Enhancing livestock manure composting efficiency through advanced biochar functionalization: A critical review

Dong Wang, Yu Liu, Xinyuan Wei, Yulong Shi, Xiaomei Xie, Haoran Li, Qingwen Zhang

PII: S2590-1826(25)00177-8

DOI: https://doi.org/10.1016/j.enceco.2025.10.010

Reference: ENCECO 351

To appear in: *Environmental Chemistry and Ecotoxicology*

Received date: 24 August 2025

Revised date: 10 October 2025

Accepted date: 10 October 2025

Please cite this article as: D. Wang, Y. Liu, X. Wei, et al., Enhancing livestock manure composting efficiency through advanced biochar functionalization: A critical review, *Environmental Chemistry and Ecotoxicology* (2024), https://doi.org/10.1016/j.enceco.2025.10.010

Enhancing livestock manure composting efficiency through advanced biochar functionalization: A critical review

Dong Wang[a], Yu Liu[a], Xinyuan Wei[a], Yulong Shi[a], Xiaomei Xie[a,b], Haoran Li[a,b], Qingwen Zhang[a,*]

[a]Agricultural Clean Watershed Research Group, Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences/Key Laboratory of Agricultural and Rural Eco-Environment, Ministry of Agriculture and Rural Affairs, Beijing, 100081, China

[b]Qingdao Engineering Research Center for Rural Environment, College of Resources and Environment, Qingdao Agricultural University, Qingdao 266109, China

*** Corresponding author**

E-mail: zhangqingwen@caas.cn (Qingwen Zhang)

Abstract

Composting of livestock and poultry manure (LPM) is a key route for nutrient recycling but faces challenges such as low humification efficiency, greenhouse gas emissions, and residual contaminants including heavy metals and antibiotics. Biochar, with its porous structure and large surface area, has shown great potential as a compost amendment. This review synthesized recent advances in functionalized biochar for LPM composting, covering preparation and modification approaches including physical activation, chemical doping, microbial colonization, composite strategies, and emerging techniques such as molecular imprinting and earthworm bioaugmentation. By comparing the differences among modification methods in terms of performance, scalability, cost, and environmental risk, and by integrating material characterization with multi-omics evidence, this review revealed how specific biochar properties influence composting parameters, microbial communities, and functional gene expression. The multifunctional roles and underlying mechanisms of biochar in optimizing composting parameters, enhancing humification, reducing carbon and nitrogen losses, immobilizing heavy metals, and removing antibiotics are systematically summarized. Finally, this study highlighted key research gaps including mechanistic links between surface chemistry and gene-level responses, and field-scale validation. This work bridged critical gaps between environmental sustainability and agricultural safety offering a comprehensive roadmap for advancing waste management strategies.

Keywords: Functionalized biochar; Livestock manure composting; Pollutant mitigation; Microbial ecology; Antibiotic resistance genes; Sustainable agriculture

1. Introduction

The rapid development of intensive livestock and poultry farming has played a crucial role in meeting the global demand for animal protein. However, it has also led to a significant increase in the production of manure, posing challenges for its effective treatment and utilization. It was reported that China's livestock and poultry manure (LPM) production reaches as high as 3.8 billion tons [1]. LPM is frequently applied directly to soil as a fertilizer owing to its rich content of organic matter, nitrogen, phosphorus, and other essential nutrients [2, 3]. However, to prevent disease and promote animal growth, heavy metals (HM) and antibiotics are often used as feed additives [1, 4, 5]. These substances are not fully absorbed by the animals, with approximately 30-90% being excreted and accumulating in manure or urine [6]. The direct application of LPM to agricultural fields introduces hazardous substances such as antibiotics, HM, and pathogens into soils, posing potential risks to human health and ecosystem stability [7, 8]. Furthermore, improper manure management can lead to soil and water eutrophication as well as increased greenhouse gas emissions [9, 10]. Therefore, developing strategies for the resource-efficient utilization of LPM while minimizing environmental pollution has become an urgent priority in agricultural and environmental science.

Aerobic composting is a controlled biochemical process in which utilizes ubiquitous microorganisms (e.g., bacteria, actinomycetes, fungi) degrade organic matter under suitable moisture conditions and an appropriate carbon-to-nitrogen (C/N) ratio, converting it into stable humus and thereby achieving the detoxification and resource-efficient utilization of LPM [11, 12]. In China, over 80% of LPM produced on farms is composted and subsequently used as organic fertilizer [13]. However, conventional composting suffers from several limitations, such as long fermentation cycles, low humification degrees, limited antibiotic degradation, and unstable HM immobilization [14-16]. Furthermore, substantial emissions of greenhouse gases (N_2O, CO_2, and CH_4) and harmful gases (NH_3) not only result in significant carbon and nitrogen losses but also exacerbate environmental issues such as the greenhouse effect [17, 18]. These drawbacks not only degrade the quality of compost products but also pose potential risks to ecosystems, thereby failing to meet the requirements of green, low-carbon, and sustainable agricultural practices. Therefore, it is imperative to identify and implement viable solutions to optimize the aerobic composting process.

Biochar (BC) is a carbon-rich, porous material derived from biomass feedstocks (e.g., crop straws, wood chips) via pyrolysis or hydrothermal carbonization, characterized by its porous structure, high specific surface area (SSA), and nutrient-rich properties [4, 19, 20]. As a compost additive, BC has shown great potential in LPM composting due to the following advantages: (1) its high porosity and low density enhance compost aeration, thereby improving microbial activity and promoting humification [21]; (2) the exceptional adsorption capacity (AC) effectively mitigates greenhouse gas and harmful gas emissions while retaining carbon and nitrogen nutrients [22]; (3) it facilitates the immobilization of HM and removal of antibiotics and antibiotic resistance genes (ARGs) [23]. Furthermore, the incorporation of BC into compost products can more effectively enhance soil fertility and promote carbon sequestration through its unique physicochemical properties [24]. However, pristine BC typically has relatively large pore sizes and limited types and numbers of surface functional groups (FG), which restricts its AC and selectivity in composting applications [25, 26]. To overcome the inherent limitations, increasing attention has been devoted to targeted BC modification strategies aimed at altering its physicochemical properties, enriching functional group types, and thereby enhancing AC and catalytic activity for optimized composting performance. For example, Gu et al. [22] reported that 3% Mg modified corn stover BC reduced CH_4, N_2O, and NH_3 emissions from pig manure compost by 66.7%, 29.0%, and 26.7%, respectively, while effectively improving compost quality and reducing environmental hazards. Following Mg modification, the SSA and pore volume (PV) of BC increased by 46.9% and 40.7%, respectively, resulting in significantly enhanced AC. Similarly, the application of 5% H_3PO_4-modified coconut shell BC in sewage sludge composting enhanced the humification index by 22.19%, while significantly reducing the bioavailable contents of Cu, Fe, Mn, Ni, Pb, and Zn by 19.32%, 35.28%, 39.72%, 41.99%, 36.28%, and 32.27%, respectively [27]. Despite extensive research on the performance and mechanisms of modified BC in LPM composting, systematic evaluations that integrate the entire chain from preparation to modification and final disposal remains lacking.

While prior research has examined the role of BC in composting, most remain fragmented in scope and fail to fully integrate BC engineering, composting microbiology, and pollutant attenuation mechanisms. To address this gap, this review systematically introduces BC preparation processes, summarizes conventional BC modification strategies, and explores the application of emerging technologies for producing functionalized BC. It deeply explores the effect and mechanism of functionalized BC in regulating the composting process of LPM. Particularly emphasize the following innovative contributions: (1) Multidimensional classification of BC modification technologies. This review provided a clear comparative framework of current BC functionalization approaches-including mechanical activation, chemical doping, microbial enhancement, composite material engineering, and emerging technologies such as molecular imprinting and carbon nanomaterials-highlighting their respective advantages, limitations, and composting applicability; (2) Mechanistic elucidation of composting enhancement. The review deciphered how BC, especially when functionalized, modulates core composting parameters (e.g., temperature, pH), accelerated humification pathways, reduced gas emissions, immobilized HM, and reduced ARGs transmission via both physicochemical interactions and microbiome shifts. (3) Microbial-ecological interface of functionalized BC. Highlight recent findings on how functionalized BC influences microbial community succession, metabolic pathway activation, and gene expression patterns during composting emerging frontier linking BC materials science with microbial ecology. Finally, this review outlines current challenges and future opportunities, providing a theoretical foundation for optimizing BC-enhanced LPM composting and promoting its large-scale implementation for sustainable agricultural waste management.

2. Preparation of Biochar

2.1. Feedstock Selection

In 2013, the International Biochar Initiative (IBI) formally defined BC as a solid material obtained from the thermochemical conversion of biomass under limited oxygen conditions [28]. As the fourth largest energy resource worldwide, biomass contributes to approximately 14% of global energy consumption, with this share rising to 23.5% in developing countries [28]. Feedstocks for BC production are diverse and can be classified into four main categories: agricultural waste (e.g., straw and manure), forestry residues (e.g., branches and bark), aquatic plants (e.g., algae and reeds), and food waste [29, 30]. The heterogeneity of biomass is mainly reflected in its organic components (e.g., protein, lignin, and cellulose), inorganic contents (e.g., minerals), moisture content, and volatile matter [29]. Generally, the properties of feedstocks significantly influence the suitability of BC for specific applications. For instance, forestry waste typically contains higher lignin content, resulting in BC with greater porosity and SSA [31]. Such BC tends to have higher carbon content and lower ash content, making it suitable as a soil amendment [32, 33]. Agricultural waste like manure and straw are rich in nutrients, making their derived BC ideal for use as organic fertilizer to enhance soil fertility and crop yield [34]. Algae-derived BC, enriched with oxygen- and nitrogen-containing FG and surface minerals like calcium, magnesium, and sulfur, exhibits excellent AC for pollutants such as sulfamethoxazole, reaching up to 4879 mg/kg [35]. Despite the promising performance of BC in applications such as soil remediation, greenhouse gas mitigation, and pollutant removal, potential environmental risks must be carefully considered. For instance, sludge-derived BC may release HM, and wood-based BC may contain polycyclic aromatic hydrocarbons (PAHs) [36].

2.2. Preparation techniques

The physical and chemical properties of BC are primarily influenced by feedstock type and pyrolysis conditions, including reaction temperature, duration, reactor type, and heating rate. Common methods for BC production include pyrolysis and hydrothermal carbonization.

2.2.1. Pyrolysis

Pyrolysis is the most widely used technique for producing BC, involving thermal treatment of biomass at 300-1000 °C under oxygen-limited conditions [37].Common pyrolysis variants include slow, intermediate, fast, microwave, flash, vacuum, and hydro. During pyrolysis, biomass components such as cellulose, hemicellulose, lignin, carbohydrates, proteins, and lipids undergo decomposition, dehydration, depolymerization, condensation, cross-linking, aromatization, isomerization, carbonization, decarboxylation, dehydrogenation, and deamination reactions, resulting in solid, liquid, and gaseous products [38, 39]. Table 1 compared the operational parameters of various pyrolysis methods.

Slow pyrolysis, typically conducted at lower temperatures with slow heating rates and longer residence times, produces BC with high SSA and carbon content, making it suitable as a soil amendment or compost additive [40]. Fast pyrolysis features higher temperatures and shorter reaction times and is primarily used for producing bio-oil. It can also yield small-particle BC with high surface activity, applicable in gas adsorption and catalysis [40]. Intermediate pyrolysis offers a compromise between slow and fast pyrolysis, balancing solid and liquid product yields while accommodating a wider range of feedstock particle sizes and enabling better process control [37]. Generally, increasing pyrolysis temperature reduces BC yield and acidic functional group content but increases basic FG, ash content, and stability [41, 42]. Flash pyrolysis rapidly heats and cools biomass at high rates, minimizing volatile loss and maximizing bio-oil yield [40]. However, the yield of coke during flash pyrolysis is limited, and there is no physical form of coke at the end of flash pyrolysis in some cases. Vacuum pyrolysis, performed under low pressure and oxygen-free conditions, removes volatiles via continuous vacuum pumping, reducing secondary reactions and enhancing bio-oil yield [43]. Microwave pyrolysis directly heats biomass using microwave energy, allowing efficient pyrolysis at lower temperatures while reducing energy consumption and pollution [44]. Moisture content plays a critical role in this method, with in situ steam enhancing impurity removal and energy transfer efficiency [37]. Hydro pyrolysis is an emerging technology that processes biomass with hydrogen under high temperature and pressure, modifying the chemical structure of BC to produce highly aromatic, hydrogen-rich char along with valuable hydrocarbons or alcohols [45].

2.2.2. Hydrothermal Carbonization

Hydrothermal carbonization (HTC) is another thermochemical method for converting high-moisture biomass into solid, coal-like products (hydrochar). It is typically carried out in a closed container at a temperature range of 180-350 °C and a pressure of 2-6 MPa [46]. Compared to conventional pyrolysis, HTC demonstrates superior suitability for high-moisture biomass by directly utilizing inherent water as the reaction medium, thereby eliminating energy-intensive feedstock dewatering or pre-drying steps [47]. The primary mechanism of HTC involves the formation of primary carbonaceous material via low-temperature heat treatment, followed by the generation of secondary char through repolymerization reactions [48]. This process typically achieves a hydrochar yield ranging from 25% to 45%, which can be utilized in applications such as adsorbents, catalysts, and carbon-based functional materials. Furthermore, HTC offers advantages including operational simplicity, lower energy demand, shorter reaction times, and reduced environmental impact, while enabling nutrient recovery and lower carbon emissions.

2.2.3. Other Methods

In addition to pyrolysis and HTC, gasification and torrefaction are also used for converting biomass into BC. Gasification involves reacting biomass with gasifying agents (e.g., H_2O, CO_2) at high temperatures to produce combustible gases (e.g., CO, H_2, CH_4) and a small amount of solid residue-BC [49]. As gas production is the primary goal, BC yield is relatively low. Torrefaction is a mild thermal treatment at 200-300 °C under inert conditions. It does not require chemical reagents and avoids secondary pollution [50]. This process removes moisture and oxygenated volatiles, thereby increasing energy density and producing BC with lower H/C and O/C ratios and higher calorific values [37].

3. Modification methods of Biochar

Although preparation methods and pyrolysis conditions have been optimized in some research, the AC of BC remains insufficient for various environmental applications [51]. Therefore, physical, chemical, and biological modification strategies are necessary to fully exploit its potential. The different modification methods of BC were shown in Fig. 1.

3.1. Physical modification

Common physical modification methods include ball milling, steam activation, and gas purging, which aim to increase the SSA, FG, and pore structure of BC. Ball milling employs the kinetic energy derived from the movement of grinding balls to induce the cleavage of chemical bonds, modify particle morphology, and generate nanoscale particles, thereby improving the physicochemical properties of BC [52]. Ball-milled BC has been demonstrated to promote phenanthrene degradation by modulating bacterial oxidative stress, with a degradation rate 2.84 times higher than that of the control group [53]. However, prolonged ball milling may reduce BC catalytic efficiency due to compaction and agglomeration effects [54]. Steam activation facilitates impurity removal and pore unblocking during BC production, ultimately optimizing pore structure [55]. Additionally, this process promotes volatile matter precipitation and increases crystalline carbon content, enhancing BC stability and aromaticity [56]. Rajapaksha et al. [57] reported that steam activation at 700 °C increased the SSA of BC by 207% and enhanced its AC for sulfamethoxazole in water by 55%, attributing the primary adsorption mechanism to electrostatic interactions. Nevertheless, the widespread implementation of this method is limited by challenges in regulating activation temperature, insufficient activation, and low yields. During gas purging modification, specific gases (e.g.,

CO_2 and N_2) interact with active sites on or within BC, resulting in changes to surface FG and optimization of the pore structure. These alterations enhance the AC, catalytic performance, or other specific functionalities of the BC. After CO_2 and N_2 blowing, the modified BC exhibits a high AC for HM lead in water, reaching a maximum of 256.4 mg/g [58], with ion exchange and complexation between HM and surface FG including C=O and -OH serving as the dominant mechanisms.

3.2. Chemical modification

Acid and alkali modification represents the most prevalent chemical treatment for BC, primarily enhancing AC by increasing SSA, optimizing pore structure, and introducing oxygen-containing FG [59]. Acid-modified BC exhibits elevated surface electronegativity, thereby improving stability, whereas alkali treatment enhances surface alkalinity and reduces hydrophilicity [60]. For instance, Chu et al. [61] demonstrated that H_3PO_4-modified wood BC achieved a 296% increase in SSA (from 411 to 1627 m^2/g) and a 383% expansion in total PV (from 0.18 to 0.87 cm^3/g). Similarly, H_3PO_4-treated plant-leaf BC showed a 43.7% enhancement in ciprofloxacin AC (from 43.48 to 62.50 mg/g), attributed to the negatively charged PO_4^{3-} group enhancing the effective binding of cations in ciprofloxacin molecules to the surface FG of BC [62]. Zhang et al. [63] demonstrated that KOH-modified bamboo BC exhibited a significantly larger SSA (526.36 m^2/g) than unmodified (91.17 m^2/g), H_2O (191.22 m^2/g), CO_2 (174.09 m^2/g), $ZnCl_2$ (96.93 m^2/g), and H_3PO_4 modified (85.52 m^2/g), achieving a CO_2 AC of 3.73 mmol/g, representing a 1.59 times enhancement over pristine BC. During the pyrolysis process, K^+ in KOH can degrade the carbon matrix, causing existing pores to expand and form new pores, thereby exhibiting excellent CO_2 capture performance [64]. Similarly, NaOH modification also increased the SSA of wheat straw BC by 4.5 times, and enhanced the interaction between electron donor-acceptor (EDA) and antibiotic FG by enriching surface -OH [65]. These changes resulted in elevated adsorption rates for bisphenol A, tetracycline, and ofloxacin in wastewater by 26.3%, 34.2%, and 72.7%, respectively. Notably, NaOH and KOH have different modification mechanisms for BC. During KOH modification, in situ-generated K atoms are intercalated between the microcrystalline carbon layers, whereas NaOH modification primarily involves surface reactions, with Na exhibiting no intercalation behavior within the carbon structure [66].

Beyond acid and alkali modification, oxidants, metal/metal compound loading, and heteroatom doping were widely used for chemical modification. Oxidants such as H_2O_2 and $KMnO_4$ exhibit potent oxidative capacity, enabling interactions with carbon atoms on BC surfaces to introduce or augment -COOH, -OH, and -COO-. Furthermore, oxidative treatment optimizes BC pore structures, yielding a more favorable pore size distribution that enhances pollutant adsorption [67]. Yue et al. [68] demonstrated that $KMnO_4$-modified corn stover BC exhibited a 3.2 times increase in SSA and a 7.7 times enhancement in oxytetracycline AC (200.4 mg/g). The dominant adsorption mechanisms were identified as hydrogen bonding, π-π interactions, and surface complexation. Beyond effectively augmenting oxygen-containing FG and micropores, $KMnO_4$ modification also introduced MnOx species, which facilitated antibiotic degradation through Mn-O complexation [69]. H_2O_2 modification of yak dung BC increased -COOH group content by 101% while reducing ash content by 42%, thereby significantly enhancing its removal capacity for aqueous HM like Pb^{2+}、Cu^{2+}、Cd^{2+}, and Zn^{2+} [70]. However, pinewood BC modified with higher-concentration H_2O_2 exhibited significantly reduced AC for methylene blue, indicating that the AC of BC is related to biomass feedstock and pollutant type [71]. As an oxidizing agent, H_2O_2 is relatively cost-effective compared to strong acids and bases. Owing to its decomposition products being H_2O and O_2, it exhibits high environmental safety. The modification with metals/metal oxides can enhance the SSA and active sites of BC, while also regulating surface charge, thereby improving both the surface properties and AC of BC [60]. There are three main methods for metal/metal oxide modification of BC: (1) mixing metal powders with BC followed by ball milling to produce metal-BC composites with enhanced dispersion; (2) co-pyrolyzing metal oxides with biomass to generate in situ functionalized BC; (3) immersing BC in a solution containing metal oxides through liquid-phase precipitation or reduction methods. The impact of different metals or metal oxides on the AC of BC largely depends on their intrinsic chemical properties, including electronic configuration, atomic size, and oxidation state [60]. Research has shown that Fe modified lincomycin fermentation residues BC exhibits excellent catalytic performance in the persulfate oxidation system, achieving a tetracycline degradation rate of 85.1% within 30 min [72].This represents a 15.5% increase in comparison to unmodified BC. Additionally, it inactivated 60.1% of antibiotic-resistant bacteria (*Pseudomonas aeruginosa* HLS-6) within 60 min, and significantly reduced the abundances of ARGs including *sul1*, *sul2*, and *intI1* by 0.05-2.74 log2. The formation of Fe_3O_4 nanoparticles on BC was found to accelerate the Fe^{2+}/Fe^{3+} redox cycle, promote electron transfer on the catalyst surface and increase the production of free radicals such as •OH and $^1O_2$, thereby promoting attacks on tetracycline molecules, resistance gene fragments, and antibiotic-resistant bacterial cells. Similarly, MnO_2-modified corn stover BC exhibited enhanced SSA and PV, which significantly facilitated electron transfer between syntrophic bacteria and methanogens in anaerobic digestion systems, ultimately increasing CH_4 production by 5.38% [73]. Heteroatom doping (e.g., N, O, S and P) represents an effective BC modification strategy, which can provide more surface FG and active sites. Zhang et al. [74] developed a novel nitrogen-doped porous BC using waste loofah as the raw material, $NaHCO_3$ as the activating agent, and urea as the nitrogen source through a one-step pyrolysis and co-activation process. Compared to the pristine loofah BC, the nitrogen-doped BC exhibited 6.3 and 5.7 times increases in SSA and total PV, respectively. It demonstrated excellent AC toward bisphenol A (BPA), with a maximum AC of 308.4 mg/g. Pore filling and π-π interactions served as primary adsorption mechanisms, while the incorporated nitrogen atoms formed multiple bonding configurations such as pyrrolic-N, graphitic-N, and pyridinic-N, providing abundant active sites for BPA adsorption. In another study, corn cobs were used as the biomass feedstock, and urea and thiourea were employed as nitrogen and sulfur sources, respectively, to prepare N-doped and S-doped BC via hydrothermal carbonization [75]. The results showed that the removal efficiencies of sulfamethazine (SMZ) by N-doped and S-doped BC, through activated peroxymonosulfate (PMS), were 3.9 and 2.9 times higher than that of unmodified BC, respectively. The incorporation of heteroatoms into the BC matrix enhanced non-radical degradation pathways, thereby significantly improving the antibiotic removal performance.

As a multifunctional material, BC modification methods have attracted increasing attention. Emerging technologies such as carbonaceous materials and molecular imprinting have been successively applied to BC modification, aiming to further enhance its performance and application scope. Carneiro et al. [76] demonstrated that graphene oxide-poultry litter BC composites enhanced Cu and Zn adsorption capacities by 16.2% and 17.7%, respectively, compared to unmodified BC, while simultaneously improving Cu/Zn bioavailability as micronutrient fertilizers for legume crops. The presence of amorphous carbon on the composite surface facilitated higher oxygen surface functionality, explaining its superior adsorption for Cu and Zn. Inyang et al. [77] used multi-walled carbon nanotubes to modify walnut and sugarcane bagasse BC and found that the modified composite materials had SSA of 351 and 390 m^2/g, respectively. The AC of the two BC composites for methylene blue in dye wastewater was significantly increased compared to unmodified BC, reaching a maximum of 6.2 mg/g. Molecular imprinting enhances the selective AC of BC by constructing specific recognition sites, enabling it to target pollutants that are present at low concentrations but exhibit high toxicity in the environment [78]. This technique is also employed for the detection and quantification of trace antibiotics in food and environmental samples. Li et al. [79] developed molecularly imprinted magnetic BC using Fe-Mn modified peanut shell BC as the functional monomer and 0.3 mg/L sulfamethoxazole solution as the template. The resulting material exhibited an SSA of 192.83 m^2/g, significantly higher than both non-imprinted magnetic BC (162.48 m^2/g) and unmodified BC (40.93 m^2/g). The imprinted cavities demonstrated superior sulfamethoxazole AC (25.65 m^2/g), representing a 1.34 times enhancement over the non-imprinted counterpart, primarily through hydrogen bonding, electrostatic interactions, hydrophobicity, and π-π stacking. Another research synthesized a molecularly imprinted magnetic BC via molecular imprinting precipitation polymerization, leading to the formation of imprinting cavities on the BC surface [80]. The material exhibited pronounced selective adsorption for oxytetracycline, even in the presence of interfering antibiotics, achieving an AC of 6.10 mg/g. Moreover, the BC demonstrated good stability and regeneration performance, with only a 9.36% decrease in oxytetracycline adsorption after seven adsorption-desorption cycles.

3.3. Biological modification

Microbial modification refers to the process by which specific functional microorganisms colonize and proliferate on the surface of BC, forming a biofilm that imparts biological activity to the BC [81]. Microbial metabolic activity can introduce FG such as -COOH, -OH, and $-NH_2$ on the surface of BC through biological oxidation/reduction reactions, thereby enhancing the AC of BC [82]. For instance, Qi et al. [83] immobilized microbial inoculants (*Bacillus subtilis*、*Bacillus cereus,* and *Citrobacter* sp) onto corn straw BC for the remediation of soil contaminated with HM uranium (U) and cadmium (Cd). The results showed that the BC acted both as a physical barrier and a nutrient source for the microbial strains, leading to reductions of 67.4% and 54.2% in bioavailable U and Cd concentrations, respectively. In addition, BC facilitated electron transfer, thereby accelerating the microbial co-precipitation and reduction of U and Cd. Zhao et al. [84] demonstrated that sludge BC modified with the *ZXY4* strain developed a highly porous structure, providing abundant active sites for adsorption. This resulted in 3.6 times increase in sulfamethoxazole uptake from wastewater. Compared to chemical modification, microbial modification offers a more sustainable approach that not only effectively tailors the surface properties of BC to enhance its AC, but also significantly reduces adverse environmental impacts.

As natural "ecosystem engineers" in soil, earthworms not only improve soil aeration and permeability through their movement and burrowing activities but also consume organic waste and utilize their gut microbiota to biodegrade antibiotics, thereby reducing soil pollution [85]. Compared to unmodified and $KMnO_4$-modified fruit-derived BC, earthworm-modified BC exhibited 1.3 and 3.6 times increases in average pore diameter, respectively, along with a significant increase in the number of surface FG. Additionally, it enhanced the abundance of carbon-cycling-related bacteria [86]. BC contained abundant extracellular enzymes (e.g., alkaline phosphatase, carboxylesterase) relevant to biogeochemical cycling and bioremediation. Earthworm modification enhances their hydrolytic activity by 8 times, primarily attributed to earthworm mucus effects rather than internal activation within the gastrointestinal tract [87]. BC serves as an effective carrier for microbially derived extracellular enzymes, while earthworms function as microbial stimulants, collectively enhancing enzymatic proliferation for pollutant degradation [88]. Research has shown that the synergistic interaction between earthworms and BC significantly enhanced the degradation of pyraclostrobin and PAHs in soil [89, 90].

3.4. Composite material modification

To further enhance the AC, reactivity, and stability of BC, composite material modification has been proposed. This approach combines the advantages of functional modifiers with those of BC to produce tailored BC-based materials with specific functionalities, thereby meeting the demands of various application fields. For example, Fe-Mn spinel oxide-modified cattle manure BC demonstrated exceptional performance as a PMS activator, achieving 98.6% removal efficiency of SMZ from wastewater [91]. The extensive conjugated graphite structure in BC induces the reconstruction of Fe 3d orbital electrons, thereby enhancing the valence state transitions of Fe and Mn as well as facilitating electron transfer processes, which collectively contribute to a significant improvement in SMZ removal efficiency. Additionally, approximately 8.6 log units of SMZ-resistant bacteria were inactivated, and the expression of associated ARGs was markedly suppressed, effectively mitigating the risk of horizontal gene transfer (HGT) during bacterial inactivation. Similarly, Fe-Mn bimetallic modification of microalgae-derived BC resulted in more than 4 times increase in both SSA and PV, thereby significantly enhancing its phosphate AC in wastewater [92]. The adsorption mechanism mainly includes functional group complexation, precipitation reaction, electrostatic attraction, and ion exchange. Zhu et al. [81] confirmed that the SSA and total PV of reed straw BC modified with ultraviolet (UV) and *Bacillus subtilis* increased by 1.4 and 1.2 times, respectively. The AC of Cd^{2+} in wastewater increased by 2.1, 1.7, and 1.2 times, respectively, compared to unmodified, *Bacillus subtilis*-modified, and UV-modified BC. UV modification increased the SSA of BC, introduced many oxygen-containing FG, and reduced the Zeta potential, promoting mechanisms such as ion exchange, surface complexation, and electrostatic interactions. Microorganisms adsorb Cd^{2+} through the surface FG of BC and produce extracellular metabolites that form chelates with Cd^{2+}. BC provides nutrients and electron donors for microorganisms, promoting their redox function and enhancing their ability to degrade pollutants.

Different modification strategies exhibit distinct performance characteristics and applicability. Physical activation (e.g., steam activation, ball milling) is cost-effective and easily scalable but provides limited control over surface chemistry and catalytic activity. Chemical modifications such as acid/alkali treatment or heteroatom doping introduce abundant functional groups, significantly improving adsorption and redox activity; however, they may cause secondary contamination if washing is inadequate and can increase operational cost. Metal-loaded BC effectively catalyzes redox reactions and promotes pollutant degradation, but excessive metal dosage may raise ecological risks due to potential leaching. Biological modification (e.g., microbial colonization, biofilm formation) offers a sustainable route for targeted pollutant removal but suffers from stability issues under fluctuating composting conditions. Composite BC and emerging hybrid materials integrate multiple mechanisms and show promising synergistic effects, but their high preparation cost and process complexity may limit large-scale application.

4. Regulation of livestock and poultry manure composting by functionalized biochar

4.1. Improve composting parameters

BC can optimize the composting environment by regulating temperature and pH (Fig. 2). Temperature serves as a critical parameter governing composting processes by directly regulating microbial activity [9]. Tang et al. [93] demonstrated that compared to unmodified BC, Fe-modified wood chips BC amendment elevated the peak temperature (74.9 ℃) in swine manure composting systems. Fe-modified BC exhibited 2.5 times increase in SSA and 1.8 times enhancement in total PV compared to unmodified BC, thereby providing favorable conditions for microbial decomposition of organic matter and generating more heat. Similarly, during swine manure composting, the co-addition of 12% wheat straw BC with modified basal salt media (MBSM) extended the thermophilic phase from 14 to 18 days and increased the peak temperature (66.8 ℃) by 5.2 ℃ compared to using 12% BC alone [94]. Generally, the temperature of LPM composting must be maintained above 50 °C for 5-10 days to meet agricultural safety standards for application [95]. Research has shown that the addition of functionalized BC enables compost to maintain at least 10 days above 50 °C, indicating its potential to enhance pathogen inactivation and ensure the biosafety of manure [21, 93]. pH serves as a critical regulatory factor influencing microbial activity and community structure during composting processes [30]. During the initial stage of composting, the decomposition of organic matter generates acidic substances, leading to a pH decrease [96]. BC typically rich in alkaline cations such as K^+ and Na^+, exhibits strong H^+ exchange capacity [97]. This effectively neutralizes acidic compounds in the compost matrix, helping to maintain the pH within an optimal range and thereby enhancing microbial activity. Gu et al. [21] found that the pH of pig manure compost products treated with Mg-modified BC was slightly lower than that treated with unmodified BC treatment. This difference was attributed to the formation of $MgNH_4PO_4 \cdot 6H_2O$ through the combination of Mg^{2+}, PO_4^{3-}, and NH_4^+. Ravindran et al. [98] found that adding 3%, 5%, and 10% rice husk BC to LPM and food waste co-composting systems increased the final pH by 0.6-1.0 compared to the control without BC. This increase was primarily attributed to enhanced organic matter mineralization, intensified ammonification, and the inherent alkalinity of the BC. The pH variations in BC-amended composting systems primarily result from the intrinsic characteristics of functionalized BC interacting with compost substrate properties [99]. Moreover, weakly alkaline fertilizers are generally preferred for soil application, as most plants thrive under slightly alkaline conditions [30]. The addition of alkaline compost helps neutralize acidic soils while enhancing nutrient availability and overall soil health.

4.2. Promote humification

The fertilizer utilization of LPM depends on compost quality. Humus content is a key indicator for evaluating compost maturity, primarily consisting of fulvic acid (FA) and humic acid (HA). The conversion of FA to HA can accelerate compost maturation and enhance the degree of humification [100]. BC enhances microbial catabolic activity by promoting microbial proliferation, supplying nutrients, and mediating electron transfer between microorganisms (Fig. 2). This facilitates the formation of humus precursors and accelerates chemical condensation reactions, ultimately leading to enhanced humus synthesis [101]. Qi et al. [24] found that compared to the CK, 5% MnO_2-modified corn stover BC (MBC) increased the concentrations of humus and HA in chicken manure compost products by 29.1% and 37.2%, respectively. The addition of MBC significantly increased the absolute abundance of humification-promoting microorganisms including *Microbacterium, Bacteroides, Kroppenstedtia, Gracilibacillus,* and *Lentibacillus*, thereby accelerating the humification process. BC could enhance microbial diversity and activity in composting, accelerating organic matter decomposition and facilitating the conversion of unstable small molecules into stable macromolecules [102]. Similarly, nano-BC facilitates the conversion of recalcitrant lignin and cellulose within the compost matrix into humic substances by enhancing microbial activity, significantly improving compost fertility compared to conventional BC treatment [103]. Wang et al. [100] demonstrated that the addition of Mn-modified bamboo powder BC (MBC) increased the HA/FA ratio by 36.5% in compost, significantly enhanced lignocellulose degradation, and ultimately promoted the humification process of the compost. On the one hand, Mn^{2+} enhanced the activity of lignin-degrading extracellular enzymes (e.g., lignin peroxidase and manganese peroxidase) while being oxidized to Mn^{3+}/Mn^{4+} through redox reactions that generated substantial •OH, collectively promoting the degradation of lignocellulosic components. On the other hand, the redox cycling of Mn facilitated electron transfer processes, providing sustained energy support for enzymatic catalysis and thereby accelerating the transformation of lignin intermediates and the polymerization of humus. Furthermore, humification facilitates the effective removal of contaminants during composting, thereby ensuring the safety of the final compost product. BC could enhance the degradation of fluoroquinolone antibiotics and the immobilization of Cu during composting by accelerating humification processes [104, 105]. Future research should integrate advanced spectroscopic and omics techniques to elucidate the precise electron transfer pathways and enzymatic mechanisms by which modified BC accelerates the conversion of FA to HA. Moreover, quantitative modeling linking BC surface chemistry, microbial consortia dynamics, and humic substance formation kinetics is needed to enable property-driven BC design for targeted humification enhancement.

4.3. Reduce gas emissions

The microbial activity and organic matter decomposition during the LPM composting process could cause the emission of irritating gases such as NH_3 and H_2S, as well as greenhouse gases such as N_2O, CO_2, and CH_4 [22, 106]. It has been reported that the losses of C and N during LPM composting reach up to 48.7% and 27.5%, respectively [107]. These nutrient losses not only reduce the agronomic value of the compost products but also pose significant ecological risks through gaseous emissions. BC showed significantly enhanced adsorption and catalytic performance after modification, thereby reducing gas emissions in compost (Fig. 2). Cao et al. [106] showed that, compared with the control group, the addition of 10% NaOH-modified corn straw BC in the process of chicken manure composting reduced the emissions of NH_3 and H_2S by 40.6% and 77.8%, respectively. NaOH modification increased the SSA, porosity, and alkaline functional group content of BC, thus enhancing its AC for NH_3. This treatment also promoted the growth of microorganisms such as *Limnochordaceae*, *Savagea,* and *IMCC26207*, which facilitate the conversion of H_2S to sulfate. Concurrently, it inhibited the decomposition and conversion of sulfate to sulfite, ultimately leading to a reduction in H_2S emissions. Additionally, elemental analysis showed that the low O/C and (O+N)/C ratios in modified BC decreased its surface polarity and hydrophilicity. The resulting inhibition of H_2O molecule penetration promoted gas adsorption. Tao et al. [103] found that adding 5% nanoscale corn straw BC produced by ball milling to manure composting increased the retention rate of total nitrogen by 63.6% and reduced NH_4^+-N loss. There were mainly three reasons: (1) The high SSA and microporous structure of nanoscale BC are conducive to the adsorption of NH_4^+-N, reducing its volatilization and leaching; (2) Nanoscale BC can promote the growth and activity of nitrifying bacteria, enhance the nitrification process in composting and the conversion of NH_4^+-N to NO_3^--N; (3) Nanoscale BC enriches the abundance of bacteria related to improving N cycle (e.g., *Desulfomicrobium* and *Chloropseudomonas*) and retention (e.g., *NB1-j*) in the composting process. Another research indicated that 3% Mg-modified corn stover BC not only serves an adsorption function during swine manure composting but also reduces N_2O and CH_4 emissions. This mitigation effect was attributed to the suppression of denitrifying bacteria, such as *Pseudoxanthomonas* and *norank-f-Methylococcaceae*, as well as anaerobic methanogenic bacteria (e.g., *Jeotgalibaca* and *Lactobacillus*). Meanwhile, this composite material reduced the emissions of NH_3 and N_2O by enhancing the expression of the *hao*, *nxrAB* and *nosZ* genes [21]. Moreover, it mitigates NH_3 emissions through the interaction of adsorbed NH_3 and NH_4^+ to form $MgNH_4PO_4{\cdot}6H_2O$ [22]. Similarly, Fe-modified BC promoted ammonium adsorption by increasing the SSA and FG (C-O, Fe-O, -OH, -COOH), while selectively enriching nitrogen-cycling microorganisms (such as *Terrisporobacter*) and enhancing the expression of nitrification (*amoA*, *hao* and *nxrA*) and nitrogen fixation genes [93]. Ultimately, this resulted in a 30% reduction in NH_3 emissions during composting. These microbial enrichments and gene activations may be attributed to the addition of modified BC, which optimized the microenvironment of the composting system, including pH, aerobic/anaerobic environment, and electron transfer capacity [91, 99]. Future research should integrate surface chemical analysis with transcriptomics to link specific functional groups with the activation of metabolic pathways, thereby further elucidating the mechanisms of gas emission reduction.

4.4. Enhance pollutant removal

Composting could partially degrade antibiotics and immobilize HMs in LPM through thermophilic conditions and microbial activity, while functionalized BC enhances this process, thereby reducing the application environmental risks of compost products (Fig. 2). BC-enhanced HM immobilization during composting is predominantly achieved through adsorption, precipitation, electrostatic attraction, ion exchange, and surface complexation mechanisms [16, 108]. Qiu et al. [27] demonstrated that the incorporation of 5% H_3PO_4-modified coconut shell BC significantly reduced the bioavailable contents of HM in the compost product, with decreases of 19.3% for Cu, 35.3% for Fe, 39.7% for Mn, 42.0% for Ni, 36.3% for Pb, and 32.3% for Zn. The porous structure of BC provides it with strong AC, which can fix HM ions in compost and form complexes, thereby reducing their bioavailability [30]. Awasthi et al. [94] showed that compared with unmodified BC treatment, the addition of mixed MBSM and BC reduced the bioavailability of Cu and Zn in pig manure compost products by 3.6% and 10.9%, respectively. MBSM exhibited strong HM immobilization capacity, while BC, with its abundant FG and high SSA, could bind metal ions and regulate microbial community structure to enhance microbial activity and humification [109]. This synergistic effect further promoted HM passivation. Chen et al. [110] observed that H_3PO_4 modification introduced abundant phosphorus-containing acidic FG and increased the SSA of wheat straw BC by 5.6 times. During swine manure composting, the phosphates introduced by BC formed metal phosphates (e.g., $Zn_2P_2O_7{\cdot}H_2O$、$Zn_2(PO_3)_4$ and $Cu_3(PO_4)_2$) through coprecipitation, while acidic FG (e.g., -COOH and -OH) provided H^+ for ion exchange with Cu^{2+} and Zn^{2+}, ultimately led to 15.2% and 36.5% reductions in bioavailable Cu and Zn contents, respectively. H_3PO_4-modified BC (PBC) treatment altered bacterial community structure and reduced the abundance of host bacteria carrying ARGs and metal resistance genes (MRGs) in compost products. Compared to the treatment without BC addition, the abundances of total MRGs (*copA*, *pcoA*, *cusA*, *tcrB* and *zntA*) and ARGs (*sul1*, *sul2*, *tetX*, *tetG*, *tetW*, *parC*, *ermF*, *ermB* and *aac(6')-Ib*) in the PBC-treated compost product were reduced by 58.8% and 66.2%, respectively, while *intI1* was completely removed. Additionally, the porous structure of BC reduces direct microbial contact and limits cell-to-cell adhesion during composting, thereby suppressing the HGT of ARGs and MRGs [111]. Zhou and Li [112] observed that the ARGs abundance in the Nano-Fe^0 modified BC (NB) amended group decreased by 12.78% during the pig manure process, while the group treated with unmodified BC increased by 28.96%. The application of NB impeded intercellular electron transfer during composting, reduced the abundance of ARG ARGs-hosting bacteria, and disrupted associated metabolic pathways, ultimately decreasing the overall abundance of ARGs. BC has abundant pores and a large number of FG including C-O, C=O and -OH, which could enhance the adsorption of antibiotics through electrostatic interactions, π-π interactions, and hydrogen bonding, accelerating the degradation of antibiotics by microorganisms [104]. Beyond physicochemical adsorption, biodegradation serves as the dominant pathway for antibiotic dissipation during composting [113]. BC enhances antibiotic degradation by promoting organic matter decomposition and elevating composting temperatures, thereby creating a thermophilic environment conducive to antibiotic breakdown. In swine manure composting amended with 10% wheat straw BC, the degradation rates of oxytetracycline, chlortetracycline, and tetracycline increased by 13.8%, 10.3%, and 23.3%, respectively [114]. The elevated temperature during the process was identified as the primary factor contributing to antibiotic removal. There are many factors that affect the surface function of BC and antibiotics, including pore structure, types and nature of surface functional groups, pH, BC dose, pollutant concentration, coexisting ions [115]. Most research have focused on the adsorption of individual antibiotics in wastewater using BC. However, this approach may not be directly applicable to actual environment, particularly complex systems like the composting process. Thus, future research should integrate advanced techniques such as in situ spectroscopy, isotope tracing, and multi-omics analysis to comprehensively elucidate the mechanisms of antibiotic removal during composting.

Although BC and its modified derivatives were widely recognized for improving composting parameters, promoting humification, reducing gas emissions and enhancing hazardous substance removal, their potential ecotoxicological risks in composting systems also warrant significant attention. Previous research has indicated that inappropriate methods for the preparation and modification of BC could lead to the formation of harmful substances including PAHs, persistent free radicals (PFRs), and perfluorochemicals (PFCs), which could pose risks to soil organisms and human health once compost was applied to agricultural land [4, 36]. PAHs exhibited high biotoxicity and can accumulate in plants and animals, ultimately entering the food chain and threatening human health [116]. Rombolà et al. [117] reported that one year after BC application, the PAHs contents in soil were approximately 6.4 times higher than in the control, reaching 153 ± 38 ng/g. Moreover, BC derived from sewage sludge or produced at low pyrolysis temperatures tends to exhibit higher bioavailability [36]. PFRs in BC, such as hydroxyl radicals ·OH and·O_2^-, possess strong oxidative capacities that can severely inhibit plant growth and development [118]. For instance, BC containing PFRs has been shown to significantly suppress seed germination and seedling growth in wheat, rice, and corn [119]. Similarly, PFCs were highly persistent organic pollutants characterized by strong C-F bonds, exceptional thermal stability, and high bioavailability [120]. Kim et al. [121] detected that perfluorooctanesulfonic acid and perfluorooctanoic acid in BC at concentrations of 15.8-16.9 ng/g. Notably, PFCs exhibit limited degradation under both aerobic and anaerobic conditions and may even transform into novel persistent compounds [122]. Future research should focus on developing standardized protocols for BC production and modification that minimize the generation of toxic byproducts, as well as establishing robust ecological risk assessment frameworks specifically designed for compost application. Such efforts are essential to ensure the safe and sustainable integration of BC technologies into modern agricultural practices.

5. Conclusions and recommendations for future

This review systematically examined the preparation and modification of BC and its multifaceted regulatory functions in livestock and poultry manure composting. It highlighted how diverse functionalization strategies, from single modification to composite and emerging material approaches, enhance the adsorption and catalytic properties of BC, leading to improved composting parameters, accelerated humification, reduced gas emissions, and effective removal of heavy metals, antibiotics, and resistance genes. A key contribution of this review was its interdisciplinary perspective, integrating principles from environmental materials science, microbial ecology, and waste management to establish functionalized BC as a core tool for advancing precision composting and sustainable waste valorization. Future research should prioritize the following areas:

(1) Tailored design of BC: Optimize BC properties (e.g., porosity, surface chemistry, reactivity) based on specific composting goals and feedstock conditions. This includes adjusting raw material selection, pyrolysis parameters, and post-treatment methods.

(2) Mechanistic understanding at the molecular and microbial level: Use omics technologies (e.g., metagenomics, transcriptomics) to explore how functionalized BC

influences microbial community succession, gene expression, and enzymatic activities throughout the composting cycle.

(3) Development of smart BC systems. Integrate BC with nanomaterials, functional coatings, or microbial consortia to create multifunctional composites capable of real-time pollutant removal, nutrient release modulation, and biosensor integration.

(4) Focus on field-scale validation of functionalized BC systems under diverse manure management scenarios to assess their practical stability, scalability, and cost-effectiveness.

In conclusion, functionalized BC represents a transformative material for the next generation of manure composting technologies. Through continued innovation in material design and mechanistic research, BC has the potential to play a pivotal role in realizing safe, circular, and climate-resilient agricultural waste management systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work is financially supported by National Key Research and Development Program of China (2023YFD1900305), Innovation Program of Chinese Academy of Agricultural Sciences (CAAS-CSAL-202302) and Ningxia Hui Autonomous Region Key Research and Development Program (2023BCF01048).

References

[1] Liu C, Li G, Qin X, Xu Y, Wang J, Wu G, et al. Profiles of antibiotic- and heavy metal-related resistance genes in animal manure revealed using a metagenomic analysis, Ecotox Environ Safe 2022;239:113655. https://doi.org/10.1016/j.ecoenv.2022.113655.

[2] Ipiales RP, Lelli G, Diaz E, Diaz-Portuondo E, Mohedano AF, Rubia MA. Study of two approaches for the process water management from hydrothermal carbonization of swine manure: Anaerobic treatment and nutrient recovery. Environ Res 2024;246:118098. https://doi.org/10.1016/j.envres.2024.118098.

[3] Sun Z, Li J, Wang X, Xia S, Zhao J. Enhanced heavy metal stabilization and phosphorus retention during the hydrothermal carbonization of swine manure by in-situ formation of $MgFe_2O_4$. Waste Manage 2024;174:96-105.

https://doi.org/10.1016/j.wasman.2023.11.024.

[4] Wang D, Shi Y, Zheng L, Liu Y, Wei X, Zhang Q. Functionalized biochar for enhancing the removal of antibiotics and resistance genes in swine manure composting: A review. J Environ Chem Eng 2025;13:116752. https://doi.org/10.1016/j.jece.2025.116752.

[5] Wang D, Liu Y, Wei X, Shi Y, Ma C, Zhang Q. Thermally treated gentamicin-activated carbon improved the soil properties without triggering resistance risk. Process Saf Environ 2025;203:107890. https://doi.org/10.1016/j.psep.2025.107890.

[6] Chen K, Li J, Lin L, Qin W, Gao Y, Hu E, et al. Occurrence, fate and control strategies of heavy metals and antibiotics in livestock manure compost land application: A review. Sci Total Environ 2024;957:177381. https://doi.org/10.1016/j.scitotenv.2024.177381.

[7] Ran X, Li S, Tejaswi Uppuluri NS, Deng Y, Su Y, Huang G, et al. Phosphorus transformation and bioavailability in livestock manure through aerobic composting and anaerobic digestion. Chem Eng J 2025;505:159285. https://doi.org/10.1016/j.cej.2025.159285.

[8] Wang D, Dong Y, Xin S, Li Y, Chen N, Liu Y, et al. Safe utilization of bioresources in gentamicin mycelial residues by thermal treatment: Antibiotic degradation, resistance gene inactivation and available nutrients promotion. Waste Manage 2024;175:245-53. https://doi.org/10.1016/j.wasman.2024.01.014.

[9] Ma J, Yang W, Li S, Yang Z, Qiao C, Liu D, et al. Comprehensive effects of tea branch biochar on antibiotic resistance profiles and C/N/S cycling in the compost microbiota of animal manure. Sci Total Environ 2024;957:177457. https://doi.org/10.1016/j.scitotenv.2024.177457.

[10] Kacprzak M, Malińska K, Grosser A, Sobik-Szołtysek J, Wystalska K, Dróżdż D, et al. Cycles of carbon, nitrogen and phosphorus in poultry manure management technologies -environmental aspects. Crit Rev Env Sci Tec 2022;53:914-38. https://doi.org/10.1080/10643389.2022.2096983.

[11] Li S, Sun K, Latif A, Si Y, Gao Y, Huang Q. Insights into the applications of extracellular laccase-aided humification in livestock manure composting. Environ Sci Technol 2022;56:7412-25. https://doi.org/10.1021/acs.est.1c08042.

[12] Wang D, Chen X, Li X, Zhang Q, Hou J, Li Y, et al. Assessing the effect of composted cyclosporin A fermentation residue as organic fertilizer: Focus on soil fertility and

antibiotic resistance. J Environ Sci 2025;157:793-803. https://doi.org/10.1016/j.jes.2025.02.008.

[13] Tang Q, Sui Q, Wei Y, Shen P, Zhang J. Swine-manure composts induce the enrichment of antibiotic-resistant bacteria but not antibiotic resistance genes in soils. J Environ Manage 2023;345:118707. https://doi.org/10.1016/j.jenvman.2023.118707.

[14] Behera S, Samal K. Sustainable approach to manage solid waste through biochar assisted composting. Energy Nexus 2022;7:100121. https://doi.org/10.1016/j.nexus.2022.100121.

[15] Chen L, Chen Y, Li Y, Liu Y, Jiang H, Li H, et al. Improving the humification by additives during composting: A review. Waste Manage 2023;158:93-106. https://doi.org/10.1016/j.wasman.2022.12.040.

[16] Sun X, Awasthi MK. Synergistic effect and mechanism analysis of biochar regulator on heavy metal passivation and microplastic degradation in sewage sludge compost. J Hazard Mater 2025;494:138551. https://doi.org/10.1016/j.jhazmat.2025.138551.

[17] Nordahl SL, Preble CV, Kirchstetter TW, Scown CD. Greenhouse gas and air pollutant emissions from composting. Environ Sci Technol 2023;57:2235-47. https://doi.org/10.1021/acs.est.2c05846.

[18] Zhang L, Fan R, Li W, Li G, Luo W, Xu Z. Unravelling biotic and abiotic mechanisms of mature compost to alleviate gaseous emissions in kitchen waste composting by metagenomic analysis. Bioresource Technol 2025;419:132102. https://doi.org/10.1016/j.biortech.2025.132102.

[19] He M, Xu Z, Hou D, Gao B, Cao X, Ok YS, et al. Waste-derived biochar for water pollution control and sustainable development. Nat Rev Earth Env 2022;3:444-60. https://doi.org/10.1038/s43017-022-00306-8.

[20] Cernansky R. Agriculture: State-of-the-art soil. Nature 2015;517:258-260. https://doi.org/10.1038/517258a.

[21] Gu X, Li H, Shi Y, Sun C, Li J, Li S. Magnesium modified biochar facilitates favorable nitrogen conversion to mitigate ammonia and nitrous oxide emissions during pig manure composting. Chem Eng J 2025;504:159073. https://doi.org/10.1016/j.cej.2024.159073.

[22] Gu X, Li H, Shi Y, Li J, Li S. Regulating bacterial dynamics by Mg-modified biochar addition to mitigate gaseous emissions during pig manure composting. J Clean Prod

2024;465:142839. https://doi.org/10.1016/j.jclepro.2024.142839.

[23] Gong X, Shi W, Zhang Z, Luo M, Zhang B, Wan S, et al. Exploring the effects of zeolite, biochar, and diatomite as additives for enhancing heavy metals passivation and eliminating antibiotic resistance genes in composts during vermicomposting of dewatered sludge and green waste. J Environ Chem Eng 2024;12:112201. https://doi.org/10.1016/j.jece.2024.112201.

[24] Qi H, Gao W, Xie L, Zhang G, Song C, Wei Z, et al. Effect of MnO_2-biochar composites on promoting humification during chicken manure composting. Biochar 2024;6:32. https://doi.org/10.1007/s42773-024-00315-4.

[25] Wang N, Pan S, Li S, Zhang M, Jiang X. Combination of magnesium modified biochar and iron oxides down-regulates phosphates transport in porous media. Chem Eng J 2024;498:155151. https://doi.org/10.1016/j.cej.2024.155151.

[26] Lv L, Yin B, Zhang D, Ji W, Liang J, Liu X, et al. Synchronous reinforcement azo dyes decolorization and anaerobic granular sludge stability by Fe, N co-modified biochar: Enhancement based on extracellular electron transfer. J Hazard Mater 2024;480:135836. https://doi.org/10.1016/j.jhazmat.2024.135836.

[27] Qiu X, Feng M, Chen R, Chen J, Zheng X, Mao X, et al. Phosphoric acid modified biochar enhanced heavy metals passivation via accelerating humification and bioremediation in sewage sludge composting. Environ Technol Inno 2025;39:104275. https://doi.org/10.1016/j.eti.2025.104275.

[28] Wen C, Liu T, Wang D, Wang Y, Chen H, Luo G, et al. Biochar as the effective adsorbent to combustion gaseous pollutants: Preparation, activation, functionalization and the adsorption mechanisms. Prog Energy Combust 2023;99:101098. https://doi.org/10.1016/j.pecs.2023.101098.

[29] Li Y, Awasthi MK, Sindhu R, Binod P, Zhang Z, Taherzadeh MJ. Biochar preparation and evaluation of its effect in composting mechanism: A review. Bioresource Technol 2023;384:129329. https://doi.org/10.1016/j.biortech.2023.129329.

[30] Ebrahimi M, Gholipour S, Mostafaii G, Yousefian F. Biochar-amended food waste compost: A review of properties. Results in Engineering 2024;24:103118. https://doi.org/10.1016/j.rineng.2024.103118.

[31] Zhang X, Gao B, Zheng Y, Hu X, Creamer AE, Annable MD, et al. Biochar for volatile organic compound (VOC) removal: Sorption performance and governing mechanisms. Bioresource Technol 2017;245:606-14. https://doi.org/10.1016/j.biortech.2017.09.025.

[32] Mukome FND, Zhang X, Silva LCR, Six J, Parikh SJ. Use of Chemical and physical characteristics to investigate trends in biochar feedstocks. J Agric Food Chem 2013;61:2196-204. https://doi.org/10.1021/jf3049142.

[33] Huang C, Chen Y, Jin L, Yang B. Properties of biochars derived from different straw at 500℃ pyrolytic temperature: Implications for their use to improving acidic soil water retention. Agr Water Manage 2024;301:108953. https://doi.org/10.1016/j.agwat.2024.108953.

[34] He Y, Zhao X, Zhu S, Yuan L, Li X, Feng Z, et al. Conversion of swine manure into biochar for soil amendment: Efficacy and underlying mechanism of dissipating antibiotic resistance genes. Sci Total Environ 2023;871:162046. https://doi.org/10.1016/j.scitotenv.2023.162046.

[35] Zhao M, Ma X, Liao X, Cheng S, Liu Q, Wang H, et al. Characteristics of algae-derived biochars and their sorption and remediation performance for sulfamethoxazole in marine environment. Chem Eng J 2022;430:133092. https://doi.org/10.1016/j.cej.2021.133092.

[36] Xiang L, Liu S, Ye S, Yang H, Song B, Qin F, et al. Potential hazards of biochar: The negative environmental impacts of biochar applications. J Hazard Mater 2021;420:126611. https://doi.org/10.1016/j.jhazmat.2021.126611.

[37] Sharma T, Hakeem IG, Gupta AB, Joshi J, Shah K, Vuppaladadiyam AK, et al. Parametric influence of process conditions on thermochemical techniques for biochar production: A state-of-the-art review. J Energy Inst 2024;113:101559. https://doi.org/10.1016/j.joei.2024.101559.

[38] Kan T, Strezov V, Evans TJ. Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. Renew Sust Energy Rev 2016;57:1126-1140. https://doi.org/10.1016/j.rser.2015.12.185

[39] Yaashikaa PR, Kumar PS, Varjani SJ, Saravanan A. Advances in production and application of biochar from lignocellulosic feedstocks for remediation of environmental pollutants. Bioresource Technol 2019;292:122030.

https://doi.org/10.1016/j.biortech.2019.122030

[40] Al-Rumaihi A, Shahbaz M, McKay G, Mackey H, Al-Ansari T. A review of pyrolysis technologies and feedstock: A blending approach for plastic and biomass towards optimum biochar yield. Renew Sust Energy Rev 2022;167:112715. https://doi.org/10.1016/j.rser.2022.112715.

[41] Das SK, Ghosh GK, Avasthe RK, Sinha K. Compositional heterogeneity of different biochar: Effect of pyrolysis temperature and feedstocks. J Environ Manage 2021;278:111501. https://doi.org/10.1016/j.jenvman.2020.111501

[42] Zhao B, O'Connor D, Zhang J, Peng T, Shen Z, Tsang DCW, et al. Effect of pyrolysis temperature, heating rate, and residence time on rapeseed stem derived biochar. J Clean Prod 2018;174:977-987. https://doi.org/10.1016/j.jclepro.2017.11.013

[43] Roy C, Chaala A. Vacuum pyrolysis of automobile shredder residues. Resour Conserv Recy 2001;32:1-27. https://doi.org/10.1016/S0921-3449(00)00088-4

[44] Godwin PM, Pan Y, Xiao H, Afzal MT. Progress in preparation and application of modified biochar for improving heavy metal ion removal from wastewater. J Bioresour Bioprod 2019;4:31-42. https://doi.org/10.21967/jbb.v4i1.180.

[45] Stummann MZ, Høj M, Gabrielsen J, Clausen LR, Jensen PA, Jensen AD. A perspective on catalytic hydropyrolysis of biomass. Renew Sust Energy Rev 2021;143:110960. https://doi.org/10.1016/j.rser.2021.110960

[46] Chen WH, Biswas PP, Zhang C, Kwon EE, Chang JS. Achieving carbon credits through biomass torrefaction and hydrothermal carbonization: A review. Renew Sust Energy Rev 2025;208:115056. https://doi.org/10.1016/j.rser.2024.115056.

[47] Yang J, Zhang Z, Wang J, Zhao X, Zhao Y, Qian J, et al. Pyrolysis and hydrothermal carbonization of biowaste: A comparative review on the conversion pathways and potential applications of char product. Sustain Chem Pharm 2023;33:101106. https://doi.org/10.1016/j.scp.2023.101106.

[48] Supraja KV, Doddapaneni TRKC, Ramasamy PK, Kaushal P, Ahammad SZ, Pollmann K, et al. Critical review on production, characterization and applications of microalgal hydrochar: Insights on circular bioeconomy through hydrothermal carbonization. Chem Eng J 2023;473:145059. https://doi.org/10.1016/j.cej.2023.145059.

[49] Akgül A, Akın SŞ, Güleç F, Kazanç F. Biochar gasification: Insights from pyrolysis atmospheres and gasification heating rates. Fuel 2024;360:130469. https://doi.org/10.1016/j.fuel.2023.130469.

[50] Lin SL, Zhang H, Chen WH, Song M, Kwon EE. Low-temperature biochar production from torrefaction for wastewater treatment: A review. Bioresource Technol 2023;387:129588. https://doi.org/10.1016/j.biortech.2023.129588.

[51] Lee HS, Shin HS. Competitive adsorption of heavy metals onto modified biochars: Comparison of biochar properties and modification methods. J Environ Manage 2021;299:113651. https://doi.org/10.1016/j.jenvman.2021.113651.

[52] Lamberti E, Viscusi G, Kiani A, Boumezough Y, Acocella MR, Gorrasi G. Efficiency of dye adsorption of modified biochar: A comparison between chemical modification and ball milling assisted treatment. Biomass Bioenerg 2024;185:107247. https://doi.org/10.1016/j.biombioe.2024.107247.

[53] Guo S, Liu X, Wang L, Liu Q, Xia C, Tang J. Ball-milled biochar can act as a preferable biocompatibility material to enhance phenanthrene degradation by stimulating bacterial metabolism. Bioresource Technol 2022;350:126901. https://doi.org/10.1016/j.biortech.2022.126901.

[54] Zhang W, Yan L, Wang Q, Li X, Guo Y, Song W, et al. Ball milling boosted the activation of peroxymonosulfate by biochar for tetracycline removal. J Environ Chem Eng 2021;9:106870. https://doi.org/10.1016/j.jece.2021.106870.

[55] Villardon A, Alcazar-Ruiz A, Dorado F, Sanchez-Silva L. Enhancing carbon dioxide uptake in biochar derived from husk biomasses: Optimizing biomass particle size and steam activation conditions. J Environ Chem Eng 2024;12:113352. https://doi.org/10.1016/j.jece.2024.113352.

[56] Lou K, Rajapaksha AU, Ok YS, Chang SX. Pyrolysis temperature and steam activation effects on sorption of phosphate on pine sawdust biochars in aqueous solutions. Chem Spec Bioavailab 2016;28:42-50. https://doi.org/10.1080/09542299.2016.1165080.

[57] Rajapaksha AU, Vithanage M, Ahmad M, Seo DC, Cho JS, Lee SE, et al. Enhanced sulfamethazine removal by steam-activated invasive plant-derived biochar. J Hazard Mater 2015;290:43-50. https://doi.org/10.1016/j.jhazmat.2015.02.046.

[58] Islam MS, Kwak JH, Nzediegwu C, Wang S, Palansuriya K, Kwon EE, et al. Biochar heavy metal removal in aqueous solution depends on feedstock type and pyrolysis purging gas. Environ Pollut 2021;281:117094. https://doi.org/10.1016/j.envpol.2021.117094.

[59] Cheng N, Wang B, Wu P, Lee X, Xing Y, Chen M, et al. Adsorption of emerging contaminants from water and wastewater by modified biochar: A review. Environ Pollut 2021;273:116448. https://doi.org/10.1016/j.envpol.2021.116448.

[60] Zhang J, Chen Z, Liu Y, Wei W, Ni BJ. Removal of emerging contaminants (ECs) from aqueous solutions by modified biochar: A review. Chem Eng J 2024;479:147615. https://doi.org/10.1016/j.cej.2023.147615.

[61] Chu G, Zhao J, Huang Y, Zhou D, Liu Y, Wu M, et al. Phosphoric acid pretreatment enhances the specific surface areas of biochars by generation of micropores. Environ Pollut 2018;240:1-9. https://doi.org/10.1016/j.envpol.2018.04.003.

[62] Iqbal J, Mohamed Al Hajeri B, Shah NS, Wilson K, Xavier C, Shaalan J, et al. Preparation of H_3PO_4 modified Sidr biochar for the enhanced removal of ciprofloxacin from water. Int J Phytoremediat 2022;24:1231-1242. https://doi.org/10.1080/15226514.2021.2025038.

[63] Zhang C, Ji Y, Li C, Zhang Y, Sun S, Xu Y, et al. The Application of biochar for CO_2 capture: Influence of biochar preparation and CO_2 capture reactors. Ind Eng Chem Res 2023;62:17168-17181. https://doi.org/10.1021/acs.iecr.3c00445.

[64] Zhang C, Sun S, He S, Wu C. Direct air capture of CO_2 by KOH-activated bamboo biochar. J Energy Inst 2022;105:399-405. https://doi.org/10.1016/j.joei.2022.10.017.

[65] Tang Y, Li Y, Zhan L, Wu D, Zhang S, Pang R, et al. Removal of emerging contaminants (bisphenol A and antibiotics) from kitchen wastewater by alkali-modified biochar. Sci Total Environ 2022;805:150158. https://doi.org/10.1016/j.scitotenv.2021.150158.

[66] Pouretedal HR, Sadegh N. Effective removal of Amoxicillin, Cephalexin, Tetracycline and Penicillin G from aqueous solutions using activated carbon nanoparticles prepared from vine wood. J Water Process Eng 2014;1:64-73. https://doi.org/10.1016/j.jwpe.2014.03.006.

[67] Ghorbani M, Konvalina P, Neugschwandtner RW, Soja G, Bárta J, Chen WH, et al. How do different feedstocks and pyrolysis conditions effectively change biochar modification

scenarios? A critical analysis of engineered biochars under H_2O_2 oxidation. Energ Convers Manage 2024;300:117924. https://doi.org/10.1016/j.enconman.2023.117924.

[68] Yue T, Cao X, Liu Q, Bai S, Zhang F, Liu L. Enhancement on removal of oxytetracycline in aqueous solution by corn stover biochar: Comparison of KOH and $KMnO_4$ modifications. Chem Eng Res Des 2023;190:353-365. https://doi.org/10.1016/j.cherd.2022.12.049.

[69] Yin K, Wang J, Tian X, Yu N, Zhang X, Zhao Y, et al. Effect of biochar-derived dissolved organic matter on tetracycline sorption by $KMnO_4$-modified biochar. Chem Eng J 2023;474:145872. https://doi.org/10.1016/j.cej.2023.145872.

[70] Wang Y, Liu R. H_2O_2 treatment enhanced the heavy metals removal by manure biochar in aqueous solutions. Sci Total Environ 2018;628-629:1139-1148. https://doi.org/10.1016/j.scitotenv.2018.02.137.

[71] Huff MD, Lee JW. Biochar-surface oxygenation with hydrogen peroxide. J Environ Manage 2016;165:17-21. https://doi.org/10.1016/j.jenvman.2015.08.046.

[72] Wang M, Wang Y, Li Y, Wang C, Kuang S, Ren P, et al. Persulfate oxidation of tetracycline, antibiotic resistant bacteria, and resistance genes activated by Fe doped biochar catalysts: Synergy of radical and non-radical processes. Chem Eng J 2023;464:142558. https://doi.org/10.1016/j.cej.2023.142558.

[73] Li Y, Zhang J, Wen X, Mazarji M, Chen S, Liu Q, et al. Advancing anaerobic digestion with MnO_2-modified biochar: Insights into performance and mechanisms. Sci Total Environ 2024;954:176303. https://doi.org/10.1016/j.scitotenv.2024.176303.

[74] Zhang H, Wu W, Ding H, Li Y, Song Y, Ding L, et al. Fabrication of modified-N-doped porous biochar and its enhanced adsorption of bisphenol-A: Critical contribution to π-π interactions by nitrogen doping. Surf Interfaces 2024;45:103880. https://doi.org/10.1016/j.surfin.2024.103880.

[75] Zhang Y, Liang S, He R, Zhao J, Lv J, Kang W, et al. Enhanced adsorption and degradation of antibiotics by doping corncob biochar/PMS with heteroatoms at different preparation temperatures: Mechanism, pathway, and relative contribution of reactive oxygen species. J Water Process Eng 2022;46:102626. https://doi.org/10.1016/j.jwpe.2022.102626.

[76] Carneiro JSdS, Leite DAdC, Castro GMd, Franca JR, Botelho L, Soares JR, et al. Biochar-

graphene oxide composite is efficient to adsorb and deliver copper and zinc in tropical soil. J Clean Prod 2022;360:132170. https://doi.org/10.1016/j.jclepro.2022.132170.

[77] Inyang M, Gao B, Zimmerman A, Zhang M, Chen H. Synthesis, characterization, and dye sorption ability of carbon nanotube-biochar nanocomposites. Chem Eng J 2014;236:39-46. https://doi.org/10.1016/j.cej.2013.09.074.

[78] Du L, Ahmad S, Liu L, Wang L, Tang J. A review of antibiotics and antibiotic resistance genes (ARGs) adsorption by biochar and modified biochar in water. Sci Total Environ 2023;858:159815. https://doi.org/10.1016/j.scitotenv.2022.159815.

[79] Li Z, Tian W, Chu M, Zou M, Zhao J. Molecular imprinting functionalization of magnetic biochar to adsorb sulfamethoxazole: Mechanism, regeneration and targeted adsorption. Process Saf Environ 2023;171:238-49. https://doi.org/10.1016/j.psep.2023.01.024.

[80] Jiao Y, Yi Y, Fang Z, Eric Tsang P. Selective removal of oxytetracycline by molecularly imprinted magnetic biochar. Bioresource Technol 2024;395:130394. https://doi.org/10.1016/j.biortech.2024.130394.

[81] Zhu C, Zhang J, Huang G, Zhu DZ. UV-modified biochar-*Bacillus subtilis* composite: An effective method for enhancing Cd(II) adsorption from water. Biochem Eng J 2024;212:109527. https://doi.org/10.1016/j.bej.2024.109527.

[82] Zhou Y, Leong SY, Li Q. Modified biochar for removal of antibiotics and antibiotic resistance genes in the aqueous environment: A review. J Water Process Eng 2023;55:104222. https://doi.org/10.1016/j.jwpe.2023.104222.

[83] Qi X, Xiao S, Chen X, Ali I, Gou J, Wang D, et al. Biochar-based microbial agent reduces U and Cd accumulation in vegetables and improves rhizosphere microecology. J Hazard Mater 2022;436:129147. https://doi.org/10.1016/j.jhazmat.2022.129147.

[84] Zhao T, Ali A, Su J, Liu S, Yan H, Xu L. Removal of sulfamethoxazole from water by biosurfactant-modified sludge biochar: Properties and mechanism. J Environ Chem Eng 2024;12:114200. https://doi.org/10.1016/j.jece.2024.114200.

[85] Raza ST, Wu J, Rene ER, Ali Z, Chen Z. Reuse of agricultural wastes, manure, and biochar as an organic amendment: A review on its implications for vermicomposting technology. J Clean Prod 2022;360:132200. https://doi.org/10.1016/j.jclepro.2022.132200.

[86] Zhu L, Wang L, Zhang J, Xu Y, Li X, Zhang M, et al. Comparison of characteristics of

biochar modified by earthworm and potassium permanganate. Environ Technol Inno 2024;35:103733. https://doi.org/10.1016/j.eti.2024.103733.

[87] Sanchez-Hernandez JC. Biochar activation with exoenzymes induced by earthworms: A novel functional strategy for soil quality promotion. J Hazard Mater 2018;350:136-143. https://doi.org/10.1016/j.jhazmat.2018.02.019.

[88] Sanchez-Hernandez JC, Ro KS, Díaz FJ. Biochar and earthworms working in tandem: Research opportunities for soil bioremediation. Sci Total Environ 2019;688:574-583. https://doi.org/10.1016/j.scitotenv.2019.06.212.

[89] Hou S, Wang J, Dai J, Boussafir M, Zhang C. Combined effects of earthworms and biochar on PAHs-contaminated soil remediation: A review. Soil Ecol Lett 2023;5:220158. https://doi.org/10.1007/s42832-022-0158-y.

[90] Zhang Q, Li S, Saleem M, Ali MY, Xiang J. Biochar and earthworms synergistically improve soil structure, microbial abundance, activities and pyraclostrobin degradation. Appl Soil Ecol 2021;168:104154. https://doi.org/10.1016/j.apsoil.2021.104154.

[91] Chen L, Wang X, Yuan M, Ni BJ, Xia S, Zhao J. Insights into the removal of sulfamethazine and sulfonamide-resistant bacteria from wastewater by Fe-Mn spinel oxide modified cow manure biochar activated peroxymonosulfate: A nonradical pathway regulated by enhanced adsorption and 3d orbital electron reconstruction. App Catal B Environ Energy 2025;361:124652. https://doi.org/10.1016/j.apcatb.2024.124652.

[92] Fu C, Zhou M, Song W, Yang G, Feng P, Chulalaksananukul W, et al. Innovative iron-manganese modified microalgae biochar for efficient phosphate iron removal from water: Preparation and adsorption mechanisms. J Water Process Eng 2024;66:106051. https://doi.org/10.1016/j.jwpe.2024.106051.

[93] Tang R, Yao S, Liu Y, Ren T, Ma J, Gong X, et al. Iron-modified biochar enhanced nitrogen retention during composting: bridging chemisorption and microbiome modulation. Chem Eng J 2025;513:162761. https://doi.org/10.1016/j.cej.2025.162761.

[94] Awasthi MK, Duan Y, Awasthi SK, Liu T, Chen H, Pandey A, et al. Emerging applications of biochar: Improving pig manure composting and attenuation of heavy metal mobility in mature compost. J Hazard Mater 2020;389:122116. https://doi.org/10.1016/j.jhazmat.2020.122116.

[95] Zhang M, Shi A, Ajmal M, Ye L, Awais M. Comprehensive review on agricultural waste utilization and high-temperature fermentation and composting. Biomass Convers Bior 2021;13:5445-5568. https://doi.org/10.1007/s13399-021-01438-5.

[96] Ma S, Shen Y, Ding J, Cheng H, Zhou H, Ge M, et al. Effects of biochar and volcanic rock addition on humification and microbial community during aerobic composting of cow manure. Bioresource Technol 2024;391:129973. https://doi.org/10.1016/j.biortech.2023.129973.

[97] Ashworth DJ, Schmidt MP, Ibekwe AM. Performance of acid- and base-modified biochars for the removal of antibiotics from water under dynamic conditions. J Environ Chem Eng 2023;11:111616. https://doi.org/10.1016/j.jece.2023.111616.

[98] Ravindran B, Karmegam N, Awasthi MK, Chang SW, Selvi PK, Balachandar R, et al. Valorization of food waste and poultry manure through co-composting amending saw dust, biochar and mineral salts for value-added compost production. Bioresource Technol 2022;346:126442. https://doi.org/10.1016/j.biortech.2021.126442.

[99] Xiao R, Awasthi MK, Li R, Park J, Pensky SM, Wang Q, et al. Recent developments in biochar utilization as an additive in organic solid waste composting: A review. Bioresource Technol 2017;246:203-213. https://doi.org/10.1016/j.biortech.2017.07.090.

[100] Wang F, Zhou F, Zhang L, Liu W, Su Y, Zhang Y, et al. Mechanisms of manganese-modified biochar and white-rot fungi in enhancing compost humification: Boosting polyphenol pathway by lignocellulose degradation. Chem Eng J 2025;507:160637. https://doi.org/10.1016/j.cej.2025.160637.

[101] Jia P, Huang Y, Zhang H, Huang Q, Chen J, Feng L, et al. Variation of microbial necromass carbon and its potential relationship with humification during composting of chicken manure with and without biochar addition. Bioresource Technol 2024;409:131258. https://doi.org/10.1016/j.biortech.2024.131258.

[102] Sun X, Awasthi MK, Syed A, Bahkali AH. Effect of cyanobacteria biochar addition on humification, fungal dynamics and its mechanism of action in pig manure composting. J Environ Chem Eng 2024;12:113755. https://doi.org/10.1016/j.jece.2024.113755.

[103] Tao R, Cui M, Li Y, Wang J, He W, Zhao Y, et al. Nanoscale biochar for fertilizer quality optimization in waste composting: Microbial community regulation. Bioresource Technol

2024;414:131571. https://doi.org/10.1016/j.biortech.2024.131571.

[104] Tong Z, Liu F, Sun B, Tian Y, Zhang J, Duan J, et al. Effect of biochars with different particle sizes on fates of antibiotics and antibiotic resistance genes during composting of swine manure. Bioresource Technol 2023;370:128542. https://doi.org/10.1016/j.biortech.2022.128542.

[105] Lee MH, Han SJ, Lee YK, Ike IA, Ok YS, Hur J. Enhancing copper binding property of compost-derived humic substances by biochar amendment: Further insight from two-dimensional correlation spectroscopy. J Hazard Mater 2020;390:121128. https://doi.org/10.1016/j.jhazmat.2019.121128.

[106] Cao Z, Zhu R, Li Y, Kakade A, Zhang S, Yuan Y, et al. Mitigation of ammonia and hydrogen sulfide emissions during aerobic composting of laying hen waste through NaOH-modified biochar. J Environ Manage 2024;365: 121634. https://doi.org/10.1016/j.jenvman.2024.121634.

[107] Zhang Z, Liu D, Qiao Y, Li S, Chen Y, Hu C. Mitigation of carbon and nitrogen losses during pig manure composting: A meta-analysis. Sci Total Environ 2021;783:147103. https://doi.org/10.1016/j.scitotenv.2021.147103.

[108] Wang Z, Zhang M, Li J, Wang J, Sun G, Yang G, et al. Effect of biochar with various pore characteristics on heavy metal passivation and microbiota development during pig manure composting. J Environ Manage 2024;352:120048. https://doi.org/10.1016/j.jenvman.2024.120048.

[109] Chen Y, Liu Y, Li Y, Wu Y, Chen Y, Zeng G, et al. Influence of biochar on heavy metals and microbial community during composting of river sediment with agricultural wastes. Bioresource Technol 2017;243:347-355. https://doi.org/10.1016/j.biortech.2017.06.100.

[110] Chen Z, Bao H, Wen Q, Wu Y, Fu Q. Effects of H_3PO_4 modified biochar on heavy metal mobility and resistance genes removal during swine manure composting. Bioresource Technol 2022;346:126632. https://doi.org/10.1016/j.biortech.2021.126632.

[111] Zhang J, Chen M, Sui Q, Tong J, Jiang C, Lu X, et al. Impacts of addition of natural zeolite or a nitrification inhibitor on antibiotic resistance genes during sludge composting. Water Res 2016;91:339-349. https://doi.org/10.1016/j.watres.2016.01.010.

[112] Zhou Y, Li Q. Preference and regulation mechanism mediated via mobile genetic

elements for antibiotic and metal resistomes during composting amended with nano ZVI loaded on biochar. Environ Pollut 2024;358:124520. https://doi.org/10.1016/j.envpol.2024.124520.

[113] Feng M, Liu Y, Yang L, Li Z. Antibiotics and antibiotic resistance gene dynamics in the composting of antibiotic fermentation waste - A review. Bioresource Technol 2023;390:129861. https://doi.org/10.1016/j.biortech.2023.129861.

[114] He X, Xiong J, Yang Z, Han L, Huang G. Exploring the impact of biochar on antibiotics and antibiotics resistance genes in pig manure aerobic composting through untargeted metabolomics and metagenomics. Bioresource Technol 2022;352:127118. https://doi.org/10.1016/j.biortech.2022.127118.

[115] Haider MIS, Liu G, Yousaf B, Arif M, Aziz K, Ashraf A, et al. Synergistic interactions and reaction mechanisms of biochar surface functionalities in antibiotics removal from industrial wastewater. Environ Pollut 2024;356:124365. https://doi.org/10.1016/j.envpol.2024.124365.

[116] Yao C, Wang B, Zhang J, Faheem M, Feng Q, Hassan M, et al. Formation mechanisms and degradation methods of polycyclic aromatic hydrocarbons in biochar: A review, J Environ Manage. 2024;357:120610. https://doi.org/10.1016/j.jenvman.2024.120610.

[117] Rombolà AG, Meredith W, Snape CE, Baronti S, Genesio L, Vaccari FP, et al. Fate of soil organic carbon and polycyclic aromatic hydrocarbons in a vineyard soil treated with biochar. Environ Sci Technol 2015;49:11037-11044. https://doi.org/10.1021/acs.est.5b02562.

[118] Yang X, Hou R, Fu Q, Li T, Li M, Cui S, et al. A critical review of biochar as an environmental functional material in soil ecosystems for migration and transformation mechanisms and ecological risk assessment. J Environ Manage. 2024;360:121196. https://doi.org/10.1016/j.jenvman.2024.121196.

[119] Liao S, Pan B, Li H, Zhang D, Xing B. Detecting free radicals in biochars and determining their ability to inhibit the germination and growth of corn, wheat and rice seedlings. Environ Sci Technol. 2014;48:8581-8587. https://doi.org/10.1021/es404250a.

[120] Godlewska P, Ok YS, Oleszczuk P. The dark side of black gold: Ecotoxicological aspects

of biochar and biochar-amended soils. J Hazard Mater. 2021;403:123833. https://doi.org/10.1016/j.jhazmat.2020.123833.

[121] Kim JH, Ok YS, Choi GH, Park BJ. Residual perfluorochemicals in the biochar from sewage sludge. Chemosphere 2015;134:435-437. https://doi.org/10.1016/j.chemosphere.2015.05.012.

[122] Zhang W, Liang Y. Effects of hydrothermal treatments on destruction of per- and polyfluoroalkyl substances in sewage sludge. Environ Pollut 2021;285:117276 https://doi.org/10.1016/j.envpol.2021.117276.

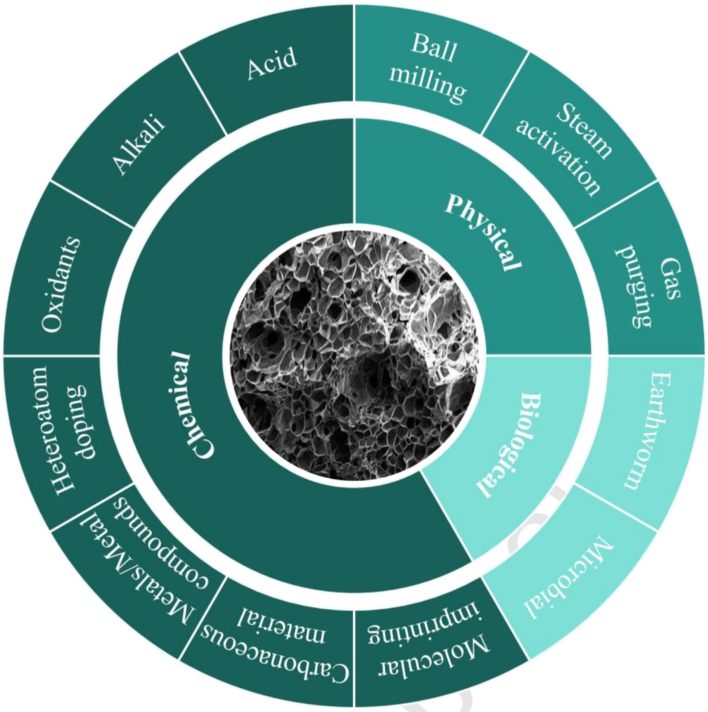

Fig. 1. Modification methods of biochar (BC).

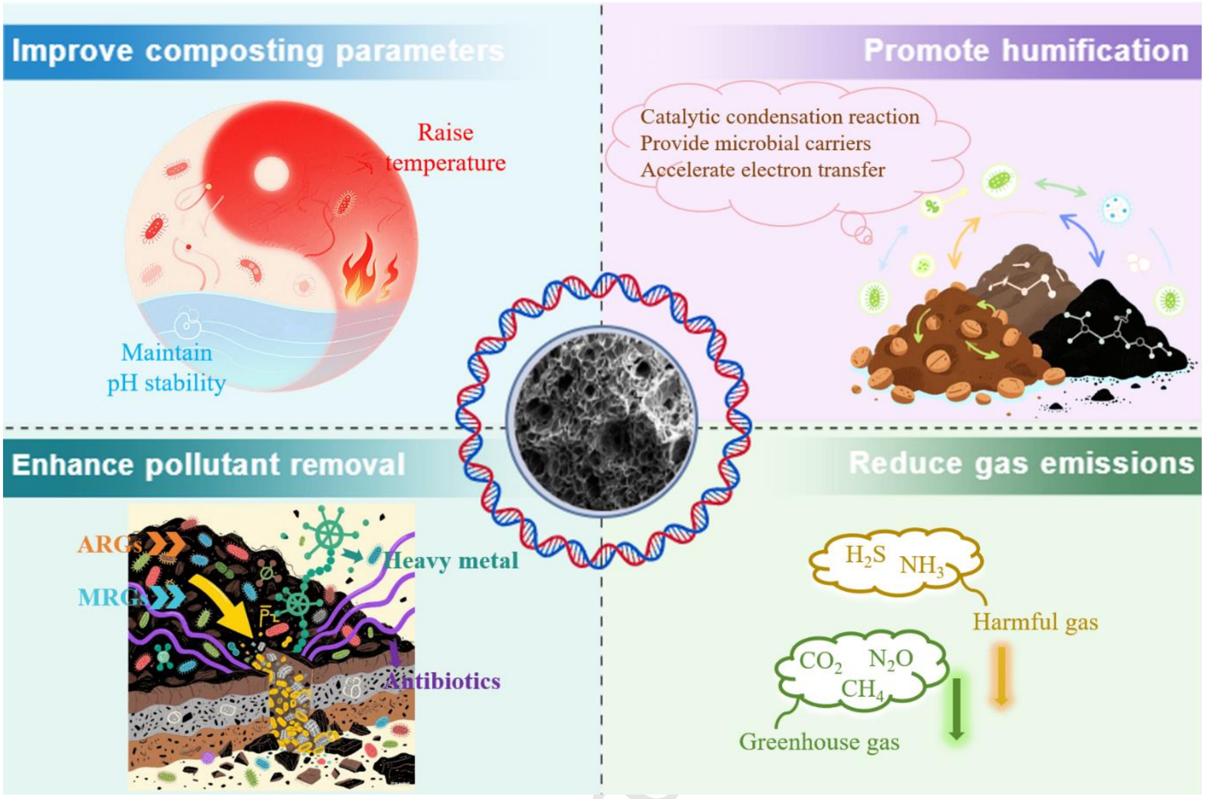

Fig. 2. Regulation of livestock and poultry manure (LPM) composting by functionalized BC.

Table 1 Comparison of different pyrolysis processes for biochar (BC).

Pyrolysis type	**Temperature (°C)**	**Heating rate (°C/s)**	**Residence time (s)**	**Pressure (MPa)**	**Particle size (nm)**
Slow pyrolysis	300-500	0.1-1.0	300-1800	0.1	5-50
Fast pyrolysis	500-1250	10-200	0.5-10	0.1	<1.0
Intermediate pyrolysis	500-650	1.0–10	5-30	0.1	1-10
Flash pyrolysis	900-1200	>1000	<1.0	0.1	<0.5
Vacuum pyrolysis	450-600	0.1-1.0	0.001-1.0	0.05-0.2	0.01-0.02
Microwave pyrolysis	300-600	-	300-1200	-	-
Hydro pyrolysis	350-450	-	~1800	5-20	5-20

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- Critically reviews functionalized biochar's role in manure composting
- Functionalized biochar enhances composting via superior adsorption and catalysis
- Unveils the interaction mechanisms linking biochar properties to microbial regulation
- Proposes research priorities for tailored biochar design and large-scale application