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Biochar

REVIEW **Open Access**

Biochar co-modification by magnetization and mineral impregnation: a step towards improved agri-environmental applications

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Abstract

Biochar has emerged as an environmentally sustainable material for addressing agri-environmental issues owing to its porous structure, versatile surface chemistry, and stability. While pristine biochars have demonstrated effectiveness in various applications, ranging from agricultural soil enhancement to contaminant immobilization, their performance is often constrained by insufficient reactivity and limited selectivity. This review begins by outlining the biochar production process, emphasizing how key factors influence its physicochemical properties and overall performance. A major barrier to practical deployment is the difficulty of recovering fine biochar particles from treated media, often requiring energy-intensive methods, which limits the scalability for agri-environmental applications. To overcome these constraints, the review explores various biochar modification methods, focusing on magnetization and mineral impregnation techniques. As such, magnetic biochars (MBCs) not only retain the adsorptive benefits of carbonaceous materials but also enable facile recovery via external magnetic fields, addressing a major obstacle in post-treatment separation. In addition, the mineral doping of MBCs further enhances surface functionality and reactivity, improving removal efficiencies for a wide spectrum of pollutants. This review critically explores the synthesis routes, structural characteristics, and functional performance of magnetized and mineral-enriched biochars, with an emphasis on their applications in environmental remediation and soil enrichment. Mechanistic insights into adsorption pathways including pore-filling, electrostatic binding, and surface complexation are detailed, along with emerging approaches involving light-assisted degradation pathways. By synthesizing laboratory findings and field-scale observations, this review identifies current improvements and limitations, and outlines key directions for future research toward the practical and scalable use of engineered biochars for more sustainable agri-environmental applications.

Keywords Pristine biochar, Magnetization, Functionalized magnetic biochar, Environmental remediation, Soil enhancement

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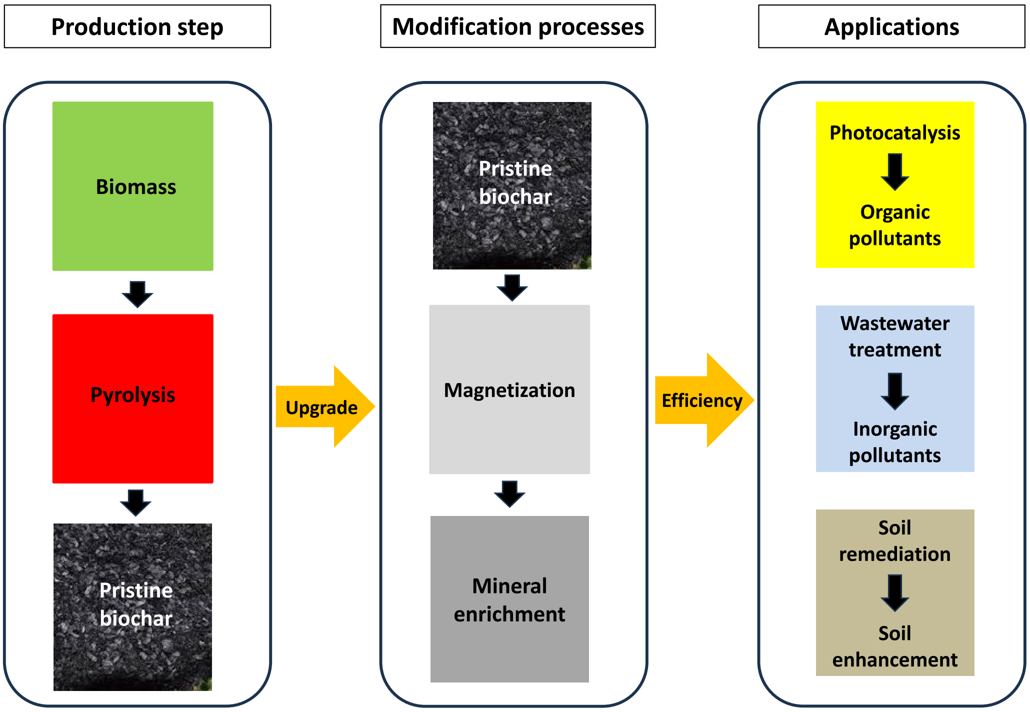
Graphical Abstract



1 Introduction

In recent decades, escalating concerns over persistent global agri-environmental issues such as soil degradation, reduced agricultural productivity, and the widespread contamination of land and water have driven an urgent global pursuit for sustainable approaches to restore the ecological balance (Grammenou et al. 2023; Saxena 2025). In a parallel context, the term 'pollution' or 'contamination' commonly refers to the presence of different compounds in concentrations above baseline thresholds, resulting in direct degradation of the impacted medium and broader environmental consequences beyond the point of origin (Vieira et al. 2024).

As a dynamic and multifaceted issue, soil pollution stems from the intricate coupling of chemical reactions, physical transformations, and biological activities, each governed by soil properties and shaped by external edapho-climatic factors. Therefore, accurate assessment of soil contaminants demands context-sensitive extraction and quantification methods that account for these variables (Vieira et al. 2024). To shed light on the magnitude of the problem, statistics worldwide speak clearly; an estimated one-third of global land resources is undergoing degradation, placing nearly three billion individuals at heightened risk due to declining ecosystem richness and reduced agricultural productivity (Hossain et al. 2020). As a result, lost agricultural productivity from land degradation is estimated to ost the global economy around 300 billion USD annually, with Sub-Saharan Africa shouldering the greatest burden accounting for nearly one-fifth of global losses (Nkonya et al. 2016). Moreover, reports show that 10 million hectares of fertile land are depleted annually, underscoring the critical toll of ongoing land degradation (Hampicke 2021). Other major contributors include industrial processes, waste treatment, and mining activities (Koul and Taak 2018; Zhang et al. 2025a).

Soil and water pollution are closely linked, often forming a self-perpetuating cycle of environmental degradation (Hillel et al. 2008). In a cyclical pollution pathway, soil and water pollution go side by side. On one hand, irrigating with contaminated water accelerates land degradation, while environmental events such as flooding and acid rain similarly deteriorate soil quality. On the other hand, processes like contaminant leaching, surface runoff, and soil erosion serve as major pathways for pollutants to enter surface and underground water systems (Havugimana et al. 2017; Pérez-Lucas et al. 2018). In addition to inorganic contaminants such as heavy metals and excess nutrients, water and soil contamination with organic pollutants epitomizes a global dilemma that presents a peril to both human well-being and the terrestrial ecosystem (Ndour et al. 2025; Shaheen et al. 2025). The term "organic pollutants" entails a huge family of contaminants with different chemical structures, physical properties, and liabilities to interaction and/or degradation as well as the transformation into other pollutants (Ratnakar and Shankar 2016). This family comprises pollutants such as organic agrochemicals (Zolgharnein et al. 2011; Kanan et al. 2022; Rasool et al. 2022), pharmaceuticals and personal care products (Chaturvedi et al. 2021; Gworek et al. 2021; Xu et al. 2021), dyes (Mudhoo et al. 2020; Markandeya et al. 2022), and other industrial pollutants (Liu et al. 2022a). Organic pollutants are generally characterized by their recalcitrance and hydrophobicity, which increase their environmental persistence and risks (Hamdi et al. 2012). As such, the development of effective remediation strategies remains a hot topic of investigation and a key research priority.

Growing concerns over environmental pollution have fueled ongoing efforts and a 'continuous rally' for innovative materials for remediation applications. Among emerging soil amendments and water remediation agents, biochar has gained considerable attention for its multifunctional role in improving soil properties, enhancing nutrient retention, immobilizing contaminants, and contributing to carbon sequestration (Liu et al. 2022b; Das et al. 2023a; Rahim et al. 2023; Hou et al. 2024). Accordingly, carbon sequestration is the process by which carbon is converted into a more stable form to prevent environmental risks related to greenhouse gas emissions (Mosa et al. 2023; Zhang et al. 2025b). This could occur via the production of biochar from the pyrolysis of abundant organic residues, where the carbon cycle is disrupted and a stable carbonaceous form that resists degradation is produced, therefore achieving a zero-waste solution (Hadroug et al. 2021; Safarian 2023; Nazim et al. 2025).

To enhance the physicochemical properties of pristine biochars, magnetization has emerged as a promising modification process owing to the higher adsorption capacity as well as the reusability of the magnetic biochar (MBC). Simultaneously, the mineral doping of biochars has also been proposed to further improve their adsorption and/or fertilizing capacity for improved agri-environmental applications. While numerous studies have explored biochar modification by magnetization and element doping separately, a comprehensive evaluation of how magnetization and mineral doping jointly influence structural properties and agri-environmental applications remains, among other research pathways, lacking. Therefore, this comprehensive review addresses existing research gaps and emphasizes the role of modification in enhancing the quality of pristine biochars. As such, the current review discusses magnetization, the subsequent enhancement via mineral doping processes and summarizes the major fields of application as well. In particular, studies on the agricultural potential of pure or doped MBC remain very scarce and mostly address the remediation of contaminated soils rather than direct agronomic benefits as a soil conditioner for croplands. This can draw attention to this unaddressed field of application whereby modified biochars can improve the soil physical properties and control nutrient retention/release to agricultural plants in a more effective way than pristine forms.

The current review is therefore organized to guide readers through: (i) the production and characterization of pristine biochars; (ii) limitations of pristine biochar use; (iii) modification techniques with an emphasis on magnetization and mineral-enrichment methods; (iv) pollutant removal pathways and mechanistic insights, including adsorption and photocatalysis; and (v) MBC current applications and future perspectives for field-scale implementation in sustainable agri-environmental management.

2 Biochar production processes

The process of biochar production is a critical step in getting a "real" or in other words, a "stable" carbon sink. Controlling the production conditions starts with the choice of a suitable feedstock and the optimization of the processes that cause the thermal decomposition of biomass (Osman et al. 2022; Upadhyay et al. 2024; Waheed et al. 2025). Biochar is a stable carbon-rich solid product that is produced from various organic waste sources, including crop residues (Hoang et al. 2022; El-Azazy et al. 2023a; Patel and Panwar 2023), forestry by-products (Ghosh et al. 2025; Wang et al. 2021b), animal manures (Rathnayake et al. 2023; Yang et al. 2023), sludge and municipal solid wastes (Varjani et al. 2019; Gan et al. 2022; Jellali et al. 2023; Li and Skelly 2023). As shown in Table 1, several methods have been reported in the literature for the production of biochar, such as pyrolysis, hydrothermal carbonization, gasification, flash carbonization, and torrefaction. Among these, pyrolysis has been the most widely used process. It involves the thermal decomposition of organic materials at temperatures varying between 250 °C and 900 °C in the absence of oxygen, which breaks down the biomass into bio-oil, gases, and charcoal (Zhu et al. 2019; Yaashikaa et al. 2020).

Hydrothermal carbonization is another efficient thermochemical process that transforms organic solid waste into valuable hydrochar at relatively low temperatures (180–250 °C) and high pressures (2–10 MPa) through carbonization, polymerization, and dehydration reactions (Shen 2020). Gasification, on the other hand, partially oxidizes materials using air, oxygen, or steam,

Table 1 Biochar production processes

Process	Temperature (°C)	Heating rate (°C s^{-1})	Pressure	Reference
Slow pyrolysis	300–700	0.1–1	–	(Tan et al. 2021b)
Fast pyrolysis	500–1200	10–200	–	(Danesh et al. 2023)
Flash pyrolysis	> 900	> 1000	–	(Li et al. 2023d)
Vacuum pyrolysis	300–700	0.1–1	0.01–0.20 MPa	(Gabhane et al. 2020)
Hydro-pyrolysis	350–600	10–300	10–17 MPa	(Oh et al. 2021)

producing a gas mixture composed of nitrogen, carbon monoxide, methane, carbon dioxide, and water. This gas can be used in turbines, combustion engines, or as a raw material for producing liquid fuels or hydrogen-rich gas (Zarei-Jelyani et al. 2024). Flash carbonization is a rapid heating process that produces high-carbon biochar in less than 30 min, typically at lower temperatures between 300 and 600 °C (Meyer et al. 2011). Torrefaction, a low-intensity pyrolysis method, heats biomass to around 300 °C in an oxygen-free environment, removing moisture and volatile components to produce biochar (Yu et al. 2017). Each of these methods influences the physicochemical properties of the produced biochar, with different types of pyrolysis being particularly suited for specific applications (Mosa et al. 2023).

3 Physico-chemical properties of pristine biochars

With a stable chemical structure, large specific surface area, high carbon content and cation exchange capacity, pristine biochars are considered versatile materials with applications in various fields (Wang and Wang 2019). The surface of biochar is typically rich in functional groups such as aldehyde (–CHO), carboxylate (–COOH), hydroxyl (–OH), amine and amide moieties, which positively contribute to its reactivity (El-Azazy et al. 2023b; Hou et al. 2022). Additionally, biochars contain high levels of organic and total carbon, along with essential micro- and macro elements like potassium, sodium, magnesium, calcium, copper, zinc, and iron. These elements, combined with biochar's high pH, extensive porosity, and abundance of surface functional groups, define its physicochemical properties, making it an effective material for various agricultural, environmental, and industrial applications (Tomczyk et al. 2020).

However, several technical factors, such as the type of feedstock and pyrolysis conditions, play a critical role in shaping the properties of pristine biochars. These variables can lead to products with widely varying characteristics, including pH, specific surface area, pore volume, cation exchange capacity (CEC), volatile matter, as well as ash and carbon content (Tomczyk et al. 2020). Almutairi et al. (2023) emphasized the importance of carefully considering both the feedstock type and the pyrolysis temperature during biochar production, as these variables have a significant impact on the biochar physicochemical properties and its short- and long-term behavior during applications. Therefore, selecting these parameters appropriately is crucial for optimizing biochar quality for specific uses and outcomes.

3.1 Feedstock type

Biomass refers to diverse solid raw materials composed of biological, organic, or inorganic components that were once part of living organisms. Biomasses can be categorized into two main types: woody biomass and non-woody biomass. Non-woody biomasses include solid waste from domestic, industrial and agricultural sources, as well as animal waste, while woody biomasses mainly consist of plants and plant-derived compounds (Cansado et al. 2025). Woody biomasses are typically characterized by a higher carbon content, density, and calorific value but lower moisture and ash contents. In contrast, non-woody feedstocks such as animal manure tend to have higher moisture, debris, voidage, and mineral content but lower density and calorific value (Mukome et al. 2013; Yaashikaa et al. 2020). Moreover, Yang et al. (2022) demonstrated that animal waste-derived biochar differs greatly from plant-derived biochar in that it contains higher levels of N and P as well as high alkalinity and many functional groups. Furthermore, Subedi et al. (2016) found that the availability of SO_4^{2-} and NO_3^- in manure-derived biochar was greater compared to biochar of lignocellulosic origin. Table 2 compares the properties of biochars generated from animal manure and plant residues. For example, biochar from rabbit manure contains 2.1% nitrogen (Cárdenas-Aguiar et al. 2022), while Japanese larch biochar contains only 0.09% nitrogen (Piash et al. 2021). This highlights the significant difference in nitrogen content between biochars made from animal manure and those made from woody material. For better management of the carbon-to-nitrogen ratio (C/N) in biochars, mixing feedstocks or biochars derived from plant residues with animal manure has often been recommended (Qiu et al. 2023).

Table 2 Effect of feedstock origin on biochar properties

Agricultural waste	Pyrolysis temperature	pH	%C	%H	% N	%O	Ash content (%)	Reference
Rabbit manure	300 °C	8.6	31.3	3.3	2.1	12.1	50.6	Cárdenas-Aguiar et al. 2022
Japanese larch		6.4	67.7	–	0.1	–	0.15	Piash et al. 2021
Cow manure	500 °C	10.7	51.2	2.5	1.8	8.6	35.5	Xu et al. 2023a
Corn straw		10.6	61.9	2.8	1.6	11.4	21.7	
Swine	550 °C	9.1	62.3	–	–	–	32.2	Ayaz et al. 2022
Oil seed rape straw		9.8	68.8	1.8	1.6	8.9	19.5	Li et al. 2023c
Dairy cattle	400–550 °C	8.3	15	3.1	2.2	33.3	23	Atienza-Martínez et al. 2020
Corn cob		7.5	73	–	0.75	–	50.0	Apori et al. 2021

3.2 Pyrolysis temperature

Variations in the structural and physicochemical properties of biochars are closely associated with the temperature of pyrolysis. Both temperature and heating rate significantly influence the biochar yield during the pyrolysis process of biomass (Wijitkosum 2022). Optimal conditions for maximizing biochar yield involve a slow heating rate and temperatures below 450 °C, which favor biochar production and lead to higher yields. In contrast, as the heating rate and temperature increase, the generation of gas and ash by-products becomes more pronounced, particularly in fast pyrolysis processes where rapid heat application results in elevated production of these by-products. Therefore, selecting appropriate pyrolysis conditions is crucial for achieving the desired biochar yield while minimizing gas and ash production (Gonzalez-Aguilar et al. 2022). For instance, the yield of rice straw biochar is 42.11% at 400 °C with a heating rate of 10 °C min^{-1}, but it drops to 37.98% when the temperature rises to 500 °C, and further declines to 35.06% at 600 °C, indicating a consistent trend of reduced yield with increasing temperature (Sakhiya et al. 2023). On the other hand, Deng et al. (2022) demonstrated that higher pyrolysis temperatures led to increased pore volume, pore size, and surface area of *Cyclocarya paliurus* biochar, enhancing its potential for various adsorption applications. Specifically, at 300 °C, the specific surface area was 681.3 $\text{m}^2\ \text{g}^{-1}$, with a pore size of 2.05 nm and a pore volume of 2.50×10^{-3} $\text{cm}^3\ \text{g}^{-1}$. As the temperature was increased to 500°C, the pore volume rose to 0.0186 $\text{cm}^3\ \text{g}^{-1}$, the pore size expanded to 19.6 nm, and the surface area increased to 754.23 $\text{m}^2\ \text{g}^{-1}$. At 700 °C, the surface area reached 784.6 $\text{m}^2\ \text{g}^{-1}$, while the pore size and volume further increased to 54.85 nm and 0.0529 $\text{cm}^3\ \text{g}^{-1}$, respectively (Deng et al. 2022).

4 Major applications of pristine biochars

4.1 Carbon capture

Biochar has significant potential for carbon capture, as its porous structure and high surface area enable strong adsorption of carbon dioxide. When incorporated into cementitious composites, biochar enhances their carbon sequestration capacity, making it a promising solution for reducing atmospheric CO_2 levels (Liu et al. 2022c). For example, the addition of 1–3% peanut shell biochar increases the CO_2 absorption capacity of these composites by 2–3% (Gupta 2021). Additionally, (Praneeth et al. 2020) found that a biochar made from maize stover improves CO_2 absorption and optimizes compressive strength at concentrations of 4–6%. Therefore, biochar can be an efficient carbon capture material that shows great promise for future applications.

4.2 Soil remediation

Using biochar to remove organic pollutants and heavy metals is an innovative and promising approach to environmental remediation (Das et al. 2023a). Biochar enhances the biodegradation of contaminants by microorganisms, acting as both an electron donor and acceptor, which promotes redox reactions and improves the breakdown of organic pollutants. By increasing the negative surface charge of variable charge soils, biochar also improves the capacity of soils to adsorb cationic nutrients and heavy metals (Das et al. 2023b). These properties make biochar highly effective for soil remediation (Zhang et al. 2025a). For instance, biochar has been shown to reduce the levels of copper and zinc in their soluble and bioavailable forms in contaminated soils (Graziano et al. 2022). Moreover, Moradi et al. (2019) found that biochar reduces the harmful effects of cadmium on saffron plants by raising soil pH, immobilizing cadmium, and decreasing its mobility. Therefore, biochar application to contaminated soils is a useful technique for environmental cleanup because of its unique physicochemical properties.

4.3 Water treatment

In the past decade, researchers have conducted multiple studies on the application of biochar for the successful removal of contaminants from aqueous solutions. As an emerging porous carbonaceous material with great potential, biochar has gained wide recognition as an effective adsorbent for removing organic contaminants, heavy metals, and excess nutrients from wastewater, making it a promising option for water treatment (Xiang et al. 2020). Accordingly, several studies have demonstrated the adaptability and efficiency of biochar in dealing with different issues related to water contamination and treatment (Xiang et al. 2020). For example, biochar showed great potential in removing crystal violet dye from aqueous environments, demonstrating its efficacy in purifying textile effluents (Wathukarage et al. 2019). Roy and Bharadvaja (2021) also observed a greater Cd and Cr removal from wastewater when using a biochar made from *Plumbago zeylanica* shoots under specific experimental conditions.

4.4 Agricultural soil conditioner

A key sustainable strategy for improving depleted soil quality is to increase its carbon content through the application of various materials, which enhances the soil's capacity to retain water and nutrients (Mohawesh et al. 2018; Hechmi et al. 2023; Mabrouk et al. 2023). One such amendment could be biochar, which has been shown to improve the physical, chemical, and biological properties of soil, thereby boosting soil fertility and agricultural productivity (Feng et al. 2023; Tsolis et al. 2023). For example, the large volume of crop and animal residues could be converted into biochar and reused within the same agricultural system, thus achieving the concept of circular economy (Khedulkar et al. 2023). Biochar application improves the water-holding capacity of arid soils, which makes it very beneficial in agricultural regions with limited water supplies (Ayaz et al. 2021). In this regard, Feng et al. (2023) showed that biochar addition at 30 t ha^{-1} reduced soil evaporation, postponed moisture loss, and increased water usage efficiency under dry climate conditions. Likewise, biochar has also been used to enhance the key properties of hydroponic substrates such as cocopeat under protected cultivation conditions (Banitalebi et al. 2021; Simiele et al. 2022).

4.5 Limitations of pristine biochars

A growing body of literature highlights several attempts to adopt the use of biochar and biochar-based materials for environmental remediation (Haider et al. 2022; Ji et al. 2022; Osman et al. 2022; Xiang et al. 2022). As previously detailed, these efforts commonly introduce biochar as a sustainable and cost-effective solution with minimal negative impact on ecosystems (Hadroug et al. 2021). Yet, the small particle size and the low density of pristine biochars have always limited these efforts (Zhang et al. 2020). In addition, the pristine biochar often lacks specific surface functionalities, and hence has a selective removal capacity. Moreover, it has a diminished pollutant degradation capability due to insufficient catalytic centers. Therefore, pristine biochar has ordinarily been recognized as an excellent reactive material that 'adsorbs' the pollutants rather than 'degrading' them. Besides, the desorption of toxic compounds back into the medium from the pollutant-biochar matrix, if not properly stabilized, remains a risk and a source of secondary pollution. Furthermore, one of the major challenges that is commonly encountered with the use of pristine biochars is the inability to separate the adsorbent-adsorbate complex from the treated medium (Li et al. 2020a; Murtaza et al. 2023; Dong et al. 2025).

As previously indicated, harnessing benefits of the biochar depends largely on the biochar quality, which is mainly related to feedstock type and pyrolysis conditions (Ibn Ferjani et al. 2020). In addition, the desirable physicochemical properties of pristine biochar such as surface reactivity could be further improved if modified (Zhang et al. 2020; Bao et al. 2022). For example, Zoroufchi Benis et al. (2020) highlighted that unmodified biochars are less efficient in adsorbing certain toxic pollutants. This inefficiency arises from the electrostatic repulsion between negatively charged anions and the negatively charged surface of the biochar. For instance, Elkhlifi et al. (2023) reported that non-engineered biochars have the traditional constraints of electric repulsion interactions with PO_4^{3-} ions at various pH levels, leading to highly inefficient enrichment with these ions from aqueous solutions. Consequently, a modification step could further boost the biochar physicochemical traits by improving the surface area, introducing active redox centers, and facilitating magnetic separation (Buss et al. 2022). In other words, biochar modification can significantly enhance the adsorption/desorption properties of pristine biochars for a better performance during application (Jellali et al. 2024a).

5 Biochar modification

Recent efforts have focused on pristine biochar modification to improve the intrinsic physicochemical properties and adsorption capabilities, thereby increasing its efficiency and applicability (Pan et al. 2022). Various methods can be employed for modifying biochar, including chemical, biological, and physical techniques (Liu et al. 2022d). Modification can occur either during or after biochar production (Matsagar and Wu 2022). Factors such as the type of raw material (feedstock), pyrolysis conditions, and the agents used for modification play crucial roles in determining the chemical and physical properties of the final product (Hafeez et al. 2022). The aim of modifying biochar is either to increase its surface area, improve its surface characteristics, or create a platform for incorporating other substances (Sizmur et al. 2017). Physical modifications, such as steam or gas activation and ball milling, occur after pyrolysis. For example, steam treatment involves passing superheated steam through charcoal at temperatures ranging from 650 to 950 °C, which increases the surface area and pore volume of pristine biochar, thereby enhancing its ability to adsorb specific chemicals (Zoroufchi Benis et al. 2020).

Chemical modification often entails adding functional groups and altering the surface porosity of raw biomass or biochar by combining it with various chemical agents (Zoroufchi Benis et al. 2020). This technique is one of the most used and includes the application of acids, alkalis, oxidizing agents, metal salts, and carbonaceous materials (Wang and Wang 2019). Recently, metal impregnation has gained attention, where metal ions such as magnesium, aluminum, silver, zinc, copper, and iron are incorporated into the biochar's surface and pores (Bushra and Remya 2024). Biological modification involves the use of microorganisms to enhance the characteristics and functions of biochar. In this process, microbes colonize the carbonaceous material, leading to biofilm development and microbial adhesion onto the surface of biochar to increase its reactivity (Azad et al. 2022).

Among the different modification methods, physical modification is often viewed as the most practical for large-scale applications due to its ease of implementation. However, chemical modification is more complex but can better tailor the characteristics of the biochar's surface for specific applications. Conversely, biological modifications, although scalable, generally necessitate longer processing times and specific conditions to effectively alter the surface properties and structure (Liu et al. 2022d). Most recently, several studies have added magnetite nanoparticles to pristine biochars, which provide magnetic properties to the surface. This process would be particularly useful for enhanced properties and the recovery of the materials post-sorption (Burbano et al. 2023).

6 Magnetic biochars

6.1 Magnetization process

The use of MBCs for decontamination can efficiently resolve the limitations of the pristine counterpart. The 'keyword' for the effectiveness of MBCs as a versatile solution for environmental decontamination is the 'ease of magnetic separation after use' (Alharbi et al. 2023). In other words, the separation of powdered pristine biochar from treatment media often necessitates the operation of complex techniques such as centrifugation and filtration, posing a significant barrier to its scalability (Zhang et al. 2021; Qu et al. 2022; Yi et al. 2020). Moreover, during these operational phases, desorption of contaminants from the biochar matrix might occur, triggering secondary pollution, thereby undermining the remediation process. Therefore, to fully harness the potential of pristine biochar in environmental remediation, it is imperative to resolve its inherent deficiencies. As such, MBCs combine the sorptive efficiency of biochar with magnetic responsiveness, offering a promising solution for contaminant removal (Qu et al. 2022; Feng et al. 2021; El-Shafie et al. 2023a).

Although iron may be inherently present in some biomass types, this alone has not been shown to yield magnetization. As a result, magnetic properties are typically conferred by treating the biomass with external iron precursors, making this step vital in MBC production (Kang et al. 2023). In general, MBC is prepared via infusion of the pristine biochar matrix with magnetic materials to enhance its adsorption capacity and facilitate the recovery of chemicals from the treated media (Chen et al. 2022b). More precisely, the magnetization process consists of introducing transition metals and their oxides into the biochar matrix, creating easily separable MBCs after use (Yi et al. 2020). Various pre- and post-pyrolysis techniques have been employed to produce MBCs, including impregnation-pyrolysis, chemical and reductive co-precipitation, and solvothermal processes (Feng et al. 2021). A schematic representation of the commonly used approaches is shown in Fig. 1. Besides, Table 3 shows a brief comparison between the different magnetization approaches in terms of cost, efficiency, and environmental compatibility.

A highly efficient and widely employed technique for synthesizing MBC is the impregnation–pyrolysis approach (Alharbi et al. 2023; Daffalla et al. 2024). This method entails impregnating the raw feedstock with metal salts—typically iron-based or other metal precursors—followed by drying and then pyrolysis under oxygen-deficient or inert conditions, enabling the one-step fabrication of MBCs with exceptional operational simplicity (Yi et al. 2020; Katibi et al. 2024). With such a setup, the synchronization of impregnation and pyrolysis allows for fine-tuning of the structural and physicochemical attributes of the resultant magnetic biochars. Moreover, the obtained MBC reveals other desirable attributes such as stability with minimal metal leaching.

Nonetheless, modulating the biochar to the magnetic precursor ratio and the pyrolysis variables (namely, temperature, inert gas, and residence time) allows for optimization of the adsorption capabilities of the

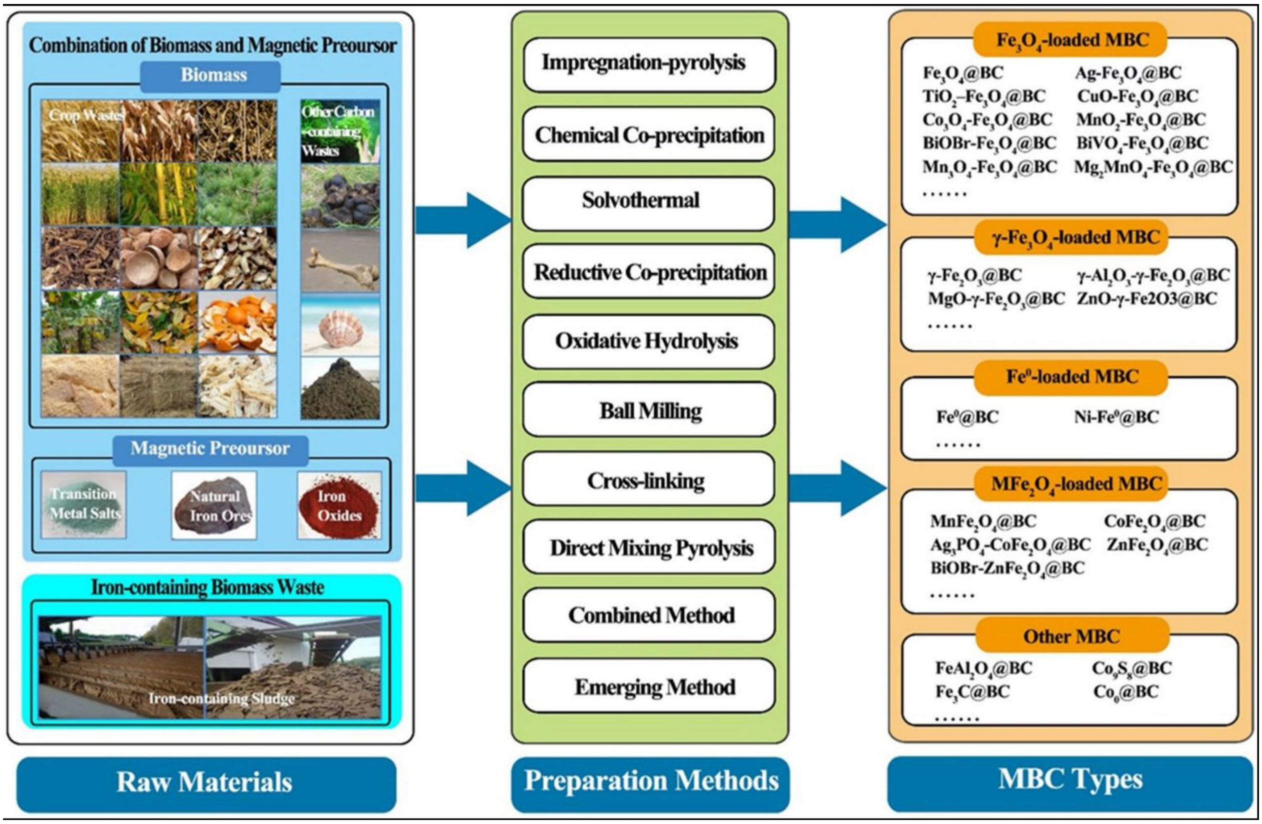


Fig. 1 Methods of preparation of magnetic biochar (denoted as MBC in the source Figure). Reproduced from Feng et al. 2021) with permission from Elsevier. License Number: 5965440787642

developed magnetic biochar (Hu et al. 2017; Daffalla et al. 2024). By and large, the pyrolysis temperature plays a key role in determining the nature of the magnetic material on the surface of the biochar and hence the magnetism. The phase conversion of hematite (300 ℃, low adsorption capacity and magnetism) to magnetite (450 ℃, better adsorption capacity and magnetism) then to wüstite and zero-valent iron (600 ℃) was noted with raising the pyrolysis temperature from 300 to 600 ℃. These phase transitions and the reduction of hematite were noted in the presence of the carbonate-treated pinewood biomass and therefore were attributed to the gases generated during the pyrolysis process from both the biomass and the carbonate (Wang et al. 2019a). In another observation, these authors revealed a gradual phase transition of iron species from magnetite to wüstite as the temperature was elevated from 600 to 1000 ℃ causing more degradation of sulfamethazine, suggesting that wüstite is more catalytically efficient in activating peroxydisulfate. Though efficient in degrading the target pollutant, the magnetization of the wüstite at 1000 ℃ was less compared to its 600 ℃ counterpart, inferring a possible difficulty in collection and separation from the treatment medium; a limitation which was addressed by the authors employing an external magnetic field (Chen et al. 2019a, b).

On the other hand, the need for high pyrolysis temperatures (hitting 1000 °C) makes it an energy-intensive process, posing significant economic drawbacks in terms of both operational costs and sustainability. While effective, the sequential progression from impregnation to pyrolysis is inherently time-intensive, which can hinder the practical applicability of this approach in time-sensitive scenarios and limit its feasibility in high-throughput or industrial-scale operations (Feng et al. 2021). Moreover, an inadequate impregnation efficiency may compromise metal incorporation, resulting in the potential release of hazardous transition metal ions during application, which poses significant environmental and health concerns (Katibi et al. 2024).

In contrast, the co-precipitation technique, one of the most frequently used magnetization approaches, does not require processing at high temperatures (Feng et al. 2021). In this approach, the feedstock is mixed with the

Table 3 Evaluation of MBC synthesis methods by cost, efficiency, and environmental impact

Synthesis approach	Cost	Efficiency	Environmental impact	Reference
Impregnation-pyrolysis	Excluding the iron precursors' cost, high-temperature pyrolysis significantly drives up production costs as it demands prolonged heating, greater energy consumption, and often more robust reactor infrastructure	Moderate to high, allows tuning of the structural and the physicochemical attributes, and hence the adsorption capabilities. But the process depends on the source biomass, and pyrolysis temperature	Generally, metal leaching is minimal, however, the incomplete impregnation might lead to secondary pollution, which is also backed up by the evolution of gas pollutants during the pyrolysis phase. Toxicity of used transition metals need to be considered	(Hu et al. 2017; Feng et al. 2021; Qu et al. 2022; Daffalla et al. 2024; Katibi et al. 2024)
Co-precipitation	Low to moderate since no need for elevated temperatures, however, this advantage is offset by the need for alkali solutions to adjust the pH and confirm the co-precipitation. The cost is enlarged where there is a need for treatment of the alkali-polluted wastewater before discharge	A product with high purity is obtained through a facile, controllable, and fast process	The excessive use of alkaline solutions and the need to treat the alkali-polluted water raise concerns over the environmental sustainability of this technique	(Feng et al. 2021; Fatimah et al. 2022; Qu et al. 2022; El-Shafie et al. 2023b; Katibi et al. 2024)
Reductive co-precipitation	Moderate where the cost of using a reductant should be considered	Very high since this approach produces Fe^0 with its high reactivity. The produced MBC is stable with controllable structure	The use of toxic reducing agents like borohydrides and the need for post-treatment. The production of hydrogen gas during the synthesis process needs special precautions	(Feng et al. 2021; Yi et al. 2020; Qu et al. 2022; Jellali et al. 2024a)
Solvothermal synthesis	Moderate to high costs could be encountered where the synthesis is operated under mild conditions but the need for reductants, alkalis, stabilizers, or surfactants could negatively impact the cost	Facile synthetic route that produces well-dispersed and uniform-sized nanoparticles. Yet, the product is of lower stability necessitating the use of stabilizers/surfactants	The use of various chemicals raises concerns on the sustainability of the solvothermal approach	(Fan et al. 2011; Liang et al. 2019; Tu et al. 2020; Feng et al. 2021; Hashemi et al. 2024)
Hydrothermal synthesis	Moderate since it operates under mild reaction conditions compared to impregnation-pyrolysis with no need for alkalis compared to co-precipitation	Improved magnetic and structural features and hence better contaminant uptake	The increased biochar yield and carbonization efficiency under elevated temperature and pressure infers minimalizing of organic loss and curbing greenhouse gas emissions, collectively lowering the overall carbon footprint. Yet, the inefficient carbonization could undermine these pluses	(Yi et al. 2020; Katibi et al. 2024; Meng et al. 2025)
Ball milling	Inexpensive, but equipment cost, and energy consumption are important considerations	Enhanced surface attributes with potential for scalability. However, the inconsistent distribution of the magnetic strength negatively affects the magnetic features of the resultant biochar	High (solvent-free, minimal waste)	(Amusat et al. 2021; Katibi et al. 2024; Fang et al. 2025)

solutions of iron (III) and iron (II) salts under nitrogen flow, and the pH is adjusted to an alkaline value, facilitating the formation of magnetite nanoparticles onto the biochar surface (Fatimah et al. 2022). This streamlined approach is straightforward, fast, and yields a product with high purity. While effective, the excessive use of alkaline reagents not only increases the cost but also requires careful handling due to their hazardous nature (Feng et al. 2021; Qu et al. 2022; Xiao et al. 2023).

In a comparison between MBCs prepared by impregnation pyrolysis and chemical co-precipitation (also followed by pyrolysis), Dong et al. (2022) prepared MBCs from deforestation residues and tested their performance towards the removal of Pb(II). They found that the iron content of the MBC prepared via co-precipitation was higher than that prepared by the impregnation–pyrolysis route, indicating superior iron retention efficiency. This was corroborated by BET and SEM analyses, which revealed that iron was predominantly confined within the pore structure of the MBC prepared via the precipitation approach, resulting in reduced surface area and pore volume. Reflecting on the Pb(II) adsorption mechanism, the lack of NaOH in the impregnation process led to reduced MBC performance for Pb(II) adsorption, as electrostatic repulsion dominated and key mechanisms like precipitation and ion exchange were minimally active—contrasting with the NaOH-assisted precipitation route.

The reductive co-deposition process involves reacting the biochar with transition metals and reducing agents like potassium or sodium borohydrides to carry out magnetization with nanoparticles and mostly zero-valent iron (Yi et al. 2020). This composition significantly enhances the material's reducing qualities, greatly increasing its capacity to remove pollutants and/or adsorb desirable chemicals (Jellali et al. 2024a). Beyond these desirable attributes, the resultant MBC is stable and has a controllable particle size. Yet, the generation of hydrogen gas as a byproduct during the synthetic procedure needs certain precautions because of safety concerns. Similarly, the use of reductants should be handled with caution (Yi et al. 2020; Feng et al. 2021; Qu et al. 2022).

Solvothermal synthesis, as a one-pot-based approach, has become a viable option for creating magnetic biochars. The process involves autoclaving a mixture of biochar, a magnetic precursor, a reducing agent, a surfactant, and a stabilizer/alkali source at 100–300 °C for a duration of 6–12 h. Ethylene glycol has been used as a reducing agent, while sodium acetate fulfills a dual role of a stabilizer, preventing particle aggregation, and an alkali source, which assists in the reduction of Fe(III) into magnetite. Surfactants, such as polyethylene glycol 4000, play a comparable role in preventing particle agglomeration as well (Fan et al. 2011; Liang et al. 2019; Tu et al. 2020; Feng et al. 2021; Hashemi et al. 2024). As a one-pot based approach, solvothermal synthesis is a facile route for synthesizing magnetic nanocomposites. The product is commonly well-dispersed and uniform-sized magnetic nanoparticles. However, high-pressure synthesis, multiple reagents, and product stability remain concerns for this approach (Feng et al. 2021; Hashemi et al. 2024).

Ball milling is another approach that has emerged as a potential cost-effective and solvent-free route to produce magnetic nanocomposites with prominent surface attributes (Li et al. 2020b; Amusat et al. 2021; Fang et al. 2025). In the procedure detailed by Li et al. (2020b), the biochar and the activated carbon were prepared via ball milling. In a subsequent step, the magnetic counterparts were prepared via ball-milling with magnetite at a mass ration of 1:3. Following such a procedure helps introduce oxygen functionalities to the surface and hence facilitate pollutant scavenging. Moreover, ball-milling has been found to increase the surface area and porosity of the ball-milled biochar compared to the non-ball-milled counterparts in several investigations (Li et al. 2020b, 2024a; Rocha et al. 2020).

Hydrothermal carbonization is another method that produces a heterogeneous mixture by reacting biomass with a metal ion solution at lower temperatures (between 100 and 300 °C) and under reaction-generated pressure (Yi et al. 2020). The use of oxidative hydrolysis is a much less studied approach encountered in the literature. The procedure simply entails the oxidative hydrolysis of iron (II) into magnetite under alkaline conditions and relatively low temperature (~ 90 °C) to prevent the formation of other iron species such as Fe_xO_y and $Fe_x(OH)_y$ (Reguyal et al. 2017). Consequently, the reaction conditions, therefore, need careful management to avoid formation of a mixture of iron species. Formation of soluble salts as byproducts is another limitation of this approach (Rocha et al. 2020). Another rarely used process is cross-linking where the biochar is first mixed with magnetite nanoparticles at a certain mass ratio and then a cross-linker such as epichlorohydrin is added (Zhou et al. 2018).

One of the common magnetization approaches encompasses a slow pyrolysis to form iron-oxide nanoparticles, where iron powder is transformed into iron oxide and then applied onto the biochar surface (Das and Mondal 2023). Due to their cost-effectiveness and eco-friendly nature, one-step synthesis methods, such as chemical precipitation and impregnation, have been widely adopted for engineering applications in MBC production (Dong et al. 2022). This expanding body of research underscores the potential of MBC as a long-term and cost-effective solution for various applications.

6.2 Magnetic biochar properties

Broadly speaking, the MBC closely mirrors the core elemental signature of the parent biomass feedstock (mainly carbon, hydrogen, and oxygen), underscoring the influence of feedstock selection on the chemical properties of the resulting material (Hassan et al. 2020; Yi et al. 2020). Yet, variations in pyrolysis conditions and the magnetization process affect the final elemental composition. In an interesting investigation, the source biomass iron content was found to impact the iron content in the resultant MBC and hence its structure and performance in capturing Cr(IV) (Yi et al. 2019). Mass balance data from the impregnation step indicated that various biomasses differed in their iron adsorption capabilities. As the uptake of metals is commonly related to the oxygen-containing functional groups, further exploration of the composition of these biomasses revealed different contents of cellulose, lignin, and hemicellulose. In a direct correlation, Yi et al. (2019) found that the biomass cellulose content is directly related to the uptake of iron. Furthermore, the variations in iron content were investigated during the pyrolysis step and were largely attributed to yield differences driven by the ash content of the biomass.

Compared to the non-modified form, MBC exhibits a significantly higher specific surface area and a well-developed pore structure, along with abundant functional groups, enhanced stability, and superior adsorption capacity (Xiao et al. 2023). Xu et al. (2023b) explained the reason for the increased number of particle structures visible on the surface of modified MBCs by the development of iron oxides during the modification process. Consequently, the magnetization process creates a more complex and textured surface compared to the unmodified biochar. El-Azazy et al. (2021) reported that MBC derived from olive stones had a higher surface area (33.82 $m^2\ g^{-1}$) and pore volume (0.166 $m^2\ g^{-1}$) compared to the pristine form (22.20 $m^2\ g^{-1}$ and 0.086 $m^2\ g^{-1}$, respectively). Likewise, Li et al. (2024b) found that MBC made from sewage sludge showed a higher surface area (63.68 $m^2\ g^{-1}$) than the same untreated form (59.38 $m^2\ g^{-1}$).

Several studies have demonstrated that MBCs can improve the adsorption capacity by up to three to four times that of pristine forms (Gabhane et al. 2020). For example, the Pb(II) adsorption capacity of an MBC made from wheat straw and hematite reached 196.9 mg g^{-1}, which was 42% higher than that of the pristine form (Zhao et al. 2019). Furthermore, Dong et al. (2023) found that the magnetic treatment significantly enhanced Pb(II) adsorption by raising the pH, increasing the negative surface charge, and improving the complexation behavior of the modified biochar. Another advantage of magnetization is the ease of recovery of the MBC from solutions through an external magnetic field, facilitating efficient separation from samples after use (Ying et al. 2023). Several research studies have shown that the majority of biochars possess a negative charge, which can alter in terms of surface charge or even pH upon magnetization (Yi et al. 2020). Additionally, MBCs have been shown to outperform conventional forms in both conductivity and capacitance, broadening their potential applications (An et al. 2022). Magnetic nanocomposites in modified biochars also feature a large surface area with notable oxygen-containing functional groups, which enhance their interaction with pollutants if applied for decontamination purposes (Zhang et al. 2023b).

6.3 Mineral-enriched magnetic biochars

Magnetic modification has primarily been performed to enhance the adsorption capacity of biochars with respect to unmodified forms (Yi et al. 2020). However, magnetization may reduce the specific surface area of biochar due to iron oxide buildup, which blocks its pores. This effect can limit the adsorption efficiency of MBCs and, in some cases, marginally improve contaminant removal with respect to the pristine form (Li et al. 2023b). For instance, biochar magnetization has been found to lower Cd(II) adsorption capacities due to reduced roles of cation exchange and Cπ-coordination pathways. Moreover, MBCs made from rice straw and sewage sludge showed decreased contributions of 31.9% and 12.1% to cation exchange capacity, and 3.4% and 31.1% to Cπ-coordination, respectively (Huang et al. 2021). Because of these limitations encountered in some cases, MBC modification has become valuable, especially in applications requiring high removal capacity of toxic metals for instance. Several modification methods have been reported in the literature, which include (but are not limited to) acid and alkaline modification, oxidation, surface modification, loading of nanoparticles, and doping with chemicals (Qu et al. 2022). The modification of MBC by element doping could be further classified into metal (examples include Fe, Mn, Zn, Cu, Al, etc.), non-metal doping (for instance using N, P, S, etc.) as well as co-doping which overlaps with the former doping approaches (Wang et al. 2023).

Several investigations have shown that metal element doping can substantially change not only the surface properties of the MBC and hence its adsorption efficiency, but also minimalize metal leaching assuming the proper choice of metal ratios (Xu et al. 2022a; Wang et al. 2023). By and large, doping the MBC with a second metal promotes an effective dispersion of the active sites on the MBC surface, increases the surface area, and boosts adsorption efficiency. Wang et al. (2023) prepared a Cu-doped MBC via co-pyrolysis of cow manure with Cu(II), Fe(III) and Zn in the presence of dicyandiamide (Wang et al. 2023). They reported enhanced catalytic performance and rapid degradation kinetics of sulfamethoxazole following the doping with Cu(II). In another investigation, Wang et al. (2019a) noticed an increase in the specific surface area and point of zero charge after loading a MBC with Ce and La, resulting in a significant enhancement of phosphate adsorption capacity from aqueous solutions. Ca-based MBC showed great potential for improving soil health by significantly increasing both the size of bacterial populations and the diversity of microbial taxa. It effectively reduced As accumulation in rice plants while promoting growth, indicating its value as a soil amendment in rice paddies (Wu et al. 2020). From their side, Lyu et al. (2024) reported that Ca–Mg–Al layered double hydroxide supported by MBC could immobilize more than 85% of As and Cd in soil. Therefore, surface functionalization can further improve the use efficiency of MBCs in various agri-environmental applications.

Remarkably, the method used to synthesize the metal-doped MBC was found to shape the morphologies of the resultant materials and hence their performance. In that context and targeting an efficient removal of Sb(V), Wang et al. (2019b) compared the impact of co-precipitation and solvothermal syntheses on the efficiency of Ce-doped MBC. They documented that magnetic saturation was lower after doping with cerium, primarily due to the compromised crystallinity as confirmed by the XRD analysis. More importantly, the solvothermal synthesis with the reductive conditions resulted in MBC with higher magnetic saturation surpassing those obtained through co-precipitation synthesis. Yet, assembling the characterization findings together, the superior performance of the Ce-doped MBC via the co-precipitation route was attributed to the higher content of the M–OH sites, which in turn helped capturing Sb(V) via H-bonding, inner sphere complexation, and electrostatic interactions.

Non-metal element impregnation, on the other hand, entails the incorporation of non-metallic heteroatom (e.g., N, P, S, etc.) into the MBC structure (Chakma et al. 2025). Such an approach has emerged as a sustainable solution to substitute the formerly mentioned metal doping (Wang et al. 2024a). Similar to the metal-doping, the existence of the non-metallic elements provides more active sites on the surface of the MBC, generates pores, improves the electron mobility, and hence facilitates and boosts the role of MBCs as adsorbents and photocatalysts (Diao et al. 2022a; Zhong et al. 2022). The literature shows several efforts on the use of N-doped MBC for the removal of sulfamethoxazole antibiotic (Diao et al. 2022a), sulfadiazine (Zhong et al. 2022), Cr(IV) (Ke et al. 2022), N,S-co-doped MBC for the removal of tetracycline (Wu et al. 2023), and P-doped MBC for the degradation of pesticides (Liang et al. 2024). For instance, Ma et al. (2024a) employed a combination of advanced synthesis techniques namely, hydrothermal nitrogen-doping, magnetic treatment, and ball milling, to engineer a co-modified biochar from sludge for selective adsorption of sulfamethoxazole. Nitrogen-doping and magnetization helped improve the functionalization of the biochar, while ball-milling further augmented the adsorptive performance of the resultant material.

7 Removal pathways of contaminants by magnetic biochars

The removal of pollutants by MBC is commonly facilitated through multiple processes, each involving one or more underlying mechanisms. These processes include adsorption (Li et al. 2020a; Yi et al 2020; Qu et al. 2022; Xiao et al. 2023), photocatalysis (Feng et al. 2021; Zhou et al. 2021; Lu et al. 2022; Rangarajan et al. 2022), and redox reactions (Yuan et al. 2017). The underlying mechanisms often work in tandem, making MBC a multifunctional and highly versatile material for environmental remediation and subsequent agricultural applications. The following sections will detail the common mechanisms involved in the removal of the different types of pollutants.

7.1 Adsorption mechanisms

Comprehending the adsorption mechanism as a pathway for the removal of organic and inorganic pollutants by MBC is a crucial way for optimized application of the MBC in different environmental remediation contexts. In general, the physicochemical traits of the MBC as well as the specific treatment conditions, and the nature of the target pollutant favor one mechanism over the other. A literature survey shows that adsorption could proceed via one or more processes with electrostatic interactions, ion-exchange, precipitation, surface complexation, π–π stacking, pore-filling, and H-bonding being the most commonly reported mechanisms (Xiao et al. 2023; Yi et al. 2020; Qu et al. 2022; Li et al. 2020a). Figure 2 shows a schematic representation of these common adsorption mechanisms in the case of heavy metal removal using magnetic biochar (Li et al. 2020a).

7.1.1 Surface functional groups-based mechanism

Surface functionalities on biochar play an instrumental role in facilitating diverse removal pathways such as electrostatic interactions, H–bonding, complexation with metal ions, and redox-driven donor–acceptor processes. Surface analysis of the biochar usually reveals that it

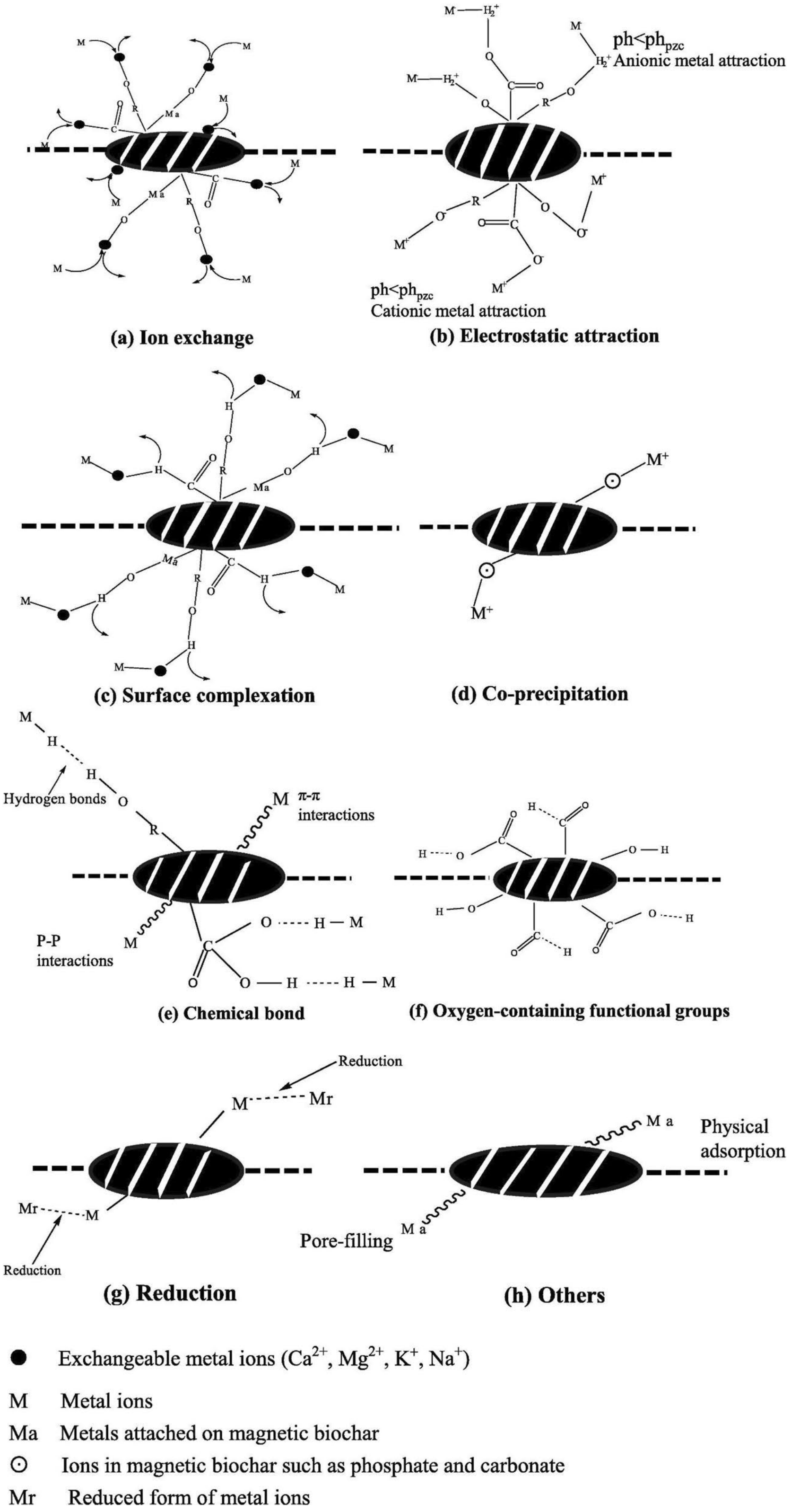


Fig. 2 Commonly reported mechanisms for the removal of heavy metals using magnetic biochar. Reproduced from Li et al. (2020a) with permission from Elsevier. License Number: 6058140394761

hosts ionizable oxygen-rich functional groups—primarily −OH and −COOH—that facilitate its interaction with the charged pollutants as shown in Fig. 2f. Given their central role, surface functional groups on biochar will be examined in the context of each removal mechanism in the sections that follow.

7.1.2 Ion-exchange mechanism

Starting with ion-exchange as a commonly reported mechanism, as shown in Fig. 2a, the process simply entails an exchange of the surface ions of MBC with the pollutant ions (Li et al. 2020a; Xiao et al. 2023). The likelihood of this mechanism occurring generally depends on the nature and the charge of the functionalities on the surface of the biochar, and the pollutant ion size (Abbas et al. 2018). Investigations have shown that there is a direct relationship between the cation exchange capacity (CEC) of the MBC and its capability to remove metal cations. The presence of cations such as Ca^{2+} and Mg^{2+} in the parent feedstock and then the Fe^{3+} ions in the MBC was found to enhance its CEC (Trakal et al. 2016; Abbas et al. 2018; Zhao et al. 2013). In a study carried out by Zhou et al. (2024), a MBC prepared from macadamia nutshells via mechanochemical activation employing iron (III) chloride was efficient for the adsorption of Cu(II) and Pb(II), with cation-exchange being the possible mechanism as evidenced by the adsorption energy values (between 8 and 16 kJ mol^{-1}). In another study, MBC prepared from cow manure and straw biochars via co-precipitation was used for the removal of Cd(II) from aqueous solutions. FT-IR characterization of the prepared MBC prior to and following the adsorption of Cd(II) showed a shift in the absorption bands of –OH and Fe–O after adsorption, confirming the involvement of these functionalities in the removal of Cd(II) via ion-exchange and complexation reaction. In a similar scenario, MBCs prepared from either tea waste or rice husks were employed for the removal of the hexavalent chromium ions, Cr (VI). FT-IR and XPS analyses showed the exchange of Cr(VI) with the –OH, C–H and $-COO^-$ functionalities as indicated by the changes in the positions of the spectral bands (Shakoor et al. 2024).

Though most of the reported studies have focused on ion-exchange as a mechanism for the removal of heavy metals by MBCs, relatively few have explored its potential role in the removal of emerging organic pollutants. In this regard, Jin et al. (2023) reported the competitive adsorptive removal of sulfamethoxazole and bisphenol A on MBC prepared from municipal sludge. They showed that the presence of Cl ions on the surface of the MBC (prepared via impregnation with iron (III) chloride) facilitated this adsorptive removal via ion-exchange. More precisely, the MBC showed a better buffering capacity compared to the pristine counterparts thanks to the exchange of the Cl ions with the OH ions under alkaline conditions. In the case of binary solutions, Jin et al. (2023) also highlighted the importance of ion-exchange of the Cl ions with the anions of both pollutants as a removal mechanism.

7.1.3 Electrostatic interaction mechanism

Electrostatic interactions occur because of the attractions between ions bearing opposite charges as shown in Fig. 2b. Electrostatic attractions, therefore, serve as the principal force for ionic bond formation, and forging a stable ionic structure facilitates the removal of the target pollutant. As the word ‘interactions’ could denote either attraction or repulsion, it could be inferred that the relationship between the pH of the pollutant solution and the MBC’s pH_{PZC} plays a fundamental role in governing these electrostatic dynamics (Abbas et al. 2018). From this perspective, several studies have been strategically tailored to engineer a charge contrast, thereby guaranteeing maximum adsorption of the target pollutant or selectively favoring the uptake of one pollutant over the other from multiple pollutant solutions.

The strength of electrostatic interactions is usually determined by the amount of the positive/negative charges on the biochar’s surface (Tan et al. 2021a). For instance, the presence of the −OH groups on the surface of the biochar was found to be the main factor in imparting its surface negative charge, and hence its capability to fix soil Cd(II) ions (Tan et al. 2020). Interestingly, H-bonding and temperature increase were found to have a negative impact on the surface negative charge, in contrast to the impact of pH and polar functionalities. In another study, the removal of Cd(II) from wastewater was performed using MBC of rice straw following a treatment with a mixture of Fe(II)/Fe(III) (Tan et al. 2017). This MBC was rich not only in the oxygen containing moieties (carbonyl, carboxyl, hydroxyl), and the aromatic structures (C = C and ether) but also in iron oxides (Fe_xO_y), as evidenced by the corresponding peaks in the FTIR spectrum. FTIR analysis further indicated a weakening and shift of the Fe–O vibrational peak, suggesting the formation of $CdFe_2O_4$. This inference was corroborated by XRD analysis, which confirmed the crystalline structure of $CdFe_2O_4$. As such, Tan et al. (2017) suggested that Cd(II) adsorption could be attributed to a chelation mechanism involving oxygen-containing functional groups, as well as isomorphic substitution within the Fe_2O_3 lattice.

Duan et al. (2025) developed an iron-doped MBC from sawdust for the removal of polystyrene microplastics with different functionalities. Measurements of zeta potential and analysis of surface functionalities on the surface of the biochar helped interpret the removal mechanism(s). Analytical outcomes showed that the removal rate and capacity were the highest in the case of carboxyl-modified polystyrene, thanks to the favored electrostatic attraction between the negatively charged polystyrene and the positively charged MBC surface at pH = 6. Under alkaline conditions, the same authors reported unexpected behavior of the magnetic biochar. Despite the electrostatic repulsion typically observed under these conditions, the MBC was reported to maintain strong adsorption performance—an outcome considered atypical. This finding could therefore infer the involvement of other mechanisms such as complexation of the carboxyl groups on the polystyrene surface with the functionalities on the magnetic biochar. In the aforementioned study of Jin et al. (2023), the pHpzc of the MBC was 4.78, therefore, at neutral pH, the negatively charged sulfamethoxazole molecule would suffer electrostatic repulsion while the neutral bisphenol A would not experience the same effect. This finding explains the favorability of bisphenol A adsorption from mixed solutions. In a similar context, the immobilization of metal cations in the soil during remediation applications could be facilitated by electrostatic interactions. More precisely, the alkaline nature of the MBC helps reduce soil acidity via the lime-effect and increase the negative charge on soil particles. Consequently, this effect facilitates the electrostatic attraction with metal cations (Xiao et al. 2023; Li et al. 2024a, b).

7.1.4 Surface complexation mechanism

Surface complexation could be simply described as the interaction of an electron donor with an electron acceptor to form a new arrangement—known as 'the complex' (Fig. 2c). The surface functionalities play a crucial role as key determinants in facilitating such a mechanism. Complex formation is another mechanism that is commonly triggered by the presence of the oxygen-containing functional moieties. The ability of oxygen-containing functionalities to donate lone electron pairs facilitates the formation of coordination complexes with heavy metal ions, thereby stabilizing metal–ligand complexes (Li et al. 2020a).

Several studies have addressed surface complexation as an adsorption mechanism by magnetic biochars. Zhu et al. (2018a) found that the removal of Eu(III) at acidic to neutral pH (2.0–7.0) is governed by the surface complexation mechanism compared to electrostatic attraction at alkaline pH values. In another study, Ca-modified MBC was used to remediate As(III) and Cd(II) binary solutions (Wu et al. 2018). The outcomes showed that the adsorption of both metals from their individual solutions was pH dependent. At an acidic pH and as expected, electrostatic repulsion could be encountered due to the repulsion between the H^+ on the surface of the MBC and the Cd(II). At pH values higher than 8, $Cd(OH)_2$ was the prominent insoluble form species. For As(III), however, the weak adsorption at highly acidic pH was attributed to the presence of iron in the solution as a result of dissolution of iron oxide following equilibrium. The high buffer capacity of the MBC caused almost no change in the removal capacity between pH 3–9. The elevated pH values (where the oxygenated functionalities become deprotonated), therefore, favor the adsorption of Cd(II) compared to As(III) via electrostatic attractions. For the binary metal solutions, adsorption of both metals was lower compared to their individual solutions implying the occurrence of competition on sorption sites irrespective of the pH value. The formation of ternary type B surface complexes by As(III) explained the synergistic behavior observed for mixture solutions (Wu et al. 2018).

In another interesting study, Yin et al. (2018) produced three activated MBCs derived from rice straw at 300, 500, and 700 °C and subsequently tested them for their ability to remove 17β-estradiol and Cu(II) from single- and dual-contaminant solutions. For individual contaminant solutions, the pH played a major role in portraying the adsorption mechanism. In the case of Cu(II), the adsorption increased as pH was increased from 2.0 to 6.0 where at lower pH, repulsion of Cu(II) with the H_3O^+ could be encountered. In the case of 17β-estradiol, at low pH values ($< pH_{PZC}$ of the biochar and the pK_a of the pollutant) or pH = 10, both the biochar and the pollutant are similarly charged (negative and positive, respectively), therefore, electrostatic repulsion is anticipated. In the binary mixture, however, an interesting behavior was observed. At low concentrations of Cu(II), adsorption of 17β-estradiol was enhanced compared to the individual solutions, which was attributed to the formation of biochar-Cu(II)-17β-estradiol or biochar-17β-estradiol-Cu(II) complexes. At higher concentrations of Cu(II), however, the competitive behavior between both pollutants was observed. To explain Cu(II) adsorption from binary systems, the study highlighted the role of coordination bonding between the *d*-electrons of Cu(II) and the deprotonated oxygenated groups as well as the π-electron interactions between Cu(II) ions and the aromatic domains of biochar. In this regard, the activated MBC prepared at 300 °C—which was the richest in oxygenated functionalities, favored Cu(II) adsorption. In contrast, the activated MBC prepared at 700 ℃ was the best adsorbent of 17β-estradiol because of carboxylic functionalities that acted as electron acceptors while the drug's fused aromatic rings and hydroxyl groups were electron donors, facilitating surface complexation (Yin et al. 2018).

7.1.5 Precipitation mechanism

The formation of insoluble material on the surface of the biochar or in the solution is commonly viewed as a major mechanism for the immobilization of inorganic contaminants (Abbas et al. 2018) (Fig. 2d). Chemical precipitation was reported as a plausible mechanism for the removal of Cu^{2+} and Pb^{2+} ions employing a Fe-modified MBC prepared from macadamia nutshells (Zhou et al. 2024). Co-precipitation was reported as one of the dominant mechanisms in the removal of Cd(II), Cu(II) and Pb(II) employing Fe/Mn oxide-modified biochar as well (Xiao et al. 2020). The latter authors confirmed the occurrence of such a mechanism using the FT-IR analysis where changes in the spectral bands were observed; and XRD analysis where changes of the diffraction patterns were noted in the case of Cd(II) and Pb(II). Such co-precipitation was instigated by confirming the presence of PO_4^{3-} and CO_3^{2-} ions in the medium.

7.1.6 Chemical bonding mechanism

The term 'chemical bonding' encompasses the strong attractive forces that bind adjacent atoms or ions together, forming the basis of molecular and crystalline architectures (Fig. 2e). Examples could include metallic, covalent, and ionic bonding. Non-covalent interactions such as hydrogen bonding (H–bonding), van der Waals forces, and π–π stacking may be less intense compared to the covalent bonds, for instance, but remain fundamentally important (Li et al. 2020a).

In this regard, Gong et al. (2025) prepared an MBC from a mixture of corn cob and red mud and then employed it for the removal of malachite green. The synthesized MBC exhibited dual functionality, serving effectively as both an adsorbent and a catalyst. Spectroscopic evidence from FTIR demonstrated shifts in the spectral bands corresponding to the –OH stretching vibration following the adsorption of malachite green and confirming the occurrence of H–bonding. XPS analysis reflected the formation of covalent bonds between the amino moiety of the dye and the MBC's surface moieties as evidenced by the appearance of a new C–N peak following the adsorption. Gong et al. (2025) attributed this peak to the primary amine functionality of the dye. Furthermore, a N-metal peak was attributed to the formation of bonds with the cations of Al or Fe(III). The occurrence of the π–π stacking was inferred from XPS analysis, where the C–C peak exhibited minimal variation in intensity.

7.1.7 Reduction-based mechanism

Oxygenated functional groups, once again, have a critical function as electron 'shuttles', promoting redox reactions, and thereby contributing to both the immobilization of heavy metals and degradation of organic pollutants (Fig. 2 g) (Gao et al. 2023; Chen et al. 2024). By and large and according to Gao et al. (2023), the term electron 'shuttles' or 'mediators' is part of the general term 'electron transfer', which includes the direct and the indirect electron donation as well as electron acceptance.

As an example, Ke et al. (2022) developed a novel N-doped magnetic biochar from peanut shells using a deep eutectic solvent system of iron(III) chloride and urea, demonstrating its effectiveness in eliminating hexavalent chromium from contaminated environments. Nitrogen doping helped to modify the surface chemistry of MBC, specifically its conjugated structure, charge profile, and basic character, and therefore, improved the remediation of metal cations. These authors attributed the elimination of Cr(VI) to multiple mechanisms, including ion exchange, cation bridging, pore filling, electrostatic attraction, surface complexation, and redox-driven processes. As for the latter mechanism, the presence of Fe(II) helped the reduction of Cr(IV) into Cr(III), while it was oxidized into FeIII). The resulting Cr(III) species can be further sequestered by the N-doped MBC via ion-exchange interactions, with Fe(III) and Fe(II) cations acting as active exchange sites. In addition, Fe(III) cations act as electrostatic mediators, bridging the negatively charged biochar surface and Cr(VI) ions. Besides, Ke et al. (2022) demonstrated that at low pH values, the protonated oxygenated functional groups facilitated the capture of Cr(IV) oxyanions. Two mechanisms were suggested, the direct reduction of Cr(IV) by the oxygen-containing groups and the indirect reduction, where Fe(III) is reduced by the biochar into Fe(II), which in turn facilitated the reduction of Cr(IV). The heteroatom, nitrogen, also facilitated the uptake of Cr(IV) either via electrostatic interactions or via cation-bridging effect. Therefore, as a summary, the upta of Cr(IV) by the N-doped MBC could be best described as 'adsorption-reduction-adsorption' (Ke et al. 2022).

7.1.8 Pore-filling mechanism

In the pore-filling mechanism, molecules of the adsorbate, whether organic or inorganic, move into the porous channels of the adsorbent material and are subsequently captured within these pores (Fig. 2 h). The structural characteristics of biochar, particularly its microporous and mesoporous architecture, directly govern the viability of the pore-filling mechanism for capturing organic pollutants (Abbas et al. 2018). Yet, and as previously indicated, the integration of magnetic nanoparticles not only enhances separation efficiency but also preserves the porous architecture essential for effective contaminant capture (Qu et al. 2022).

Therefore, the porous structure of the MBC plays an important role in capturing the target pollutant (Yi et al. 2020; Katibi et al. 2024; Liu et al. 2020a). Jin et al. (2023) reported that the size of bisphenol A is smaller than that of sulfamethoxazole, therefore, the former could fit better in the pores of the magnetic biochar. The study carried out by Zhang et al. (2023d) showed that the removal of tetracyclines and fluoroquinolones was attributed to a similar pore-filling mechanism, enabled by the mesoporous nature and high surface area of magnetite-enriched poplar biochar. More precisely, the biochar pores were sufficiently large to accommodate the 3D size of the antibiotics under investigation. Besides, micropore-filling was one of the mechanisms reported for the removal of 17β-estradiol employing MBC from lotus seedpod (Katibi et al. 2024).

7.2 Degradation of organic pollutants via photocatalysis

7.2.1 Generalities

Magnetic biochars serve not only as adsorbents for various organic and inorganic contaminants but also as effective and economical catalysts (Majamo et al. 2023). By utilizing the MBC, pollutants can be more efficiently degraded through the activation of strong oxidizing agents, such as hydrogen peroxide or persulfate in a strategy commonly defined as “advanced oxidation processes” (Wang et al. 2021a; Chen et al. 2022a; Tian et al. 2022b; Song et al. 2023). The application of such a strategy serves to transform the organic contaminants into non-hazardous inorganic by-products (Yang et al. 2020). Therefore, the use of MBCs offers a synergistic mechanism for remediating pollutants by adsorption and photocatalytic degradation. The catalytic ability of MBCs is largely due to abundant oxygenated functional groups (OFGs), persistent free radicals (PFRs), magnetic properties, and graphite-like structure (Feng et al. 2021). For instance, MBC made from floc showed a strong potential to catalyze peroxydisulfate activation, significantly enhancing the breakdown of contaminants like tetracycline (Zhuo et al. 2023).

Additionally, a research study carried out by Anak Erison et al. (2022) highlights impregnated MBC as a sustainable catalyst in biodiesel synthesis, demonstrating improved reusability and reduced environmental impact when compared to conventional catalysts. This variety of catalytic uses highlights the adaptability and environmental advantages of magnetic biochars. The following section details the performance of photocatalyst-loaded MBCs in degrading organic pollutants in different environmental contexts with focus on catalytic mechanisms. A summary of the commonly adopted mechanisms is given in Fig. 3. In another context, MBC use increases the generation of methane by the selective enrichment of anaerobic bacteria on its surface. Magnetic biochar provides a workable way to stop methanogen loss in anaerobic digesters, guaranteeing more effective and long-lasting biomethanation procedures (Qin et al. 2017). Magnetic biochar can also boost biogas production during anaerobic digestion of organic waste by increasing the number of microorganisms involved in hydrolysis and methanogenesis. It also alters the microbial population composition, potentially enhancing the overall efficiency of the digestion process (Zhang et al. 2023c). These benefits make MBC use a promising and sustainable solution for addressing solid waste management and pollution challenges.

7.2.2 Photocatalytic degradation mechanism

Overall, the photocatalytic degradation mechanism of organic pollutants proceeds via free radicals. One of the common mechanisms is the persulfate-based strategy. Nonetheless, the free radical of sulfate, $SO_4^{\cdot-}$ shows better criteria and hence superior performance compared to the hydroxyl free radical for example. Compared to the latter, the sulfate free radical possesses a longer half-life of 30–40 μs while that of the hydroxyl is only 20 ns. As such, the stability of sulfate is higher with better selectivity. Most importantly, the sulfate-based advanced oxidation strategies can be operated at a wide pH range (2–8) opening the door for various applications. Additionally, the redox potential of the sulfate free radical is higher compared to that of hydroxyl free radicals (Zhang et al. 2015; Wang et al. 2017, 2021a; Yang et al. 2020; Feng et al. 2021; Liu et al. 2022c; Tian et al. 2022b; Song et al. 2023). The use of photocatalyst-loaded pristine biochar for the degradation of organic pollutants has been a subject of many investigations employing several mechanisms (Bhattacharya et al. 2024; Fazal et al. 2020; Ouyang et al. 2019; Yu et al. 2021). Even so, the limited degradation competencies of the pristine biochar together with the complexities of recycling remain key challenges hindering its practical applicability (Liu et al. 2022c).

As already stated, magnetic biochars offer substantial advantages. On one hand, the use of biochar backbone serves to prevent the aggregation of the magnetic species and hence improves their dispersion and degradation rate and efficiency, especially for persulfate-mediated mechanisms (Gao et al. 2020; Liu et al. 2022c). On the other hand, the presence of several functionalities on the surface of the porous biochar together with the structural defects and the PFRs, all contribute to activating the persulfate and supporting its degradation capabilities (Dong et al. 2019; Fang et al. 2015; Huang et al. 2020; Luo et al. 2022). In other words, the MBC structural defects facilitate the reduction of the persulfate O–O bond energy and hence its stability leading to persulfate activation and release of the free radical. The magnetic biochar also can prevent the leakage of the magnetic particles and hence

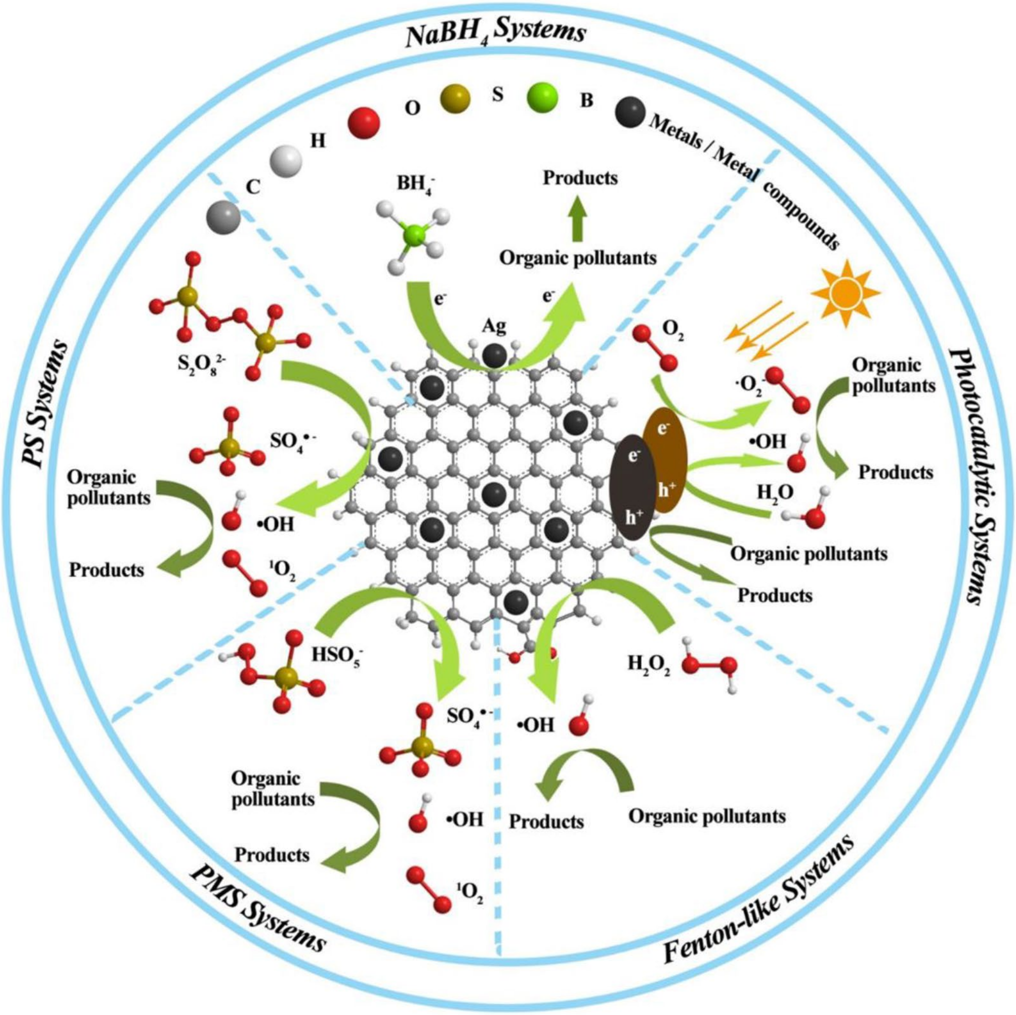


Fig. 3 A summary of the commonly adopted mechanisms for degrading organic pollutants using magnetic biochars. As defined by the authors: PS: Peroxydisulfate, PMS: Peroxymonosulfate, Reproduced from Feng et al. (2021) with permission from Elsevier. License Number: 5965440787642

offer more sorptive sites (Feng et al. 2021; Zhou et al. 2020). Figure 4a shows the persulfate activation pathways using the magnetic biochar (Liu et al. 2022c), while Fig. 4b is a scheme revealing the degradation of tetracycline (antibiotic) on a Mn-doped MBC via a persulfate activation mechanism (Huang et al. 2020).

Another conventional approach for degrading organic pollutants in different environmental matrices is Fenton oxidation. In this strategy, the iron (II) species react with hydrogen peroxide to generate the hydroxyl free radicals (•OH) (Fig. 3) (Feng et al. 2021; Jiang et al. 2023; Song et al. 2024). Generally, Fenton oxidation is simple, easy to operate, fast, ecofriendly with a good degradation efficacy, and does not require energy (Jain et al. 2018; Li et al. 2022; Song et al. 2024; Tian et al. 2022b; Xu and Wang 2012). Nonetheless, in the traditional Fenton processes, oxidation is restricted by the narrow pH range with a probability for metal leaching. The use of hydrogen peroxide requires careful storage and use (Tian et al. 2022b). Therefore, application of Fenton processes alone is likely to hurt the ecosystem, and the process costs could prevent its applicability. The use of biochar as a carbonaceous backbone could overcome these restrictions (Usman et al. 2023). The presence of biochar allows for a better treatment efficacy while lowering the process cost and allowing for better performance at different pH values. The specific use of MBCs as a support in this case forms a heterogeneous Fenton-like system, facilitates recoverability, and hence reduces the chance for secondary pollution (Feng et al. 2021; Tu et al. 2020; Xu et al. 2022b).

On the other hand, the development of an efficient photocatalytic system is generally limited by the possibility of electron pair-hole recombination with a

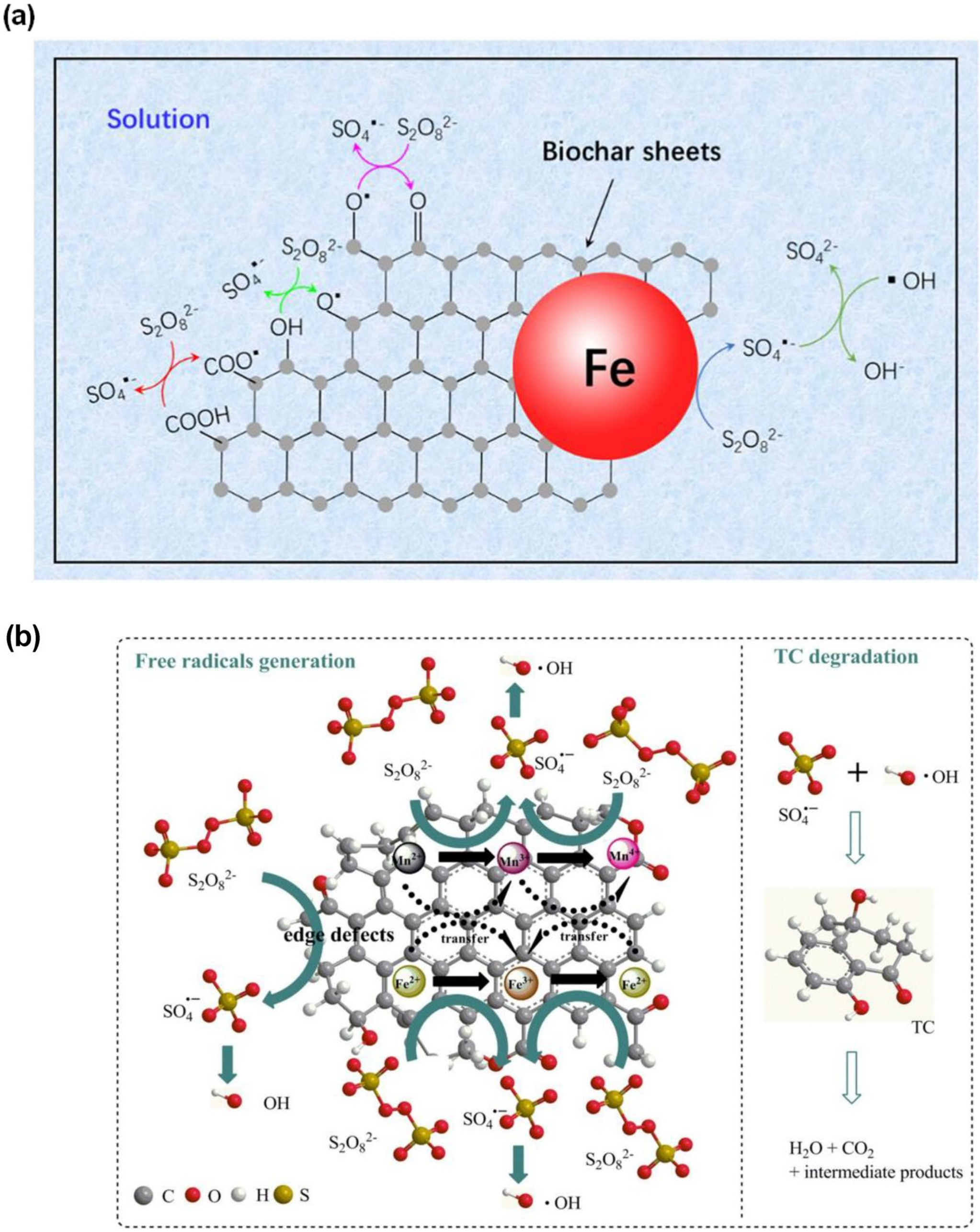


Fig. 4 **a** Persulfate-based degradation of organic pollutants employing magnetic biochar, reproduced from Huang et al. (2020) with permission from Elsevier (License Number: 5971780599357)

difficulty in recovery from the treatment matrix (Chen et al. 2019a, b; Meng and Zhang 2016). The use of biochar as an adsorptive support with good conductive features facilitates the separation of the electron pair-hole and hence minimizes their recombination (Li et al. 2019b; Pi et al. 2015). Once again, the presence of the MBC not only minimizes the aggregation of the photocatalytic species and supports their dispersibility but also allows for a better recovery of the adsorbent-photocatalyst material (Cai et al. 2025; Xu et al. 2024). Other MBC-mediated catalytic systems used for the degradation of organic pollutants are shown in Fig. 3. In conclusion, biochar modification aims to enhance its physico-chemical properties, which in turn activates all the above-mentioned mechanisms for a better efficiency of MBCs during various applications.

8 Major agri-environmental applications of magnetic biochars

8.1 Water treatment

The presence of a high content of contaminants in wastewater represents a serious threat to both the environmental quality and human health (Moukadiri et al. 2024; Santhosh et al. 2024). The use of MBCs for the removal of heavy metals or the recovery of valuable nutrients from effluents has become the major field of research and scientific publications to date (Silva et al. 2020; Yi et al. 2020; Singh and Jadeja 2025). This is justified by both their relatively high adsorption effectiveness and their separation ease from aqueous solutions through magnets instead of centrifugation and filtration processes (Yi et al. 2020). Subsequently, these recovered metal-loaded MBCs can be regenerated and reused again for several consecutive adsorption cycles (Chin et al. 2022). As indicated in Table 4, the removal efficiency of contaminants from aqueous solutions by MBCs seems to be dependent on the material properties that vary according to the pyrolysis process, surface modification, and the adsorption experimental conditions.

8.1.1 Effect of pyrolysis temperature

It is worth mentioning that MBC properties are largely influenced by the pyrolysis conditions and particularly the temperature. Typically, higher pyrolysis temperatures (up to 800 °C) commonly result in a more developed porosity and a larger specific surface area. For example, increasing pyrolysis temperature from 300 to 700 °C increased the total surface area by more than 522%, and its pH of point zero charge (pHpzc) by more than 2.1 units (from 6.72 to 8.85) (Gong and Chi 2022). The surface area of micropores has also substantially increased from less than 1 $m^2 g^{-1}$ at 300 °C to more than 223 $m^2 g^{-1}$ at 700 °C. Moreover, this operation increased the aromaticity of the biochar that was confirmed by the increase of the C–H peak intensity in the FTIR spectra. Altogether, these factors resulted in a net increase of Pb(II) and Cd(II) adsorption capacities (Gong and Chi 2022). For instance, Pb(II) adsorption capacity increased from 151.6 mg g^{-1} by 45.1% and 96.7%, respectively, when the pyrolysis temperature increased from 300 °C to 500 °C and then to 700 °C (Gong and Chi 2022). A similar finding was reported by Khan et al. (2020) when investigating Cd(II) removal by a MBC derived from corn waste straws. They found that Cd(II) removal increased by more than 63.4% when the pyrolysis temperature varied from 600 to 800 °C. Moreover, Wu et al. (2021b) showed that increasing the pyrolysis temperature from 400 to 500 °C improved Pb(II), Cu(II) and Zn(II) retention by 6.7%, 16.0%, and 111.7%, respectively. This was mainly attributed to the enhancement of both the textural properties (increase in surface area by 12.4% and pore volume by 20%) and surface richness with various functional oxygenic groups.

Nevertheless, opposite results have also been reported by some studies. For instance, Yang et al. (2024a) reported that increasing the pyrolysis temperature from 300 to 500 °C of a MBC derived from corn straw decreased the adsorption capacities of Pb(II) and As(III) from 117.1 to 73.6 mg g^{-1}, and from 10.8 to 7.8 mg g^{-1}, respectively. This finding was observed despite the increase of the BET (Brunauer–Emmett–Teller) surface area from 13.0 to 23.0 $m^2 g^{-1}$. The higher removal efficiency at lower pyrolysis temperature was attributed to the more abundant dissolved organic matter contents in organic functional groups (especially C–O and C–C groups). Moreover, for magnetic microalgae-derived biochars, Tian et al. (2025) showed that the removal efficiency of Cd(II), Cu(II), and Zn(II) decreased when the temperature increased from 200 to 400 °C. This finding emphasizes the complexity of the heavy metals' adsorption process by magnetic biochars that is dependent on various parameters including the nature of the feedstock, the type of modification, the pyrolysis temperature, and the heavy metal properties.

8.1.2 Effect of modification methods

The structural, textural and surface chemistry properties of MBCs highly affect contaminant removal from aqueous solutions. Compared to raw MBCs, surface modification usually enhances the adsorption capacity allowing a better removal efficiency (Jia et al. 2019; Lv et al. 2020; Hu et al. 2025). As previously mentioned, numerous modification methods have been adopted. They encompass the use of acids (Chen et al. 2023b; Cai et al. 2024; Latifian et al. 2024), bases (Fan et al. 2023; Jiao et al. 2023; Zhang et al. 2023a), metal salts (Jia et al. 2019; Lv et al. 2020; Maneechakr and Mongkollertlop 2020; Lyu et al. 2022), other specific chemical mixtures (Li et al. 2019a; Truong et al. 2022; Singh et al. 2023), clays (Hu et al. 2025), and calcium carbonates (Wu et al. 2018). The thermal treatment of MBCs through calcination at high temperatures was also tested to improve the surface properties (Oladipo et al. 2019).

Typically, MBC activation with alkaline reagents (i.e., KOH) significantly improves the properties of the resulting material and its capacity for removing heavy metals. For instance, a KOH-modified walnut shell MBC exhibits a hierarchical honeycomb structure with exceptionally high BET surface area (914.0 $m^2 g^{-1}$) and pore volume (0.499 cm3 g^{-1}), as well as a rich surface with

Table 4 Use of magnetic biochars for contaminant adsorption from aqueous solutions under various experimental conditions* (T: pyrolysis/adsorption temperature; G: pyrolysis gradient; t: pyrolysis/adsorption time; TPV: total pore volume; C_0: initial concentration; D: adsorbent dose; Q_m: maximal adsorption capacity)

Feedstock	Pretreatment condition	Pyrolysis condition	Post-treatment condition	BET-N_2 surface area (m^2g^{-1})	TPV (cm^3g^{-1})	pHpzc	Element	Adsorption condition	Qm (mg g^{-1}) or (%)	Mechanism	Reference
Microalgae *Desmodesmus* sp. CHX1	Mixing with K_2FeO_4 at a mass ratio of 1:4	T = 200 °C; t = 1 h	–	176.3	0.11	7.54	Cd	C_0 = 10–200 mg/L; D = 1 g/L; pH = 5; t = 24 h; T = 20 °C	59.1	Physical adsorption, complexation, cation–π interactions	(Tian et al. 2025)
							Cu		43.8		
							Zn		36.4		
							Pb		147.2		
							Mn		17.7		
Rosemary leaves	Mixing with 10% H_3PO_4 at a mass ratio 1:5	T = 220 °C; t = 2 h	Impregnation with a 0.1 M of Fe_3O_4	62.7	0.27		Co	C_0 = 10–100 mg/L ; D = 0.4 g/L; pH = 6; t = 0.42 h	121.2	Ion exchange, electrostatic interactions, precipitation, complexation	(Arabkhani et al. 2023)
						–	Pb		106.5		
Peanut hulls	Impregnation with $FeCl_3$ .6H_2O solution	Hydro-thermal reaction	Impregnation with hexamethylene diamine	62.4	0.34	–	Cr	C_0 = 25–250 mg/L; D = 1 g/L pH = 2; t = 23 h; T = 25 °C	142.9	Reduction, Van der Waals forces, electrostatic attraction	(Cai et al. 2019)
Rice straw	–	T=300 °C; t=2 h	Impregnation with β-cyclodextrin and Fe_3O_4 100 mL DI water containing NaH_2PO_4, EDTA and HO(CH_2CH_2O) nH and then mixed with alginate solution	–	–	–	Pb	C_0 = 50-300 mg/L ; D = 0.5 g/L ; pH = 5; t = 3 h; T = 25 °C	451.5	Electrostatic attraction and complexation, π-π interaction, pore filling, host guest interaction and H bonding	(Chen et al. 2023a)
								Idem, T = 40 °C	455.9		
								Idem, T = 55 °C	547.4		
Cow litter	–	T = 350 °C; t = 4 h	Magnetite co-precipitation with $FeSO_4$.7H_2O and $Fe(NO_3)_3$ then mixing with 5% CH_3COOH solution containing a phosphate rock. Mixture calcination at 350 °C for 1 h	13.66	0.05	–	Cd	C_0 = 0–490 mg/L; D = 1.2 g/L; pH = 5; t = 6 h; T = 25 °C	120.9	Precipitation, ion exchange, complexation, and cation–π interactions	(Chen et al. 2023b)
								Idem, T = 35 °C	127.5		
								Idem, T = 45 °C	132.8		
							Pb	C_0 = 0–160 mg/L ; D = 1.8 g/L ; pH = 5; t = 6 h; T = 25 °C	451.2		
								Idem, T = 35 °C	478.2		
								Idem, T=45 °C	486.8		

Table 4 (continued)

Feedstock	Pretreatment condition	Pyrolysis condition	Post-treatment condition	BET-N_2 surface area (m^2g^{-1})	TPV (cm^3g^{-1})	pHpzc	Element	Adsorption condition	Qm (mg g^{-1}) or (%)	Mechanism	Reference
Sludge	Impregnation with $FeCl_3.6H_2O$ solution	T = 300 °C; t = 1 h	–	77.924	0.210	–	Pb	C_0 = 5–200 mg/L	45.7	Chemical adsorption and physical adsorption through complexation reactions, ion exchange, π-π bonding in carboxyl groups, pore filling, electrostatic adsorption, and oxidation	(Deng et al. 2024)
							Sb		45.3		
Tea waste	Hydrothermal carbonization; Impregnation with $FeCl_3·6H_2O$ and $KHCO_3$ solution	T = 700 °C; G = 5°C/min t = 2 h	–	1072	0.66		Cu	C_0 = 5–50 mg/L; D = 0.5g/L; pH = 6; t = 24 h; T = 25 °C	17.3	N/O functional groups complexation and electrostatic interaction,	(Fan et al. 2023)
Peanut shell	Impregnation with the mixture solution of Mn^{2+} Fe^{3+}	T = 150 °C; t = 24 h	–	54.65	–	–	Cr	C_0=0-100 mg/L; D=1 g/L pH= 4; t=8 h; T=25 °C	46.51	Electrostatic interaction, surface complexation and chemical precipitation.	(Han et al. 2022)
Poplar sawdust	Impregnation with sulfuric acid solution	T = 500 °C; G = 10°C/min; t = 1 h	Magnetite co-precipitation with $FeCl_3·6H_2O$, and $FeSO_4·7H_2O$	7.9	0.055	5.7	Pb	C_0=30-50 mg/L ; D=0.08g/L ; pH= 7; t=0.17h; T=25°C	114.9	–	(Latifian et al. 2024)
Paulownia tree leaves	Impregnation with $FeCl_3$solution	T = 600 °C; t = 1 h	Mixing with CeO_2 and MoS_2 in a polyethylene glycol solution, heating at 240 °C for 2 h.	127.6	0.087	3.68	Pb	C_0 = 5–300 mg/L; D =1 g/L	263.4	Electrostatic attraction, Cπ–Pb(II) bond interaction, and complexation	(Li et al. 2019a)
Cow manure	–	T = 800 °C	Magnetite co-precipitation with $FeCl_3·6H_2O$, and $FeSO_4·7H_2O$	47.1	7.948	–	Cd	C_0 = 0–100 mg/L ; D = 14 g/L; pH = 5; t = 24 h; T = 25 °C	58.8	Surface complexation and ion exchange	(Li et al. 2023d)
Corn straw		T = 600 °C		144.8	1.923			C_0 = 0–100 mg/L; D = 12 g/L; pH = 8; t = 24 h; T = 25 °C	22.9		

Table 4 (continued)

Feedstock	Pretreatment condition	Pyrolysis condition	Post-treatment condition	BET-N_2 surface area (m^2g^{-1})	TPV (cm^3g^{-1})	pHpzc	Element	Adsorption condition	Qm ($mg\ g^{-1}$) or (%)	Mechanism	Reference
Banana peels	Impregnation with $FeCl_3·6H_2O$ solution	T = 600 °C; t = 5 h	–	276.9	–	–	Cd	C_0 = 10–350 mg/L; D = 5 g/L pH = 8; t = 24 h; T = 25 °C	21.82	Ion exchange, surface complexation, and precipitation	(Limmun et al. 2024)
Peanut hull	Impregnation with 2 M $FeCl_3$solution	T = 550 °C	–	243.23	0.14	–	Cr	C_0 = 10–350 mg/L; D = 5 g/L pH = 6; t = 72 h; T = 25 °C	6.6	Electrostatic adsorption, complexation, and reduction	(Liu et al. 2024)
Rice straw	–	T = 500 °C; t = 1.5 h	Impregnation with HCl at a ratio 10:1, then impregnation with acid mine drainage and $FeSO_4·7H_2O$ solution	130.89	0.22	–	Pb	C_0 = 0–500 mg/L; D = 4 g/L pH = 7; t = 24 h; T = 25 °C	329.7	Physical adsorption, ion exchange, electrostatic attraction, and complexation	(Long et al. 2023)
							Zn		103.7		
Chinese traditional herb residues	–	T = 300 °C; t = 2 h	Magnetite co-precipitation with $FeCl_3·6H_2O$, and $FeSO_4·7H_2O$	59.3	0.199	–	Cr	C_0 = 5–500 mg/L; D = 2 g/L pH = 2; t = 1.5 h; T = 25 °C	45.5	Electrostatic attraction, and precipitation	(Shang et al. 2016)
Oil palm fronds	–	T = 300 °C; t = 3 h	Magnetite co-precipitation with $FeCl_3·6H_2O$, and $FeSO_4·7H_2O$	182.8	1.394	5.64	Cu	C_0 = 10–50 mg/L; D = 2.5 g/L; pH = 5.4; t = 2 h; T = 26 °C	47.5	Pore filling effect, complexation, electrostatic attraction and ion exchange	(Shitu et al. 2024)
Waste pine needles	–	T = 500 °C; G = 10 °C/min	Impregnation with Fe_3O_4, then mixing with 3-aminopropyl triethoxysilane	–	–	4.85	Cd	C_0 = 0–50 mg/L pH = 3; t = 2 h; T = 26 °C	23.2	Lone pair donation, cation exchange, reduction and complexation	(Singh et al. 2023)
								Idem, pH = 11	125.0		
							Pb	C_0 = 0–50 mg/L pH = 3; t = 2 h; T = 26 °C	26.3		
								Idem, pH = 11	142.9		
Rice husk	Impregnation with $Fe(NO_3)_3·9H_2O$ in methanol solution	T = 600 °C; G = 10 °C/min; t = 1.5 h	Impregnation with $KMnO_4$ and activation at T=600 °C for 0.5 h	137.0	0.112	8.51	Pb	C_0 = 10–500 mg/L; D = 2.5 g/L; t = 24 h; T = 25 °C	148.6	Precipitation, π interactions, complexation, and electrostatic attraction	(Sun et al. 2019)
							Cd		76.9		

Table 4 (continued)

Feedstock	Pretreatment condition	Pyrolysis condition	Post-treatment condition	BET-N_2 surface area (m^2g^{-1})	TPV (cm^3g^{-1})	pHpzc	Element	Adsorption condition	Qm (mg g^{-1}) or (%)	Mechanism	Reference
Sewage sludge	Mixing with Fe_3O_4	T=800 °C; G=5°C/mint=2 h	-	63.7	0.089	-	Pb	D = 2 g/L; pH = 6; t = 2 h; T = 25 °C	113.64	Precipitation, complexation, cation exchange, and electrostatic attraction	(Tian et al. 2022a)
								Idem, T = 35 °C	131.58		
								Idem, T = 45 °C	151.52		
							Cd	D = 2 g/L; pH = 6; t = 2 h; T = 25 °C	101.01		
								Idem, T = 35 °C	106.38		
								Idem, T = 45 °C	109.89		
Brown microalgae	–	T = 700 °C; G = 10°C/min; t = 2 h	Impregnation with a solution containing $FeCl_3·6H_2O$, thylenediamine, sodium acetate trihydrate then hydrothermal at T=200°C for 6 h	66.5	0.358	10.1	Cu	C_0 = 5–40 mg/L D = 0.2 g/L t = 12 h T = 25 °C	92.6	Electrostatic interaction, complexation, surface precipitation, and ion exchange	(Truong et al. 2022)
								Idem, T = 20 °C	97.1		
								Idem, T = 25 °C	105.3		
								Idem, T=30°C	109.9		
								Idem, T=35°C	122.0		
Ginkgo leaves	–	T = 700 °C; G = 10 °C/min; t = 3 h	Manganese ferrite co-precipitation with $KMnO_4$ and $FeSO_4.7H_2O$	79.3	–	7.4	As	C_0 = 2–50 mg/L; D = 0.2 g/L; pH = 7; t = 24 h; T = 25 °C	142.18	Electrostatic interaction, surface complexation, hydrogen bonding, and π - π interactions	(Wen et al. 2021)
spruce sawdust	Mixing with $FeCl_3·6H_2O$	T = 200 °C; t = 15 min	Mixing with iron salt + pyrolysis at 600 °C	94	0.002	–	PO_4^{3-}	C_0 = 5–25 mg/L D = 2 g/L; t = 3 h; T = 22 °C	25%	Complexation with Fe_2O_3 particles, pore filling effect	(Tomin and Yazdani 2022)
			Mixing with iron salt + pyrolysis at 800 °C						30%		
		T = 300 °C; t = 15 min	Mixing with iron salt + pyrolysis at 600 °C						18%		
			Mixing with iron salt + pyrolysis at 800 °C						25%		
Phragmites australis	Mixing with Fe_3O_4	T = 600 °C; t = 25 min	–	232.69	–	4.3	PO_4^{3-}	C_0 = 50 mg/L; D = 0.1 g/L; t = 1440 min; T = 25 °C	7.22	Electrostatic attraction, complexation	(Wang et al. 2019c)
			Doping with Ce	279.16		4.6			12.5		
			Doping with La	236.02		5.0			20.5		

Table 4 (continued)

Feedstock	Pretreatment condition	Pyrolysis condition	Post-treatment condition	BET-N_2 surface area (m^2g^{-1})	TPV (cm^3g^{-1})	pHpzc	Element	Adsorption condition	Qm (mg g^{-1}) or (%)	Mechanism	Reference
Corn straw	–	T = 600 °C; t = 1.5 h	Mixing with $FeCl_3$ for 24 h under continuous agitation	48.41	0.0159	–	NO_3^-	C_0 = 30 mg/L; D = 0.05 g/L; pH = 6; t = 1400 min; T = 25 °C	3.48	Electrostatic attraction, pore filling, and surface functional groups	(Tan et al. 2022)

*Missing parameters in the Table indicates that related data are not available in the reference source various functional groups including Fe–O, C–O–C, –COOC–, C=C and C–N bands (Jiao et al. 2023). This allowed a significant and efficient removal of Cr(VI) (230.6 mg g^{-1}) that occurred through a combination of electrostatic attraction, ion exchange, complexation, and reduction into Cr(III). Similarly, a high BET surface area (937.1 m^2 g^{-1}) and pore volume (0.562 cm g^{-1}) were also observed for a KOH pre-treated magnetic biochar derived from the pyrolysis at 700 °C of Chinese aquatic herb residues (Zhang et al. 2023a). These values are 62.0 and 5.9 times higher than those measured for the same magnetic biochar without pre-treatment with KOH. Moreover, Zhang et al. (2023a) found that the KOH-modified MBC is rich in various oxygenic functional groups such as –OH, C–O, and Fe–O, which allows a high removal capacity of Cr(VI) (175.4 mg g^{-1}). The involved mechanisms were explored through the use of several specific analyses (i.e., FTIR, XPS) on the material before and after Cr(VI) adsorption. Results show that Cr(VI) removal was ensured through the combination of pore filling, complexation with –OH, Fe–O, and C=O, electrostatic attraction (with $HCrO_4^-$) at low pH values, and reduction into Cr(III).

Modification with acidic solutions has also been used to improve the adsorption efficiency of MBCs in removing contaminants. For instance, Wu et al. (2022) showed that the modification with hydrochloric acid of a magnetic sludge biochar enhanced ammonium adsorption capacity by 10.7% as compared to the untreated magnetic form. They attributed this increase to the improvement of electrostatic attraction and ion exchange processes as the main adsorption mechanisms. Wang et al. (2024b) synthesized MBC from Chinese herb residues and modified it with a 2% acetic solution, chitosan and glutaraldehyde. They showed that the resultant material had modest textural properties with a BET surface area of 18.4 m^2 g^{-1} and a total pore volume of only 0.102 cm^3 g^{-1}. However, the removal capacities of this modified MBC for As(III), Cr(VI), and Pb(II) were relatively high (45.9, 52.2, and 59.9 mg g^{-1}, respectively). This was imputed to its distinctive surface chemistry properties and composition allowing adsorption through the combination of various mechanisms including complexation with –COOH, –OH, and $–NH_2$, cation exchange with Na^+, K^+, and Mg^{2+}, electrostatic attraction, and also reduction of Cr(VI) into Cr(III) and oxidation of As(III) into As(V). A comparable Cr(VI) removal capacity of 55.5 mg g^{-1} was reported for a H_3PO_4-modified MBC from Typha leaves (Cai et al. 2024). Moreover, high removal capacities of Pb(II) were reported for a H_2SO_4-modified magnetic biochar from poplar sawdust (114.9 mg g^{-1}) (Latifian et al. 2024), and a calcined magnetic biochar from cow litter modified with acetic acid containing a phosphate rock (451.2 mg g^{-1}) (Chen et al. 2023b). This significant removal rate was mainly attributed to the presence of the rock phosphate. Indeed, the use of mechanistic analysis showed that phosphates and carbonates on the surface of the modified MBC contribute to the removal of more than 54% of the overall Pb(II) through precipitation. Moreover, around 24% of Pb(II) adsorbed amount was exchanged with Ca(II) from the phosphate rock.

Magnetic biochar modification with metal salts can improve their adsorbing properties for toxic heavy metals as well. For instance, Maneechakr and Mongkollertlop (2020) showed that the treatment of MBC derived from palm kernel cake residues with $KMnO_4$ significantly enhances the properties of the resulting biochar. Indeed, MnO_2 nanoparticles deposition onto the surface of the MBC contributed to achieving a relatively high BET surface area (89.4 m^2 g^{-1}). In addition, this MBC had also a rich surface with various oxygenic functional groups that allowed the removal of Pb(II), Cd(II), Cr(III), and Hg(II) at 49.6, 18.6, 19.9, and 13.7 mg g^{-1}, respectively. In another study, Sun et al. (2019) showed that the post-modification with $KMnO_4$ of an MBC made from rice husks improved Pb(II) and Cd(II) adsorption by 8.7 and 7.9 times respectively, compared to the unmodified form. This significant performance was observed despite a decrease in BET surface area by 50.2% due to pore blockage with Mn nanoparticles. This was explained by the improvement of the surface chemistry of the modified magnetic biochar. Accordingly, the pHpzc increased from 6.78 to 8.51, which favored metal removal by precipitation. Moreover, heavy metals complexation was improved due to the involvement of several oxygenic functional groups such as –OH, –COOH, and O-Mn. Likewise, a relatively high Sb(V) adsorption capacity of 21.9 mg g^{-1} was also measured for a nano-cerium-doped MBC made from *Phragmites australis* biomass. This adsorption rate was much higher than that found for the non-doped biochar (1.7 mg g^{-1}) (Table 4).

It is worth mentioning that MBCs decoration with layered double hydroxides (LDHs) through the simultaneous impregnation with bivalent (i.e., Ca, Mg, Ni, Zn, etc.) and trivalent cations (Al, Fe, Ga, etc.) was found to be an interesting method for an efficient removal of heavy metals from aqueous solutions. For example, Jia et al. (2019) synthesized a MBC from oil-tea camellia shells and then functionalized it with Mg/Fe-LDHs through impregnation with a solution of $Fe(NO_3)_3$ and $Mg(NO_3)_2$. The success of the functionalization step was confirmed with XRD, FTIR, and SEM/EDS analysis, which confirmed the formation of $Mg_6Fe_2CO_3(OH)_{16}·4H_2O$ precipitate at the surface of the biochar, the apparition of new CO_3^{2-}-based functional groups, and the net increase of Mg and Fe peaks intensity. Moreover, this step enhanced the BET surface area and the total pore volume by 129.6%, and 197.8%, respectively, and decreased the average pore size from 20.1 to 7.0 nm. Consequently, this functionalization resulted in an increase of Pb(II) adsorption capacity from 67.1 to 476.2 mg g^{-1} (Jia et al. 2019). In another study, the functionalization of a MBC derived from wheat straw at 600 °C with Mg/Al LDHs increased Cd(II) adsorption by 2.4 times. This same modified MBC was further doped with sodium carbonates, which increased Cd(II) removal by a factor of 3.7 due to carbonate anions intercalation within the Mg/Al LDHs. This amelioration was mainly attributed to $CdCO_3$ precipitation, complexation with functional groups and cation exchange with Mg(II) (Lv et al. 2020). A similar trend was reported by Lyu et al. (2022) who investigated the simultaneous removal of As(III) and Cd(II) from aqueous solutions with a bamboo-derived MBC cross-linked with Ca/Mg/Al LDHs composite. Consequently, the modified MBC had much higher adsorption capacity for both As(III) (256.3 mg g^{-1}) and Cd(II) (320.7 mg g^{-1}) than the unloaded form.

Some other studies have used specific mixtures of chemicals to obtain MBCs with outstanding properties for contaminant removal. For instance, Li et al. (2019a) modified a magnetic biochar generated from the pyrolysis of paulownia tree leaves at 550 °C with a mixture of cerium oxide (CeO_2) and molybdenum disulfide (MoS_2). They showed that after this treatment, the original BET surface area (89.4 m^2 g^{-1}) and total pore volume (0.032 cm^3 g^{-1}) increased by more than 1.4, and 2.7 times, respectively. Moreover, the surface chemistry of this modified MBC was significantly enhanced through the enrichment with several functional groups such as Ce–O, –OH, Mo–S, O–H, and C=C, which significantly enhanced Pb(II) removal. Moreover, this modified-magnetic biochar acquired a superparamagnetic state allowing its easy separation from aqueous solutions after decontamination. Singh et al. (2023) post-modified MBC produced from pine needles at 500 °C with 3-aminopropyl triethoxysilane to incorporate amine and silane groups onto the biochar surface. Eventually, the functionalized form had rich surface with various functional groups involving Si–C or Si–O–C, Si–O–Fe, $-NH_2$, C–O, O–H, and C=O. This surface richness, especially in silane and amine groups allowed an efficient removal of both Pb(II) (142.9 mg g^{-1}) and Cd(II) (125 mg g^{-1}). A similar trend was observed when investigating Cu(II) removal by a microalgae-derived biochar modified with a solution containing $FeCl_3.6H_2O$, ethylenediamine, and sodium acetate trihydrate (Truong et al. 2022).

8.1.3 Effect of experimental conditions

8.1.3.1 Contact time The removal of heavy metals by MBCs usually occurs according to the three consecutive steps as follows: (i) a rapid removal due to the availability of numerous adsorption sites at the surface of the adsorbent, (ii) a much slower adsorption rate imputed to metal intraparticle diffusion, and (iii) an equilibrium state characterized by constant adsorbed amounts, corresponding to a full saturation status (Jellali et al. 2021). The required time to reach this equilibrium depends not only on the MBC properties but also on the metal type. Related durations of 40 min, 1.5 h, 4 h, 8 h, and 60 h were observed respectively for thallium removal by a magnetic-illite biochar (Hu et al. 2025), Cu(II) removal by a magnetic macadamia nutshell-derived biochar, Pb removal by a magnetic corn straw-derived biochar (Yang et al. 2024a), Cr(VI) removal by a magnetic *Typha* leaves (Cai et al. 2024), and Cr(VI) by a magnetic peanut hull-derived biochar. Lower contact times result in lower energy expenses and are usually preferred in case of full-scale applications (Jellali et al. 2024b).

8.1.3.2 Initial aqueous pH The pH of effluents is a key parameter that significantly affects contaminant removal by magnetic biochars. In fact, this parameter influences not only metal speciation but also the protonation degree of the functional groups and consequently the overall charge of the MBC particles. When the aqueous pH value is lower than the pHpzc, the MBC surface is mainly positively charged. This will result in a repulsion of the cationic metals and attraction of the negatively charged forms. For instance, Cr(VI) exists in different forms versus the aqueous pH: it is found as $HCrO^{4-}$ and Cr_2O^{7-} for pH values between 0.7 and 6.5 and as CrO_4^{2-} for pH higher than 6.5 (Unceta et al. 2010). Therefore, Cr(VI) removal is usually larger in acidic media where its anionic forms are attracted to positively charged MBC particles (Shang et al. 2016; Zhang et al. 2023a). However, when the effluent has a pH value higher than pHpzc, the MBC surface will be negatively charged and consequently will attract the positively charged heavy metals. For example, Maneechakr and Mongkollertlop, (2020) reported that increasing the aqueous pH from 3.0 to 9.0 increases Pb(II) adsorption by a palm kernel cake-derived MBC by around 100%. Furthermore, the protonation degree of MBCs usually decreases with the increase of the effluent pH values, which allows the presence of adsorption sites with oxygen and nitrogen, and therefore improves removal performance (Qu et al. 2022).

8.1.3.3 Contaminant and biochar concentrations Typically, the adsorption performance of MBCs rises with the increase of contaminant initial concentration (C_0). This is due to the higher gradient concentration between the aqueous solution and the porosity of magnetic biochars. For instance, the presence of large amounts of heavy metals will increase the probability of good contact with the active adsorption sites of the magnetic biochar (Khanzada et al. 2024). The adsorption of heavy metals may reach a quasi-plateau for high initial concentrations. The curve giving the adsorbed amount onto the MBC against the residual heavy metal concentration in the aqueous solution is usually used to predict the related adsorption capacities through theoretical models (i.e., Langmuir, Dubinin-Radushkevitch, etc.). Table 4 gives the calculated adsorption capacities for various heavy metals by numerous MBCs at different initial concentration ranges. On the other hand, for a constant initial heavy metal concentration, the removal efficiency rises as the dose of the adsorbent increases until reaching a plateau corresponding to a saturation of the MBC adsorption sites. The required doses to reach this maximum efficiency depend on both the heavy metal properties and MBC adsorption ability. For example, this plateau was observed for 1.5 g L^{-1} of a magnetic-illite biochar used to remove thallium added at 10 mg L^{-1} (Hu et al. 2025), and for 6 mg L^{-1} of MBC made from *Conocarpus erectus* leaves used to remove cobalt at 10 mg L^{-1} as well (Qasim et al. 2023).

8.2 Effect of competitive ions

Most studies regarding contaminant adsorption by MBCs have been carried out using synthetic solutions. Chen et al. (2023b) indicated that increasing the ionic strength of these solutions by adding foreign ions, especially at high concentrations, reduces the adsorption capacities of heavy metals. For example, the co-presence of HCO_3^{2-} and PO_4^{3-} ions highly affected the adsorption of the latter on MBC due to strong competition over adsorption sites (Wang et al. 2019c). Very few studies have validated the efficiency of raw/modified MBCs for mineral removal from actual wastewater. In this context, Li et al. (2018) used an aminothiourea chitosan-strengthened magnetic biochar for the treatment of an actual mine water from an abandoned iron mine site having Al(III), Fe(III), Zn(II), Pb(II), Cd(II), Cu(II), and Mn(II) concentrations of 278.1, 301.3, 368.6, 1.8, 4.9, 0.3, and 28.2 mg L^{-1}. They showed that for a contact time of 6 h, a relatively small dose of the modified biochar (1.25 g L^{-1}) succeeded to remove around 100% of Cd(II), Pb(II), and Cu(II), 75.3% of Mn(II), 23.3% of Zn(II), 12.1% of Fe(III), and 7.6% Al(III). The loaded-modified MBC was then easily separated from the treated wastewater using a magnet.

8.3 Agricultural applications of magnetic biochars

In crop production systems, MBC has primarily been studied for its role in restoring croplands contaminated with heavy metals, due to its strong adsorption capacity. By immobilizing heavy metals and reducing their bioavailability, MBC supports agricultural soil remediation, which in turn improves crop health and productivity (Alazzaz et al. 2023; Ma et al. 2024b). As such, its current use has largely been limited to soil remediation purposes rather than as a regular soil amendment for crop production improvement (Xiao et al. 2023). This is supported by the much less published data that address MBC application for specific agricultural purposes compared to the pristine form (Adebajo et al. 2022; Farid et al. 2022; Zhu et al. 2023). As mentioned previously, MBC presents a compelling alternative to unmodified biochar due to its magnetic properties, which allow easier separation from the environment. This feature reduces the risk of secondary pollution, a common issue with conventional powdered biochar that is difficult to recover once applied (Bowden-Green and Briens 2016).

8.3.1 Agricultural soil remediation

Magnetic biochar offers promising solutions for improving soil quality and addressing environmental challenges through pollution control. By increasing the carbon content and elevating soil pH, magnetic biochar enhances metal immobilization in treated soils, as metals become less soluble in more alkaline environments (Diao et al. 2022b). Magnetic biochar also influences the soil microbial community, promoting beneficial metal-stabilizing microorganisms such as Actinobacteriota, Pontibacter, and Alkaliphilus, while reducing the abundance of metal bioavailability-associated groups like Proteobacteria and Bacteroidota. These microbial shifts not only contribute to metal stabilization but also improve the overall stability and diversity of soil microorganisms (Diao et al. 2022b; Li et al. 2024b).

Among various approaches for addressing metal contamination, immobilization/stabilization is a particularly effective method for reducing the bioavailability of toxic trace elements like As and Cd in soil (Lyu et al. 2024). Magnetic biochar, in this context, serves as an effective amendment for contaminated soils, with removal efficiencies as high as 41.3% for Cr and a demonstrated ability to significantly reduce bioavailable forms of Cd and As in polluted environments (Liu et al. 2020b; Wan et al. 2020; Prangmoo et al. 2024). For instance, the functional groups on magnetic biochar, such as C–N, C–H, and C=C, play a crucial role in binding heavy metals like Cr(VI), further enhancing its detoxification potential (Cui et al. 2022). With a recovery rate of 65% and the capacity to reduce substantial percentages of heavy metals from polluted soils within a day, MBC has become a pivotal tool in agri-environmental rehabilitation, combining nutrient recycling with heavy metal stabilization to improve soil health and sustainability (Xiao et al. 2023; Ahmed Khan et al. 2024).

Leveraging MBC as a soil amendment could open new pathways for sustainable crop production, improving soil quality while minimizing potential environmental impacts due to contaminated soils and/or the use of agrochemicals. Lu et al. (2018) mentioned that magnetization-based surface alteration could significantly increase plant production and provide relative benefits for managing some damaged environments. For instance, this modified biochar has increasingly been recognized for its ability to extract and recycle excess nitrogen from soils, which not only mitigates nitrogen runoff but also enables nitrogen recovery for use as a slow-release fertilizer, advancing a circular economy approach (Xin et al. 2017; Ghassemi-Golezani and Rahimzadeh 2022; Zhuo et al. 2023). Likewise, when incorporated into the composting process, the MBC enhances the pore structure and functional groups at the compost interface, creating more accessible sites for microbial activity and nutrient interactions. Additionally, it improves nutrient management by stabilizing nitrogen, promoting functional nitrogen gene expression, and enhancing nitrogen availability for plant uptake after soil application (You et al. 2024). Table 5 summarizes the agricultural benefits related to MBC use under different experimental conditions.

8.3.1.1 Use of modified MBCs in agricultural systems As previously mentioned, the modification of MBC using mineral doping improves its physicochemical properties needed for enhanced applications (Hu et al. 2025; Jia et al. 2019; Lv et al. 2020). For example, Ca-doped MBC showed great potential for improving soil health by significantly increasing both the size of bacterial populations and the diversity of microbial taxa. It also effectively reduced As accumulation in rice plants while promoting growth, indicating its value as a soil amendment in rice paddies (Wu et al. 2020). By stabilizing As in a less bioavailable form and enhancing plant development through proper application rates, this Ca-doped MBC offers substantial benefits for agricultural practices (Wu et al. 2020). In another study, Lyu et al. (2024) reported that Ca–Mg–Al layered double hydroxide supported by magnetic biochar had the ability to immobilize more than 85% of As and Cd in soil.

To advance research in the agricultural field, it is essential to study a wider range of minerals used to enhance magnetic biochars such as macro-elements, given their critical role in plant growth and soil condition-depending availability (Zhu et al. 2018b). In this regard, literature describing the modification and direct agricultural application of nutrient-modified magnetic biochars is almost nonexistent. As we previously described, modification with chemicals has mostly been directed towards environmental applications with subsequent agronomic benefits when applicable. For instance, Luo et al. (2023) used urea to prepare N-modified magnetic biochar-based persulfate for a successful removal of the antifungal drug metronidazole (99.6%) with respect to the non-doped catalyst (7.66%). Likewise, Liang et al. (2024) showed that a P-doped magnetic biochar exhibited remarkable catalytic activity for the degradation of common organic pesticides in an aqueous environment for water decontamination.

Recent studies have found that biochars modified with P could not only effectively immobilize soil metals, but also promote plant growth as a fertilizer by releasing more available phosphorus in soil (Bao et al. 2022; Beatrice et al. 2022). Accordingly, Liu et al. (2019) found that MgO-modified MBC exhibited high removal efficiency of phosphate, which could be later applied in agricultural production systems as a slow-release fertilizer. Likewise, Zhu et al. (2023) prepared an efficient P adsorbent using an Mg/La-modified MBC and subsequently used the P-loaded material as a fertilizer to promote the seed germination and growth of ryegrass (*Lolium perenne* L.) with respect to the unloaded adsorbent and/or the original magnetic biochar. In a comparative study with a conventional chemical fertilizer, Khajavi-Shojaei et al. (2023) found that $MgCl_2$-modified biochar-based slow N-release fertilizer increased corn plant growth, chlorophyll content and leaf area by 37.1%, 13.6%, and 30.4%, respectively. Therefore, further studies should explore how mineral-enriched MBCs, in particular with deficient or recalcitrant nutrients, affect soil and crop productivity over the long term, focusing not only on decontamination but also on the improvement of soil properties, nutrient release and uptake by agricultural plants, and cost-effectiveness as compared to pristine forms and conventional soil amendments.

9 Conclusions

In most published data, magnetic biochars have shown higher efficiency for the remediation of contaminated media compared to pristine forms. This is due to improved surface functionalities and subsequently all related adsorption/degradation mechanisms. As environmental pollution has become a global issue, effluent treatment and to a lesser extent soil remediation using MBCs have been the hot research topics worldwide. Interestingly, the adsorption and catalytic properties of MBCs could be further improved via surface doping with minerals. These co-modified biochars have been successfully tested for environmental applications. Nevertheless, investigating the direct use of these mineral-impregnated MBCs as soil conditioners for the improvement of crop production could provide new insights into agricultural applications, which have been limited to pristine forms so far. This includes examining how these modified

Table 5 Agricultural benefits of magnetic biochar use under different experimental conditions

Feed stock	Application rate	Synthesis condition	Soil condition	Environmental effect	Plant species	Agronomic effect	Reference
Coconut shell	2% dry weight	co-pyrolysis	Paddy field around a livestock farm	Enhanced DTPA-Cu immobilization, decreased copper biotoxicity by 76% due to more active adsorption sites, *in situ* promotion of Cu adsorption.	Lettuce	Enhanced biomass growth	(Ma et al. 2024b)
Wheat straw	0.5–2%	Pyrolysis of potassium ferrate (K_2FeO_4) at 700 °C in a tube furnace as an enhancing agent	Cd-contaminated soil	Reduced Cd bioavailability increased microbial diversity, increased pH, EC, Fe content, and soil enzyme activity; enhanced Cd conversion to less bioavailable forms	Wheat	Increased grain yield by 40.3%, increased antioxidant activity and photosynthesis, hindered Cd translocation, decreased Cd translocation in edible parts	(Fu et al. 2024)
Eucalyptus wood or pig manure compost	2%	Chemical co-precipitation with Fe_3O_4	Cd-, Zn-, and Pb-contaminated paddy soil	Decreased availability of heavy metals, reduced metal translocation, increased iron plaque development on roots, reduced P availability	Common reed	Reduced biomass and photosynthetic ability; lower biomass of soil bacteria and fungi	(Wu et al. 2021a)
Humic acid–magnetic biochar derived from straw	5%	*In situ* precipitation of iron oxides on straw biochar	saline–alkali soil	Increased water content (13.8%), accessible phosphorus (9.4 mg/kg), available potassium (29.5 mg/kg), and soil organic matter (33.9 g/kg)	Chinese cabbage	Increased plant height, soluble protein content, chlorophyll content, and germination rate (83.3%); decreased soluble sugar content	(Li et al. 2023a)
Wheat straw biochar	7.5 %	Wheat straw chips combined with Fe^{3+}/Fe^{2+} solution	Naturally Pb-polluted soils	Reduced Pb levels in contaminated soils by 25.1% to 42.1%.	Ryegrass	Decreased Pb amount in ryegrass by about 30%	(Gong et al. 2020)
Dry fermentation residue	2%	Fe_3O_4-loaded biochar	Pb contaminated loamy-sand soil	Formed Fe/Mn oxide-bound forms from accessible Pb; possible precipitation of Pb with OH^-, PO_4^{3-}, and SO_4^{2-} liberated from biochar	Ryegrass	Reduced absorption of Pb but adverse effects on plant growth	(Duan et al. 2022)
Sewage sludge	5%	Solvent-free method: Biochar with iron-based magnetic particles	Cd-, Zn-, Pb-contaminated soil	Reduced the amount of extractable Cd and Zn by 54.1% and 59.5%, respectively; made the transition to the residual fraction easier; increased CEC, SOM, and pH	–	Soil microbial network showed greater complexity and stability after biochar application	(Li et al. 2024b)
Wheat straw	7.5%	Feedstock pyrolyzed then mixed with Fe^{3+}/Fe^{2+} solution	Cd-contaminated paddy soil	Better extraction of Cd (21.5% to 31.5%) from the exchangeable fraction	Perennial ryegrass	Decreased the amount of Cd in ryegrass by almost 70%, plant growth unaffected	(Gong et al. 2021)

Table 5 (continued)

Feed stock	Application rate	Synthesis condition	Soil condition	Environmental effect	Plant species	Agronomic effect	Reference
Date palm	2%	1:1 molar ratio $FeCl_2$:Fe_2SO_4, NaOH was used to elevate pH to 11.	Mining-polluted soil	Reduced metal concentrations by up to 70% for Cu and Zn; a greater pH rise by 0.38–0.53 units; Cd and Pb levels below detection limits	Wheat	Maximum decrease of metal absorption; increase of biomass by 33.8%	(Alazzaz et al. 2023)

materials would effectively adsorb/release nutrients in soil/substrate systems, support sustainable crop yields, and contribute to global food security.

Abbreviations

BET	Brunauer-Emmett-Teller
CEC	Cation exchange capacity
LDHs	Layered double hydroxides
MBC	Magnetic biochar
pHpzc	PH of point zero charge

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Data availability
Data are available upon request.

Declarations

Consent to participate
Not applicable.

Competing interest
The authors declare no competing interests.

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References

Abbas Z, Ali S, Rizwan M, Zaheer IE, Malik A, Riaz MA, Shahid MR, Zia ur Rehman M, Al-Wabel MI (2018) A critical review of mechanisms involved in the adsorption of organic and inorganic contaminants through biochar. Arab J Geosci 11:1–23

Adebajo SO, Oluwatobi F, Akintokun PO, Ojo AE, Akintokun AK, Gbodope IS (2022) Impacts of rice-husk biochar on soil microbial biomass and agronomic performances of tomato (*Solanum lycopersicum* L.). Sci Rep 12(1):1787. https://doi.org/10.1038/s41598-022-05757-z

Ahmed Khan B, Ahmad M, Bolan N, Farooqi A, Iqbal S, Mickan B, Solaiman ZM, Siddique KHM (2024) A mechanistic approach to arsenic adsorption and immobilization in aqueous solution, groundwater, and contaminated paddy soil using pinecone magnetic biochar. Environ Res 245:117922. https://doi.org/10.1016/j.envres.2023.117922

Alazzaz A, Rafique MI, Al-Swadi H, Ahmad M, Alsewaileh AS, Usman ARA, Al-Wabel MI, Al-Farraj ASF (2023) Date palm-magnetized biochar for in-situ stabilization of toxic metals in mining-polluted soil: evaluation using single-step extraction methods and phytoavailability. Int J Phytoremediation 25:1687–1698. https://doi.org/10.1080/15226514.2023.2187633

Alharbi AF, Alotaibi AA, Gomaa HEM, Abahussain AAM, Abdel Azeem SM (2023) Magnetic biochar by one-step impregnation pyrolysis of *Peganum harmala* L. for removal of rhodamine B. Adsorpt Sci Technol 2023:9993465. https://doi.org/10.1155/2023/9993465

Almutairi AA, Ahmad M, Rafique MI, Al-Wabel MI (2023) Variations in composition and stability of biochars derived from different feedstock types at varying pyrolysis temperature. J Saudi Soc Agric Sci 22:25–34. https://doi.org/10.1016/j.jssas.2022.05.005

Amusat SO, Kebede TG, Dube S, Nindi MM (2021) Ball-milling synthesis of biochar and biochar–based nanocomposites and prospects for removal of emerging contaminants: a review. J Water Process Eng 41:101993. https://doi.org/10.1016/j.jwpe.2021.101993

An H, Liu T, Xiao X, Liu M, Hu Y, Wei P, Yao W, Tang X, Lai Y, Luo X (2025) Magnetic biochar-supported nanoscale zero-valent iron for remediation of arsenic and cadmium-contaminated soils: the role of free radicals. Environ Res 276:121484

An T, Chang Y, Xie J, Cao Q, Liu Y, Chen C (2022) Deciphering physicochemical properties and enhanced microbial electron transfer capacity by magnetic biochar. Bioresour Technol 363:127894. https://doi.org/10.1016/j.biortech.2022.127894

Anak Erison AE, Tan YH, Mubarak NM, Kansedo J, Khalid M, Abdullah MO, Ghasemi M (2022) Life cycle assessment of biodiesel production by using impregnated magnetic biochar derived from waste palm kernel shell. Environ Res 214:114149. https://doi.org/10.1016/j.envres.2022.114149

Apori SO, Byalebeka J, Murongo M, Ssekandi J, Noel GL (2021) Effect of co-applied corncob biochar with farmyard manure and NPK fertilizer on tropical soil. Resour Environ Sustain 5:100034. https://doi.org/10.1016/j.resenv.2021.100034

Arabkhani P, Asfaram A, Sadegh F (2023) Green and low-temperature synthesis of the magnetic modified biochar under the air atmosphere for the adsorptive removal of heavy metal ions from wastewater: CCD-RSM experimental design with isotherm, kinetic, and thermodynamic studies. Environ Sci Pollut Res Int 30(57):120085–120102. https://doi.org/10.1007/s11356-023-30469-w

Atienza-Martínez M, Ábrego J, Gea G, Marías F (2020) Pyrolysis of dairy cattle manure: evolution of char characteristics. J Anal Appl Pyrolysis 145:104724. https://doi.org/10.1016/j.jaap.2019.104724

Ayaz M, Feizienė D, Tilvikienė V, Akhtar K, Stulpinaitė U, Iqbal R (2021) Biochar role in the sustainability of agriculture and environment. Sustainability 13:3. https://doi.org/10.3390/su13031330

Ayaz M, Feizienė D, Feiza V, Tilvikienė V, Baltrėnaitė-Gedienė E, Khan A (2022) The impact of Swine manure biochar on the physical properties and microbial activity of Loamy soils. Plants 11:1729. https://doi.org/10.3390/plants11131729

Azad D, Pateriya RN, Arya R, Sharma RK (2022) Biological treatment for biochar modification: opportunities, limitations, and advantages. In: Ramola S, Mohan D, Masek O, Méndez A, Tsubota T (eds) Engineered biochar. Springer Nature Singapore, pp 85–104. https://doi.org/10.1007/978-981-19-2488-0_6

Banitalebi G, Mosaddeghi MR, Shariatmadari H (2021) Evaluation of physico-chemical properties of biochar-based mixtures for soilless growth media. J Mater Cycles Waste Manag 23:950–964. https://doi.org/10.1007/s10163-021-01181-z

Bao Z, Shi C, Tu W, Li L, Li Q (2022) Recent developments in modification of biochar and its application in soil pollution control and ecoregulation. Environ Pollut 313:120184. https://doi.org/10.1016/j.envpol.2022.120184

Beatrice A, Varco JJ, Dygert A, Atsar FS, Solomon S, Thirumalai RVKG, Pittman CU Jr, Mlsna T (2022) Lead immobilization in simulated polluted soil by Douglas fir biochar-supported phosphate. Chemosphere 292:133355. https://doi.org/10.1016/j.chemosphere.2021.133355

Bhattacharya S, Hossain SA, Bhowal A, Das P (2024) Integral approach of adsorption and photo-degradation of Bisphenol A using pyrolyzed rice straw biochar coated with metal oxide: batch, mechanism and optimization. Sādhanā 49:38. https://doi.org/10.1007/s12046-023-02364-0

Bowden-Green B, Briens L (2016) An investigation of drum granulation of biochar powder. Powder Technol 288:249–254. https://doi.org/10.1016/j.powtec.2015.10.046

Burbano AA, Gascó G, Horst F, Lassalle V, Méndez A (2023) Production, characteristics and use of magnetic biochar nanocomposites as sorbents. Biomass Bioenergy 172:106772. https://doi.org/10.1016/j.biombioe.2023.106772

Bushra B, Remya N (2024) Biochar from pyrolysis of rice husk biomass—characteristics, modification and environmental application. Biomass Convers Biorefin 14(5):5759–5770. https://doi.org/10.1007/s13399-020-01092-3

Buss W, Wurzer C, Manning DA, Rohling EJ, Borevitz J, Mašek O (2022) Mineral-enriched biochar delivers enhanced nutrient recovery and carbon dioxide removal. Commun Earth Environ 3:67

Cai W, Wei J, Li Z, Liu Y, Zhou J, Han B (2019) Preparation of amino-functionalized magnetic biochar with excellent adsorption performance for Cr(VI) by a mild one-step hydrothermal method from peanut hull. Colloids Surf A Physicochem Eng Asp 563:102–111. https://doi.org/10.1016/j.colsurfa.2018.11.062

Cai Y, Yang J, Ran Z, Bu F, Chen X, Shaaban M, Peng Q (2024) Optimizing *Typha* biochar with phosphoric acid modification and ferric chloride impregnation for hexavalent chromium remediation in water and soil. Chemosphere 354:141739. https://doi.org/10.1016/j.chemosphere.2024.141739

Cai H, Niu Y, Guan T, You X, Ma X, Zhang X (2025) Highly efficient charge carrier separation in ZnO-NiFe2O4@biochar Z-scheme heterojunction mediated by persistent free radicals for metronidazole degradation. Chem Eng J 505:159577. https://doi.org/10.1016/j.cej.2025.159577

Cansado IPDP, Mourão PAM, Castanheiro JE, Geraldo PF, Suhas SSR, Cano BL (2025) A review of the biomass valorization hierarchy. Sustainability 17:335. https://doi.org/10.3390/su17010335

Cárdenas-Aguiar E, Méndez A, Paz-Ferreiro J, Gascó G (2022) The effects of rabbit manure-derived biochar on soil health and quality attributes of two mine tailings. Sustainability 14:1866. https://doi.org/10.3390/su14031866

Chakma S, Hasan M, Rakshit SK, Kozinski J, Kang K (2025) Review of recent advances in the design, synthesis, and modification of biochar for remediation of heavy metal pollution in water. Can J Chem Eng 2025:1–27

Chaturvedi P, Shukla P, Giri BS, Chowdhary P, Chandra R, Gupta P, Pandey A (2021) Prevalence and hazardous impact of pharmaceutical and personal care products and antibiotics in environment: a review on emerging contaminants. Environ Res 194:110664. https://doi.org/10.1016/j.envres.2020.110664

Chen M, Dai Y, Guo J, Yang H, Liu D, Zhai Y (2019a) Solvothermal synthesis of biochar@$ZnFe_2O_4$/BiOBr Z-scheme heterojunction for efficient photocatalytic ciprofloxacin degradation under visible light. Appl Surf Sci 493:1361–1367. https://doi.org/10.1016/j.apsusc.2019.04.160

Chen YD, Bai S, Li R, Su G, Duan X, Wang S, Ren NQ, Ho SH (2019b) Magnetic biochar catalysts from anaerobic digested sludge: production, application and environment impact. Environ Int 126:302–308

Chen K, Zhou L, Xu W, Hu Z, Jia M, Liu L (2022a) A novel way of activating peroxysulfate by zero-valent copper and ferroferric oxide co-modified biochar to remove bisphenol A in aqueous solution: performance, mechanism and potential toxicity. Appl Catal A Gen 636:118575. https://doi.org/10.1016/j.apcata.2022.118575

Chen Y, Li L, Wen Q, Yang R, Zhao Y, Rao X, Li J, Xu S, Song H (2022b) Oxidative magnetic modification of pristine biochar assisted by ball-milling for removal of methylene blue and tetracycline in aqueous solution. Sustainability 14:9349. https://doi.org/10.3390/su14159349

Chen T, Wen X, Li X, He J, Yan B, Fang Z, Zhao L, Liu Z, Han L (2023a) Single/co-adsorption and mechanism of methylene blue and lead by β-cyclodextrin modified magnetic alginate/biochar. Bioresour Technol 381:129130. https://doi.org/10.1016/j.biortech.2023.129130

Chen Y, Mao W, Yang W, Niazi NK, Wang B, Wu P (2023b) A novel phosphate rock-magnetic biochar for Pb^{2+} and Cd^{2+} removal in wastewater: characterization, performance and mechanisms. Environ Technol Innov 32:103268. https://doi.org/10.1016/j.eti.2023.103268

Chen J, Zhou J, Zheng W, Leng S, Ai Z, Zhang W, Yang Z, Jianping Y, Xu Z, Cao J (2024) A complete review on the oxygen-containing functional groups of biochar: formation mechanisms, detection methods, engineering, and applications. Sci Total Environ 946:174081

Chin JF, Heng ZW, Teoh HC, Chong WC, Pang YL (2022) Recent development of magnetic biochar crosslinked chitosan on heavy metal removal from wastewater—modification, application and mechanism. Chemosphere 291:133035. https://doi.org/10.1016/j.chemosphere.2021.133035

Cui B, Chen Z, Wang F, Zhang Z, Dai Y, Guo D, Liang W, Liu Y (2022) Facile synthesis of magnetic biochar derived from Burley tobacco stems towards enhanced Cr(VI) removal: performance and mechanism. Nanomaterials 12:678. https://doi.org/10.3390/nano12040678

Daffalla S, Da'na E, Taha A, El-Aassar MR (2024) Synthesis of a novel magnetic biochar from lemon peels via impregnation-pyrolysis for the removal of Methyl Orange from wastewater. Magnetochemistry 10:95

Danesh P, Niaparast P, Ghorbannezhad P, Ali I (2023) Biochar production: recent developments, applications, and challenges. Fuel 337:126889.https://doi.org/10.1016/j.fuel.2022.126889

Das S, Mondal S (2023) Synthesis of magnetic biochar derived from waste wood of *Acacia auriculiformis* for the removal of arsenic. Environ Nanotechnol Monit Manag 20:100893. https://doi.org/10.1016/j.enmm.2023.100893

Das SK, Ghosh GK, Avasthe R (2023a) Application of biochar in agriculture and environment, and its safety issues. Biomass Convers Biorefin 13:1359–1369. https://doi.org/10.1007/s13399-020-01013-4

Das SK, Ghosh GK, Avasthe R (2023b) Biochar application for environmental management and toxic pollutant remediation. Biomass Convers Biorefin 13:555–566. https://doi.org/10.1007/s13399-020-01078-1

Deng R, Lan Z, Shang X, Fang S (2022) Effects of biochar application pyrolyzed at different temperatures on soil properties, growth and leaf secondary metabolite accumulation in *Cyclocarya paliurus*. Forests 13:10. https://doi.org/10.3390/f13101572

Deng S, Ren B, Hou B, Deng X, Deng R, Zhu G, Cheng S (2024) Adsorption of Sb(III) and Pb(II) in wastewater by magnetic γ-Fe_2O_3-loaded sludge biochar: performance and mechanisms. Chemosphere 349:140914. https://doi.org/10.1016/j.chemosphere.2023.140914

Diao Y, Shan R, Li M, Gu J, Yuan H, Chen Y (2022a) Efficient adsorption of a sulfonamide antibiotic in aqueous solutions with N-doped magnetic biochar: performance, mechanism, and reusability. ACS Omega 8:879–892

Diao Y, Zhou L, Ji M, Wang X, Dan Y, Sang W (2022b) Immobilization of Cd and Pb in soil facilitated by magnetic biochar: metal speciation and microbial community evolution. Environ Sci Pollut Res Int 29:71871–71881. https://doi.org/10.1007/s11356-022-20750-9

Dong CD, Chen CW, Hung CM (2019) Persulfate activation with rice husk-based magnetic biochar for degrading PAEs in marine sediments. Environ Sci Pollut Res 26:33781–33790. https://doi.org/10.1007/s11356-018-2423-2

Dong J, Shen L, Shan S, Liu W, Qi Z, Liu C, Gao X (2022) Optimizing magnetic functionalization conditions for efficient preparation of magnetic biochar and adsorption of Pb(II) from aqueous solution. Sci Total Environ 806:151442. https://doi.org/10.1016/j.scitotenv.2021.151442

Dong J, Jiang P, Wang H, Lu R, Liu Y, Li Y, Gan Y, Bolan N (2023) Influence of biomass feedstocks on magnetic biochar preparation for efficient Pb(II) removal. Environ Technol Innov 32:103363. https://doi.org/10.1016/j.eti.2023.103363

Dong M, Jiang M, He L, Zhang Z, Gustave W, Vithanage M, Niazi NK, Chen B, Zhang X, Wang H, He F (2025) Challenges in safe environmental applications of biochar: identifying risks and unintended consequence. Biochar 7:12. https://doi.org/10.1007/s42773-024-00412-4

Duan X, Chen X, Shi L, Cao Y, Liang Y, Huang C, Cao Y (2025) Functionality-dependent removal efficiency and mechanisms of polystyrene microplastics by a robust magnetic biochar. J Environ Chem Eng 13:115509

El-Azazy M, Nabil I, Hassan SS, El-Shafie AS (2021) Adsorption characteristics of pristine and magnetic olive stones biochar with respect to clofazimine. Nanomaterials 11:963. https://doi.org/10.3390/nano11040963

El-Azazy M, El-Shafie AS, Fawzy S, Rooney DW, Osman AI (2023a) Competitive adsorptive removal of promazine and promethazine from wastewater using olive tree pruning biochar: operational parameters, kinetics, and equilibrium investigations. Environ Sci Pollut Res Int 30:82387–82405. https://doi.org/10.1007/s11356-023-27688-6

El-Azazy M, El-Shafie AS, Al-Saad K (2023b) Application of infrared spectroscopy in the characterization of lignocellulosic biomasses utilized in wastewater treatment. In: El-Azazy M, Al-Saad K, El-Shafie AS (eds) Infrared spectroscopy—perspectives and applications. IntechOpen. https://doi.org/10.5772/intechopen.108878

Elkhlifi Z, Lahori AH, Shahib II, Iftikhar J, Wang S, He L, Meili L, Gendy EA, Sharma P, Chen Z (2023) Comparative assessment of phosphate adsorption properties and mechanisms on Mg/Al-engineered sewage sludge biochar in aqueous solution. J Water Process Eng 56:104443. https://doi.org/10.1016/j.jwpe.2023.104443

El-Shafie AS, Karamshahi F, El-Azazy M (2023a) Turning waste avocado stones and montmorillonite into magnetite-supported nanocomposites for the depollution of methylene blue: adsorbent reusability and performance optimization. Environ Sci Pollut Res Int 30:118764–118781. https://doi.org/10.1007/s11356-023-30538-0

El-Shafie AS, Barah FG, Abouseada M, El-Azazy M (2023b) Performance of pristine versus magnetized orange peels biochar adapted to adsorptive removal of daunorubicin: eco-structuring, kinetics and equilibrium studies. Nanomaterials 13:1444. https://doi.org/10.3390/nano13091444

Fan T, Pan D, Zhang H (2011) Study on formation mechanism by monitoring the morphology and structure evolution of nearly monodispersed Fe_3O_4 submicroparticles with controlled particle sizes. Ind Eng Chem Res 50:9009–9018. https://doi.org/10.1021/ie200970j

Fan S, Fan X, Wang S, Li B, Zhou N, Xu H (2023) Effect of chitosan modification on the properties of magnetic porous biochar and its adsorption performance towards tetracycline and Cu2+. Sustain Chem Pharm 33:101057. https://doi.org/10.1016/j.scp.2023.101057

Fang G, Liu C, Gao J, Dionysiou DD, Zhou D (2015) Manipulation of persistent free radicals in biochar to activate persulfate for contaminant degradation. Environ Sci Technol 49:5645–5653. https://doi.org/10.1021/es5061512

Fang Y, Ni X, Xiao Q, Huang S, López-Valdivieso A (2025) Iron-based materials synthesized by mechanical ball milling for environmental contaminants removal: progress and prospects. Int J Environ Res 19:12. https://doi.org/10.1007/s41742-024-00671-w

Farid IM, Siam HS, Abbas MHH, Mohamed I, Mahmoud SA, Tolba M, Abbas HH, Yang X, Antoniadis V, Rinklebe J, Shaheen SM (2022) Co-composted biochar derived from rice straw and sugarcane bagasse improved soil properties, carbon balance, and zucchini growth in a sandy soil: a trial for enhancing the health of low fertile soils. Chemosphere 292:133389. https://doi.org/10.1016/j.chemosphere.2021.133389

Fatimah I, Purwiandono G, Sahroni I, Wijayana A, Faraswati M, Dwi Putri A, Oh W-C, Doong R (2022) Magnetically-separable photocatalyst of magnetic biochar from snake fruit peel for rhodamine B photooxidation. Environ Nanotechnol Monit Manag 17:100669. https://doi.org/10.1016/j.enmm.2022.100669

Fazal T, Razzaq A, Javed F, Hafeez A, Rashid N, Amjad US, Ur Rehman MS, Faisal A, Rehman F (2020) Integrating adsorption and photocatalysis: a cost effective strategy for textile wastewater treatment using hybrid biochar-TiO_2 composite. J Hazard Mater 390:121623. https://doi.org/10.1016/j.jhazmat.2019.121623

Feng Z, Yuan R, Wang F, Chen Z, Zhou B, Chen H (2021) Preparation of magnetic biochar and its application in catalytic degradation of organic pollutants: a review. Sci Total Environ 765:142673. https://doi.org/10.1016/j.scitotenv.2020.142673

Feng W, Wang T, Yang F, Cen R, Liao H, Qu Z (2023) Effects of biochar on soil evaporation and moisture content and the associated mechanisms. Environ Sci Eur 35:66. https://doi.org/10.1186/s12302-023-00776-7

Fu H, Ma S, Wang L, Xue W, Xiong S, Sui F, Liu H, Li C, Li G, Duan R, Zhao P (2024) Hierarchically porous magnetic biochar as an amendment for wheat (*Triticum aestivum* L.) cultivation in alkaline Cd-contaminated soils: impacts on plant growth, soil properties and microbiota. Chemosphere 352:141295. https://doi.org/10.1016/j.chemosphere.2024.141295

Gabhane JW, Bhange VP, Patil PD, Bankar ST, Kumar S (2020) Recent trends in biochar production methods and its application as a soil health conditioner: a review. SN Appl Sci 2:1307. https://doi.org/10.1007/s42452-020-3121-5

Gan Z, Zhuang X, Cen K, Ba Y, Zhou J, Chen D (2022) Co-pyrolysis of municipal solid waste and rice husk gasification tar to prepare biochar: an optimization study using response surface methodology. Fuel 330:125574. https://doi.org/10.1016/j.fuel.2022.125574

Gao Y, Champagne P, Blair D, He O, Song T (2020) Activated persulfate by iron-based materials used for refractory organics degradation: a review. Water Sci Technol 81:853–875. https://doi.org/10.2166/wst.2020.190

Gao Y, Sun Y, Song W, Jia Y, Li A, Wang S (2023) Intrinsic properties of biochar for electron transfer. Chem Eng J 475:146356

Ghassemi-Golezani K, Rahimzadeh S (2022) Biochar modification and application to improve soil fertility and crop productivity. Agriculture (Pol'nohospodárstvo) 68:45–61. https://doi.org/10.2478/agri-2022-0005

Ghosh D, Page-Dumroese DS, Han H, Anderson N (2025) Role of biochar made from low-value woody forest residues in ecological sustainability and carbon neutrality. Soil Sci Soc Am J 89:e20793. https://doi.org/10.1002/saj2.20793

Gong H, Chi J (2022) Contribution of different mechanisms to Pb^{2+} and Cd^{2+} sorption on magnetic wheat straw biochars: impact of pyrolysis temperature and DOM in biochar. J Environ Chem Eng 10:107851. https://doi.org/10.1016/j.jece.2022.107851

Gong R, Li H, Liu, Fu LJ, Yi J, Feng D (2025) Preparation of novel multifunctional magnetic biochar integrating adsorption and degradation and application in printing and dyeing wastewater. J Contaminant Hydrol 274:104652. https://doi.org/10.1016/j.jconhyd.2025.104652

Gonzalez-Aguilar AM, Cabrera-Madera VP, Vera-Rozo JR, Riesco-Ávila JM (2022) Effects of heating rate and temperature on the thermal pyrolysis of expanded polystyrene post-industrial waste. Polymers 14:4957. https://doi.org/10.3390/polym14224957

Grammenou A, Petropoulos PA, Thalassinos G, Rinklebe J, Shaheen SM, Vasileios A (2023) Biostimulants in the soil–plant interface: agro-environmental implications—a review. Earth Syst Environ 7:583–600. https://doi.org/10.1007/s41748-023-00349-x

Graziano M, Martín-Peinado FJ, Delgado-Moreno L (2022) Application of biochar for the restoration of metal(loid)s contaminated soils. Appl Sci 12:4. https://doi.org/10.3390/app12041918

Gupta S (2021) Carbon sequestration in cementitious matrix containing pyrogenic carbon from waste biomass: a comparison of external and internal carbonation approach. J Build Eng 43:102910. https://doi.org/10.1016/j.jobe.2021.102910

Gworek B, Kijeńska M, Wrzosek J, Graniewska M (2021) Pharmaceuticals in the soil and plant environment: a review. Water Air Soil Pollut 232:145. https://doi.org/10.1007/s11270-020-04954-8

Hadroug S, Jellali S, Jeguirim M, Kwapinska M, Hamdi H, Leahy JJ, Kwapinski W (2021) Static and dynamic investigations on leaching/retention of nutrients from raw poultry manure biochars and amended agricultural soil. Sustainability 13:1212. https://doi.org/10.3390/su13031212

Hafeez A, Pan T, Tian J, Cai K (2022) Modified biochars and their effects on soil quality: a review. Environments 9:60. https://doi.org/10.3390/environments9050060

Haider FU, Wang X, Zulfiqar U, Farooq M, Hussain S, Mehmood T, Naveed M, Li Y, Liqun C, Saeed Q, Ahmad I, Mustafa A (2022) Biochar application for remediation of organic toxic pollutants in contaminated soils; an update. Ecotoxicol Environ Saf 248:114322. https://doi.org/10.1016/j.ecoenv.2022.114322

Hamdi H, Benzarti S, Aoyama I, Jedidi N (2012) Rehabilitation of degraded soils containing aged PAHs based on phytoremediation with alfalfa (*Medicago sativa* L.). Int Biodeterior Biodegrad 67:40–47. https://doi.org/10.1016/j.ibiod.2011.10.009

Hampicke U (2021) Germany's agriculture and UN's sustainable development goal 15. In: Buckmann V (ed) Transitioning to sustainable life on land. MDPI Books, pp 103–131

Han J, Liu R, Wang H, Qiu M, Hu B (2022) Fabrication of porous biochar decorated with MnFe2O4 magnetic nanoparticle for high effective removal of Cr(VI) ion in solution. Desalin Water Treat 268:36–47. https://doi.org/10.5004/dwt.2022.28617

Hashemi E, Norouzi M-M, Sadeghi-Kiakhani M (2024) Magnetic biochar as a revolutionizing approach for diverse dye pollutants elimination: a comprehensive review. Environ Res 261:119548. https://doi.org/10.1016/j.envres.2024.119548

Hassan M, Liu Y, Naidu R, Parikh SJ, Du J, Qi F, Willett IR (2020) Influences of feedstock sources and pyrolysis temperature on the properties of biochar and functionality as adsorbents: a meta-analysis. Sci Total Environ 744:140714

Havugimana E, Bhople BS, Kumar A, Byiringiro E, Mugabo JP, Kumar A (2017) Soil pollution–major sources and types of soil pollutants. Environ Sci Eng 11:53–86

Hechmi S, Zoghlami RI, Mokni-Tlili S, Benzarti S, Moussa M, Jellali S, Hamdi H (2023) Agricultural applications. In: Palm trees and fruits residues. Elsevier, pp 223–243. https://doi.org/10.1016/B978-0-12-823934-6.00011-3

Hillel D, Braimoh AK, Vlek PLG (2008) Soil degradation under irrigation, In: Braimoh AK, Vlek PLG (eds) Land use and soil resources. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-6778-5_6

Hoang AT, Goldfarb JL, Foley AM, Lichtfouse E, Kumar M, Xiao L, Ahmed SF, Said Z, Luque R, Bui VG, Nguyen XP (2022) Production of biochar from crop residues and its application for anaerobic digestion. Bioresour Technol 363:127970. https://doi.org/10.1016/j.biortech.2022.127970

Hossain A, Krupnik TJ, Timsina J, Mahboob MG, Chaki AK, Farooq M, Rajan B, Shah F, Hasanuzzaman M (2020) Agricultural land degradation: processes and problems undermining future food security. In: Fahad S et al (eds) Environment, climate, plant and vegetation growth. Springer, Cham. https://doi.org/10.1007/978-3-030-49732-3_2

Hou J, Yu J, Li W, He X, Li X (2022) The effects of chemical oxidation and high-temperature reduction on surface functional groups and the adsorption performance of biochar for sulfamethoxazole adsorption. Agronomy 12:2. https://doi.org/10.3390/agronomy12020510

Hou R, Zhang J, Fu Q, Li T, Gao S, Wang R, Zhao S, Zhu B (2024) The boom era of emerging contaminants: a review of remediating agricultural soils by biochar. Sci Total Environ 931:172899

Hu X, Xu J, Wu M, Xing J, Bi W, Wang K, Ma J, Liu X (2017) Effects of biomass pre-pyrolysis and pyrolysis temperature on magnetic biochar properties. J Anal Appl Pyrolysis 127:196–202. https://doi.org/10.1016/j.jaap.2017.08.006

Hu S, Liu Y, Wei L, Luo D, Wu Q, Huang X, Xiao T (2025) Remediation of thallium-contaminated groundwater using magnetic illite–biochar: structural characteristics, performance and mechanisms. J Environ Chem Eng 13:115106. https://doi.org/10.1016/j.jece.2024.115106

Huang D, Zhang Q, Zhang C, Wang R, Deng R, Luo H, Li T, Li J, Chen S, Liu C (2020) Mn doped magnetic biochar as persulfate activator for the degradation of tetracycline. Chem Eng J 391:123532. https://doi.org/10.1016/j.cej.2019.123532

Huang F, Zhang S-M, Wu R-R, Zhang L, Wang P, Xiao R-B (2021) Magnetic biochars have lower adsorption but higher separation effectiveness for Cd^{2+} from aqueous solution compared to nonmagnetic biochars. Environ Pollut 275:116485. https://doi.org/10.1016/j.envpol.2021.116485

Ibn Ferjani A, Jellali S, Akrout H, Limousy L, Hamdi H, Thevenin N, Jeguirim M (2020) Nutrient retention and release from raw exhausted grape marc biochars and an amended agricultural soil: static and dynamic investigation. Environ Technol Innov 19:100885. https://doi.org/10.1016/j.eti.2020.100885

Jain B, Singh AK, Kim H, Lichtfouse E, Sharma VK (2018) Treatment of organic pollutants by homogeneous and heterogeneous fenton reaction processes. Environ Chem Lett 16:947–967. https://doi.org/10.1007/s10311-018-0738-3

Jellali S, Azzaz A, Jeguirim M, Hamdi H, Mlayah A (2021) Use of lignite as a low-cost material for cadmium and copper removal from aqueous solutions: assessment of adsorption characteristics and exploration of involved mechanisms. Water 13:164. https://doi.org/10.3390/w13020164

Jellali S, Khiari B, Al-Harrasi M, Charabi Y, Al-Sabahi J, Al-Abri M, Usman M, Al-Raeesi A, Jeguirim M (2023) Industrial sludge conversion into biochar and reuse in the context of circular economy: impact of pre-modification processes on pharmaceuticals removal from aqueous solutions. Sustain Chem Pharm 33:101114. https://doi.org/10.1016/j.scp.2023.101114

Jellali S, Hadroug S, Al-Wardy M, Hamdi H, Al-Sabahi J, Bekri I, Al-Raeesi A, Hamdi W, Jeguirim M (2024a) Synthesis of Mg-, Al- and Mg/Al-date palm fronds modified biochars: characterization and investigations on phosphorus adsorption characteristics. C R Chim 27:1–14. https://doi.org/10.5802/crchim.329

Jellali S, Hadroug S, Al-Wardy M, Hamdi H, Al-Sabahi J, Zorpas A, Hamdi W, Al-Raeesi A, Jeguirim M (2024b) Phosphorus recovery from aqueous solutions by a Mg/Al-modified biochar from date palm wastes in column mode: adsorption characteristics and scale-up design parameters assessment. Biomass Convers Biorefin. https://doi.org/10.1007/s13399-024-06435-y

Ji M, Wang X, Usman M, Liu F, Dan Y, Zhou L, Campanaro S, Luo G, Sang W (2022) Effects of different feedstocks-based biochar on soil remediation: a review. Environ Pollut 294:118655. https://doi.org/10.1016/j.envpol.2021.118655

Jia Y, Zhang Y, Fu J, Yuan L, Li Z, Liu C, Zhao D, Wang X (2019) A novel magnetic biochar/MgFe-layered double hydroxides composite removing Pb^{2+} from aqueous solution: isotherms, kinetics and thermodynamics. Colloids Surf A Physicochem Eng Asp 567:278–287. https://doi.org/10.1016/j.colsurfa.2019.01.064

Jiang T, Wang B, Gao B, Cheng N, Feng Q, Chen M, Wang S (2023) Degradation of organic pollutants from water by biochar-assisted advanced oxidation processes: mechanisms and applications. J Hazard Mater 442:130075. https://doi.org/10.1016/j.jhazmat.2022.130075

Jiao Y, Xu Q, Hu Y, Wu J, Su X (2023) Pyrolysis co-activation synthesized magnetic biochar for efficient removal of Cr(VI) from aqueous solution. Mater Chem Phys 295:127080. https://doi.org/10.1016/j.matchemphys.2022.127080

Jin R, Zhao C, Song Y, Qiu X, Li C, Zhao Y (2023) Competitive adsorption of sulfamethoxazole and bisphenol A on magnetic biochar: mechanism and site energy distribution. Environ Pollut 329:121662

Kanan S, Moyet M, Obeideen K, El-Sayed Y, Mohamed AA (2022) Occurrence, analysis and removal of pesticides, hormones, pharmaceuticals, and other contaminants in soil and water streams for the past two decades: a review. Res Chem Intermed 48:3633–3683. https://doi.org/10.1007/s11164-022-04778-7

Kang K, Hu Y, Khan I, He S, Fatehi P (2023) Recent advances in the synthesis and application of magnetic biochar for wastewater treatment. Bioresour Technol 390:129786. https://doi.org/10.1016/j.biortech.2023.129786

Katibi KK, Shitu IG, Yunos KFM, Rabaah SA, Iwar T, Adamu SB, Umar AM, Adebayo KR (2024) Unlocking the potential of magnetic biochar in wastewater purification: a review on the removal of bisphenol A from aqueous solution. Environ Monit Assess 196:492. https://doi.org/10.1007/s10661-024-12574-6

Ke Z, Mei M, Liu J, Du P, Zhang B, Wang T, Chen S, Li J (2022) Deep eutectic solvent assisted facile and efficient synthesis of nitrogen-doped magnetic biochar for hexavalent chromium elimination: mechanism and performance insights. J Clean Prod 357:132012

Khajavi-Shojaei S, Moezzi A, Norouzi Masir M, Taghavi M (2023) Synthesis modified biochar-based slow-release nitrogen fertilizer increases nitrogen use efficiency and corn (*Zea mays* L.) growth. Biomass Convers Biorefinery 13:593–601. https://doi.org/10.1007/s13399-020-01137-7

Khan ZH, Gao M, Qiu W, Islam MS, Song Z (2020) Mechanisms for cadmium adsorption by magnetic biochar composites in an aqueous solution. Chemosphere 246:125701. https://doi.org/10.1016/j.chemosphere.2019.125701

Khanzada AK, Al-Hazmi HE, Kurniawan TA, Majtacz J, Piechota G, Kumar G, Ezzati P, Saeb MR, Rabiee N, Karimi-Maleh H, Lima EC, Mąkinia J (2024) Hydrochar as a bio-based adsorbent for heavy metals removal: a review of production processes, adsorption mechanisms, kinetic models, regeneration and reusability. Sci Total Environ 945:173972. https://doi.org/10.1016/j.scitotenv.2024.173972

Khedulkar AP, Pandit B, Dang VD, Doong R (2023) Agricultural waste to real worth biochar as a sustainable material for supercapacitor. Sci Total Environ 869:161441. https://doi.org/10.1016/j.scitotenv.2023.161441

Koul B, Taak P (2018) Soil pollution: causes and consequences. In: Koul B, Taak P (eds) Biotechnological strategies for effective remediation of polluted soils. Springer, Singapore, pp 1–37. https://doi.org/10.1007/978-981-13-2420-8_1

Latifian B, Taghizade Firozjaee T, Abdi J (2024) Synthesis of biochar-iron oxide magnetic nanocomposite for efficient and rapid removal of Pb(II) heavy metal from water. Water Pract Technol 19:181–199. https://doi.org/10.2166/wpt.2023.223

Li R, Liang W, Huang H, Jiang S, Guo D, Li M, Zhang Z, Ali A, Wang JJ (2018) Removal of cadmium(II) cations from an aqueous solution with aminothiourea chitosan strengthened magnetic biochar. J Appl Polym Sci 135:46239. https://doi.org/10.1002/app.46239

Li R, Deng H, Zhang X, Wang JJ, Awasthi MK, Wang Q, Xiao R, Zhou B, Du J, Zhang Z (2019a) High-efficiency removal of Pb(II) and humate by a

CeO_2–MoS_2 hybrid magnetic biochar. Bioresour Technol 273:335–340. https://doi.org/10.1016/j.biortech.2018.10.053

Li S, Wang Z, Zhao X, Yang X, Liang G, Xie X (2019b) Insight into enhanced carbamazepine photodegradation over biochar-based magnetic photocatalyst Fe_3O_4/BiOBr/BC under visible LED light irradiation. Chem Eng J 360:600–611. https://doi.org/10.1016/j.cej.2018.12.002

Li X, Wang C, Zhang J, Liu J, Liu B, Chen G (2020a) Preparation and application of magnetic biochar in water treatment: a critical review. Sci Total Environ 711:134847. https://doi.org/10.1016/j.scitotenv.2019.134847

Li Y, Zimmerman AR, He F, Chen J, Han L, Chen H, Hu X, Gao B (2020b) Solvent-free synthesis of magnetic biochar and activated carbon through ball-mill extrusion with Fe_3O_4 nanoparticles for enhancing adsorption of methylene blue. Sci Total Environ 722:137972. https://doi.org/10.1016/j.scitotenv.2020.137972

Li S, Huang D, Cheng M, Wei Z, Du L, Wang G, Chen S, Lei L, Chen Y, Li R (2022) Application of sludge biochar nanomaterials in Fenton-like processes: degradation of organic pollutants, sediment remediation, sludge dewatering. Chemosphere 307:135873. https://doi.org/10.1016/j.chemosphere.2022.135873

Li S, Skelly S (2023) Physicochemical properties and applications of biochars derived from municipal solid waste: a review. Environ Adv 13:100395. https://doi.org/10.1016/j.envadv.2023.100395

Li C, Wang Z, Xu Y, Sun J, Ruan X, Mao X, Hu X, Liu P (2023a) Analysis of the effect of modified biochar on saline-alkali soil remediation and crop growth. Sustainability 15:5593. https://doi.org/10.3390/su15065593

Li H, Yuan Z, Ding S, Yuan J (2023b) Adsorption of lead ions by magnetic carbon: comparison of magnetic carbon properties and modification methods. J Environ Chem Eng 11:110136. https://doi.org/10.1016/j.jece.2023.110136

Li Y, Gupta R, Zhang Q, You S (2023c) Review of biochar production via crop residue pyrolysis: development and perspectives. Bioresour Technol 369:128423. https://doi.org/10.1016/j.biortech.2022.128423

Li Z, Niu R, Yu J, Yu L, Cao D (2023d) Removal of cadmium from aqueous solution by magnetic biochar: adsorption characteristics and mechanism. Environ Sci Pollut Res Int 31:6543–6557. https://doi.org/10.1007/s11356-023-31664-5

Li H, Ni Z, Kang Z, Sheng H, Wang Y, Chen M, Qian L (2024a) Research progress on synthesis mechanism and performance evaluation of ball milling biochar-iron based materials. Npj Mater Sustain 2:18. https://doi.org/10.1038/s44296-024-00022-y

Li J, Sun Y, Fang M, Guo Z, Zhang B, Chen T, Liu Y, Yang T, Zhuang L (2024b) The potential of magnetic biochar prepared by a solvent-free method as a soil amendment: metal immobilization performance, soil microbial co-occurrence network and community assembly mechanism. J Environ Chem Eng 12:113565. https://doi.org/10.1016/j.jece.2024.113565

Liang S, Shi S, Zhang H, Qiu J, Yu W, Li M, Gan Q, Yu W, Xiao K, Liu B, Hu J, Hou H, Yang J (2019) One-pot solvothermal synthesis of magnetic biochar from waste biomass: formation mechanism and efficient adsorption of Cr(VI) in an aqueous solution. Sci Total Environ 695:133886. https://doi.org/10.1016/j.scitotenv.2019.133886

Liang X, Zhao Y, Liu B, Li J, Cui L, Wang C, Yang Q (2024) Phosphorus doped magnetic biochar activated PMS for effective degradation of pesticide in water: targeted regulation of interfacial charge transfer by phosphorus doping. Sep Purif Technol 340:126739. https://doi.org/10.1016/j.seppur.2024.126739

Limmun W, Limmun W, Borkowski JJ, Ishikawa N, Pairintra R, Chungcharoen T, Phanchindawan N, Maneesri W, Pewpa O, Ito A (2024) Eco-friendly magnetic biochar from Leb Mu Nang banana peel: response surface methodology optimization for Cd(II) adsorption from synthetic wastewater. Bioresour Technol Rep 25:101743. https://doi.org/10.1016/j.biteb.2023.101743

Liu J, Jiang J, Aihemaiti A, Meng Y, Yang M, Xu Y, Gao Y, Zou Q, Chen X (2019) Removal of phosphate from aqueous solution using MgO-modified magnetic biochar derived from anaerobic digestion residue. J Environ Manage 250:109438. https://doi.org/10.1016/j.jenvman.2019.109438

Liu N, Liu Y, Tan X, Li M, Liu S, Hu X, Zhang P, Dai M, Xu W, Wen J (2020a) Synthesis a graphene-like magnetic biochar by potassium ferrate for 17β-estradiol removal: effects of Al_2O_3 nanoparticles and microplastics. Sci Total Environ 715:136723

Liu Y, Huang J, Xu H, Zhang Y, Hu T, Chen W, Hu H, Wu J, Li Y, Jiang G (2020b) A magnetic macro-porous biochar sphere as vehicle for the activation and removal of heavy metals from contaminated agricultural soil. Chem Eng J 390:124638. https://doi.org/10.1016/j.cej.2020.124638

Liu J, Zhao L, Liu Q, Li J, Qiao Z, Sun P, Yang Y (2022a) A critical review on soil washing during soil remediation for heavy metals and organic pollutants. Int J Environ Sci Technol 19:601–624. https://doi.org/10.1007/s13762-021-03144-1

Liu J, Liu G, Zhang W, Li Z, Xing F, Tang L (2022b) Application potential analysis of biochar as a carbon capture material in cementitious composites: a review. Constr Build Mater 350:128715. https://doi.org/10.1016/j.conbuildmat.2022.128715

Liu T, Yao B, Luo Z, Li W, Li C, Ye Z, Gong X, Yang J, Zhou Y (2022c) Applications and influencing factors of the biochar-persulfate based advanced oxidation processes for the remediation of groundwater and soil contaminated with organic compounds. Sci Total Environ 836:155421. https://doi.org/10.1016/j.scitotenv.2022.155421

Liu Z, Xu Z, Xu L, Buyong F, Chay TC, Li Z, Cai Y, Hu B, Zhu Y, Wang X (2022d) Modified biochar: synthesis and mechanism for removal of environmental heavy metals. Carbon Res 1:8. https://doi.org/10.1007/s44246-022-00007-3

Liu Y, Liang Y, Cui W, Zhai H, Ji M (2024) Efficient removal of Cr(VI) from wastewater by magnetic biochar derived from peanut hull. Water Air Soil Pollut 235:100. https://doi.org/10.1007/s11270-024-06912-0

Long X, Zhang R, Rong R, Wu P, Chen S, Ao J, An L, Fu Y, Xie H (2023) Adsorption characteristics of heavy metals Pb^{2+} and Zn^{2+} by magnetic biochar obtained from modified AMD sludge. Toxics 11:590. https://doi.org/10.3390/toxics11070590

Lu HP, Li ZA, Gascó G, Méndez A, Shen Y, Paz-Ferreiro J (2018) Use of magnetic biochars for the immobilization of heavy metals in a multi-contaminated soil. Sci Total Environ 622:892–899. https://doi.org/10.1016/j.scitotenv.2017.12.056

Lu Y, Cai Y, Zhang S, Zhuang L, Hu B, Wang S, Chen J, Wang X (2022) Application of biochar-based photocatalysts for adsorption-(photo)degradation/reduction of environmental contaminants: mechanism, challenges and perspective. Biochar 4:45. https://doi.org/10.1007/s42773-022-00173-y

Luo J, Yi Y, Ying G, Fang Z, Zhang Y (2022) Activation of persulfate for highly efficient degradation of metronidazole using Fe(II)-rich potassium doped magnetic biochar. Sci Total Environ 819:152089. https://doi.org/10.1016/j.scitotenv.2021.152089

Luo J, Yi Y, Fang Z (2023) Nitrogen-rich magnetic biochar prepared by urea was used as an efficient catalyst to activate persulfate to degrade organic pollutants. Chemosphere 339:139614. https://doi.org/10.1016/j.chemosphere.2023.139614

Lv Q, Wang H, Zhang M, Xue J, Yang J (2020) Synthesis of magnetic biochar/carbonate intercalated Mg–Al layered double hydroxides for enhanced Cd(II) removal from aqueous solution. Desalin Water Treat 207:258–269. https://doi.org/10.5004/dwt.2020.26428

Lyu P, Li L, Huang X, Wang G, Zhu C (2022) Pre-magnetic bamboo biochar cross-linked Ca Mg Al layered double-hydroxide composite: High-efficiency removal of As(III) and Cd(II) from aqueous solutions and insight into the mechanism of simultaneous purification. Sci Total Environ 823:153743. https://doi.org/10.1016/j.scitotenv.2022.153743

Lyu P, Li L, Huang J, Ye J, Zhu C (2024) Magnetic biochar-supported layered double hydroxide for simultaneous remediation of As and Cd in soil: effectiveness, retention durability, and insight into a new immobilization mechanism. J Clean Prod 434:140136. https://doi.org/10.1016/j.jclepro.2023.140136

Ma Y, Yao Y, Deng Z, Zeng C, Liu Y, Ma J, Zhang Z (2024a) Hydrothermal N-doping, magnetization and ball milling co-functionalized sludge biochar design and its selective adsorption of trace concentration sulfamethoxazole from waters. Chemosphere 363:142855

Ma W, Han R, Zhang W, Zhang H, Chen L, Zhu L (2024b) 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.2024.120058

Mabrouk O, Hamdi H, Sayadi S, Al-Ghouti MA, Abu-Dieyeh M, Kogbara R, Al-Sharshani A, Abdalla O, Solim S, Zouari N (2023) Recycling of gas-to-liquid sludge as a potential organic amendment: effect on soil and cotton properties under hyperarid conditions. J Environ Manage 348:119319. https://doi.org/10.1016/j.jenvman.2023.119319

Majamo SL, Amibo TA, Bedru TK (2023) Synthesis and application of biomass-derived magnetic biochar catalyst for simultaneous esterification and trans-esterification of waste cooking oil into biodiesel: modeling and optimization. Mater Renew Sustain Energy 12:147–158. https://doi.org/10.1007/s40243-023-00236-5

Maneechakr P, Mongkollertlop S (2020) Investigation on adsorption behaviors of heavy metal ions (Cd^{2+}, Cr^{3+}, Hg^{2+} and Pb^{2+}) through low-cost/active manganese dioxide-modified magnetic biochar derived from palm kernel cake residue. J Environ Chem Eng 8:104467. https://doi.org/10.1016/j.jece.2020.104467

Markandeya MD, Shukla SP (2022) Hazardous consequences of textile mill effluents on soil and their remediation approaches. Cleaner Eng Technol 7:100434. https://doi.org/10.1016/j.clet.2022.100434

Matsagar BM, Wu KC-W (2022) Agricultural waste-derived biochar for environmental management. In: Biochar in agriculture for achieving sustainable development goals. Elsevier, pp 3–13. https://doi.org/10.1016/B978-0-323-85343-9.00026-4

Meng X, Zhang Z (2016) Bismuth-based photocatalytic semiconductors: introduction, challenges and possible approaches. J Mol Catal A Chem 423:533–549. https://doi.org/10.1016/j.molcata.2016.07.030

Meng H, Chen Z, Wei W, Xu J, Duan H, Zheng M, Ni B-J (2025) Magnetic hydrochar for sustainable wastewater management. NPJ Mater Sustain 3:7. https://doi.org/10.1038/s44296-024-00047-3

Meyer S, Glaser B, Quicker P (2011) Technical, economical, and climate-related aspects of biochar production technologies: a literature review. Environ Sci Technol 45:9473–9483. https://doi.org/10.1021/es201792c

Mohawesh O, Coolong T, Aliedeh M, Alqaraleh S (2018) Greenhouse evaluation of biochar to enhance soil properties and plant growth performance under arid environment. Bulg J Agric Sci 24:1012–1019

Moradi R, Pourghasemian N, Naghizadeh M (2019) Effect of beeswax waste biochar on growth, physiology and cadmium uptake in saffron. J Clean Prod 229:1251–1261. https://doi.org/10.1016/j.jclepro.2019.05.047

Mosa A, Mansour MM, Soliman E, El-Ghamry A, Alfy ME, El Kenawy AM (2023) Biochar as a soil amendment for restraining greenhouse gases emission and improving soil carbon sink: current situation and ways forward. Sustainability 15:1206. https://doi.org/10.3390/su15021206

Moukadiri H, Noukrati H, Ben Youcef H, Iraola I, Trabadelo V, Oukarroum A, Malka G, Barroug A (2024) Impact and toxicity of heavy metals on human health and latest trends in removal process from aquatic media. Int J Environ Sci Technol 21:3407–3444. https://doi.org/10.1007/s13762-023-05275-z

Mudhoo A, Ramasamy DL, Bhatnagar A, Usman M, Sillanpää M (2020) An analysis of the versatility and effectiveness of composts for sequestering heavy metal ions, dyes and xenobiotics from soils and aqueous milieus. Ecotoxicol Environ Saf 197:110587. https://doi.org/10.1016/j.ecoenv.2020.110587

Mukome FND, Zhang X, Silva LCR, Six J, Parikh SJ (2013) Use of chemical and physical characteristics to investigate trends in biochar feedstocks. J Agric Food Chem 61:2196–2204. https://doi.org/10.1021/jf3049142

Murtaza G, Ahmed Z, Eldin SM, Ali I, Usman M, Iqbal R, Rizwan M, Abdel-Hameed UK, Haider AA, Tariq A (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

Nazim M, Ghafoor A, Hussain A, Tabassum M, Nawaz A, Ahmad M, Muhammad M, Ali M (2025) Biochar as a climate-smart agricultural practice: reducing greenhouse gas emissions and promoting sustainable farming. Phyton-Int J Exp Botany 94:65–99

Ndour PMS, Langrand J, Fontaine J, Lounès-Hadj Sahraoui A (2025) Exploring the significance of different amendments to improve phytoremediation efficiency: focus on soil ecosystem services. Environ Sci Pollut Res Int 32:485–513

Nkonya E, Mirzabaev A, Von Braun J (2016) Economics of land degradation and improvement—a global assessment for sustainable development. Springer Open, p 686. https://doi.org/10.1007/978-3-319-19168-3

Oh S, Lee J, Lam SS, Kwon EE, Ha J-M, Tsang DCW, Ok YS, Chen W-H, Park Y-K (2021) Fast hydropyrolysis of biomass conversion: a comparative review. Bioresour Technol 342:126067. https://doi.org/10.1016/j.biortech.2021.126067

Oladipo AA, Ahaka EO, Gazi M (2019) High adsorptive potential of calcined magnetic biochar derived from banana peels for Cu^{2+}, Hg^{2+}, and Zn^{2+} ions removal in single and ternary systems. Environ Sci Pollut Res Int 26:31887–31899. https://doi.org/10.1007/s11356-019-06321-5

Osman AI, Fawzy S, Farghali M, El-Azazy M, Elgarahy AM, Fahim RA, Maksoud MIAA, Ajlan AA, Yousry M, Saleem Y, Rooney DW (2022) Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review. Environ Chem Lett 20:2385–2485. https://doi.org/10.1007/s10311-022-01424-x

Ouyang D, Chen Y, Yan J, Qian L, Han L, Chen M (2019) Activation mechanism of peroxymonosulfate by biochar for catalytic degradation of 1,4-dioxane: important role of biochar defect structures. Chem Eng J 370:614–624. https://doi.org/10.1016/j.cej.2019.03.235

Pan L, Mao L, Zhang H, Wang P, Wu C, Xie J, Yu B, Sial MU, Zhang L, Zhang Y, Zhu L, Jiang H, Zheng Y, Liu X (2022) Modified biochar as a more promising amendment agent for remediation of pesticide-contaminated soils: modification methods, mechanisms, applications, and future perspectives. Appl Sci 12:11544. https://doi.org/10.3390/app122211544

Patel MR, Panwar NL (2023) Biochar from agricultural crop residues: environmental, production, and life cycle assessment overview. Resour Conserv Recycl Adv 19:200173. https://doi.org/10.1016/j.rcradv.2023.200173

Pérez-Lucas G, Vela N, El Aatik A (2018) Environmental risk of groundwater pollution by pesticide leaching through the soil profile. In: Larramendy M, Soloneski S (eds) Pesticides-use and misuse and their impact in the environment. IntechOpen.

Pi L, Jiang R, Zhou W, Zhu H, Xiao W, Wang D, Mao X (2015) G-C_3N_4 modified biochar as an adsorptive and photocatalytic material for decontamination of aqueous organic pollutants. Appl Surf Sci 358:231–239. https://doi.org/10.1016/j.apsusc.2015.08.176

Piash MI, Iwabuchi K, Itoh T, Uemura K (2021) Release of essential plant nutrients from manure- and wood-based biochars. Geoderma 397:115100. https://doi.org/10.1016/j.geoderma.2021.115100

Praneeth S, Guo R, Wang T, Dubey BK, Sarmah AK (2020) Accelerated carbonation of biochar reinforced cement-fly ash composites: enhancing and sequestering CO_2 in building materials. Constr Build Mater 244:118363. https://doi.org/10.1016/j.conbuildmat.2020.118363

Prangmoo Y, Choolaaied O, Phanchindawan N, Limmun W, Chungcharoen T (2024) Investigating the optimization of magnetic biochar production from rubber seed shells for enhanced Cr(VI) removal efficiency. E3S Web Conf 514:02002. https://doi.org/10.1051/e3sconf/202451402002

Qasim HM, Abudi ZN, Alzubaidi LA (2023) Cobalt ion removal using magnetic biochar obtained from *Conocarpus erectus* leaves. Biomass Conv Biorefinery 13:16865–16875. https://doi.org/10.1007/s13399-022-02307-5

Qin Y, Wang H, Li X, Cheng JJ, Wu W (2017) Improving methane yield from organic fraction of municipal solid waste (OFMSW) with magnetic rice-straw biochar. Bioresour Technol 245:1058–1066. https://doi.org/10.1016/j.biortech.2017.09.047

Qiu J, Fernandes De Souza M, Robles-Aguilar AA, Ghysels S, Ok YS, Ronsse F, Meers E (2023) Improving biochar properties by co-pyrolysis of pig manure with bio-invasive weed for use as the soil amendment. Chemosphere 312:137229. https://doi.org/10.1016/j.chemosphere.2022.137229

Qu J, Shi J, Wang Y, Tong H, Zhu Y, Xu L, Wang Y, Zhang B, Tao Y, Dai X, Zhang H, Zhang Y (2022) Applications of functionalized magnetic biochar in environmental remediation: a review. J Hazard Mater 434:128841. https://doi.org/10.1016/j.jhazmat.2022.128841

Rahim HU, Allevato E, Radicetti E, Carbone F, Stazi SR (2023) Research trend of aging biochar for agro-environmental applications: a bibliometric data analysis and visualization of the last decade (2011–2023). J Soil Sci Plant Nutr 23:4843–4855

Rangarajan G, Jayaseelan A, Farnood R (2022) Photocatalytic reactive oxygen species generation and their mechanisms of action in pollutant removal with biochar supported photocatalysts: a review. J Clean Prod 346:131155

Rasool S, Rasool T, Gani KM (2022) A review of interactions of pesticides within various interfaces of intrinsic and organic residue amended soil environment. Chem Eng J Adv 11:100301. https://doi.org/10.1016/j.ceja.2022.100301

Rathnayake D, Schmidt H, Leifeld J, Mayer J, Epper CA, Bucheli TD, Hagemann N (2023) Biochar from animal manure: a critical assessment on technical feasibility, economic viability, and ecological impact. GCB Bioenergy 15:1078–1104. https://doi.org/10.1111/gcbb.13082

Ratnakar A, Shankar S (2016) An overview of biodegradation of organic pollutants. Int J Sci Innov Res 4:73–91

Reguyal F, Sarmah AK, Gao W (2017) Synthesis of magnetic biochar from pine sawdust via oxidative hydrolysis of $FeCl_2$ for the removal sulfamethoxazole from aqueous solution. J Hazard Mater 321:868–878. https://doi.org/10.1016/j.jhazmat.2016.10.006

Rocha LS, Pereira D, Sousa É, Otero M, Esteves VI, Calisto V (2020) Recent advances on the development and application of magnetic activated carbon and char for the removal of pharmaceutical compounds from waters: a review. Sci Total Environ 718:137272. https://doi.org/10.1016/j.scitotenv.2020.137272

Roy A, Bharadvaja N (2021) Efficient removal of heavy metals from artificial wastewater using biochar. Environ Nanotechnol Monit Manag 16:100602. https://doi.org/10.1016/j.enmm.2021.100602

Safarian S (2023) Performance analysis of sustainable technologies for biochar production: a comprehensive review. Energy Rep 9:4574–4593

Sakhiya AK, Vijay VK, Kaushal P (2023) Development of rice straw biochar through pyrolysis to improve drinking water quality in arsenic and manganese contaminated areas. Surf Interface 36:102582. https://doi.org/10.1016/j.surfin.2022.102582

Santhosh K, Kamala K, Ramasamy P, Musthafa MS, Almujri SS, Asdaq SMB, Sivaperumal P (2024) Unveiling the silent threat: Heavy metal toxicity devastating impact on aquatic organisms and DNA damage. Mar Pollut Bull 200:116139. https://doi.org/10.1016/j.marpolbul.2024.116139

Saxena V (2025) Water quality, air pollution, and climate change: investigating the environmental impacts of industrialization and urbanization. Water Air Soil Pollut 236:73

Shaheen SM, Ullah H, Wu Y, Mosa A, Fang Y, Shi Y, Liu J, Kumar M, Zhang H, Zhang B (2025) Remediation of emerging inorganic contaminants in soils and water using pristine and engineered biochar: a review. Biochar 7:34

Shakoor MB, Khalil U, Ali S, Sharif F, Ahmad SR, Rizwan M, Jilani A, Al-Ghanim KA, Sarker PK (2024) Microwave-assisted magnetic biochar for removal of hexavalent chromium from aqueous solution. Environ Pollut Bioavailability 36:2368590

Shang J, Pi J, Zong M, Wang Y, Li W, Liao Q (2016) Chromium removal using magnetic biochar derived from herb-residue. J Taiwan Inst Chem Eng 68:289–294. https://doi.org/10.1016/j.jtice.2016.09.012

Shen Y (2020) A review on hydrothermal carbonization of biomass and plastic wastes to energy products. Biomass Bioenergy 134:105479. https://doi.org/10.1016/j.biombioe.2020.105479

Shitu IG, Katibi KK, Tafida RA, Iya SGD, Alotaibi KM, Babani S, Amusa AA, Elbidi M, Katibi MT, Mallik S (2024) Synthesis and characterization of magnetic biochar nanocomposite from oil palm fronds for efficient copper (II) ion removal from leachate. Clean Technol Environ Policy. https://doi.org/10.1007/s10098-024-03041-4

Silva TCF, Vergütz L, Pacheco AA, Melo LF, Renato NS, Melo LCA (2020) Characterization and application of magnetic biochar for the removal of phosphorus from water. An Acad Bras Cienc 92:e20190440. https://doi.org/10.1590/0001-3765202020190440

Simiele M, Argentino O, Baronti S, Scippa GS, Chiatante D, Terzaghi M, Montagnoli A (2022) Biochar enhances plant growth, fruit yield, and antioxidant content of cherry tomato (*Solanum lycopersicum* L.) in a soilless substrate. Agriculture 12:1135. https://doi.org/10.3390/agriculture12081135

Singh V, Pant N, Sharma RK, Padalia D, Rawat PS, Goswami R, Singh P, Kumar A, Bhandari P, Tabish A, Deifalla AM (2023) Adsorption studies of Pb(II) and Cd(II) heavy metal ions from aqueous solutions using a magnetic biochar composite material. Separations 10:389. https://doi.org/10.3390/separations10070389

Singh J, Jadeja R (2025) Recent advances in agricultural waste derived magnetic biochar for removal of heavy metal ions: mechanistic insights and technological innovation. J Mol Struct 1325:141005. https://doi.org/10.1016/j.molstruc.2024.141005

Sizmur T, Fresno T, Akgül G, Frost H, Moreno-Jiménez E (2017) Biochar modification to enhance sorption of inorganics from water. Bioresour Technol 246:34–47. https://doi.org/10.1016/j.biortech.2017.07.082

Song T, Kang X, Guo C, He Z, Ge M (2023) Recent advances in persulfate activation by magnetic ferrite-carbon composites for organic contaminants degradation: role of carbon materials and environmental application. J Environ Chem Eng 11:109087. https://doi.org/10.1016/j.jece.2022.109087

Song J, Zhu L, Yu S, Li G, Wang D (2024) The synergistic effect of adsorption and Fenton oxidation for organic pollutants in water remediation: an overview. RSC Adv 14:33489–33511. https://doi.org/10.1039/D4RA03050H

Subedi R, Taupe N, Pelissetti S, Petruzzelli L, Bertora C, Leahy JJ, Grignani C (2016) Greenhouse gas emissions and soil properties following amendment with manure-derived biochars: influence of pyrolysis temperature and feedstock type. J Environ Manage 166:73–83. https://doi.org/10.1016/j.jenvman.2015.10.007

Sun C, Chen T, Huang Q, Wang J, Lu S, Yan J (2019) Enhanced adsorption for Pb(II) and Cd(II) of magnetic rice husk biochar by $KMnO_4$ modification. Environ Sci Pollut Res Int 26:8902–8913. https://doi.org/10.1007/s11356-019-04321-z

Tan Z, Wang Y, Kasiulienė A, Huang C, Ai P (2017) Cadmium removal potential by rice straw-derived magnetic biochar. Clean Technol Environ Policy 19:761–774. https://doi.org/10.1007/s10098-016-1264-2

Tan Z, Yuan S, Hong M, Zhang L, Huang Q (2020) Mechanism of negative surface charge formation on biochar and its effect on the fixation of soil Cd. J Hazard Mater 384:121370. https://doi.org/10.1016/j.jhazmat.2019.121370

Tan XF, Zhu SS, Wang RP, Chen YD, Show PL, Zhang FF, Ho SH (2021a) Role of biochar surface characteristics in the adsorption of aromatic compounds: pore structure and functional groups. Chin Chem Lett 32:2939–2946. https://doi.org/10.1016/j.cclet.2021.04.059

Tan H, Lee CT, Ong PY, Wong KY, Bong CPC, Li C, Gao Y (2021b) A review on the comparison between slow pyrolysis and fast pyrolysis on the quality of lignocellulosic and lignin-based biochar. IOP Conf Ser Mater SciEng 1051:012075. https://doi.org/10.1088/1757-899X/1051/1/012075

Tan W-T, Zhou H, Tang S-F, Zeng P, Gu J-F, Liao B-H (2022) Enhancing Cd(II) adsorption on rice straw biochar by modification of iron and manganese oxides. Environ Pollut 300:118899. https://doi.org/10.1016/j.envpol.2022.118899

Tian J, Guo K, Sun Y, Lin R, Chen T, Zhang B, Liu Y, Yang T (2022a) Solvent-free synthesis of magnetic sewage sludge-derived biochar for heavy metal removal from wastewater. Int J Environ Res Public Health 20:155. https://doi.org/10.3390/ijerph20010155

Tian K, Shi F, Cao M, Zheng Q, Zhang G (2022b) A review of persulfate activation by magnetic catalysts to degrade organic contaminants: mechanisms and applications. Catalysts 12:1058. https://doi.org/10.3390/catal12091058

Tian X, Chu S, Hu Y, Luo L, Lin X, Wang H (2025) Removal of heavy metals from single- and multi-metal solution by magnetic microalgae-derived biochar. J Water Process Eng 69:106622. https://doi.org/10.1016/j.jwpe.2024.106622

Tomczyk A, Sokołowska Z, Boguta P (2020) Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Rev Environ Sci Bio/technol 19:191–215. https://doi.org/10.1007/s11157-020-09523-3

Tomin O, Yazdani MR (2022) Production and characterization of porous magnetic biochar: before and after phosphate adsorption insights. J Porous Mater 29:849–859. https://doi.org/10.1007/s10934-022-01217-1

Trakal L, Veselská V, Šafařík I, Vítková M, Číhalová S, Komárek M (2016) Lead and cadmium sorption mechanisms on magnetically modified biochars. Bioresour Technol 203:318–324

Truong Q-M, Ho P-N-T, Nguyen T-B, Chen W-H, Bui X-T, Kumar Patel A, Rani Singhania R, Chen C-W, Dong C-D (2022) Magnetic biochar derived from macroalgal *Sargassum hemiphyllum* for highly efficient adsorption of Cu(II): influencing factors and reusability. Bioresour Technol 361:127732. https://doi.org/10.1016/j.biortech.2022.127732

Tsolis V, Barouchas P (2023) Biochar as soil amendment: the effect of biochar on soil properties using vis-nir diffuse reflectance spectroscopy, biochar aging and soil microbiology—a review. Land 12:1580. https://doi.org/10.3390/land12081580

Tu Y, Peng Z, Huang J, Wu X, Kong L, Liang Z, Yang L, Lin Z (2020) Preparation and characterization of magnetic biochar nanocomposites via a modified solvothermal method and their use as efficient heterogeneous fenton-like catalysts. Ind Eng Chem Res 59:1809–1821. https://doi.org/10.1021/acs.iecr.9b04590

Unceta N, Séby F, Malherbe J, Donard OFX (2010) Chromium speciation in solid matrices and regulation: a review. Anal Bioanal Chem 397:1097–1111. https://doi.org/10.1007/s00216-009-3417-1

Upadhyay V, Choudhary KK, Agrawal SB (2024) Use of biochar as a sustainable agronomic tool, its limitations and impact on environment: a review. Discover Agric 2:20. https://doi.org/10.1007/s44279-024-00033-2

Usman M, Monfort O, Gowrisankaran S, Hameed BH, Hanna K, Al-Abri M (2023) Dual functional materials capable of integrating adsorption and Fenton-based oxidation processes for highly efficient removal of pharmaceutical contaminants. J Water Process Eng 52:103566. https://doi.org/10.1016/j.jwpe.2023.103566

Varjani S, Kumar G, Rene ER (2019) Developments in biochar application for pesticide remediation: current knowledge and future research directions. J Environ Manage 232:505–513. https://doi.org/10.1016/j.jenvman.2018.11.043

Vieira DCS, Yunta F, Baragaño D, Evrard O, Reiff T, Silva V, de la Torre A, Zhang C, Panagos P, Jones A (2024) Soil pollution in the European Union–an outlook. Environ Sci Policy 161:103876

Waheed A, Xu H, Qiao X, Aili A, Yiremaikebayi Y, Haitao D, Muhammad M (2025) Biochar in sustainable agriculture and climate mitigation: mechanisms, challenges, and applications in the circular bioeconomy. Biomass Bioenergy 193:107531. https://doi.org/10.1016/j.biombioe.2024.107531

Wan X, Li C, Parikh SJ (2020) Simultaneous removal of arsenic, cadmium, and lead from soil by iron-modified magnetic biochar. Environ Pollut 261:114157. https://doi.org/10.1016/j.envpol.2020.114157

Wang J, Liao Z, Ifthikar J, Shi L, Du Y, Zhu J, Xi S, Chen Z, Chen Z (2017) Treatment of refractory contaminants by sludge-derived biochar/persulfate system via both adsorption and advanced oxidation process. Chemosphere 185:754–763. https://doi.org/10.1016/j.chemosphere.2017.07.084

Wang J, Wang S (2019) Preparation, modification and environmental application of biochar: a review. J Clean Prod 227:1002–1022. https://doi.org/10.1016/j.jclepro.2019.04.282

Wang S, Zhao M, Zhou M, Zhao Y, Li YC, Gao B, Feng K, Yin W, Ok YS, Wang X (2019a) Biomass facilitated phase transformation of natural hematite at high temperatures and sorption of Cd^{2+} and Cu^{2+}. Environ Int 124:473–548

Wang L, Wang J, Wang Z, Feng J, Li S, Yan W (2019b) Synthesis of Ce-doped magnetic biochar for effective Sb(V) removal: performance and mechanism. Powder Technol 345:501–508. https://doi.org/10.1016/j.powtec.2019.01.0221

Wang L, Wang J, He C, Lyu W, Zhang W, Yan W, Yang L (2019c) Development of rare earth element doped magnetic biochars with enhanced phosphate adsorption performance. Colloids Surf A Physicochem Eng Asp 561:236–243. https://doi.org/10.1016/j.colsurfa.2018.10.082

Wang C, Huang R, Sun R, Yang J, Sillanpää M (2021a) A review on persulfates activation by functional biochar for organic contaminants removal: synthesis, characterizations, radical determination, and mechanism. J Environ Chem Eng 9:106267. https://doi.org/10.1016/j.jece.2021.106267

Wang T, Li G, Yang K, Zhang X, Wang K, Cai J, Zheng J (2021b) Enhanced ammonium removal on biochar from a new forestry waste by ultrasonic activation: characteristics, mechanisms and evaluation. Sci Total Environ 778:146295. https://doi.org/10.1016/j.scitotenv.2021.146295

Wang C, Dai H, Liang L, Li N, Cui X, Yan B, Chen G (2023) Enhanced mechanism of copper doping in magnetic biochar for peroxymonosulfate activation and sulfamethoxazole degradation. J Hazard Mater 458:132002. https://doi.org/10.1016/j.jhazmat.2023.132002

Wang L, Zhang J, Cheng D, Guo W, Cao X, Xue J, Haris M, Ye Y, Ngo HH (2024a) Biochar-based functional materials for the abatement of emerging pollutants from aquatic matrices. Environ Res 252:119052

Wang C, Qiao J, Yuan J, Tang Z, Chu T, Lin R, Wen H, Zheng C, Chen H, Xie H, Peng C, Tan Y (2024b) Novel chitosan-modified biochar prepared from a Chinese herb residue for multiple heavy metals removal: characterization, performance and mechanism. Bioresour Technol 402:130830. https://doi.org/10.1016/j.biortech.2024.130830

Wathukarage A, Herath I, Iqbal MCM, Vithanage M (2019) Mechanistic understanding of crystal violet dye sorption by woody biochar: implications for wastewater treatment. Environ Geochem Health 41:1647–1661. https://doi.org/10.1007/s10653-017-0013-8

Wen Z, Xi J, Lu J, Zhang Y, Cheng G, Zhang Y, Chen R (2021) Porous biochar-supported $MnFe_2O_4$ magnetic nanocomposite as an excellent adsorbent for simultaneous and effective removal of organic/inorganic arsenic from water. J Hazard Mater 411:124909. https://doi.org/10.1016/j.jhazmat.2020.124909

Wijitkosum S (2022) Biochar derived from agricultural wastes and wood residues for sustainable agricultural and environmental applications. Int Soil Water Conserv Res 10:335–341. https://doi.org/10.1016/j.iswcr.2021.09.006

Wu J, Huang D, Liu X, Meng J, Tang C, Xu J (2018) Remediation of As(III) and Cd(II) co-contamination and its mechanism in aqueous systems by a novel calcium-based magnetic biochar. J Hazard Mater 348:10–19. https://doi.org/10.1016/j.jhazmat.2018.01.011

Wu J, Li Z, Huang D, Liu X, Tang C, Parikh SJ, Xu J (2020) A novel calcium-based magnetic biochar is effective in stabilization of arsenic and cadmium co-contamination in aerobic soils. J Hazard Mater 387:122010. https://doi.org/10.1016/j.jhazmat.2019.122010

Wu J, Huang R, Zhou Q, Lu H, Li F, Wu K, Li Z (2021a) Magnetic biochar reduces phosphorus uptake by *Phragmites australis* during heavy metal remediation. Sci Total Environ 758:143643. https://doi.org/10.1016/j.scitotenv.2020.143643

Wu Q, Dong S, Wang L, Li X (2021b) Single and competitive adsorption behaviors of Cu^{2+}, Pb^{2+} and Zn^{2+} on the biochar and magnetic biochar of pomelo peel in aqueous solution. Water 13:868. https://doi.org/10.3390/w13060868

Wu J, Wang T, Shi N, Min F, Pan W-P (2022) Hierarchically porous biochar templated by in situ formed ZnO for rapid Pb^{2+} and Cd^{2+} adsorption in wastewater: experiment and molecular dynamics study. Environ Pollut 302:119107. https://doi.org/10.1016/j.envpol.2022.119107

Wu W, Wang R, Chang H, Zhong N, Zhang T, Wang K, Ren N, Ho SH (2023) Rational electron tunning of magnetic biochar via N, S co-doping for intense tetracycline degradation: efficiency improvement and toxicity alleviation. Chem Eng J 458:141470

Xiang W, Zhang X, Chen J, Zou W, He F, Hu X, Tsang DCW, Ok YS, Gao B (2020) Biochar technology in wastewater treatment: a critical review. Chemosphere 252:126539. https://doi.org/10.1016/j.chemosphere.2020.126539

Xiang L, Harindintwali JD, Wang F, Redmile-Gordon M, Chang SX, Fu Y, He C, Muhoza B, Brahushi F, Bolan N, Jiang X, Ok YS, Rinklebe J, Schaeffer A, Zhu Y, Tiedje JM, Xing B (2022) Integrating biochar, bacteria, and plants for sustainable remediation of soils contaminated with organic pollutants. Environ Sci Technol 56:16546–16566. https://doi.org/10.1021/acs.est.2c02976

Xiao J, Hu R, Chen G, Xing B (2020) Facile synthesis of multifunctional bone biochar composites decorated with Fe/Mn oxide micro-nanoparticles: physicochemical properties, heavy metals sorption behavior and mechanism. J Hazard Mater 399:123067

Xiao B, Jia J, Wang W, Zhang B, Ming H, Ma S, Kang Y, Zhao M (2023) A review on magnetic biochar for the removal of heavy metals from contaminated soils: preparation, application, and microbial response. J Hazardous Mater Adv 10:100254. https://doi.org/10.1016/j.hazadv.2023.100254

Xin O, Yitong H, Xi C, Jiawei C (2017) Magnetic biochar combining adsorption and separation recycle for removal of chromium in aqueous solution. Water Sci Technol 75:1177–1184. https://doi.org/10.2166/wst.2016.610

Xu L, Wang J (2012) Magnetic nanoscaled Fe_3O_4/CeO_2 composite as an efficient Fenton-like heterogeneous catalyst for degradation of 4-chlorophenol. Environ Sci Technol 46(18):10145–10153. https://doi.org/10.1021/es300303f

Xu Y, Yu X, Xu B, Peng D, Guo X (2021) Sorption of pharmaceuticals and personal care products on soil and soil components: influencing factors and mechanisms. Sci Total Environ 753:141891. https://doi.org/10.1016/j.scitotenv.2020.141891

Xu J, Ma Q, Feng W, Zhang X, Lin Q, You C, Wang X (2022a) Removal of methyl orange from water by Fenton oxidation of magnetic coconut-clothed biochar. RSC Adv 12:24439–24446. https://doi.org/10.1039/D2RA03545F

Xu S, Wen L, Yu C, Li S, Tang J (2022b) Activation of peroxymonosulfate by $MnFe_2O_4$@ BC composite for bisphenol A degradation: the coexisting of free-radical and non-radical pathways. Chem Eng J 442:136250

Xu Q, Xiong C, Fan J, Zhang F, Wang J, Xu Q, Yin W, Wang S, Wang X (2023a) Assessing the efficiency and mechanism of copper adsorption onto biochars derived from corn straw and cow manure. Water Air Soil Pollut 234:390. https://doi.org/10.1007/s11270-023-06385-7

Xu Z, Zhang B, Wang T, Liu J, Mei M, Chen S, Li J (2023b) Environmentally friendly crab shell waste preparation of magnetic biochar for selective phosphate adsorption: mechanisms and characterization. J Mol Liq 385:122436. https://doi.org/10.1016/j.molliq.2023.122436

Xu W, Qin R, Cao G, Qiang Y, Lai M, Lu Y (2024) Magnetic composite photocatalyst $NiFe_2O_4$/$ZnIn_2S_4$/biochar for efficient removal of antibiotics in water under visible light: performance, mechanism and pathway. Environ Pollut 360:124602. https://doi.org/10.1016/j.envpol.2024.124602

Yaashikaa PR, Kumar PS, Varjani S, Saravanan A (2020) A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. Biotechnol Rep 28:e00570. https://doi.org/10.1016/j.btre.2020.e00570

Yang L, Chen Y, Ouyang D, Yan J, Qian L, Han L, Chen M, Li J, Gu M (2020) Mechanistic insights into adsorptive and oxidative removal of monochlorobenzene in biochar-supported nanoscale zero-valent iron/persulfate system. Chem Eng J 400:125811. https://doi.org/10.1016/j.cej.2020.125811

Yang X, Hinzmann M, Pan H, Wang J, Bolan N, Tsang DCW, Ok YS, Wang S-L, Shaheen SM, Wang H, Rinklebe J (2022) Pig carcass-derived biochar caused contradictory effects on arsenic mobilization in a contaminated paddy soil under fluctuating controlled redox conditions. J Hazard Mater 421:126647. https://doi.org/10.1016/j.jhazmat.2021.126647

Yang H, Lee C-G, Lee J (2023) Utilizing animal manure-derived biochar in catalytic advanced oxidation processes: a review. J Water Process Eng 56:104545. https://doi.org/10.1016/j.jwpe.2023.104545

Yang X, Deng D, Liu Z, Ke W, Xue S, Zhu F (2024a) Pb/As simultaneous removal from soil leachate of Pb/Zn smelting sites by magnetic biochar. J Environ Manage 365:121526. https://doi.org/10.1016/j.jenvman.2024.121526

Yang X, Liang D, Li Q, Chang H, Chen Z, Liu X (2024b) A novel biochar derived from *Prunella vulgaris* L. residue of Chinese herbs for eco-efficient removal of four heavy metals from water: optimization, mechanism, assessment and recycle. Process Saf Environ Prot 192:79–92. https://doi.org/10.1016/j.psep.2024.10.019

Yi Y, Tu G, Zhao D, Tsang PE, Fang Z (2019) Biomass waste components significantly influence the removal of Cr(VI) using magnetic biochar derived from four types of feedstocks and steel pickling waste liquor. Chem Eng J 360:212–220

Yi Y, Huang Z, Lu B, Xian J, Tsang EP, Cheng W, Fang J, Fang Z (2020) Magnetic biochar for environmental remediation: a review. Bioresour Technol 298:122468. https://doi.org/10.1016/j.biortech.2019.122468

Yin Z, Liu Y, Liu S, Jiang L, Tan X, Zeng G, Li M, Liu S, Tian S, Fang Y (2018) Activated magnetic biochar by one-step synthesis: enhanced adsorption and coadsorption for 17β-estradiol and copper. Sci Total Environ 639:1530–1542. https://doi.org/10.1016/j.scitotenv.2018.05.130

Ying Z, Zhang T, Li H, Liu X (2023) Adsorptive removal of aflatoxin B1 from contaminated peanut oil via magnetic porous biochar from soybean dreg. Food Chem 409:135321. https://doi.org/10.1016/j.foodchem.2022.135321

You X, Wang S, Chen J (2024) Magnetic biochar accelerates microbial succession and enhances assimilatory nitrate reduction during pig manure composting. Environ Int 184:108469. https://doi.org/10.1016/j.envint.2024.108469

Yu KL, Lau BF, Show PL, Ong HC, Ling TC, Chen W-H, Ng EP, Chang J-S (2017) Recent developments on algal biochar production and characterization. Bioresour Technol 246:2–11. https://doi.org/10.1016/j.biortech.2017.08.009

Yu F, Tian F, Zou H, Ye Z, Peng C, Huang J, Zheng Y, Zhang Y, Yang Y, Wei X, Gao B (2021) *Zno*/biochar nanocomposites via solvent free ball milling for enhanced adsorption and photocatalytic degradation of methylene blue. J Hazard Mater 415:125511. https://doi.org/10.1016/j.jhazmat.2021.125511

Yuan Y, Bolan N, Prévoteau A, Vithanage M, Biswas JK, Ok YS, Wang H (2017) Applications of biochar in redox-mediated reactions. Bioresour Technol 246:271–281

Zarei-Jelyani F, Salahi F, Zarei-Jelyani M, Rahimpour MR (2024) Various industrial wastes to energy technologies. In: Encyclopedia of renewable energy, sustainability and the environment. Elsevier, pp 17–28. https://doi.org/10.1016/B978-0-323-93940-9.00212-7

Zhang B-T, Zhang Y, Teng Y, Fan M (2015) Sulfate radical and its application in decontamination technologies. Crit Rev Environ Sci Technol 45:1756–1800. https://doi.org/10.1080/10643389.2014.970681

Zhang A, Li X, Xing J, Xu G (2020) Adsorption of potentially toxic elements in water by modified biochar: a review. J Environ Chem Eng 8:104196. https://doi.org/10.1016/j.jece.2020.104196

Zhang P, Duan W, Peng H, Pan B, Xing B (2021) Functional biochar and its balanced design. ACS Environ Au 2:115–127. https://doi.org/10.1021/acsenvironau.1c000

Zhang D, Zhou D, Lu L, Zhang M, Lü T, Huang J, Zhao H, Zhou J, Rinklebe J (2023a) Preferential, synergistic sorption and reduction of Cr(VI) from chromium–rhodamine B mixed wastewater by magnetic porous biochar derived from wasted *Myriophyllum aquaticum* biomass. Environ Pollut 327:121593. https://doi.org/10.1016/j.envpol.2023.121593

Zhang N, Reguyal F, Praneeth S, Sarmah AK (2023b) A green approach of biochar-supported magnetic nanocomposites from white tea waste: production, characterization and plausible synthesis mechanisms. Sci Total Environ 886:163923. https://doi.org/10.1016/j.scitotenv.2023.163923

Zhang Y, Xiang Y, Xu R, Huang J, Deng J, Zhang X, Wu Z, Huang Z, Yang Z, Xu J, Xiong W, Li H (2023c) Magnetic biochar promotes the risk of mobile genetic elements propagation in sludge anaerobic digestion. J Environ Manage 335:117492. https://doi.org/10.1016/j.jenvman.2023.117492

Zhang X, Zhen D, Liu F, Chen R, Peng Q, Wang Z (2023d) An achieved strategy for magnetic biochar for removal of tetracyclines and fluoroquinolones: adsorption and mechanism studies. Bioresour Technol 369:128440

Zhang H, Zhao B, Song Y, Yang Y, Cai L, Miao Q, Jiang T (2025a) Soil contamination in contaminated sites with key standards: a global analysis and perspective. J Hazard Mater 494:138724

Zhang S, Wang S, Zhang J, Wang B, Wang H, Liu L, Cao C, Shi M, Liu Y (2025b) Research on the application of biochar in carbon sequestration: a bibliometric analysis. Energies 18:2745

Zhao L, Cao X, Mašek O, Zimmerman A (2013) Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. J Hazard Mater 256:1–9

Zhao Y, Zhang R, Liu H, Li M, Chen T, Chen D, Zou X, Frost RL (2019) Green preparation of magnetic biochar for the effective accumulation of Pb(II): performance and mechanism. Chem Eng J 375:122011. https://doi.org/10.1016/j.cej.2019.122011

Zhong J, Feng Y, Yang B, Xiong Q, Ying GG (2022) Accelerated degradation of sulfadiazine by nitrogen-doped magnetic biochar-activated persulfate: role of oxygen vacancy. Sep Purif Technol 289:120735

Zhou X, Liu Y, Zhou J, Guo J, Ren J, Zhou F (2018) Efficient removal of lead from aqueous solution by urea-functionalized magnetic biochar: Preparation, characterization and mechanism study. J Taiwan Inst Chem Eng 91:457–467. https://doi.org/10.1016/j.jtice.2018.04.018

Zhou H, Zhu X, Chen B (2020) Magnetic biochar supported α-MnO_2 nanorod for adsorption enhanced degradation of 4-chlorophenol via activation of peroxydisulfate. Sci Total Environ 724:138278. https://doi.org/10.1016/j.scitotenv.2020.138278

Zhou X, Zhu Y, Niu Q, Zeng G, Lai C, Liu S, Huang D, Qin L, Liu X, Li B (2021) New notion of biochar: a review on the mechanism of biochar applications in advannced oxidation processes. Chem Eng J 416:129027

Zhou J, He Y, Huang L, Xu A, Zhao Y, Wang J, He G, Fan S, Huang Z (2024) Preparation of magnetic biochar from macadamia nutshell pretreated by $FeCl_3$-assisted mechanochemical activation for adsorption of heavy metals. J Environ Chem Eng 12:113122

Zhu Y, Zheng C, Wu S, Song Y, Hu B (2018a) Interaction of Eu(III) on magnetic biochar investigated by batch, spectroscopic and modeling techniques. J Radioanal Nucl Chem 316:1337–1346

Zhu J, Li M, Whelan M (2018b) Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: a review. Sci Total Environ 612:522–537. https://doi.org/10.1016/j.scitotenv.2017.08.095

Zhu X, Li Y, Wang X (2019) Machine learning prediction of biochar yield and carbon contents in biochar based on biomass characteristics and pyrolysis conditions. Bioresour Technol 288:121527. https://doi.org/10.1016/j.biortech.2019.121527

Zhu J, Rui T, You Y, Shen D, Liu T (2023) Magnetic biochar with Mg/La modification for highly effective phosphate adsorption and its potential application as an algaecide and fertilizer. Environ Res 231:116252. https://doi.org/10.1016/j.envres.2023.116252

Zhuo S-N, Sun H, Wang Z-Y, Ren H-Y, Xing D-F, Ren N-Q, Liu B-F (2023) A magnetic biochar catalyst with dual active sites of Fe_3C and Fe_4N derived from floc: the activation mechanism for persulfate on degrading organic pollutant. Chem Eng J 455:140702. https://doi.org/10.1016/j.cej.2022.140702

Zolgharnein J, Shahmoradi A, Ghasemi J (2011) Pesticides removal using conventional and low-cost adsorbents: a review. Clean: Soil, Air, Water 39:1105–1119. https://doi.org/10.1002/clen.201000306

Zoroufchi Benis K, Motalebi Damuchali A, Soltan J, McPhedran KN (2020) Treatment of aqueous arsenic—a review of biochar modification methods. Sci Total Environ 739:139750. https://doi.org/10.1016/j.scitotenv.2020.139750