.org/10.1007/s11157-020-09523-3
37. Gaurav GK, Mehmood T, Cheng L, et al. (2020) Water hyacinth as a biomass: a review. *J Clean Prod* 277: 122214. https://doi.org/10.1016/j.jclepro.2020.122214
38. Raza M, Inayat A, Ahmed A, et al. (2021) Progress of the pyrolyzer reactors and advanced technologies for biomass pyrolysis processing. *Sustainability* 13: 11061. https://doi.org/10.3390/su131911061
39. Huang X, Cao JP, Zhao XY, et al. (2016) Pyrolysis kinetics of soybean straw using thermogravimetric analysis. *Fuel* 169: 93–98. https://doi.org/10.1016/j.fuel.2015.12.011
40. Zaker A, Chen Z, Wang X, et al. (2019) Microwave-assisted pyrolysis of sewage sludge: a review. *Fuel Process Technol* 187: 84–104. https://doi.org/10.1016/j.fuproc.2018.12.011
41. Li Y, Xing B, Ding Y, et al. (2020) A critical review of the production and advanced utilization of biochar via selective pyrolysis of lignocellulosic biomass. *Bioresour Technol* 312: 123614. https://doi.org/10.1016/j.biortech.2020.123614
42. Khan TA, Saud AS, Jamari SS, et al. (2019) Hydrothermal carbonization of lignocellulosic biomass for carbon rich material preparation: a review. *Biomass Bioenergy* 130: 105384. https://doi.org/10.1016/j.biombioe.2019.105384
43. Manyà JJ, García-Morcate D, González B (2020) Adsorption performance of physically activated biochars for post combustion CO_2 capture from dry and humid flue gas. *Appl Sci* 10: 376. https://doi.org/10.3390/app10010376
44. Enaime G, Baçaoui A, Yaacoubi A, et al. (2020) Biochar for wastewater treatment—conversion technologies and applications. *Appl Sci* 10: 3492. https://doi.org/10.3390/app10103492
45. Zaied BK, Rashid M, Nasrullah M, et al. (2020) A comprehensive review on contaminants removal from pharmaceutical wastewater by electrocoagulation process. *Sci Total Environ* 726: 138095. https://doi.org/10.1016/j.scitotenv.2020.138095
46. Nidheesh PV, Gopinath A, Ranjith N, et al. (2021) Potential role of biochar in advanced oxidation processes: a sustainable approach. *Chem Eng J* 405: 126582. https://doi.org/10.1016/j.cej.2020.126582
47. Yin ZX, Zhang YY, Liu JX, et al. (2024) Quantitative mechanisms for the Cd^{2+} adsorption increased by sewage-sludge biochar but decreased by rice-straw biochar after melamine modification. *J Environ Chem Eng* 12: 114430. https://doi.org/10.1016/j.jece.2024.114430
48. Nand S, Kumar S, Pratap B, et al. (2024) Arsenic removal using de-oiled mentha biomass biochar: adsorption kinetics and the role of iron modification. *J Clean Prod* 482: 144247. https://doi.org/10.1016/j.jclepro.2024.144247
49. Yang S, Liu G, Hou J, et al. (2025) Combining torrefaction pretreatment and activation for avermectin mycelial residues biochar upgradation and structural modification. *Fuel* 384: 133933. https://doi.org/10.1016/j.fuel.2024.133933
50. Zhu X, Wang Z, Teng Y, et al. (2024a) Green modification of biochar with poly (aspartic acid) enhances the remediation of Cd and Pb in water and soil. *J Environ Manage* 370: 122642. https://doi.org/10.1016/j.jenvman.2024.122642

51. Liu C, Wang W, Wu R, et al. (2020a) Preparation of acid- and alkali-modified biochar for removal of methylene blue pigment. *ACS Omega* 5: 30906–30922 https://doi.org/10.1021/acsomega.0c03688
52. Zhang X, Zhang H, Cai S, et al. (2025) Efficient removal of tetracycline by boosting persulfate activation with ball milling biochar derived from iron-rich paper sludge. *J Water Process Eng* 69: 106858. https://doi.org/10.1016/j.jwpe.2024.106858
53. Ren J, Zhang Y, Wang H, et al. (2024) Adsorption of dibenzofuran by modified biochar derived from microwave gasification: impact factors and adsorption mechanism. *J Anal Appl Pyrol* 183: 106831. https://doi.org/10.1016/j.jaap.2024.106831
54. He H, Zhou Z, Tian H, et al. (2024) Effect of Ni-modified biochar-based catalysts on steam reforming of biomass and plastics for hydrogen production. *J Energy Inst* 119: 101960. https://doi.org/10.1016/j.joei.2024.101960
55. Lamberti E, Viscusi G, Kiani A, et al. (2024) Efficiency of dye adsorption of modified biochar: a comparison between chemical modification and ball milling treatment. *Biomass Bioenergy* 185: 107247. https://doi.org/10.1016/j.biombioe.2024.107247
56. Zhao L, Zhang Y, Wang L, et al. (2022) Effective removal of Hg(II) and MeHg from aqueous environment by ball milling aided thiol-modification of biochars: effect of different pyrolysis temperatures. *Chemosphere* 294: 133820. https://doi.org/10.1016/j.chemosphere.2022.133820
57. Al-Rabaiai A, Menezes-Blackburn D, Al-Ismaily S, et al. (2024) Biochar pH reduction using elemental sulfur and biological activation using compost or vermicompost. *Bioresour Technol* 401: 130707. https://doi.org/10.1016/j.biortech.2024.130707
58. Vandecasteele B, Viaene J, Castejón-del Pino R, et al. (2024) S-enhanced microbial activation of biochars and processed grass fibers for circular horticulture. *Sci Total Environ* 957: 177760. https://doi.org/10.1016/j.scitotenv.2024.177760
59. Zhu L, Wang L, Zhang J, et al. (2024b) Comparison of characteristics of biochar modified by earthworm and potassium permanganate. *Environ Technol Innov* 35: 103733. https://doi.org/10.1016/j.eti.2024.103733
60. Peng C, Cai Z, Liang H, et al. (2024) Fungal pretreatment of reed derived metal salt embedded biochar for improved toluene conversion as a tar model compound. *Energy* 313: 133936. https://doi.org/10.1016/j.energy.2024.133936
61. Abbas HMM, Rais U, Altaf MM, et al. (2024) Microbial-inoculated biochar for remediation of salt and heavy metal contaminated soils. *Sci Total Environ* 954: 176104. https://doi.org/10.1016/j.scitotenv.2024.176104
62. Chen Z, Jin P, Liu Q, et al. (2025) Decade-long successive biochar amendment enhances wheat production and increases crop system resistance to unfavorable meteorological factors. *Field Crops Res* 322: 109743. https://doi.org/10.1016/j.fcr.2025.109743
63. Nosratabad NA, Yan Q, Cai Z, et al. (2024) Exploring nanomaterial-modified biochar for environmental remediation applications. *Heliyon* 10: e37123. https://doi.org/10.1016/j.heliyon.2024.e37123
64. Budimir F, Ptacek CJ, Amos RT, et al. (2024) Chromium isotope fractionation during the removal of hexavalent chromium by oak-based biochar. *Chemosphere* 369: 143880. https://doi.org/10.1016/j.chemosphere.2024.143880

65. Campion L, Bekchanova M, Malina R, et al. (2023) The costs and benefits of biochar production and use: a systematic review. *J Clean Prod* 408: 137138. https://doi.org/10.1016/j.jclepro.2023.137138.
66. Sohi SP, Krull E, Lopez-Capel E, et al. (2010) A review of biochar and its use and function in soil. *Adv Agron* 105: 47–82. https://doi.org/10.1016/S0065-2113(10)05002-9
67. Deng J, He D, Zhu X, et al. (2024) Biochar amendment shifts bacterial keystone taxa regulating soil phosphorus dynamics. *Appl Soil Ecol* 201: 105521. https://doi.org/10.1016/j.apsoil.2024.105521
68. Jaffar MT, Zhen S, Han J, et al. (2024) Orange peel biochar: An effective amendment to improve maize resilience under salinity stress by regulating soil enzymatic activities and nutrient uptake. *Ind Crops Prod* 222: 120081. https://doi.org/10.1016/j.indcrop.2024.120081
69. Chen S, Xia X, Ding Y, et al. (2024) Changes in aggregate-associated carbon pools and chemical composition of topsoil organic matter following crop residue amendment in forms of straw, manure and biochar in a paddy soil. *Geoderma* 448: 116967. https://doi.org/10.1016/j.geoderma.2024.116967
70. Li H, Gui Y, Zhang J, et al. (2025a) Simultaneous alkali/air activation for hierarchical pore development in biochar for catalytic formic acid dehydrogenation. *Biomass Bioenergy* 193: 107549. https://doi.org/10.1016/j.biombioe.2024.107549
71. Li P, Ma T, Chen H, et al. (2025b) Enhancement of hydrogen-rich gas production by co-pyrolysis of biomass and plastics: Feedstock synergistic effects and Ni/Co modified biochar-based catalysts. *Fuel* 385: 134184. https://doi.org/10.1016/j.fuel.2025.134184
72. Luo B, Tian Z, Wang C, et al. (2024) Highly stable Co@ biochar catalysts encapsulated in biochar for efficient lignin hydrogenolysis to valuable monophenols. *Ind Crops Prod* 222: 120076. https://doi.org/10.1016/j.indcrop.2024.120076
73. Rupasinghe M, Zhang Z, Mendis P, et al. (2025) Carbon sequestering biochar incorporated cementitious composites: evaluation of hygrothermal, mechanical and durability characteristics. *Cem Concr Compos* 157: 105864. https://doi.org/10.1016/j.cemconcomp.2024.105864
74. Zhang J, Ge X, Qiu X, et al. (2024) Estimation of carbon sequestration potential and air quality impacts of biochar production from straw in China. *Environ Pollut* 363: 125304. https://doi.org/10.1016/j.envpol.2024.125304
75. Liu H, Wang X, Song X, et al. (2022) Generalists and specialists decomposing labile and aromatic biochar compounds and sequestering carbon in soil. *Geoderma* 428: 116176. https://doi.org/10.1016/j.geoderma.2022.116176
76. Zhao X and Grossart HP (2024) Enhancing crop yield and microbial diversity in saline-affected paddy soil through biochar amendment under aquaculture wastewater irrigation. *Eur J Soil Biol* 123: 103681. https://doi.org/10.1016/j.ejsobi.2024.103681
77. Sharma P, Abrol V, Nazir J, et al. (2025) Optimizing soil properties, water use efficiency, and crop yield through biochar and organic manure integration in organic soil. *J Environ Manag* 373: 123673. https://doi.org/10.1016/j.jenvman.2024.123673
78. Dong L, Wang J, Zhou Z, et al. (2025) Construction of flexible porous 3D biochar based on electrospun rice straw-derived cellulose acetate with excellent adsorption properties toward organic pollutants. *Int J Biol Macromol* 289: 138820. https://doi.org/10.1016/j.ijbiomac.2024.138820

79. Su Y, Qu F, Meng Y, et al. (2024) Microbial-induced carbonate precipitation (MICP) modified biochar for low-carbon cementitious materials. *Constr Build Mater* 451: 138644. https://doi.org/10.1016/j.conbuildmat.2024.138644
80. Zou Z, Qin Y, Zhang T, et al. (2023) Enhancing road performance of lead-contaminated soil through biochar-cement solidification: an experimental study. *J Environ Manage* 348: 119315. https://doi.org/10.1016/j.jenvman.2023.119315
81. Madzin Z, Zahidi I, Talei A, et al. (2025) Optimising spent mushroom compost biochar for heavy metal removal: Mechanisms and kinetics in mine water treatment. *J Water Process Eng* 69: 106829. https://doi.org/10.1016/j.jwpe.2024.106829
82. Zeng S, He Y, Li X, et al. (2025) Ferromagnetically modified N self-doped tea residue biochar three-dimensional electrode for the treatment of tetracycline in high salt water environment. *Colloids Surf A Physicochem Eng Asp* 707: 135956. https://doi.org/10.1016/j.colsurfa.2024.135956
83. Li T, Gao C, Yang T, et al. (2024) Magnetic nano-Fe3O4 modified powdered coconut shell biochar for COD deep removal from oil-field produced water. *Chem Phys Lett* 856: 141612. https://doi.org/10.1016/j.cplett.2024.141612
84. Adewuyi A (2020) Chemically modified biosorbents and their role in the removal of emerging pharmaceutical waste in the water system. *Water* 12: 1551. https://doi.org/10.3390/w12061551
85. Grobelak A, Czerwińska K, Murtaś A (2019) General considerations on sludge disposal, industrial and municipal sludge, In: Vara Prasad MN, de Campos Favas PJ, Vithanage M, et al., *Industrial and Municipal Sludge: Emerging Concerns and Scope for Resource Recovery*, UK: Butterworth-Heinemann, 135–153. https://doi.org/10.1016/j.envres.2020.110656
86. Saha A and Basak BB (2020) Scope of value addition and utilization of residual biomass from medicinal and aromatic plants. *Ind Crops Prod* 145: 111979. https://doi.org/10.1016/j.indcrop.2019.111979
87. Liu Z, Wang Z, Chen H, et al. (2021) Hydrochar and pyrochar for sorption of pollutants in wastewater and exhaust gas: a critical review. *Environ Pollut* 268: 115910. https://doi.org/10.1016/j.envpol.2020.115910
88. Liang JY, Zhang WX, Yao XW, et al. (2023) New insights into co-adsorption of Cr^{6+} and chlortetracycline by a new fruit peel based biochar composite from water: behavior and mechanism. *Colloids Surf A Physicochem Eng Asp* 672: 131764. https://doi.org/10.1016/j.colsurfa.2023.131764
89. Feng Q, Wang B, Chen M, et al. (2021) Invasive plants as potential sustainable feedstocks for biochar production and multiple applications: a review. *Resour Conserv Recycl* 164: 105204. https://doi.org/10.1016/j.resconrec.2020.105204
90. Machrouhi A, Alilou H, Farnane M, et al. (2019) Statistical optimization of activated carbon from *Thapsia transtagana* stems and dyes removal efficiency using central composite design. *J Sci Adv Mater Devices* 4: 544–553 https://doi.org/10.1016/j.jsamd.2019.09.002
91. Putro JN, Ju YH, Soetaredjo FE, et al. (2021) Biosorption of dyes, In: Sharma SK, *Green Chemistry and Water Remediation: Research and Applications*, Netherlands: Elsevier, 99–133. https://doi.org/10.1016/B978-0-12-817742-6.00004-9
92. Tao HY, Ge H, Shi J, et al. (2020) The characteristics of oestrone mobility in water and soil by the addition of Ca-biochar and Fe–Mn-biochar derived from *Litchi chinensis* Sonn. *Environ Geochem Health* 42: 1601–1615. https://doi.org/10.1007/s10653-019-00477-2

93. Nguyen TB, Do QH, Chen CW, et al. (2024) Decoration of marigold flower-like CoMo LDH on reinforced cow manure-derived biochar as an effective peroxymonosulfate activator for degradation of Bisphenol A in water. *J Environ Chem Eng* 12: 114699. https://doi.org/10.1016/j.jece.2024.114699
94. Baldikova E, Pospiskova K, Safarik I (2020) Removal of Bisphenol A using magnetically responsive spruce chip biochar. *Chem Eng Technol* 43: 168–171. https://doi.org/10.1002/ceat.201800616.
95. Wang RZ, Huang DL, Liu YG, et al. (2020a) Synergistic removal of copper and tetracycline from aqueous solution by steam-activated bamboo-derived biochar. *J Hazard Mater* 384: 121470. https://doi.org/10.1016/j.jhazmat.2019.121470
96. Nguyen VT, Hung CM, Nguyen TB, et al. (2019) Efficient heterogeneous activation of persulfate by iron-modified biochar for removal of antibiotics from aqueous solution: a case study of tetracycline removal. *Catalysts* 9: 49. https://doi.org/10.3390/catal9010049
97. Zhou Y, He Y, He Y, et al. (2019) Analyses of tetracycline adsorption on alkali-acid modified magnetic biochar: site energy distribution consideration. *Sci Total Environ* 650: 2260–2266. https://doi.org/10.1016/j.scitotenv.2018.09.393
98. Razali NSM, Ikhwanuddin M, Maulidiani M, et al. (2024) Ecotoxicological impact of heavy metals on wild mud crabs (Scylla olivacea) in Malaysia: an integrative approach of omics, molecular docking and human risk assessment. *Sci Total Environ* 946: 174210. https://doi.org/10.1016/j.scitotenv.2024.174210
99. Pochampally SV, Letourneau E, Abdulraheem I, et al. (2024) Metal-organic-framework and walnut shell biochar composites for lead and hexavalent chromium removal from aqueous environments. *Chemosphere* 367: 143572. https://doi.org/10.1016/j.chemosphere.2024.143572
100. Zhou R, Zhang M, Li J, et al. (2020b) Optimization of preparation conditions for biochar derived from water hyacinth by using response surface methodology (RSM) and its application in Pb^{2+} removal. *J Environ Chem Eng* 8: 104198. https://doi.org/10.1016/j.jece.2020.104198
101. Gopinath A, Divyapriya G, Srivastava V, et al. (2021) Conversion of sewage sludge into biochar: a potential resource in water and wastewater treatment. *Environ Res* 194: 110656. https://doi.org/10.1016/j.envres.2020.110656
102. Vasconcelos LP, Albuquerque AA, Ribeiro KR, et al. (2024) Comparison of adsorption potential of methylene blue and 17β-stradiol on biochar, activated biochar and catalytic biochar from lignocellulosic waste. *J Ind Eng Chem* 144: 585–595. https://doi.org/10.1016/j.jiec.2024.10.004
103. Gautam N and Das G (2024) Adsorption of antiviral and antibiotics by recyclable biochar derived from *Dillenia indica*: Impact of pyrolysis temperature and duration. *Colloids Surf A Physicochem Eng Asp* 703: 135265. https://doi.org/10.1016/j.colsurfa.2024.135265
104. Haziq JM, Amalina IF, Syukor AA, et al. (2020) Phytoremediation: treating Eutrophic Lake at KOTASAS lakeside, Kuantan by aquatic macrophytes. *IOP Conf Ser Mater Sci Eng* 736: 022017. https://doi.org/10.1088/1757-899X/736/2/022017
105. Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. (2022) Geneva: World Health Organization. Licence: CC BY-NC-SA 3.0 IGO. Available from: https://iris.who.int/server/api/core/bitstreams/69c17edd-ee26-425b-9d34-33799377e886/content.
106. Rehman K, Fatima K, Fatima F, et al. (2018) Prevalence of exposure of heavy metals and their impact on health consequences. *J Cell Biochem* 119: 157–184. https://doi.org/10.1002/jcb.26234

107. Oladimeji TE, Oyedemi M, Emetere ME, et al. (2024) Review on the impact of heavy metals from industrial wastewater effluent and removal technologies. *Heliyon* 10: e40370. https://doi.org/10.1016/j.heliyon.2024.e40370
108. World Health Organization (2017) Guidelines for drinking-water quality. Available from: http://www.who.int/water_sanitation_health/dwq/gdwq0506.pdf.
109. Järup L (2003) Hazards of heavy metal contamination. *Br Med Bull* 68: 167–182. https://doi.org/10.1093/bmb/ldg032
110. Vidu R, Matei E, Predescu AM, et al. (2020) Removal of heavy metals from wastewaters: A challenge from current treatment methods to nanotechnology applications. *Toxics* 8: 101. https://doi.org/10.3390/toxics8040101
111. Wang Y, Zeng Z, Tian X, et al. (2018) Production of bio-oil from agricultural waste by using a continuous fast microwave pyrolysis system. *Bioresour Technol* 269: 162–168. https://doi.org/10.1016/j.biortech.2018.08.067
112. Liu C, Ye J, Lin Y, et al. (2020) Removal of Cadmium (II) using water hyacinth (Eichhornia crassipes) biochar alginate beads in aqueous solutions. *Environ Pollut* 264: 114785. https://doi.org/10.1016/j.envpol.2020.114785
113. Liu Z, Singer S, Tong Y, et al. (2018) Characteristics and applications of biochars derived from wastewater solids. *Renew Sustain Energy Rev* 90: 650–664. https://doi.org/10.1016/j.rser.2018.02.040
114. Tang S, Shao N, Zheng C, et al. (2019) Amino-functionalized sewage sludge-derived biochar as sustainable efficient adsorbent for Cu(II) removal. *Waste Manag* 90: 17–28. https://doi.org/10.1016/j.wasman.2019.04.042
115. Arrebola J, Rodriguez-Fernandez N, Caballero A (2020) Decontamination of wastewater using activated biochar from agricultural waste: a practical experiment for environmental sciences students. *J Chem Educ* 97: 4137–4144. https://doi.org/10.1021/acs.jchemed.0c00202
116. Nyamunda BC, Chivhanga T, Guyo U, et al. (2019) Removal of Zn(II) and Cu(II) ions from industrial wastewaters using magnetic biochar derived from water hyacinth. *J Eng* 2019: 5656983. https://doi.org/10.1155/2019/5656983
117. Zhang Y, Zhu C, Liu F, et al. (2019) Effects of ionic strength on removal of toxic pollutants from aqueous media with multifarious adsorbents: a review. *Sci Total Environ* 646: 265–279. https://doi.org/10.1016/j.scitotenv.2018.07.279
118. Tran TCP, Nguyen TP, Nguyen TTN, et al. (2021) Enhancement of phosphate adsorption by chemically modified biochars derived from Mimosa pigra invasive plant. *Case Stud Chem Environ Eng* 4:100117. https://doi.org/10.1016/j.cscee.2021.100117
119. Mi X, Li G, Zhu W, et al. (2016) Enhanced adsorption of orange II using cationic surfactant modified biochar pyrolyzed from cornstalk. *J Chem* 2016: 8457030. https://doi.org/10.1155/2016/8457030
120. Rani A, Tiwari S, Sharma G, et al. (2024) Improved carboxylate density in functionalized biochar for methylene blue adsorption. *ChemSelect* 9: e202404209. https://doi.org/10.1002/slct.202404209
121. Rizwan M, Lin Q, Chen X, et al. (2020a) Synthesis, characterization and application of magnetic and acid modified biochars following alkaline pretreatment of rice and cotton straws. *Sci Total Environ* 714: 136532. https://doi.org/10.1016/j.scitotenv.2020.136532

122. Wang Y, Li H, Lin S (2022) Advances in the study of heavy metal adsorption from water and soil by modified biochar. *Water* 14: 3894. https://doi.org/10.3390/w14233894
123. Hou R, Zhu B, Wang L, et al. (2024) Mechanism of clay mineral modified biochar simultaneously immobilizes heavy metals and reduces soil carbon emissions. *J Environ Manage* 361: 121252. https://doi.org/10.1016/j.jenvman.2024.121252
124. Rizwan M, Lin Q, Chen X et al. (2020) Comparison of Pb^{2+} adsorption and desorption by several chemically modified biochars derived from steam exploded oil-rape straw. *Appl Ecol Environ Res* 18: 6181–6197. https://doi.org/10.15666/aeer/1805_61816197
125. Qiu B, Tao X, Wang H, et al. (2021) Biochar as a low-cost adsorbent for aqueous heavy metal removal: a review. *J Anal Appl Pyrol* 155: 105081. https://doi.org/10.1016/j.jaap.2021.105081
126. Murtaza G, Ahmed Z, Eldin SM, et al. (2023) Biochar as a green sorbent for remediation of polluted soils and associated toxicity risks: a critical review. *Separations* 10: 197. https://doi.org/10.3390/separations10030197
127. Wu W, Li J, Lan T, et al. (2017) Unraveling sorption of lead in aqueous solutions by chemically modified biochar derived from coconut fiber: a microscopic and spectroscopic investigation. *Sci Total Environ* 576: 766–774. https://doi.org/10.1016/j.scitotenv.2016.10.163
128. Gotore O, Masere TP, Muronda MT (2024) The immobilization and adsorption mechanisms of agro-waste based biochar: a review on the effectiveness of pyrolytic temperatures on heavy metal removal. *Environ Chem Ecotoxicol* 6: 92–103. https://doi.org/10.1016/j.enceco.2024.04.002
129. Phiri Z, Moja NT, Nkambule TT, et al. (2024) Utilization of biochar for remediation of heavy metals in aqueous environments: a review and bibliometric analysis. *Heliyon* 10: e25785. https://doi.org/10.1016/j.heliyon.2024.e25785
130. Novak JM, Lima I, Xing B, et al. (2009) Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. *Ann Environ Sci* 3: 195–206.
131. Mitchell PJ, Dalley TS, Helleur RJ (2013) Preliminary laboratory production and characterization of biochars from lignocellulosic municipal waste. *J Anal Appl Pyrolysis* 99: 71–78. https://doi.org/10.1016/j.jaap.2012.10.025
132. Wongrod S, Simon S, Guibaud G, et al. (2018) Lead sorption by biochar produced from digestates: consequences of chemical modification and washing. *J Environ Manage* 219: 277–284. https://doi.org/10.1016/j.jenvman.2018.04.108
133. Ma W, Han R, Zhang W, et al. (2024) Magnetic biochar enhanced copper immobilization in agricultural lands: Insights from adsorption precipitation and redox. *J Environ Manage* 352: 120058. https://doi.org/10.1016/j.jenvman.2023.120058
134. Wang X, Guo Z, Hu Z, et al. (2020) Recent advances in biochar application for water and wastewater treatment: a review. *Peer J* 8: e9164. https://doi.org/10.7717/peerj.9164
135. Zhu X, Liu Y, Zhou C, et al. (2014) A novel porous carbon derived from hydrothermal carbon for efficient adsorption of tetracycline. *Carbon* 77: 627–636. https://doi.org/10.1016/j.carbon.2014.05.067
136. Vigneshwaran S, Sirajudheen P, Karthikeyan P, et al. (2021) Fabrication of sulfur-doped biochar derived from tapioca peel waste with superior adsorption performance for removal of Malachite green and Rhodamine B dyes. *Surf Interfaces* 23: 100920. https://doi.org/10.1016/j.surfin.2020.100920

137. Rizwan M, Eisa MH, Zada A, et al. (2025) Cutting edge advancements in biochar applications: thermochemical, fermentative, photocatalytic and electrocatalytic hydrogen production and storage. *Fuel* 402: 136016. https://doi.org/10.1016/j.fuel.2025.136016

AIMS Press

© 2026 the Author(s), licensee AIMS Press. This is an open access article distributed under the terms of the Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0)