



Targeted regulation of biochar-strengthened microorganisms for effective removal of antibiotics from the environment

Jinli Wang^{1,2} · Xueying Li^{1,2} · Minghan Li³ · Haibo Sun^{1,2} · Jingyi Hou^{1,2} · Yang Yang^{1,2} · Yunshan Liang^{1,2} · Pufeng Qin^{1,2} · Yuan Yang^{1,2} · Zhibin Wu^{1,2}

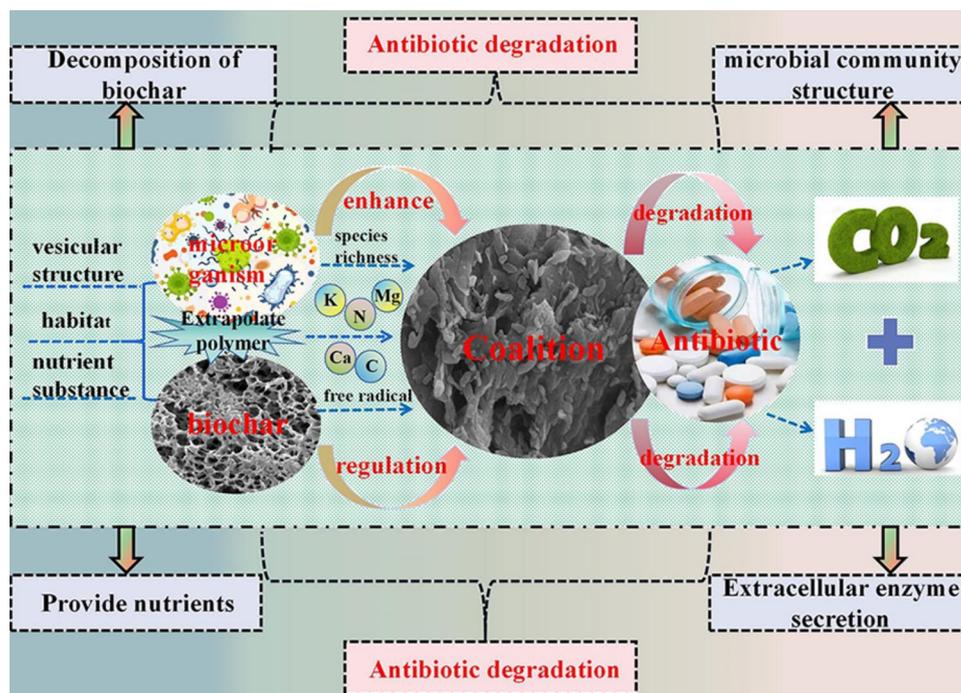
Received: 11 December 2024 / Accepted: 7 July 2025

© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2025

Abstract

In recent years, the excessive use of antibiotics has resulted in serious environmental pollution. The accumulation of antibiotics and their metabolites in soil and water not only exacerbates environmental stress, but also poses a direct threat to human health. While biochar-enhanced microbial remediation has emerged as a promising strategy, the targeted regulation of biochar–microbe interactions for optimized antibiotic removal remains underexplored. This study systematically dissects the effectiveness of biochar-regulated enhanced microorganisms for antibiotic removal. By integrating rationality characteristics with functionality features and considering their practical applications across various microorganisms, we have discovered that customized biochar modification can significantly enhance the degradation efficiency of antibiotics by microorganisms. The paper further identifies the targeted regulation measures of biochar as a microbial modulator enhancer, the role of biochar in microorganisms, and the potential application of biochar-regulated enhanced microorganisms in the environment. Finally, it also discusses the challenges and future prospects, providing new insights for addressing antibiotic pollution in the environment.

Graphical abstract



Extended author information available on the last page of the article

Keywords Antibiotic · Regulatory biochar · Organic pollutants · Micro-biological degradation

Introduction

Antibiotics, as pivotal agents for controlling and preventing bacterial infections, are extensively employed in fields such as healthcare, livestock rearing, and aquaculture (Kümmerer 2009; Liu 2021). Global antibiotic consumption surged from 21.1 billion defined daily doses in 2000 to 34.8 billion in 2015, with developing countries accounting for 76% of this increase (Klein et al. 2018). This escalation has created a persistent contamination cycle—over 40% of administered antibiotics enter ecosystems through incomplete metabolism and improper disposal, with detectable residues in 65% of global river systems (Larsson and Flach 2022). Studies indicate that the annual consumption of antibiotics ranges vastly from 50 to 200,000 metric tons (Massé et al. 2014). Alarmingly, over 40% of administered antibiotics enter ecosystems through incomplete metabolism and improper disposal, with

detectable residues in 65% of global river systems (Zhou and Chen 2024). These persistent contaminants threaten ecosystem integrity by inducing antibiotic resistance genes, which have increased 300% in agricultural soils since 2000 (Shuai Zhang et al. 2023a, b, c, d). Hence, there is a pressing need to seek innovative, effective, and sustainable remediation technologies to alleviate these environmental challenges.

However, traditional microbial remediation strategies face critical limitations. The main manifestations are as follows: The design principles linking biochar properties to microbial community assembly remain poorly quantified (Zhang et al. 2023a, b, c, d); Molecular-scale mechanisms of biochar-mediated electron transfer and enzyme induction are inadequately resolved (Zhao et al. 2023); past researches have indicated that the strategic deployment of biochar combined with microbial remediation strategies has emerged as a highly promising approach to ameliorating antibiotic

Table 1 Research on the combination of biochar and microorganisms for antibiotics in recent five years

Biochar	Microorganism	Combination mode	Result	References
Biochar derived from grapefruit peel	Microbial cell	Combination of both	Removal of more than 80% of sulfonamides antibiotics	Cheng et al. (2020)
Biochar	Soil microorganism	Biochar induced microorganisms	Remove the tetracycline	Liu et al. (2020a, b, c)
Mushroom residue biochar	<i>Bacillus subtilis</i> , fermenting bacteria	Biochar as an amendment	Reduced resistance gene	Huang et al. (2021)
Corn cob biochar	<i>Bacillus stercorarius</i>	Biochar as an amendment	Reduced resistance gene	Zhang et al. (2021a, b)
Chinese medicine residue biochar	<i>Bacillus cereus</i>	Bacteria are fixed to biochar	80% aureomycin removed	Sinan Zhang and Wang (2021)
Cow dung biochar	<i>Acidothermus sp/ Sphingomonas sp</i>	Combination of both	60% tetracycline removed	Yue et al. (2021)
Pig manure biochar	<i>bacillus</i>	Biochar immobilization	97.42% sulfamethoxazole was removed	Xi Chen et al. (2023a, b)
Iron modified biochar	<i>Methanobacterium/Geobacterium</i>	Biochar as an amendment	46% sulfamethoxazole removed	Ni et al. (2023)
Apple branch biochar	<i>Bacillus cereus</i>	Combination of both	Reduced resistance gene	Duan et al. (2023)
Sludge biochar	<i>Anaerobic ammonification bacteria</i>	Biochar as an amendment	Reduced tetracycline inhibition	Liu et al. (2023a, b, c, d)
Straw biochar	<i>Achromobacter denitrifying</i>	Biochar assisted	More than 95% of oxytetracycline was removed	Shudong Zhang et al. (2023a, b, c, d)
Algal biochar	chlorella	Biochar assisted	83.3% tetracycline was removed	Shuang Wang et al. (2023a, b, c, d, e, f)
Algal biochar	<i>Aspergillus oryzae</i> - <i>Microcystis aeruginosa</i>	Combination of both	More than 60% tetracycline removed	Nie et al. (2023)
Chicken manure and rice husk biochar	<i>Bacillus subtilis</i>	Combination of both	Remove resistance gene	Wu et al. (2024)
Modified biochar	<i>Pseudomonas aeruginosa</i>	Biochar assisted	More than 99.59% of oxytetracycline was removed	Shudong Zhang et al. (2024)

contamination (Table 1). This synergy centers on the interplay between biochar's adsorptive kinetics and its regulatory influence on microbial communities, offering a novel and significant dual-action strategy to enhance the biodegradation of antibiotics (Jia et al. 2023). Biochar, a carbonaceous material produced through the pyrolysis of biomass under anoxic conditions (Singh et al. 2023), has traditionally been valued for its agronomic benefits, including soil amendment, carbon sequestration, and water retention capabilities (Pandey et al. 2023). Yet, due to its intrinsic physicochemical attributes—such as an expansive surface area (Hou et al. 2024), high porosity, and a rich array of functional groups (Cuong and Hou 2024)—it has shown capacity for adsorbing a variety of pollutants, thereby extending its utility to environmental remediation (Issaka et al. 2022). In the context of antibiotics, these properties facilitate the immobilization of these compounds, effectively reducing their bioavailable concentrations and thereby mitigating their impact on ecosystems and health (Jiang et al. 2022). Concurrently, the role of biochar as an ecological niche that fosters microbial growth and activity has garnered substantial interest (Ma et al. 2023). Its structural complexity and nutrient retaining capacity create a protective milieu that not only supports but also enhances the viability and functional diversity of microbial populations (Liu et al. 2023a, b, c, d). In turn, this is hypothesized to accelerate the rate of antibiotic degradation, utilizing naturally occurring metabolic pathways to decompose these intricate molecules (Mitchell et al. 2023). Although biochar possesses potential, comprehending how to harness biochar to amplify the degradation of antibiotics in the environment by microbes necessitates an exhaustive understanding of the interplay between the characteristics of biochar and microbial dynamics (Mitchell et al. 2023). The efficacy of the regulated biochar depends on myriad factors, encompassing adsorptive capacity, regulatory mechanisms, and chemical functionality (He et al. 2023a, b). Furthermore, the complexity of biochar–microbe interactions is modulated by a spectrum of environmental variables such as the physicochemical properties of biochar (Harindintwali et al. 2020), inclusive of pH, temperature, and surface area, all of which can significantly influence the efficiency and directionality of antibiotic degradation pathways (Li et al. 2022a, b; Yu et al. 2020).

This review critically evaluates engineered biochar's role in enhancing microbial antibiotic degradation across environmental matrices. We systematically analyze biochar-mediated microbial augmentation mechanisms, focusing on pollutant clearance optimization and environmental remediation efficacy. The synergy between biochar–microbe interactions enables resource recovery while maintaining ecological integrity, particularly in agricultural systems contaminated with antibiotic residues. Through mechanistic dissection of biochar–microbial consortia interfaces, we

identify current knowledge gaps and propose prioritized research directions to advance sustainable pollutant mitigation strategies.

Targeted regulation measures of biochar as microbial modulators

Biochar's efficacy as an effective microbial carrier can be amplified through targeted modification of its intrinsic properties, encompassing porosity, surface chemistry, and stability, thereby endowing it with the functionality of a regulatory agent (Krzyszczak et al. 2022). Such strategic adjustments are designed to enhance the habitat for microbes by altering the biochar's internal structure and stability, consequently stimulating the growth and diversity of beneficial microbes while suppressing undesirable ones (Wang et al. 2024). Consequently, a multitude of studies have focused on enhancing the applicability of microbes to pollutants by altering the physicochemical properties of biochar (Haider et al. 2021; Han et al. 2023; Liang et al. 2020). This approach not only fosters the proliferation and activity of specific microorganisms but also enhances biochar's innate adsorption and transformation capacities for particular pollutants through microbial action, thus achieving a dual benefit in environmental management (Kim et al. 2020).

Boosting specific surface area

The specific surface area of biochar is regulated through the manipulation of parameters in its production process (Dou et al. 2022), such as the pyrolysis temperature, retention time, feedstock type (Table 2), and pretreatment methods (Saghir et al. 2022) (Fig. 1a). Studies have indicated that a higher surface area enhances microbial adhesion. Wang and colleagues synthesized an iron-modified biochar material using a green solvent, polyethylene glycol 200, and $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ through a single-step pyrolysis method. This material boasted a specific surface area of $407 \text{ m}^2 \text{ g}^{-1}$, which augmented the efficacy of microbial immobilization. The findings suggest that an increased specific surface area improves the surface structure and roughness of biochar materials, promotes microbial attachment on its surface, and escalates the degradation efficiency of phenanthrene (Wang et al. 2023a, b, c, d, e, f). Elucidating the method of enhancing the specific surface area of biochar through modification illustrates that this augmentation furnishes additional adsorption points and expands the area of active sites (Liu et al. 2020a, b, c). This expansion facilitates the adsorption of pollutant molecules onto the biochar, where they engage synergistically with microbes, culminating in effective degradation (Sharma et al. 2024). In a concurrent study, Fan synthesized calcium precipitated nanoparticles (CPN) atop

Table 2 Removal of antibiotics by biochar from different biomass

Biomass	Pyrolysis temp (°C)	Antibiotic	Removal conditions	Removal on rate (%)	Removal mechanism	References
Cotton stalk and bits of wood	500	Quinolone	Activating oxidants to generate	60	Transformation of free radicals	Zhang et al. (2021a, b)
Corn stalk	500	Norfloxacin	Persulfate activated with corn stalk biochar	94.21	Changes in functional groups	Wang et al. (2019)
Pig manure	300	Oxytetracycline	High temperatures produce a lot of humus	96.58	Conversion of compost to humus	Liu et al. (2023a, b, c, d)
Pig manure	500	Oxytetracycline	High temperatures produce a lot of humus	99.18	Conversion of compost to humus	Liu et al. (2023a, b, c, d)
Pig manure	700	Oxytetracycline	High temperatures produce a lot of humus	100	Conversion of compost to humus	Liu et al. (2023a, b, c, d)
Sewage sludge	600	Tetracycline	Hydrothermal modification to form catalyst	99	Free radical pathway and non-free radical pathway are the main pathways	Fan et al. (2023a, b)
Rice waste	800	Tetracycline	Hydrothermal carbonization and pyrolysis	96.02	Pore filling, electrostatic attraction, π - π interaction	Zhang et al. (2023a, b, c, d)
Malt rootlets	900	Sulfamethoxazole	Biochar activated persulfate oxidation of SMX from waste malt roots	94	Surface functional groups play a role	Kemmou et al. (2018)
Bagasse and bamboo and hickory chips	450	Sulfamethoxazole	Biochar activation	83.3	Hydrophobic interaction, π - π interaction	Kemmou et al. (2018)
Bagasse and bamboo and hickory chips	450	Sulfapyridine	Pyrolysis condition	89.6	Hydrophobic interaction, π - π interaction	Huang et al. (2020a, b)

sludge as an amalgamated template scaffold, thereby enlarging the surface area of sludge-derived biochar and enhancing the adsorption of tetracycline (TC) (Fig. 1b). Characterization and adsorption experiments revealed that the modified biochar (FBC) possessed a commendable specific surface area (448.55 mg g^{-1}), which stabilized its morphological structure and elevated its adsorption capacity for tetracycline to 65.43 mg g^{-1} (Fan et al. 2023a, b). Similarly, in a different inquiry, Chen and colleagues crafted nitrogen-doped magnetic porous biochar (NMPBs) through a three-step synthesis involving pre-solution, co-dissolution, and co-precipitation with seaweed as the precursor. The modified biochar exhibits an expansive surface area of $1531 \text{ m}^2/\text{g}$, endowing them with a formidable adsorption capacity for sulfamethoxazole, achieving a removal efficacy of 502 mg g^{-1} (Chen et al. 2024). These studies demonstrate that the internal pore structure of the modified biochar provides an abundance of surface area, and through tailored modification techniques, one can further augment the openness and number of these pores, thereby significantly increasing the specific surface area (Liao et al. 2021). The resultant biochar can enhance their adsorption abilities for pollutants via chemical adsorption or ion exchange, thus leveraging more surface area for the sequestration of contaminants, as depicted in Fig. 1c.

Consequently, biochar possessing the highest specific surface areas demonstrates the most robust adsorption capacities for pollutants and exhibits elevated removal efficiencies under modification (Ma et al. 2021). This substantiates the notion that enhancing the adsorption capabilities and the efficacy of microbial-mediated antibiotic removal can be achieved by precise manipulation of biochar specific surface areas (Fig. 1d). However, it is not a given that the performance of all modified biochar will invariably improve. Initially, modification processes may alter other critical properties of the biochar, such as structural stability and biodegradability (Almutairi et al. 2023). For instance, the control of pyrolysis temperature and excessive activation may result in the degradation of the pore structure, thereby affecting its structural integrity (Fig. 1e). Moreover, an increase in specific surface area tends to raise the production costs of biochar, potentially reducing its economic viability for large-scale applications (Zhang et al. 2023a, b, c, d). Besides, although an augmented specific surface area can adsorb more pollutants, the complete disassociation of pollutants from the biochar and their release into the environment would necessitate subsequent complex treatment processes (An et al. 2023). Therefore, when the amplification of specific surface area is considered to enhance adsorption

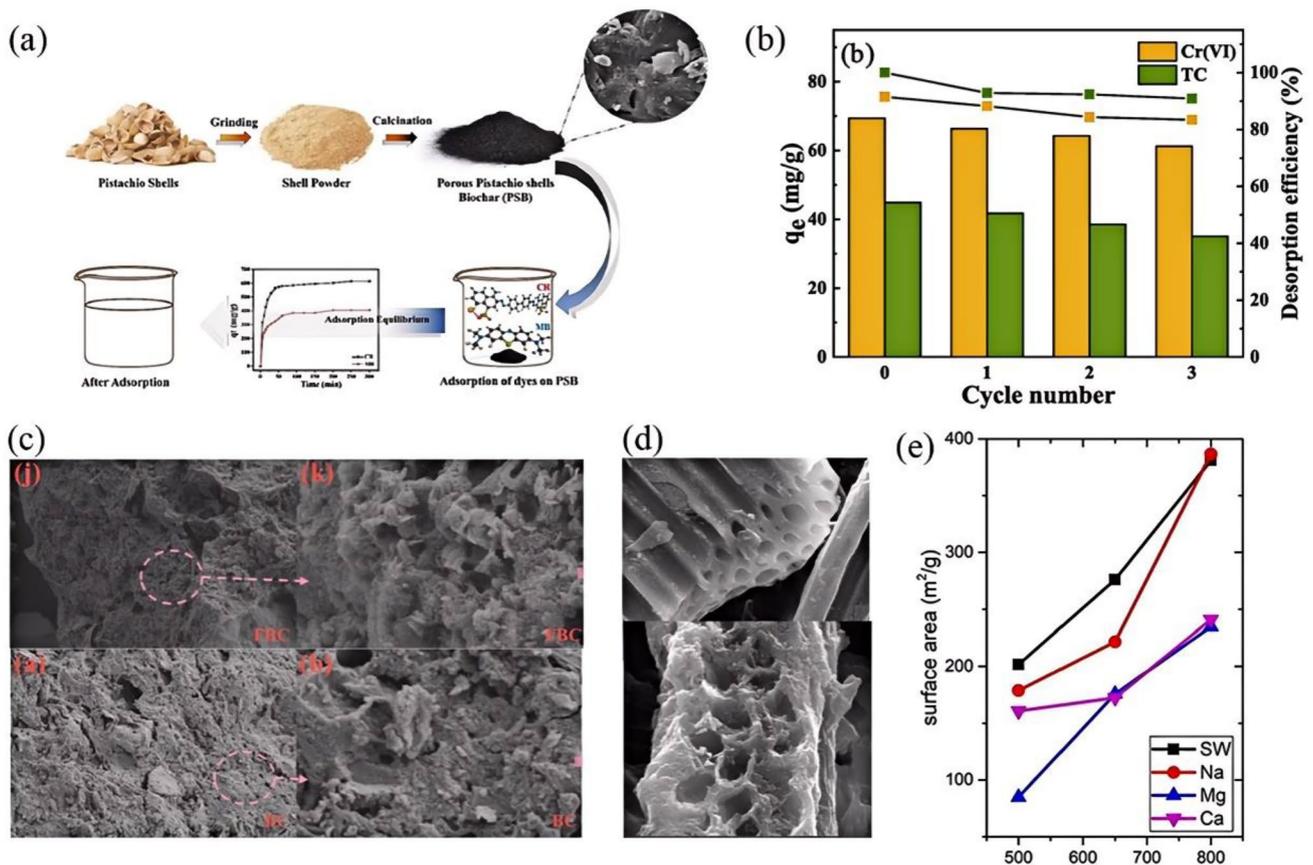


Fig. 1 The impact of biochar specific surface area as a carrier on microorganisms. **a** The fabrication process influences the specific surface area of biochar (Saghir et al. 2022) Copyright 2022,Elsevier. **b** The modified biochar enhances the removal effects on tetracycline (Qu et al. 2021) Copyright 2021,Elsevier. **c** A comparison between Scanning Electron Microscopy images of non-modified and modified

biochar (Fan et al. 2023a, b) Copyright 2023,Elsevier. **d** The specific surface area of the modified biochar has been significantly magnified (Wang et al. 2022a, b) Copyright 2022,Elsevier. **e** The preparation temperature of the biochar impacts the specific surface area (Wang et al. 2023a, b, c, d, e, f) Copyright 2022,Elsevier

capacity, it is crucial to weigh other factors comprehensively, including the fundamental characteristics of the biochar, its stability during preparation, and the complexity of follow-up treatments, to minimize potential adverse effects as much as possible during regulation.

Altering surface potential

Modulating biochar redox potential represents an effective strategy to enhance microbial antibiotic removal efficiency (Yu et al. 2023). The variation in redox potential within biochar is closely linked to pH levels. By adjusting redox potential, one can influence the surface charge status and pH of biochar in the environment (Fig. 2a) (Jin et al. 2024), thereby impacting the activity and efficiency of microorganisms in antibiotic removal.

Specifically, modulating the redox potential of biochar can alter its surface electrical properties, causing it to exhibit different redox potentials under varying pH conditions (Zeng

et al. 2024). The surface charge variation of biochar critically governs antibiotic adsorption through three interrelated mechanisms: pH-dependent protonation/deprotonation of functional groups, pKa-regulated speciation of antibiotic species, and electrostatic interactions between these charged entities. In a study, magnetized biochar prepared by dry methods showed positive surface charge when pH was higher than 5.67, while displaying a negative surface charge when pH was below 5.67(Fig. 2b) (Hu et al. 2024). Magnetic biochar exhibits a similar pH-dependent pattern in its impact on antibiotic removal. When the pH drops below 2.0, antibiotics typically carry a positive charge, causing the surface zeta potential of magnetic biochar to also be positive. As a result, there is strong electrostatic repulsion and Lewis acid–base interactions between antibiotics and biochar, leading to lower adsorption rates (Cho et al. 2023). As the pH increases, anions in biochar become more prevalent at higher pH levels, creating an adsorption effect that aids in the removal of antibiotics (Ahmed et al. 2017). Another

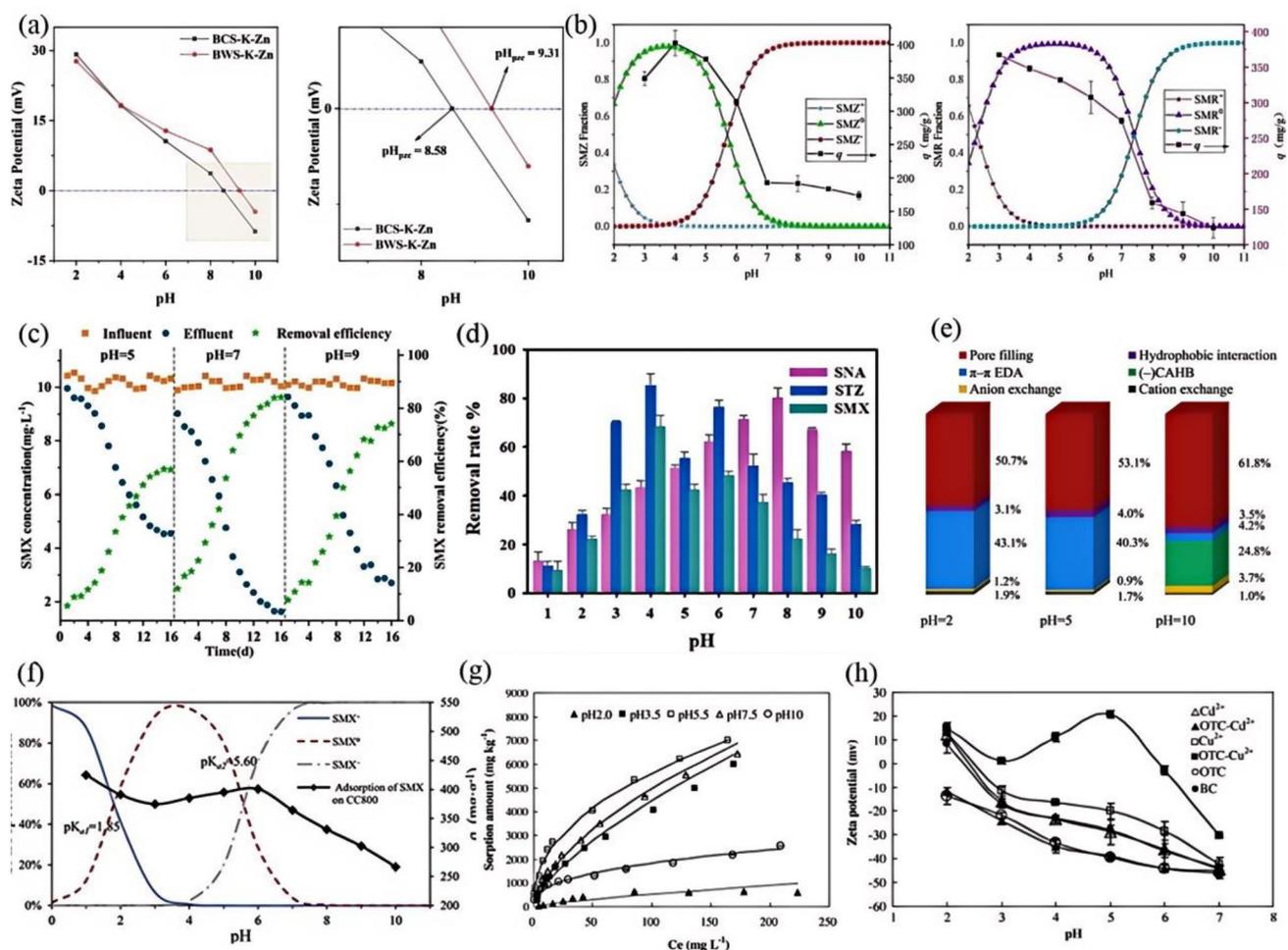


Fig. 2 Effects of biochar at different potentials. **a** The Zeta potential map of the biochar affects its surface charge state and its environmental pH value (Jin et al. 2024) Copyright 2024, Elsevier. **b** Effect of pH values on magnetic biochar versus antibiotics (Hu et al. 2024) Copyright 2024, Elsevier. **c** Effect of pH values on changes in antibiotic concentration and removal rate (Xi Chen et al. 2023a, b) Copyright 2023, Elsevier. **d** The influence of pH on adsorption efficiency (Xuefei Tan et al. 2022) Copyright 2022, Elsevier. **e** The distribution of

antibiotic adsorption mechanisms under differing pH conditions (Li et al. 2022a, b) Copyright 2022, Elsevier. **f** The charge borne by modified biochar under disparate pH circumstances affects the elimination of antibiotics (Li et al. 2022a, b) Copyright 2022, Elsevier. **g** Zeta potentials of modified biochar prior to and following the adsorption of tetracycline (Jia et al. 2013) Copyright 2013, Elsevier. **h** Isotherms of tetracycline adsorption onto biochar under varying pH values (Jia et al. 2013) Copyright 2013, Elsevier

study suggests that the immobilization of *Bacillus subtilis* on biochar for the removal of antibiotics shows an 84.10% removal efficiency for sulfonamide antibiotics at a pH of 7.0. However, the removal efficiency of sulfonamide antibiotics decreases at pH 5.0 and 9.0 (Fig. 2c) (Hu et al. 2024). The surface charge of biochar and the surface charge morphology of antibiotics are both influenced by the pH of the solution, leading to this effect (Esfandiar et al. 2022). When biochar is combined with *Bacillus subtilis*, it carries a positive charge at $pH < 8.3$ and a negative charge at $pH > 8.3$, while sulfonamide antibiotics carry a positive charge at $pH < 1.6$, remain neutral at $pH = 1.6-5.7$, and become negatively charged at $pH > 5.7$ (Chen et al. 2022). The findings indicate that at a pH of 7, the electrostatic attraction between antibiotics

and biochar, as well as the optimal growth pH of microorganisms, ensure the efficient adsorption of antibiotics and their bioconversion (Huang et al. 2020a, b). Therefore, the pH value, serving as an indicator of the solution's acidity or alkalinity, directly influences its surface charge characteristics and functional group status. By optimizing these interactions through the changes in the electrical potential of biochar at different pH values, more efficient removal of antibiotics can be achieved (Fig. 2d) (Xi Chen et al. 2023a, b). The removal mechanism involves cation and anion exchange, with changes in pH leading to alterations in electrical potential, while π - π interactions offer numerous adsorption sites (Fig. 2e) (Xuefei Tan et al. 2022). From a microbial perspective, the alteration in biochar electrical

potential can influence microbial metabolic activity and enhance microbial survival efficiency. By regulating the electrical potential of biochar, the formation and maintenance of specific microbial communities with high removal efficiency for antibiotics can be promoted, thereby enhancing the process of biological degradation (Fig. 2f) (Li et al. 2022a, b). Furthermore, an optimal pH level contributes to maintaining the stability of antibiotic adsorption on the surface of biochar (Fig. 2g) (Jia et al. 2013). Especially those with a positive charge (Fig. 2h) (Jia et al. 2013), which helps prevent antibiotics from premature detachment under microbial action, ensuring that antibiotics can be fully utilized and degraded by microorganisms.

In summary, modulating biochar redox potential and pH represents an effective strategy to enhance microbial antibiotic removal efficiency. The changes in redox potential and pH value produce a coupling effect through interrelated mechanisms: The interplay between pH and redox potential critically regulates biogeochemical processes in biochar-amended systems: pH governs the protonation/deprotonation equilibrium of biochar's surface functional groups, thereby modulating both surface charge density and availability of redox-active sites, while the prevailing redox potential determines the thermodynamic driving force for electron transfer that sustains microbial respiratory chains and enzymatic catalysis efficiency; crucially, the Eh–pH coupling creates distinct biogeochemical niches by thermodynamically constraining or enabling specific microbial metabolic pathways through combined effects on electron donor/acceptor availability and cellular redox homeostasis. This synergistic regulation ultimately shapes microbial community functions and biogeochemical cycling in biochar-mediated environments.

Grafting functional groups

Functional groups serve as pivotal mediators of biochar–microbe interactions, with specific chemical moieties directly modulating microbial adhesion, enzymatic activity, and antibiotic degradation pathways. The dominant oxygen-containing groups and nitrogenous functionalities exhibit distinct roles in microbial processes (Qiu et al. 2024) (Fig. 3a). Carboxyl groups enhance microbial adhesion through proton exchange mechanisms—their pH-dependent protonation creates negatively charged surfaces that promote electrostatic interactions with bacterial cell membranes (Dai et al. 2023).

The thermal sensitivity of functional group formation necessitates precise pyrolysis control. XPS analysis reveals that low-temperature biochar (300–450 °C) retains 2.3 mmol/g oxygen-containing groups versus 0.7 mmol/g in high-temperature counterparts (750 °C) (Janu et al. 2021) (Fig. 3b). This thermal gradient directly impacts microbial functionality – microcosm experiments show

Pseudomonas putida biofilm formation increases 62% on 400 °C biochar versus 700 °C material, correlating with surface carboxyl density (Xuefei Tan et al. 2022) (Fig. 3c). Strategic co-doping of N and S creates zwitterionic surfaces that maintain microbial viability across pH 4–9, as demonstrated by 85% survival rate of *Bacillus subtilis* under extreme conditions versus 45% in unmodified systems (Xu et al. 2021).

Recent advances in functionalization techniques enable targeted microbial regulation. Aminated biochar prepared through NH₃ plasma treatment shows 3.2-fold higher laccase adsorption capacity (Q_{max} = 148 mg/g) through Schiff base formation with enzyme lysine residues (Liu et al. 2023a, b, c, d). Quinone-rich surfaces from KMnO₄ oxidation enhance extracellular electron transfer by 210%, validated by 78% increase in *Geobacter sulfurreducens* cytochrome c expression (Zhao et al. 2023). These engineered interfaces create microhabitats supporting higher antibiotic degradation rates compared to conventional biochar, while maintaining > 90% microbial viability through pH buffering and nutrient retention mechanisms (Fig. 3d).

Studies indicate that biochar's reusability is closely tied to its structural integrity and functional group retention after multiple regeneration cycles. For instance, chemical regeneration effectively desorbs antibiotics by reversing pH-dependent adsorption mechanisms, while thermal regeneration can restore biochar's porosity by removing adsorbed contaminants and pyrolyzing residual organic matter (Fig. 4). For example, magnetic biochar composites exhibit excellent stability over 5–10 cycles, retaining > 80% adsorption capacity for sulfonamides due to robust Fe–O–C bonding and pore structure preservation (Chu et al. 2022). Similarly, microalgae-derived biochar maintained 85% tetracycline removal after six cycles via NaOH regeneration, attributed to preserved oxygen-rich functional groups (Siyu Wang et al. 2023a, b, c, d, e, f). However, repeated regeneration may reduce surface area due to pore blockage or functional group degradation, emphasizing the need for optimized protocols. Microbial-assisted regeneration, where biochar serves as a biofilm carrier, also shows promise by combining biodegradation with adsorption renewal (Bocşa et al. 2023). Future work should focus on balancing regeneration efficiency, cost, and environmental impacts while assessing long-term stability under real-world conditions.

Therefore, the distribution of functional groups within biochar wields significant influence, affecting its capacity to manage pollutants within environmental settings (Ngo et al. 2023). Research has demonstrated that strategically regulating the pyrolysis process can enhance the yield of biochar (Table 3), thereby optimizing its physicochemical properties and greatly increasing its adsorption capacity for antibiotics in the environment (Liu et al. 2021).

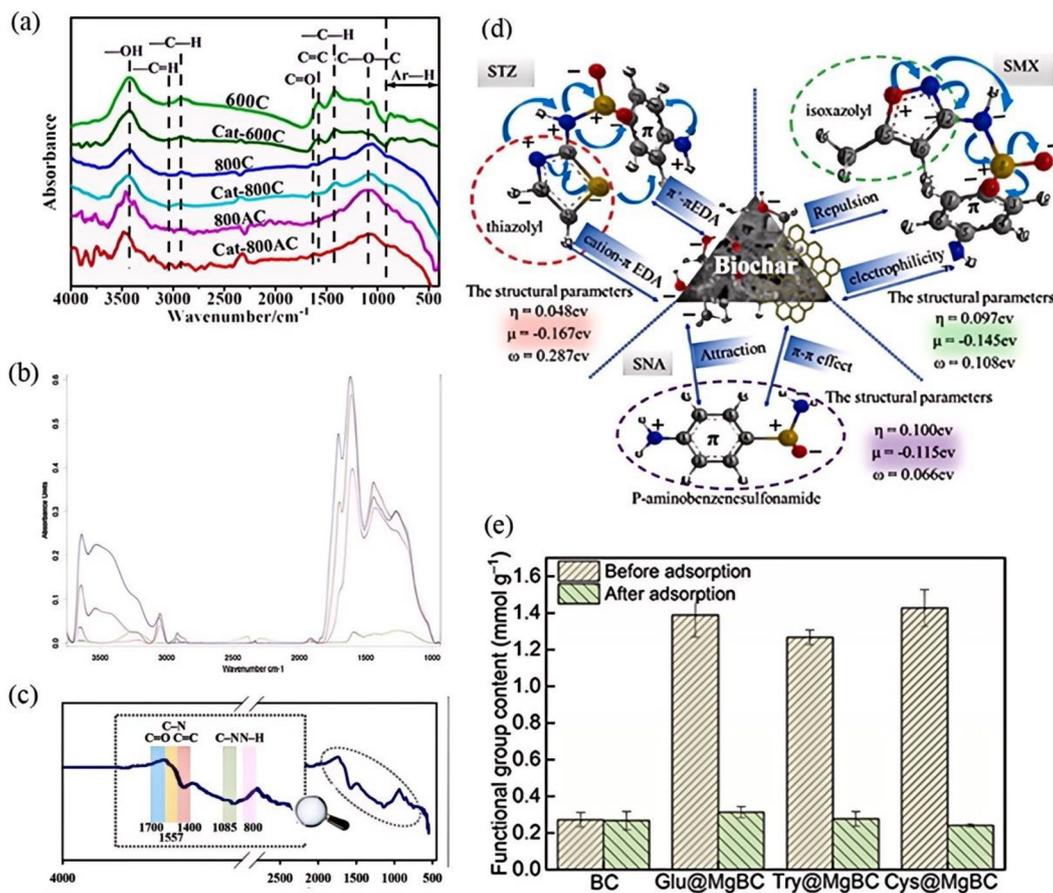


Fig. 3 The influences of functional groups on the surface properties of biochar. **a** Functional groups evinced by modified biochar catalyzed by three distinct catalysts (Qiu et al. 2024) Copyright 2024, Elsevier. **b** Functional groups displayed by regulated padauk sawdust biochar at varying pyrolysis temperatures as denoted by FTIR (Janu et al. 2021) Copyright 2021, Elsevier. **c** The FTIR of biochar

(Xuefei Tan et al. 2022) Copyright 2022, Elsevier. **d** The adsorption mechanisms of antibiotics formed by the effects of the biochar's functional groups (Xuefei Tan et al. 2022) Copyright 2022, Elsevier. **e** The quantity of functional groups within modified biochar (Li et al. 2023a, b) Copyright 2023, Elsevier

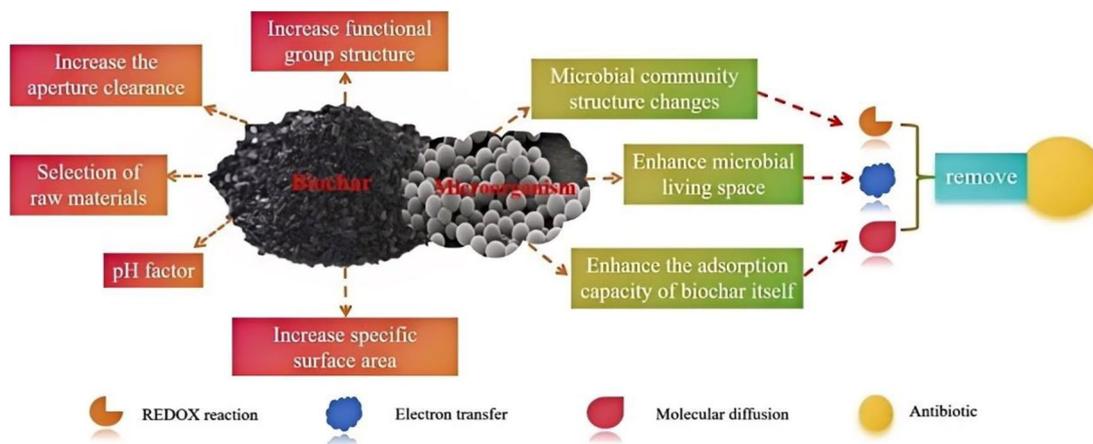


Fig. 4 Schematic diagram of biochar and microbial binding mechanism

Table 3 Effects of raw material selection and pyrolysis temperature on biochar

Pyrolysis method	Biomass type	Main product	Temperature (°C)	Productive rate (wt. %)	Reference
Pyrolysis	Straw	Biochar	500	14.83	Muzyka et al. (2023)
Pyrolysis	Straw	Biochar	700	16.93	Muzyka et al. (2023)
Pyrolysis	Non-woven	Biochar liquid	250	25.1	Illingworth et al. (2013)
Pyrolysis	Non-woven	Biochar liquid	950	21.50	Illingworth et al. (2013)
Pyrolysis	Pigeon pea stalk	Low biochar	600	4.70	Sahoo et al. (2021)
Pyrolysis	Bamboo	Low biochar	600	5.11	Sahoo et al. (2021)
Pyrolysis	Wood	Biochar liquid Gas	850	–	Itoh et al. (2020)
Pyrolysis	Manure	Biochar liquid Gas	850	–	Itoh et al. (2020)
Hydrothermal	Coconut	Biochar liquid	250	26.7	Liu et al. (2013)
Hydrothermal	Eucalyptus leaves	Biochar liquid	250	25.0	Liu et al. (2013)
Hydrothermal	Wetland plants	Biochar liquid	260	27.1	Cui et al. (2020)
Hydrothermal	Corn husk	Biochar liquid	260	27.66	Heidari et al. (2019)
Hydrothermal	Rice husk	Biochar liquid	200	15.7	Heidari et al. (2019)
Hydrothermal	Sugar Cane	Biochar Gas	175	18	Heidari et al. (2019)
Microwave-assisted	Corn stover	Biochar Oil Gas	550	29.26	Wan et al. (2009)
Microwave-assisted	Horse manure	Gas Biochar liquid	550	35.5	Mong et al. (2020)
Microwave-assisted	Wood sawdust	Gas Biocha	480	65	Borges et al. (2014)
Microwave-assisted	Corn stover	Gas Biocha	560	64	Borges et al. (2014)

Roles of biochar for microbial

Providing attachment site

The porous structure of biochar can provide attachment sites for microbial survival by increasing the microbial population (Quilliam et al. 2013). It is well recognized that biochar serves as an appropriate attachment site, as its production process generates numerous micropores, mesopores, and macropores, providing the necessary space and environment for microbial growth and metabolism (Lehmann et al. 2011).

Biochar's porosity architecture fundamentally determines microbial colonization patterns through three key mechanisms: Physical protection—pore networks create

microhabitats shielding microbes from predation and environmental stressors (Lehmann et al. 2011; Tomczyk et al. 2020); Mass transfer regulation—interconnected macropores facilitate oxygen/nutrient diffusion while mesopores provide high surface area for biofilm formation (Zhang et al. 2018); Interface engineering—nanopores generate localized high-concentration zones of signaling molecules to stimulate quorum sensing (Lehmann et al. 2011; Tomczyk et al. 2020). Our analysis reveals that optimal colonization occurs when biochar pore diameters exceed microbial cell sizes by 5–tenfold, allowing unrestricted movement while maintaining protective confinement (Palansooriya et al. 2019). For instance, *Pseudomonas aeruginosa* demonstrates 82% higher viability in biochar with dominant 10–30 µm pores compared to < 5 µm pore structures (Liu et al. 2021).

Table 4 Comparative summary of biochar–microorganism composites for antibiotic remediation

Biochar Source & Pyrolysis Temp	Microorganism	Antibiotic	Matrix	Key Conditions	Removal Efficiency (%)	Major Mechanism	Reference
Wheat straw (500 °C)	<i>Bacillus subtilis</i>	Tetracycline	Soil	pH 7, 25 °C, 7 days	85	Adsorption & biodegradation	Zhang et al. (2021a, b)
Wood chips (700 °C)	<i>Pseudomonas putida</i>	Sulfamethoxazole	Water	pH 6.5, 30 °C, 24 h	92	Biochar-mediated electron transfer	Li et al. (2022a, b)
Coconut shell (400 °C)	<i>Aspergillus niger</i> (fungus)	Ciprofloxacin	Soil	pH 5–9, 25 °C, 30 days	78	Chelation & enzymatic degradation	Wang et al. (2020)

The microbial attachment efficiency varies significantly across biochar types (Table 4). High-temperature biochars (> 500 °C) develop hierarchical pore systems with 2.3–4.7 times greater bacterial loading capacity than low-temperature variants. Specifically, wheat straw biochar pyrolyzed at 700 °C achieves 1.8×10^7 CFU/g microbial colonization through its 412 m²/g surface area and 0.68 cm³/g pore volume, outperforming pinewood biochar (287 m²/g, 0.49 cm³/g) by 37% (Zhang et al. 2018). Surface roughness metrics ($R_a = 1.2\text{--}3.8$ μm) show strong correlation ($R^2 = 0.89$) with *Actinobacteria* adhesion rates, where poultry manure-derived biochar exhibits 2.1-fold higher R_a values than lignocellulosic feedstocks (Palansooriya et al. 2019). Mineral-rich biochars (Ca/Mg > 5%) demonstrate enhanced fungal hyphae penetration (38–62% increase) via cation-bridging mechanisms between chitinous cell walls and biochar surfaces (Kasozi et al. 2010). These structural and compositional differences underscore the need for feedstock-specific design rules in microbial carrier development.

nutrients resources for microbial survival

Biochar is a material rich in various nutrients, such as C, N, P, K, S, Mg, Ca, and others. It is a product obtained through the pyrolysis of biomass materials such as waste, residues, and manure, and it also contains the essential trace elements required for microbial growth, providing them with survivability (Rodríguez-Vila et al. 2016).

When the nutrients in biochar are utilized by microorganisms, they provide the substances necessary for metabolism and growth, thereby enhancing the species richness (Ok et al. 2020). Some nutrients in biochar can be retained on the surface, which also has a beneficial impact on the growth and reproduction of microorganisms. Researchers have found that microorganisms present in waste can stabilize organic matter through biochemical processes and produce organic corrosive substances such as phosphorus and nitrogen (Cooperband 2000). These corrosive substances can ultimately serve as amendments to improve soil quality and increase nutrient utilization, thus promoting plant growth. Studies by various researchers have confirmed this. A key advantage of biochar is its provision of nutritional value, directly supplying nutrients to plants and improving the species richness of microorganisms in the soil, thereby enhancing soil fertility and plant growth (Jien and Wang 2013). Furthermore, experiments have shown that biochar not only contains carbon elements, but also trace amounts of phosphorus and sulfur. With the correction of biochar, the content of phosphorus and sulfur in biomass increases. Analysis of above-ground biomass quality demonstrates an overall increase in the main nutrients brought by biochar, including sulfur, nitrogen, calcium, magnesium, and manganese.

When the nutrients needed by microorganisms can provide elements such as sulfur and phosphorus for plant growth in the soil, the increase in microbial nutrients may have a positive impact on the utilization of plant nutrients and plant growth (Mukherjee et al. 2011).

In discussing the nutrient provision of biochar to microorganisms, we must delve into the potential impact of biochar addition on the microbial environment (Fox et al. 2014). For example, the addition of biochar to soil often triggers changes in the nutrient content of the soil, or indirectly affects microbial diversity. This is mainly due to the decisive role of soil nutrient quality in microbial community construction, and the addition of biochar tends to enhance the content of nutrients such as phosphorus, nitrogen, and metal ions in the soil (Warnock et al. 2007). Furthermore, biochar affects the absorption of nutrients by different microorganisms. Although fungi have an advantage in absorbing macromolecular polymer nutrients (e.g., total carbon and total nitrogen content > 200 mm), while bacteria lack this absorption capacity. For example, many fungal species perform better in the accumulation of nutrients and water, which may give them a greater competitive advantage in the presence of biochar (Ascough et al. 2010). However, bacteria can meet their own needs by dissolving bound phosphorus, and the growth of mycelium can also help bacteria or fungi to absorb more nutrients (Yuan et al. 2016). In addition, certain bacterial strains can produce compounds that promote their own growth. For example, *Pseudomonas aeruginosa* can dissolve phosphates and other key nutrients, forming a phosphate solution that can be directly utilized and absorbed by microorganisms, thereby providing the necessary nutrients for microorganisms (Kothamasi et al. 2006).

Consequently, biochar possesses distinctive physical and chemical attributes, including an expansive specific surface area, pronounced porosity, and a stable carbon framework, coupled with an abundance of functional groups, which enable it to efficaciously store and supply essential nutrients required by soil microbes. This slow-release mechanism offers a sustained source of nutrition for microbial growth. However, despite biochar's unique physicochemical properties that facilitate the effective adsorption and storage of nutrients within the environment, the balance between adsorption and release, as well as biochar's selectivity toward specific nutrients and microbes, demands further investigation. In addition, the mechanisms by which microbes utilize the nutrients provided by the addition of biochar and the subsequent impact on the microbial community's structure and function remain inadequately understood. Therefore, it is imperative that we acquire a more comprehensive understanding of the intricate interactions between biochar and microbes, to better facilitate the removal of antibiotics in environmental contexts.

Co-metabolism and enzyme induction

Biochar, as a porous carbonaceous material, is endowed with a vast specific surface area, intricate pore architecture, and a wealth of surface functional groups (Tran et al. 2016). These characteristics render biochar an ideal substrate for microbes, fostering their adhesion and proliferation as depicted. The interplay between microbes and biochar transcends mere physical attachment; it encompasses the chemical stimulation of microbial activity and the enhancement of co-metabolic processes (Zhu et al. 2024). Recent studies provide quantitative evidence of biochar-induced enzyme activation. Iron-modified biochar increased microbial reductase activity by 2.3-fold (from 12.4 to 28.7 U/mg protein) and oxidase activity by 1.8-fold (18.1 to 32.6 U/mg protein) during bisphenol A degradation (Wang et al. 2022a, b). Similarly, magnetic anaerobic digestion residue biochar enhanced penicillin acylase catalytic efficiency by 210%, reaching $4.7 \times 10^3 \text{ M}^{-1} \text{ s}^{-1}$ compared to $1.5 \times 10^3 \text{ M}^{-1} \text{ s}^{-1}$ in free enzyme systems (Chauhan et al. 2023). Aminated biochar prepared through NH_3 plasma treatment demonstrated $148 \text{ mg} \cdot \text{g}^{-1}$ laccase adsorption capacity, 3.2 times higher than unmodified biochar ($46 \text{ mg} \cdot \text{g}^{-1}$), through Schiff base formation with enzyme lysine residues (Pinheiro 2021).

Co-metabolism represents an indirect biotransformation process that occurs when microbes utilize non-growth substrates (Fig. 5a). In this context, biochar serves as an auxiliary substrate for microbial metabolism, enhancing the microbial capacity to metabolize specific pollutants. Investigations have revealed that the incorporation of biochar markedly enhances the microbial degradation of a mixture of polycyclic aromatic hydrocarbons—specifically, 50 mg/L phenanthrene (PHE) and 10 mg/L pyrene (PYR)—with the observed biodegradation by various biochar-amended microorganisms surging from 18.3 to 32.5% (Li et al. 2021). The enhancement is attributable to the addition of biochar, which inevitably furnishes microorganisms with supplementary nutrients, thereby facilitating their robust growth and altering the community composition of the microbes by augmenting the abundance of degradative bacteria (Fig. 5b) (Li et al. 2021). In another study, microorganisms were immobilized on biochar, leveraging the symbiotic metabolic interaction between the two to facilitate the removal of sulfonamide antibiotics (Fig. 5c) (Li et al. 2021). Within the yeast concentration range of 3 to $9 \text{ g} \cdot \text{L}^{-1}$, the removal efficiency progressively increased with the elevation of yeast concentration, escalating the removal rate from 51.91 to 84.17% (Fig. 5d) (Xi Chen et al. 2023a, b). This is attributed to yeast serving as a crucial carbon source that enhances the co-metabolism between biochar and microorganisms. With an increase in the carbon source dosage, the addition of yeast maximally facilitates the growth and activity of microorganisms on the biochar, thereby effectuating the efficient

degradation of antibiotics (Ali et al. 2021). Concurrently, the functional groups present on the biochar surface are capable of forming complexes with pollutants in the environment, thus rendering these contaminants more amenable to microbial utilization and transformation. This process, in turn, enhances the activity and stability of specific enzymes, promoting the degradation of pollutants (Yu et al. 2022). Investigations have revealed that the addition of biochar affects the abundance and diversity of microorganisms in soil, with dehydrogenase and urease activities generally escalating in tandem with the amount of biochar integrated (Amoakwah et al. 2022). The activity of dehydrogenases signifies the overall metabolic vigor of cells; the supplementation of biochar catalyzes the enzymatic dynamism of the microorganisms, thereby facilitating a more favorable elimination of antibiotics (Bowles et al. 2014). In addition, another study proved that the binding of iron-containing biochar with microorganisms can effectively remove bisphenol A. When introducing iron-containing biochar at a dose of $0.05 \text{ g} \cdot \text{L}^{-1}$, the removal rate of bisphenol A reached 74.1% (Fig. 5e). Through degradation pathway analysis, it was found that iron-containing biochar significantly improved the activities of reductase and oxidase in microorganisms. Co-metabolism is the main reason to enhance the degradation of bisphenol A (Wang et al. 2022a, b). Hence, the enzyme induction mechanism involves the stimulation of specific enzyme expression by biochar, enzymes which are indispensable for the microbial degradation of pollutants. The engineered biochar, rich in organic matter, acts as an inductive substrate to amplify microbial activity, thereby promoting the generation of additional target enzymes and expediting the transformation and diminution of pollutants via cometabolism (Estévez et al. 2024).

In conclusion, the activation of microbial activity via the regulation of biochar plays an integral role in antibiotic decomposition, with mechanisms co-metabolism and enzyme induction being pivotal. However, the efficacy of these mechanisms is influenced by a gamut of factors which encompass the type of antibiotic, the properties of the biochar, and the unique characteristics and adaptability of the microorganisms. As such, for specific application, judicious design and optimization are requisite to augment environmental and economic benefits, while concurrently mitigating potential adverse impacts. Future research should focus on elucidating and enhancing the efficiency of this process, addressing the limitations of current methodologies, and evaluating and managing any ensuing secondary pollution issues.

Regulatory molecular mechanisms.

Biochar orchestrates antibiotic biodegradation through multidimensional molecular mechanisms, including

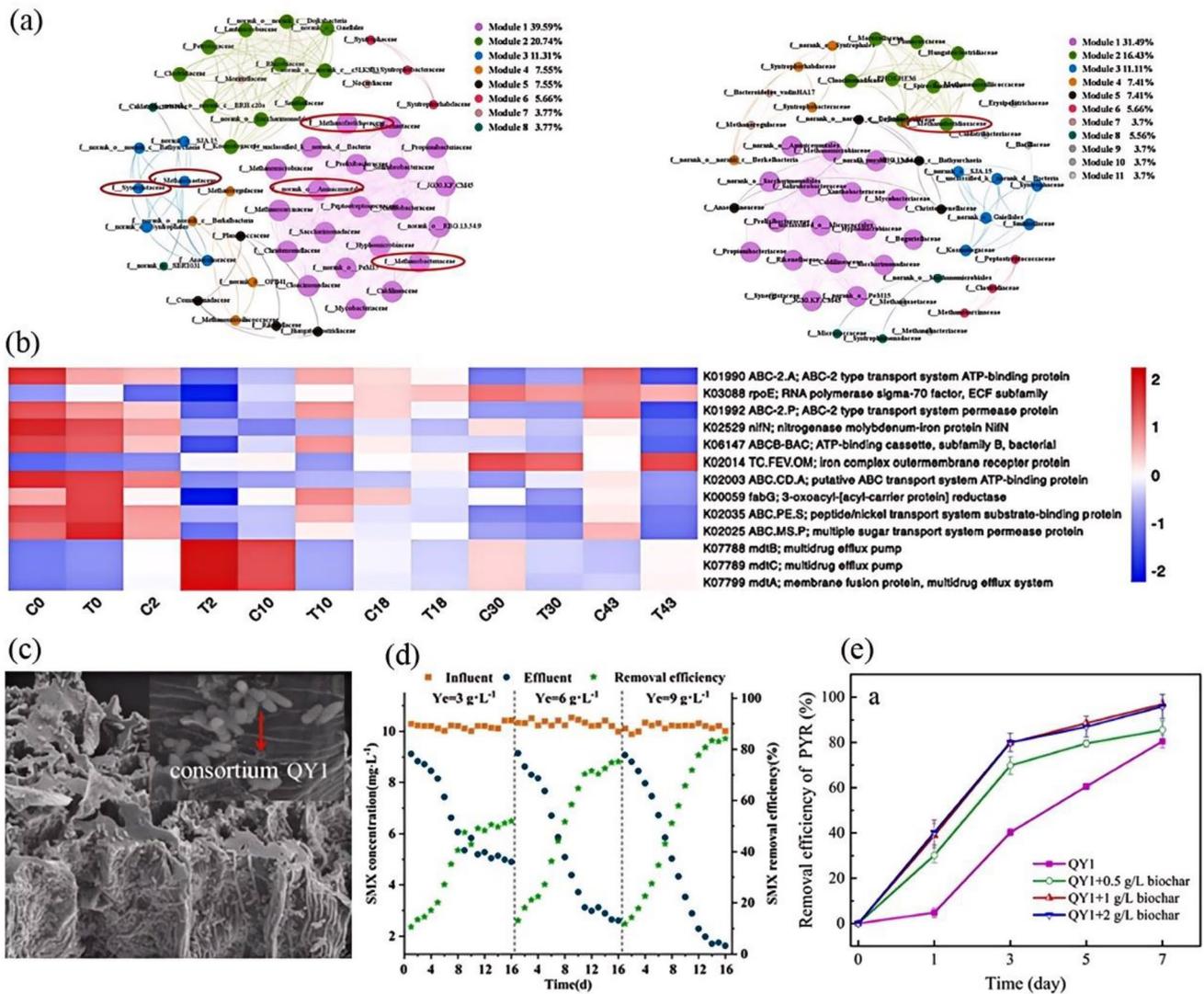


Fig. 5 The intimate cotransformation and enzyme-mediated synergy between biochar and microorganisms. **a** The microbial interaction network within the biochar sphere exhibits notable differences when compared to the control group (Li et al. 2023a, b) Copyright 2023, Elsevier. **b** Pertaining to the relevant metabolic genes bridging biochar and microorganisms (Wang et al. 2023a, b, c, d, e, f) Copyright 2023, Elsevier. **c** The SEM imagery of microbes anchored upon the

biochar (Li et al. 2021) Copyright 2021, Elsevier. **d** The influence of fluctuations in yeast extract concentrations within the carbon sources utilized in biochar-microbe cometabolism on antibiotic abatement (Xi Chen et al. 2023a, b) Copyright 2023, Elsevier. **e** The collaborative impact of biochar-microbe complexes on the degradation of polycyclic aromatic compounds (Li et al. 2021) Copyright 2021, Elsevier

electron transfer modulation, enzymatic activity enhancement, and biofilm synergism. These molecular-, cellular-, and community-level interactions collectively drive efficient antibiotic transformation and mineralization. For instance, iron-modified biochar (Fe-BC) demonstrates Fe³⁺/Fe²⁺-mediated Fenton reaction catalysis, generating hydroxyl radicals that directly cleave tetracycline's phenolic hydroxyl and dimethylamino groups. Under Fe-BC/*Pseudomonas* synergy, tetracycline degradation efficiency reaches 74.1% (Yang et al. 2023). Magnetic anaerobic digestion residue biochar immobilizes penicillin

acylase via π - π stacking and salt bridge effects, achieving 2.1-fold catalytic activity enhancement. The Fe₃O₄ core in SAMB activates peroxymonosulfate, accelerating β -lactam ring cleavage in penicillin G sodium from 0.015 to 0.042 min⁻¹ (Yustres et al. 2025). Concurrently, biochar functions as microbial refugia through interface engineering: In biofilm-biochar electron transfer systems, woodchip-derived biochar (specific surface area > 500 m²/g) enriches *electroactive Geobacter spp.*, achieving 158% tetracycline degradation enhancement via riboflavin-mediated transmembrane electron transfer (Jia et al. 2024).

Application of biochar to enhance microorganisms in the environment

Microorganisms play a ubiquitous role in the removal of antibiotics and thus, with the assistance of regulated

biochar to enhance microbial activity, they bear significant potential for improving antibiotic removal efficiency in the environment (Table 5). This role manifests prevalently in various environmental matrices such as soil, water, and other ecosystems (Table 6).

Table 5 Several strains of microorganisms that degrade antibiotics have been reported

Antibiotics	microorganism	Concentration (mg/L)	Removal rate (%)	Elapsed time (days)	Reference
Sulfadiazine	<i>B. subtilis</i> WD23	1000	92	2.5	Yang et al. (2021)
	<i>B. subtilis</i> X1				
	<i>B. licheniformis</i> LS04 <i>B. amyloliquefaciens</i>	1000	89	2.5	
Sulfamethoxazole	<i>B. vallismortis</i> fmb-103@ <i>Streptomyces ipomoeae</i>	1000	88	2.5	Yang et al. (2021)
	<i>Aeromonas caviae</i> strain GLB-10	250	100	3	Wang et al. (2023a, b, c, d, e, f)
	white-rot fungi	10	90–92	10	Aydin (2016)
sulfamethoxazole	<i>Achromobacter</i> sp.	50	79.45	5	hui Liang and Hu (2019)
	<i>Achromobacter</i> sp.	50	63.10	5	hui Liang and Hu (2019)
	<i>Ochrobactrum</i> sp.	5	45.2	12	Mulla et al. (2018)
	<i>Labrys</i> sp.	5	62.2	12	Mulla et al. (2018)
	<i>Gordonia</i> sp.	5	51.4	12	Mulla et al. (2018)
Tetracycline	white-rot fungi	1.5	88	10	Aydin (2016)
	<i>P. chrysosporium</i>	60	80	35	Liu et al. (2024)
	<i>Trichoderma harzianum</i>	250	95	21	Ahumada-Rudolph et al. (2016)
	<i>Trichoderma harzianum</i>	250	85	21	Ahumada-Rudolph et al. (2016)
	sp. AEPI 0–0	100	85	4	Ye et al. (2023)
	sp. AEPI 0–0	100	90	7	Ye et al. (2023)
	<i>Sphingobacterium</i> sp.	128	50	3	Ghosh et al. (2009)
	<i>Pseudomonas</i> sp.	50	92.86	7	Xiuli Chen et al. (2023a, b)
	<i>Achromobacter</i> sp.	50	83.7	7	Xiuli Chen et al. (2023a, b)
Terramycin	<i>Trichoderma deliquescens</i>	250	92	21	Ahumada-Rudolph et al. (2016)
	<i>Trichoderma harzianum</i>	250	85	21	Ahumada-Rudolph et al. (2016)
	<i>Talaromyces atrovirens</i>	250	83	21	Ahumada-Rudolph et al. (2016)
	<i>Penicillium crustosum</i>	250	73	21	Ahumada-Rudolph et al. (2016)
	<i>Rhodotorula mucilaginosa</i>	250	72	21	Ahumada-Rudolph et al. (2016)
Cloxacillin	<i>Leptosphaerulina</i> sp.	15	50	7	Copete-Pertuz et al. (2018)
Dicloxacillin	<i>Leptosphaerulina</i> sp.	15	47	8	Copete-Pertuz et al. (2018)
Ciprofloxacin	<i>Paraclostridium</i> sp.	20	80	3	Fang et al. (2021)

Table 6 Microbial colonization capacity of biochar from different feedstocks

Feedstock	Pyrolysis Temp (°C)	Surface Area (m ² /g)	Pore Volume (cm ³ /g)	Bacterial Loading (CFU/g)	Fungal Hyphae Density (µm/µm ²)	Reference
Wheat straw	700	412 ± 15	0.68 ± 0.03	1.8 × 10 ⁷	2.4 ± 0.3	Wang et al. (2023a, b, c, d, e, f)
Pine wood	700	287 ± 22	0.49 ± 0.05	1.3 × 10 ⁷	1.7 ± 0.2	Li et al. (2022a, b)
Poultry manure	600	158 ± 18	0.35 ± 0.04	2.1 × 10 ⁷	3.9 ± 0.4	Li et al. (2022a, b)
Sewage sludge	800	632 ± 29	1.02 ± 0.06	2.6 × 10 ⁷	1.2 ± 0.1	Palansooriya et al. (2019)

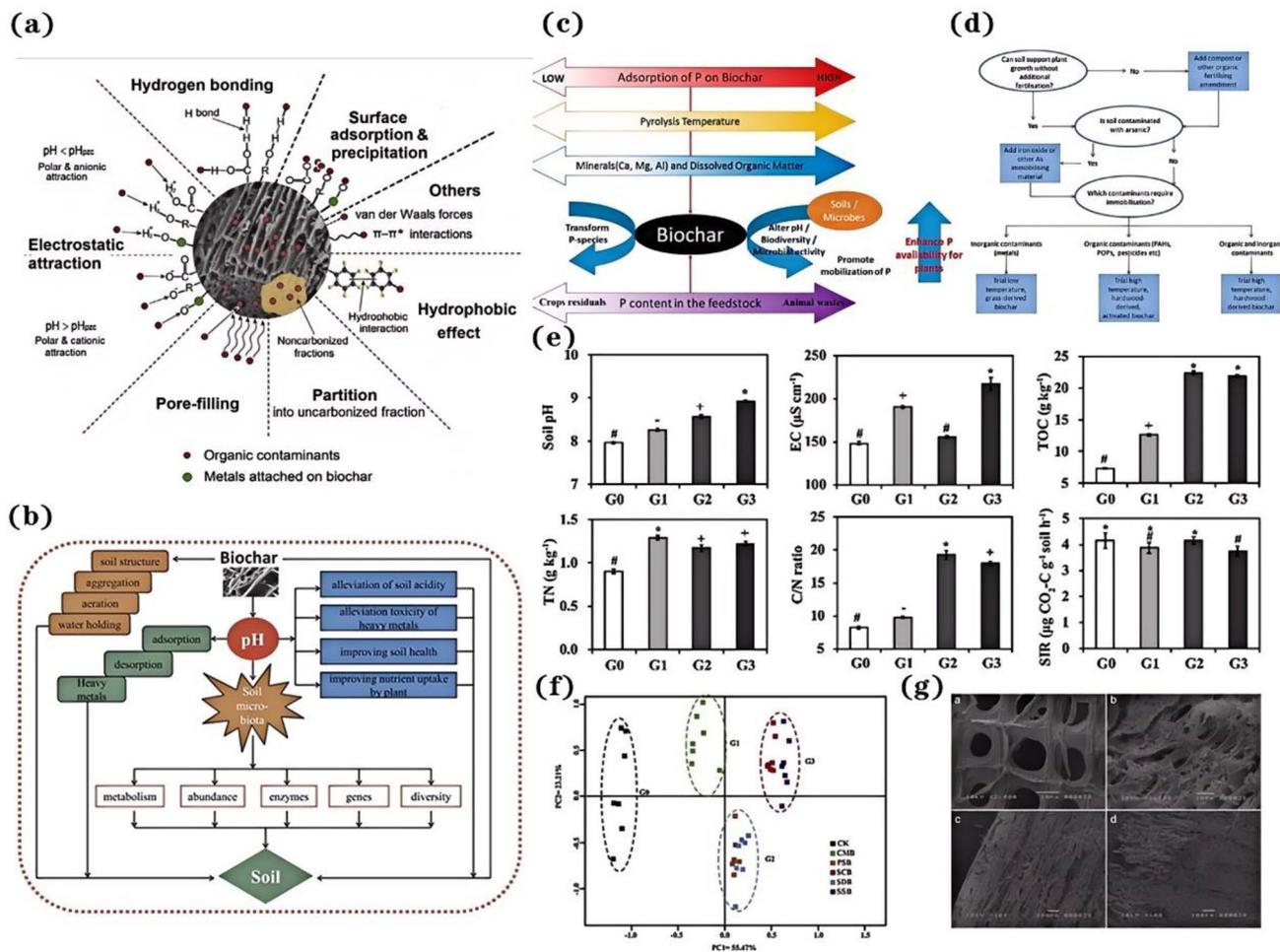


Fig. 6 Physical and chemical properties and positive effects of biochar in soil degradation. **a** The main mechanism of biochar stabilization of organic pollutants in soil (Guo et al. 2020) Copyright 2020, Frontiers. **b** An overview of the mechanism of biochar effects on soil properties (Shaaban et al. 2018) Copyright 2018, Elsevier. **c** The role of biochar in the phosphorus cycle. **d** Simplified diagrams of various biochar types can be tested on contaminated soil (Shaaban et al. 2018) Copyright 2018, Elsevier. **e** Soil pH, biochar free (EC), total

organic carbon (TOC), G2 (PSB MB) and G3 (SCB and SSB) Soil, electrical conductivity (EC), total nitrogen, C/N ratio and substrate induced respiration (SIR) (Yue et al. 2019) Copyright 2019, Elsevier. **f** Principal Component Analysis (PCA) of Soil Biochar for Improving Soil Properties (Yue et al. 2019) Copyright 2019, Elsevier. **g** Internal structure diagram of biochar induced degradation of piebald fungi at 300–400 °C (Ascough et al. 2010) Copyright 2010, Taylor & Francis

Removal of antibiotics from soil

The contamination of antibiotics in soil is widespread, exerting adverse effects on soil microbial communities and ecological balance (Fan et al. 2022). Recent studies demonstrate that biochar–microbe systems achieve remarkable antibiotic removal efficiencies through synergistic mechanisms. Reported that modified ball-milled wheat straw biochar enhanced tetracycline degradation from 42.1 to 78.6% within 30 days, attributed to its 29.1-fold increased surface area promoting microbial colonization and enzymatic activity. This performance was further validated in field trials where biochar amendment reduced chlortetracycline residues by 63–71% in agricultural soils through combined adsorption

and biotransformation pathways (Huang et al. 2020a, b). Observed 84.3% sulfamethoxazole removal efficiency using reed-derived biochar (500 °C pyrolysis) in contaminated paddy soils, The system maintained > 75% removal efficiency across three successive crop cycles, demonstrating remarkable stability (Wei et al. 2024). Comparatively, demonstrated 92.4% ciprofloxacin elimination in livestock manure-amended soils through Fe–Mn modified biochar application (Gross et al. 2024), where biochar's redox-active surfaces facilitated microbial extracellular electron transfer (Fig. 6).

In the study conducted by Wu et al., (2023), the application of biochar derived from reed biomass facilitated the turnover of soil nutrients, leading to a reinforcement of

the bacterial network in the treated soil. The research indicated that the addition of reed biochar resulted in respective increases of 7.42%, 14.09%, and 4.94% in soil moisture content. Furthermore, in the nitrogen (N) cycle, biochar treatment significantly enhanced the abundance of *nifH* (65.33%) and *nirK* (90.03%) ($P < 0.05$) (Liu et al. 2020a, b, c). This has resulted in a significantly uniform dispersion of bacterial communities, enhancing bacterial stability. This phenomenon arises from the crucial role of soil moisture content as a key driving factor for bacterial abundance, diversity, and activity. Moreover, the reed biochar prepared exhibits elevated porosity and surface area, thereby providing more habitat space and nutrients for microorganisms in the soil, consequently promoting microbial growth and reproduction (Yue et al. 2019). The reed was thoroughly ground and sieved (100-mesh sieve, pore size of 0.15 mm) after being dried at 105 °C for 12 h. The heating rate was controlled at 10 °C/min, and when the temperature reached 300 °C, the reed biochar was maintained for 2 h. In the soil environment, the application of reed biochar (T60) significantly elevated the abundance of early-stage *nifH* (65.33%) and *nirK* (90.03%) ($P < 0.05$), concurrently exhibiting a moderate increase in the copy number of ammonia-oxidizing bacteria *amoA* (26.90%) within the same time frame (Wu et al. 2023). Peanut shell biochar was prepared by slow pyrolysis of peanut shell waste in an oxygen-limited atmosphere, with a heating rate of 4 °C/min and a heating time of approximately 120 min at a temperature of 500 °C. The application of peanut shell biochar at rates of 1% and 3% significantly increased the abundance of Gram-negative bacteria and fungi in rice soil (Dominchin et al. 2021). On the other hand, the utilization of modified ball-milled biochar derived from wheat straw demonstrated a significant impact on the species richness and diversity of microorganisms in the soil, thereby enhancing the degradation of tetracycline in the soil upon the addition of biochar (Sun et al. 2022). The research findings indicate that the modified ball-milled biochar exhibited an increase in specific surface area ranging from 1.4 to 29.1 times. The addition of modified ball-milled biochar resulted in an augmentation of the adsorption capacity for volatile organic compounds by 1.3–13.0 times, with a maximum adsorption capacity for acetone reaching 103.4 mg g⁻¹. The alteration of soil microbial community structure and the subsequent degradation of antibiotics were attributed to mechanisms involving surface adsorption, π – π interactions, hydrophobic interactions, and hydrogen bonding facilitated by the biochar (Xiang et al. 2020).

Although the mechanisms underlying the impact of the interaction between biochar and microorganisms on the degradation of antibiotics in soil are not yet fully understood, some studies suggest several possible mechanisms for the degradation of antibiotics through the biochar–microorganism interaction in soil (Cui et al. 2021). Among these, (I)

biochar, through the adsorption of nutrients and ions on the soil surface, can provide essential elements for soil microorganisms (Lopez Penalver et al. 2013); (II) biochar alters crucial properties of the soil microbiota, such as moisture content, pH, and oxygen conditions, thereby affecting the microbial habitat (Daghrir and Drogui 2013); (III) the addition of biochar results in changes in enzyme activity, accelerating the cycling of certain elements in the soil (Lehmann et al. 2011); (IV) the binding of biochar with microorganisms enhances the adsorption and degradation of pollutants in the soil (Cross and Sohi 2013); (V) biochar contains signaling molecules that facilitate communication with microorganisms, achieved through the binding of molecules in adsorption and hydrolysis reactions (Motasemi and Afzal 2013). Hence, it can be inferred that the microbial–biochar combination plays a positive role in the degradation of pollutants in the soil.

The application of regulated biochar and microorganisms in soil for antibiotic degradation demonstrates promising prospects for environmental remediation. Biochar has the capacity to enhance soil structure, increase soil fertility, and improve water and nutrient retention, thereby promoting microbial growth and reproduction. Microorganisms, in turn, can mitigate the residue and diffusion of antibiotics in soil through mechanisms such as surface adsorption, π – π interactions, hydrophobic interactions, and hydrogen bonding. However, when utilizing the combination of biochar and microorganisms for soil remediation, attention must be given to potential toxicity issues. Freshly prepared biochar may contain elevated levels of pyrolysis by-products, which could impact soil quality. Therefore, in future research, the selection of biochar should prioritize pollution and toxicity removal over cost considerations. Only through such remediation approaches can an efficient soil restoration system be established, playing a crucial role in addressing antibiotic pollution in the future.

Removal of antibiotics from water

Emerging biochar–microbe hybrid systems demonstrate exceptional antibiotic removal capabilities in real wastewater matrices through synergistic adsorption–biodegradation mechanisms (Hung et al. 2022; Salam et al. 2023). Recent pilot-scale implementations reveal 92.4 ± 3.1% sulfamethoxazole removal in hospital wastewater using magnetic biochar–*Pseudomonas* consortia biofilms, outperforming conventional activated sludge systems (68.2 ± 5.7%) through enhanced electron transfer mediated by quinone groups (Chen et al. 2023a, b). Full-scale applications in pharmaceutical park wastewater treatment achieved 85–89% fluoroquinolone elimination through daily biochar supplementation to sequencing batch reactors, maintaining stable performance over 180-day operation (Zhang et al. 2023a, b, c, d). Critical

antibiotic class-specific adsorption efficiencies emerge from comparative studies (Table 7).

Research indicates that utilizing ball-milled biochar for the degradation of antibiotics in water yields a satisfactory removal efficiency. By employing raw materials extracted from sugarcane bagasse, bamboo, and walnut shells and subjecting them to ball milling at a temperature of 450 °C, ball-milled biochar exhibits removal rates of 83.3% for sulfonamide antibiotics and 89.6% for sulfapyridine in water. Similarly, when ball-milled biochar prepared at 450 °C is tested in real wastewater solutions, the maximum adsorption capacities for sulfonamide antibiotics and sulfapyridine in actual wastewater are 25.7 mg g⁻¹ and 58.6 mg g⁻¹, respectively (Huang et al. 2020a, b). This is attributed to the generation of a series of functional groups through ball-milling, resulting in the adsorption of sulfonamide substances on biochar. This adsorption is influenced by various mechanisms, including hydrophobic interactions, π - π interactions, hydrogen bonding, electrostatic interactions, and pH effects (Zheng et al. 2013). Especially noteworthy is the indication that, following ball-milling, the specific surface area and functional groups of biochar may increase, thereby enhancing the removal efficiency in aquatic environments (Xiaofei Tan et al. 2015). In the immobilization technique of biochar-fixed microorganisms, biochar prepared from *Forsythia suspensa* and *Lonicera japonica* as pyrolysis feedstock, with a temperature controlled at 500 °C, heating rate of 10 °C/min, and a residence time of 1 h, was utilized as the carrier to immobilize *Bacillus subtilis*. When the inoculum size was 10%, the dosage was 0.5 g, the particle size of the biochar was 0.097–0.15 mm, and the immobilization time was 36 h, the removal efficiency of tetracycline in water was 82.34%. The composite formed after immobilization exhibited an enhancement of 3.29–27.48% compared to individual bacterial colonies and an increase of 8.76–25.16% compared to a single biochar (Sinan Zhang and Wang 2021). In other words, regulating the interaction between biochar and microorganisms proves advantageous for the removal of antibiotics in water. Additionally, the biochar–biofilm reactor technology demonstrates commendable degradation efficiency in the removal of antibiotics from aquatic systems (Gutiérrez et al. 2021). It is achieved through the biofilm adsorption and immobilization of microbial communities, resulting

in the formation of a biochar–microorganism association. This process harnesses the adsorption capacity of biochar, coupled with the chemical reactions arising from the redox reactions initiated by the immobilized microbial community, to effectively remove and degrade organic compounds, nutrient elements, and other pollutants in wastewater (Xia et al. 2022). Hence, through the biochar–biofilm reactor technology, agricultural waste, wood, and other resources can be utilized for the preparation of biochar. In the preparation process, various microbial strains such as nitrifying bacteria and denitrifying bacteria can be introduced to facilitate the biochar–microorganism association. This promotes the formation and growth of biochar while providing a conducive environment for microbial survival. Consequently, this approach is more favorable for the removal of antibiotics from water (Xi Chen et al. 2023a, b).

From this, it is evident that techniques such as biochar adsorption, the synergistic action of biochar–microbe composites, and biochar–biofilm reactors enhance the activity and survival efficiency of microorganisms. The heightened microbial activity, supported by the energy generated through aerobic respiration, facilitates their growth and metabolism. This results in the formation of a microbial community capable of exchanging ions with the medium, thereby achieving degradation effects. Simultaneously, enzymes, acting as catalysts during the microbial degradation process, react with the water source, decomposing antibiotics, and ultimately forming water and carbon dioxide. Such technologies not only contribute to an enhanced degradation efficiency to a certain extent but also facilitate the circular utilization of resources, demonstrating strong sustainability.

Removal in other environments

While its application in aquatic and soil environments has been expounded upon in preceding sections, it is significant to note that the potential utilization of biochar in conjunction with microorganisms for the removal of residual antibiotics in other environments also holds considerable relevance.

The study demonstrates a significant reduction in total methane emissions when treated with corn stalk biochar, bamboo biochar, woody biochar, and coconut shell biochar,

Table 7 Performance comparison of biochar–microbe systems for major antibiotic classes

Antibiotic Class	Biochar Type	Surface Area (m ² /g)	Max Adsorption (mg/g)	Hybrid System Efficiency	Reference
Sulfonamides	Fe ₃ O ₄ @Woodchip BC	527	148.3 (SMX)	92.4% (HRT = 8 h)	Chen et al. (2023a, b)
Tetracyclines	KOH-activated BC	1315	337.6 (TC)	88.7% (pH = 7)	Khan et al. (2022)
Fluoroquinolones	Algae-derived BC	842	215.4 (CIP)	84.2% (30°C)	Li et al. (2023a, b)
Macrolides	N-doped Sludge BC	673	76.8 (ERY)	67.3% (DO = 2 mg/L)	Li et al. (2023a, b)

resulting in decreases of $26.1 \pm 2.3\%$, $15.5 \pm 2.1\%$, $22.4 \pm 3.1\%$, and $17.1 \pm 2.1\%$, respectively. Specifically, the addition of corn stalk biochar leads to a reduction in total volatilization of ammonia and methane by 21.5–38.5% and 6.1–22.2%, respectively (Chen et al. 2017). This indicates that biochar prepared from corn stalks possesses a higher specific surface area, pore volume, total acidic functional groups, and cation exchange capacity (CEC). It exhibits adsorption capabilities for gases, thereby mitigating the emissions of methane and the volatilization of ammonia in the air. In a study investigating the maturity and gas emissions during composting using corn stalk biochar and pig manure biochar, both types of biochar reduced total greenhouse gas emissions. Methane emissions increased by 28.6–71.5%, while nitrous oxide (N₂O) emissions decreased by 13.3%. Additionally, both biochar additives resulted in a reduction of 18.6–44.2% in dimethyl sulfide (Me₂S) emissions (Liu et al. 2023a, b, c, d). Therefore, corn stalk biochar and pig manure biochar exhibit superior performance, enabling the synergistic reduction of greenhouse gas and odor emissions during the composting process. Microbial remediation in the air has also demonstrated feasibility. In this study accelerating the degradation of organic compounds, the addition of thermotolerant nitrifying bacterial agents resulted in a reduction of 32.2% and 34.6% in accumulated ammonia and nitrous oxide emissions, respectively. This clearly illustrates that inoculating thermotolerant nitrifying bacteria is beneficial for reducing nitrogen gas emissions and regulating bacterial communities (Zhao et al. 2023). In addition, for the remediation of polluted air, the use of aerobic and moderately temperature-tolerant bacteria can enhance degradation efficiency. This is because, under specific moderate temperature conditions, bacteria can associate with inorganic and organic compounds in the exhaust gases, providing essential nutrients for their survival and metabolism (Andriani et al. 2014). In this process, bacterial degradation involves utilizing metabolic pathways to break down pollutants in the air, ultimately forming water and carbon dioxide (Sanchez-Monedero et al. 2018). Therefore, biochar can adsorb antibiotic molecules from the air, immobilizing them on its surface. Subsequently, the introduction of suitable microbial communities allows them to grow and proliferate on the surface of biochar, utilizing their metabolic pathways to degrade antibiotic molecules in the air (Van den Berg et al. 2008). The advantage of this method lies in the effective removal of antibiotic molecules from the air through biochar adsorption, while the microbial communities employ their metabolic pathways to transform antibiotic molecules into biodegradable compounds, thereby reducing their impact on the environment and ecosystems (Behera and Prasad 2020). It is noteworthy that the amalgamation of biochar with microbial colonies for the purpose of antibiotic molecular eradication within various environments is indeed a process of complexity, necessitating the nuanced tuning of biochar in tandem with the

cultivation of select microbial colonies congruous for achieving optimal removal efficiency.

Given the immature technology concerning the synergistic use of biochar and microorganisms for antibiotic removal in other environments, it necessitates further exploration into their environmental impact. Despite the potential beneficial implications of this union, consideration must also be given to any inhibitory effects that may arise. Moreover, extensive research into a wider range of antibiotics is prerequisite to the strategic enhancement of microbial remediation capabilities through more effective biochar regulation. By comprehending the application and regulatory mechanisms, a more holistic understanding of the interplay between biochar and microorganisms can be garnered, paving the way for innovative avenues and strategies in environmental management.

Comparative analysis of biochar–microbial systems and other remediation technologies

Biochar–microbial systems offer distinct advantages over conventional remediation technologies, though their suitability depends on context-specific factors. Compared to chemical oxidation, which achieves rapid antibiotic degradation but generates toxic byproducts and requires high energy input, biochar–microbe systems operate under ambient conditions, minimize secondary pollution, and leverage natural biodegradation pathways (Chen et al. 2021). However, they may exhibit slower kinetics for high-concentration contaminants. In contrast to phytoremediation, which relies on plant uptake and rhizosphere interactions but struggles with deep soil contamination and long remediation cycles, biochar–microbial systems provide targeted adsorption and microbial immobilization, enabling efficient antibiotic removal in both surface and sub-surface environments (Gupta et al. 2022). Unlike traditional bioremediation, which often fails under antibiotic stress due to microbial inhibition, biochar enhances microbial resilience via nutrient provision and habitat stabilization. For instance, biochar-amended systems achieve 70–90% sulfonamide removal in 48 h, outperforming unamended microbial consortia (40–60%) and matching advanced oxidation processes (85–95%) while avoiding chemical residuals (Xi Chen et al. 2023a, b). Nevertheless, challenges such as biochar production costs, variability in feedstock performance, and long-term stability in complex matrices must be weighed against the scalability and cost-effectiveness of alternatives like constructed wetlands or adsorption resins.

Conclusion

This investigation revisits the enhancement of biochar as a biomaterial scaffold, leveraging its physicochemical properties and exceptional biocompatibility to support microbial

proliferation, while targeting biochar modulation to augment microbial applications within environmental contexts. It delves into the intricacies of the interactive mechanisms between the two, harnessing biochar's capacity to amplify microbial potency in the eradication of antibiotics from the environment, thereby underscoring the pivotal role of biochar regulation in optimizing microbial efficacy.

Future perspectives

While biochar-enhanced bioremediation shows potential, four critical constraints require scrutiny. System efficacy hinges on biochar characteristics (feedstock type, pyrolysis parameters), causing performance variability across environments. Biochar sourced from metal-contaminated biomass risks introducing toxic elements, potentially causing secondary pollution. Long-term biochar stability remains questionable—aging via oxidation or fragmentation may degrade adsorption capacity and re-release immobilized antibiotics/byproducts. Excessive nutrient affinity (N/P) could disrupt microbial metabolism, potentially suppressing non-target microbiota while enhancing antibiotic resistance gene dissemination through horizontal transfer. Scalability faces energy-economic paradoxes: high-temperature pyrolysis and chemical modifications demand intensive energy inputs, compromising cost-efficiency for field applications. Mitigation requires standardized biochar characterization protocols, comprehensive life-cycle analysis, and longitudinal ecological impact assessments.

To advance biochar–microbe systems for antibiotic remediation, focus on microalgae-derived biochar and nitrogen-doped magnetic variants exhibiting enhanced π – π EDA interactions, particularly through surface functionality and hierarchical porosity. Optimal preparation requires pyrolysis at 300–500 °C using steam-exploded straw or municipal sludge precursors that enhance bacterial chemotaxis. Targeted chemical modifications should engineer macropore–mesopore networks and $\text{Fe}^{3+}/\text{Fe}^{2+}$ redox couples, as demonstrated by Fe-modified biochar achieving 74.1% bisphenol A mineralization efficiency via Fenton-like activation of laccase. Operational parameters necessitate pH 6.5–7.8 optimization and $\text{Ca}^{2+}/\text{Mg}^{2+}$ co-ion critical controls to regulate hydrophobic partitioning. Next-phase research must develop convolutional neural networks predicting ARG suppression pathways while implementing field-scale biochar-ozonation hybrids with metagenomics-proteomics integration for mechanistic validation.

Acknowledgements The authors gratefully acknowledge the National Natural Science Foundation of China (No. 51808215, 41877491). Hunan provincial special project for the construction of National Innovation Demonstration Zone of Chenzhou (2022sfq41). Innovation platform and talent plan of Hunan Province (2020RC2056), the Science

and Technology Achievement Transformation and Industrialization Plan of Hunan Province (2020NK2001).

Author contributions Jinli Wang: Conceptualization, Investigation, Data curation, Writing—Original Draft. Xueying Li: Writing—Review and Editing. Minghan Li: Data curation. Haibo Sun: Writing—Review and Editing. Yang Yang: Conceptualization. Jingyi Hou: Writing—Review and Editing. Yunshan Liang: Conceptualization, Supervision, Supervision. Pufeng Qin: Conceptualization, Supervision, Supervision. Yuan Yang: Conceptualization. Zhibin Wu: Conceptualization, Writing—Review and Editing, Supervision, Validation, Project administration.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

References

- Ahmed MB, Zhou JL, Ngo HH, Guo W, Johir MAH, Sornalingam K (2017) Single and competitive sorption properties and mechanism of functionalized biochar for removing sulfonamide antibiotics from water. *Chem Eng J* 311:348–358. <https://doi.org/10.1016/j.cej.2016.11.106>
- Ahumada-Rudolph R, Novoa V, Sáez K, Martínez M, Rudolph A, Torres-Diaz C, Becerra J (2016) Marine fungi isolated from Chilean fjord sediments can degrade oxytetracycline. *Environ Monit Assess* 188:1–10. <https://doi.org/10.1007/s10661-016-5475-0>
- Ali A, Wu Z, Li M, Su J (2021) Carbon to nitrogen ratios influence the removal performance of calcium, fluoride, and nitrate by *Acinetobacter* H12 in a quartz sand-filled biofilm reactor. *Bioresour Technol* 333:125154. <https://doi.org/10.1016/j.biortech.2021.125154>
- 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(1):25–34. <https://doi.org/10.1016/j.jssas.2022.05.005>
- Amoakwah E, Arthur E, Frimpong KA, Lorenz N, Rahman MA, Nziguheba G, Islam KR (2022) Biochar amendment impacts on microbial community structures and biological and enzyme activities in a weathered tropical sandy loam. *Appl Soil Ecol* 172:104364. <https://doi.org/10.1016/j.apsoil.2021.104364>
- An Q, Ran B, Deng S, Jin N, Zhao B, Song J, Fu S (2023) Peanut shell biochar immobilized *Pseudomonas hibiscicola* strain L1 to remove electroplating mixed-wastewater. *J Environ Chem Eng* 11(2):109411. <https://doi.org/10.1016/j.jece.2023.109411>
- Andriani D, Wresta A, Atmaja TD, Saepudin A (2014) A review on optimization production and upgrading biogas through CO₂ removal using various techniques. *Appl Biochem Biotechnol* 172:1909–1928. <https://doi.org/10.1007/s12010-013-0652-x>
- Ascough PL, Sturrock CJ, Bird MI (2010) Investigation of growth responses in saprophytic fungi to charred biomass. *Isot Environ Health Stud* 46(1):64–77. <https://doi.org/10.1080/10256010903388436>
- Aydin S (2016) Enhanced biodegradation of antibiotic combinations via the sequential treatment of the sludge resulting from pharmaceutical wastewater treatment using white-rot fungi *Trametes versicolor* and *Bjerkandera adusta*. *Appl Microbiol Biotechnol* 100:6491–6499. <https://doi.org/10.1007/s00253-016-7473-0>

- Behera B, Prasad R (2020) Air pollution and controlling measures. *Environ Technol Sustain*. <https://doi.org/10.1038/scientificamerican0588-42>
- Bocşa M, Pinteş S, Lung I, Opreş O, Stegarescu A, Humayun M, Bellucci S (2023) Biochar-based adsorbents for pesticides, drugs, phosphorus, and heavy metal removal from polluted water. *Separations* 10(10):533. <https://doi.org/10.3390/separations10100533>
- Borges FC, Du Z, Xie Q, Trierweiler JO, Cheng Y, Wan Y, Chen P (2014) Fast microwave assisted pyrolysis of biomass using microwave absorbent. *Biores Technol* 156:267–274. <https://doi.org/10.1016/j.biortech.2014.01.038>
- Bowles TM, Acosta-Martínez V, Calderón F, Jackson LE (2014) Soil enzyme activities, microbial communities, and carbon and nitrogen availability in organic agroecosystems across an intensively-managed agricultural landscape. *Soil Biol Biochem* 68:252–262. <https://doi.org/10.1016/j.soilbio.2013.10.004>
- Chauhan S, Shafi T, Dubey BK, Chowdhury S (2023) Biochar-mediated removal of pharmaceutical compounds from aqueous matrices via adsorption. *Waste Dispos Sustain Energy* 5(1):37–62. <https://doi.org/10.1007/s42768-022-00118-y>
- Chen L, Wang M, Sun Q, Zhao Z, Han J, Ji R, Cheng H (2024) A three-step process to produce biochar with good magnetism, high specific surface area, and high levels of nitrogen doping for the efficient removal of sulfamethoxazole. *Sep Purif Technol* 333:125940. <https://doi.org/10.1016/j.seppur.2023.125940>
- Chen W, Liao X, Wu Y, Liang JB, Mi J, Huang J, Li X (2017) Effects of different types of biochar on methane and ammonia mitigation during layer manure composting. *Waste Manag* 61:506–515. <https://doi.org/10.1016/j.wasman.2017.01.014>
- Chen X, Ke Y, Zhu Y, Xu M, Chen C, Xie S (2023a) Enrichment of tetracycline-degrading bacterial consortia: microbial community succession and degradation characteristics and mechanism. *J Hazard Mater* 448:130984. <https://doi.org/10.1016/j.jhazmat.2023.130984>
- Chen X, Lin H, Dong Y, Li B, Liu C, Yin T (2022) Mechanisms underlying enhanced bioremediation of sulfamethoxazole and zinc (II) by *Bacillus* sp. SDB4 immobilized on biochar. *J Clean Prod* 370:133483. <https://doi.org/10.1016/j.jclepro.2022.133483>
- Chen X, Lin H, Dong Y, Li B, Liu C, Zhang L, Jin Q (2023b) Enhanced simultaneous removal of sulfamethoxazole and zinc (II) in the biochar-immobilized bioreactor: performance, microbial structures and gene functions. *Chemosphere* 338:139466. <https://doi.org/10.1016/j.chemosphere.2023.139466>
- Chen Y-D, Duan X, Zhou X, Wang R, Wang S, Ren N-Q, Ho S-H (2021) Advanced oxidation processes for water disinfection: features, mechanisms and prospects. *Chem Eng J* 409:128207. <https://doi.org/10.1016/j.cej.2020.128207>
- Cheng D, Ngo HH, Guo W, Chang SW, Nguyen DD, Li J, Nguyen TAH (2020) Applying a new pomelo peel derived biochar in microbial cell for enhancing sulfonamide antibiotics removal in swine wastewater. *Bioresour Technol* 318:123886. <https://doi.org/10.1016/j.biortech.2020.123886>
- Cho S-H, Jung S, Park J, Lee S, Kim Y, Lee J, Kwon EE (2023) Strategic use of crop residue biochars for removal of hazardous compounds in wastewater. *Bioresour Technol*. <https://doi.org/10.1016/j.biortech.2023.129658>
- Chu Z, Zheng B, Wang W, Li Y, Yang Y, Yang Z (2022) Magnetic nitrogen-doped biochar for adsorptive and oxidative removal of antibiotics in aqueous solutions. *Sep Purif Technol* 297:121508. <https://doi.org/10.1016/j.seppur.2022.121508>
- Cooperband LR (2000) Composting: art and science of organic waste conversion to a valuable soil resource. *Lab Med* 31(5):283–290. <https://doi.org/10.1309/W286-LQF1-R2M2-1WNT>
- Copete-Pertuz LS, Plácido J, Serna-Galvis EA, Torres-Palma RA, Mora A (2018) Elimination of isoxazolyl-penicillins antibiotics in waters by the ligninolytic native Colombian strain *Leptosphaerulina* sp. considerations on biodegradation process and antimicrobial activity removal. *Sci Total Environ* 630:1195–1204. <https://doi.org/10.1016/j.scitotenv.2018.02.244>
- Cross A, Sohi SP (2013) A method for screening the relative long-term stability of biochar. *Gcb Bioenergy* 5(2):215–220. <https://doi.org/10.1111/gcbb.12035>
- Cui Q, Xia J, Yang H, Liu J, Shao P (2021) Biochar and effective microorganisms promote *Sesbania cannabina* growth and soil quality in the coastal saline-alkali soil of the Yellow River Delta, China. *Sci Total Environ* 756:143801. <https://doi.org/10.1016/j.scitotenv.2020.143801>
- Cui X, Lu M, Khan MB, Lai C, Yang X, He Z, Yan B (2020) Hydrothermal carbonization of different wetland biomass wastes: phosphorus reclamation and hydrochar production. *Waste Manag* 102:106–113. <https://doi.org/10.1016/j.wasman.2019.10.034>
- Cuong DV, Hou C-H (2024) Enhancing phosphorus removal through layered double hydroxide-decorated biochars: Unveiling pore structure and surface functionalization. *J Taiwan Inst Chem Eng* 155:105273. <https://doi.org/10.1016/j.jtice.2023.105273>
- Daghrir R, Drogui P (2013) Tetracycline antibiotics in the environment: a review. *Environ Chem Lett* 11:209–227. <https://doi.org/10.1007/s10311-013-0404-8>
- Dai C, Zhang JB, Gao M-T, Zhang Y, Li J, Hu J (2023) Effects of functional group loss on biochar activated persulfate in-situ remediation of phenol pollution in groundwater and its countermeasures. *J Environ Manage* 341:118076. <https://doi.org/10.1016/j.jenvman.2023.118076>
- Dominchin MF, Verdenelli RA, Berger MG, Aoki A, Meriles JM (2021) Impact of N-fertilization and peanut shell biochar on soil microbial community structure and enzyme activities in a Typic Haplustoll under different management practices. *Eur J Soil Biol* 104:103298. <https://doi.org/10.1016/j.ejsobi.2021.103298>
- Dou S, Ke X-X, Shao Z-D, Zhong L-B, Zhao Q-B, Zheng Y-M (2022) Fish scale-based biochar with defined pore size and ultrahigh specific surface area for highly efficient adsorption of ciprofloxacin. *Chemosphere* 287:131962. <https://doi.org/10.1016/j.chemosphere.2021.131962>
- Duan M, Li Z, Yan R, Zhou B, Su L, Li M, Zhang Z (2023) Mechanism for combined application of biochar and *Bacillus cereus* to reduce antibiotic resistance genes in copper contaminated soil and lettuce. *Sci Total Environ* 884:163422. <https://doi.org/10.1016/j.scitotenv.2023.163422>
- Esfandiari N, Suri R, McKenzie ER (2022) Competitive sorption of Cd, Cr, Cu, Ni, Pb and Zn from stormwater runoff by five low-cost sorbents; effects of co-contaminants, humic acid, salinity and pH. *J Hazard Mater* 423:126938. <https://doi.org/10.1016/j.jhazmat.2021.126938>
- Estévez S, de Boer S, Feijoo G, Moreira MT (2024) Environmental perspective of an enzyme-based system for the removal of antibiotics present in wastewater. *Clean Environ Syst* 12:100171. <https://doi.org/10.1016/j.cesys.2024.100171>
- Fan J, Liu C, Guo D, Han L, Zhang C, Jin H (2022) Biochar and biochar-poly(lactic acid) composite enhance biodegradation of hexachlorobenzene in soil by altering microbial community. *Appl Soil Ecol* 177:104521. <https://doi.org/10.1016/j.apsoil.2022.104521>
- Fan X, Zhang W, Liu Y, Shi S, Cui Y, Zhao Z, Hou J (2023a) Hydrothermal synthesis of sewage sludge biochar for activation of persulfate for antibiotic removal: efficiency, stability and mechanism. *Environ Res* 218:114937. <https://doi.org/10.1016/j.envres.2022.114937>
- Fan Y, Su J, Wang Z, Liu S, Li X, Hou C (2023b) Improvement of the specific surface area of biochar by calcium-precipitated nanoparticles synthesized by microbial induction as a template skeleton: removal mechanism of tetracycline in water. *J Environ Manage* 348:119279. <https://doi.org/10.1016/j.jenvman.2023.119279>

- Fang H, Oberoi AS, He Z, Khanal SK, Lu H (2021) Ciprofloxacin-degrading *Paraclostridium* sp. isolated from sulfate-reducing bacteria-enriched sludge: optimization and mechanism. *Water Res* 191:116808. <https://doi.org/10.1016/j.watres.2021.116808>
- Fox A, Kwapinski W, Griffiths BS, Schmalenberger A (2014) The role of sulfur- and phosphorus-mobilizing bacteria in biochar-induced growth promotion of *Lolium perenne*. *FEMS Microbiol Ecol* 90(1):78–91. <https://doi.org/10.1111/1574-6941.12374>
- Ghosh S, Sadowsky M, Roberts M, Gralnick J, LaPara T (2009) *Sphingobacterium* sp. strain PM2-P1-29 harbours a functional tet (X) gene encoding for the degradation of tetracycline. *J Appl Microbiol* 106(4):1336–1342. <https://doi.org/10.1111/j.1365-2672.2008.04101.x>
- Gross A, Bromm T, Polifka S, Fischer D, Glaser B (2024) Long-term biochar and soil organic carbon stability—evidence from field experiments in Germany. *Sci Total Environ* 954:176340. <https://doi.org/10.1016/j.scitotenv.2024.176340>
- Gupta A, Bhatt Y, Rais N, Nagella P, Vasantha V (2022) Bioremediation of antibiotics as a pollutant in soil. In: *Microbial and biotechnological interventions in bioremediation and phytoremediation*, pp 375–403
- Gutiérrez M, Grillini V, Pavlović DM, Verlicchi P (2021) Activated carbon coupled with advanced biological wastewater treatment: a review of the enhancement in micropollutant removal. *Sci Total Environ* 790:148050. <https://doi.org/10.1016/j.scitotenv.2021.148050>
- Haider FU, Coulter JA, Cheema SA, Farooq M, Wu J, Zhang R, Liqun C (2021) Co-application of biochar and microorganisms improves soybean performance and remediate cadmium-contaminated soil. *Ecotoxicol Environ Saf* 214:112112. <https://doi.org/10.1016/j.ecoenv.2021.112112>
- Han J, Zhang J, Meng J, Cai Y, Cheng M, Wu S, Li Z (2023) Characterization of modified rice straw biochar in immobilizing *Bacillus subtilis* 168 and evaluation on its role as a novel agent for zearalenone-removal delivery. *J Hazard Mater* 453:131424. <https://doi.org/10.1016/j.jhazmat.2023.131424>
- Harindintwali JD, Zhou J, Yang W, Gu Q, Yu X (2020) Biochar-bacteria-plant partnerships: eco-solutions for tackling heavy metal pollution. *Ecotoxicol Environ Saf* 204:111020. <https://doi.org/10.1016/j.ecoenv.2020.111020>
- He Y, Zhao X, Zhu S, Yuan L, Li X, Feng Z, Liu Y (2023a) Conversion of swine manure into biochar for soil amendment: efficacy and underlying mechanism of dissipating antibiotic resistance genes. *Sci Total Environ* 871:162046. <https://doi.org/10.1016/j.scitotenv.2023.162046>
- He Z, Hou R, Fu Q, Li T, Zhang S, Su A (2023b) Evolution mechanism of soil hydrothermal parameters under freeze–thaw cycles: regulatory significance of straw and biochar. *J Clean Prod* 385:135787. <https://doi.org/10.1016/j.jclepro.2022.135787>
- Heidari M, Dutta A, Acharya B, Mahmud S (2019) A review of the current knowledge and challenges of hydrothermal carbonization for biomass conversion. *J Energy Inst* 92(6):1779–1799. <https://doi.org/10.1016/j.joei.2018.12.003>
- Hou D, Cui X, Liu M, Qie H, Tang Y, Leng W, Yang W (2024) Degradation of trichloroethylene by biochar supported nano zero-valent iron (BC-nZVI): the role of specific surface area and electrochemical properties. *Sci Total Environ* 908:168341. <https://doi.org/10.1016/j.scitotenv.2023.168341>
- Hu W, Niu Y, Shen T, Dong K, Wang D (2024) Magnetic biochar prepared by a dry process for the removal of sulfonamides antibiotics from aqueous solution. *J Mol Liquids*. <https://doi.org/10.1039/D0RA07499C>
- Huang B, Jia H, Han X, Gou J, Huang C, Wang J, Zhang C (2021) Effects of biocontrol *Bacillus* and fermentation bacteria additions on the microbial community, functions and antibiotic resistance genes of prickly ash seed oil meal-biochar compost. *Bioresour Technol* 340:125668. <https://doi.org/10.1016/j.biortech.2021.125668>
- Huang F, Li K, Wu R-R, Yan Y-J, Xiao R-B (2020a) Insight into the Cd²⁺ biosorption by viable *Bacillus cereus* RC-1 immobilized on different biochars: roles of bacterial cell and biochar matrix. *J Clean Prod* 272:122743. <https://doi.org/10.1016/j.jclepro.2020.122743>
- Huang J, Zimmerman AR, Chen H, Gao B (2020b) Ball milled biochar effectively removes sulfamethoxazole and sulfapyridine antibiotics from water and wastewater. *Environ Pollut* 258:113809. <https://doi.org/10.1016/j.envpol.2019.113809>
- Hui Liang D, Hu Y (2019) Simultaneous sulfamethoxazole biodegradation and nitrogen conversion by *Achromobacter* sp. JL9 using with different carbon and nitrogen sources. *Bioresour Technol* 293:122061. <https://doi.org/10.1016/j.biortech.2019.122061>
- Hung C-M, Chen C-W, Huang C-P, Lam SS, Dong C-D (2022) Peroxy-monosulfate activation by a metal-free biochar for sulfonamide antibiotic removal in water and associated bacterial community composition. *Bioresour Technol* 343:126082. <https://doi.org/10.1016/j.biortech.2021.126082>
- Illingworth J, Williams PT, Rand B (2013) Characterisation of biochar porosity from pyrolysis of biomass flax fibre. *J Energy Inst* 86(2):63–70. <https://doi.org/10.1179/1743967112Z.0000000046>
- Issaka E, Fapohunda FO, Amu-Darko JNO, Yeboah L, Yakubu S, Varjani S, Bilal M (2022) Biochar-based composites for remediation of polluted wastewater and soil environments: challenges and prospects. *Chemosphere* 297:134163. <https://doi.org/10.1016/j.chemosphere.2022.134163>
- Itoh T, Fujiwara N, Iwabuchi K, Narita T, Mendbayar D, Kamide M, Matsumi Y (2020) Effects of pyrolysis temperature and feedstock type on particulate matter emission characteristics during biochar combustion. *Fuel Process Technol* 204:106408. <https://doi.org/10.1016/j.fuproc.2020.106408>
- Janu R, Mrlik V, Ribitsch D, Hofman J, Sedláček P, Bielská L, Soja G (2021) Biochar surface functional groups as affected by biomass feedstock, biochar composition and pyrolysis temperature. *Carbon Resources Convers* 4:36–46. <https://doi.org/10.1016/j.crcon.2021.01.003>
- Jia M, Wang F, Bian Y, Jin X, Song Y, Kengara FO, Jiang X (2013) Effects of pH and metal ions on oxytetracycline sorption to maize-straw-derived biochar. *Bioresour Technol* 136:87–93. <https://doi.org/10.1016/j.biortech.2013.02.098>
- Jia P, Wang X, Liu S, Hua Y, Zhou S, Jiang Z (2023) Combined use of biochar and microbial agent can promote lignocellulose degradation and humic acid formation during sewage sludge-reed straw composting. *Bioresour Technol* 370:128525. <https://doi.org/10.1016/j.biortech.2022.128525>
- Jia Y, Ou Y, Khanal SK, Sun L, Shu W-S, Lu H (2024) Biochar-based strategies for antibiotics removal: mechanisms, factors, and application. *ACS ES&T Eng* 4(6):1256–1274. <https://doi.org/10.1021/acsestengg.3c00605>
- Jiang B, Tian J, Chen H, Zheng H, Xu Z, Lin Y (2022) Heavy metals migration and antibiotics removal in anaerobic digestion of swine manure with biochar addition. *Environ Technol Innov* 27:102735. <https://doi.org/10.1016/j.eti.2022.102735>
- Jien S-H, Wang C-S (2013) Effects of biochar on soil properties and erosion potential in a highly weathered soil. *CATENA* 110:225–233. <https://doi.org/10.1016/j.catena.2013.06.021>
- Jin Y, Zhang B, Guo Z, Lin J, Chen G, Chen S, Su Y (2024) Biochar with improved performance prepared based on “micro-explosive reaction” conjecture for effective removal of antibiotics. *Fuel* 361:130733. <https://doi.org/10.1016/j.fuel.2023.130733>
- Kemmu L, Frontistis Z, Vakros J, Manariotis ID, Mantzavinos D (2018) Degradation of antibiotic sulfamethoxazole by biochar-activated persulfate: factors affecting the activation and

- degradation processes. *Catal Today* 313:128–133. <https://doi.org/10.1016/j.cattod.2017.12.028>
- Kim DG, Choi D, Cheon S, Ko S-O, Kang S, Oh S (2020) Addition of biochar into activated sludge improves removal of antibiotic ciprofloxacin. *J Water Process Eng* 33:101019. <https://doi.org/10.1016/j.jwpe.2019.101019>
- Klein EY, Van Boeckel TP, Martinez EM, Pant S, Gandra S, Levin SA, Laxminarayan R (2018) Global increase and geographic convergence in antibiotic consumption between 2000 and 2015. *Proc Natl Acad Sci U S A* 115(15):E3463–E3470. <https://doi.org/10.1073/pnas.1717295115>
- Kothamasi D, Kothamasi S, Bhattacharyya A, Kuhad RC, Babu C (2006) Arbuscular mycorrhizae and phosphate solubilising bacteria of the rhizosphere of the mangrove ecosystem of Great Nicobar island, India. *Biol Fertil Soils* 42:358–361. <https://doi.org/10.1007/s00374-005-0035-8>
- Krzyszczak A, Dybowski MP, Zarzycki R, Kobyłecki R, Oleszczuk P, Czech B (2022) Long-term physical and chemical aging of biochar affected the amount and bioavailability of PAHs and their derivatives. *J Hazard Mater* 440:129795. <https://doi.org/10.1016/j.jhazmat.2022.129795>
- Kümmerer K (2009) Antibiotics in the aquatic environment—a review—part II. *Chemosphere* 75(4):435–441. <https://doi.org/10.1016/j.chemosphere.2008.12.006>
- Larsson DJ, Flach C-F (2022) Antibiotic resistance in the environment. *Nat Rev Microbiol* 20(5):257–269. <https://doi.org/10.1038/s41579-021-00649-x>
- Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D (2011) Biochar effects on soil biota—a review. *Soil Biol Biochem* 43(9):1812–1836. <https://doi.org/10.1016/j.soilbio.2011.04.022>
- Li A, Ye C, Jiang Y, Deng H (2023a) Enhanced removal performance of magnesium-modified biochar for cadmium in wastewaters: role of active functional groups, processes, and mechanisms. *Bioresour Technol* 386:129515. <https://doi.org/10.1016/j.biortech.2023.129515>
- Li D, Ping Q, Guo W, Chen Y, Wang L, Li Y (2023b) Evaluating effects of biochar on anaerobic digestion of dewatered waste activated sludge: digester performance, microbial co-metabolism and underlying mechanism. *Chemosphere* 341:140139. <https://doi.org/10.1016/j.chemosphere.2023.140139>
- Li J, Jia Y, Zhong J, Liu Q, Li H, Agranovski I (2022a) Use of calcium alginate/biochar microsphere immobilized bacteria *Bacillus sp.* for removal of phenol in water. *Environ Challenges* 9:100599. <https://doi.org/10.1016/j.envc.2022.100599>
- Li M, Yin H, Zhu M, Yu Y, Lu G, Dang Z (2021) Co-metabolic and biochar-promoted biodegradation of mixed PAHs by highly efficient microbial consortium QY1. *J Environ Sci (China)* 107:65–76. <https://doi.org/10.1016/j.jes.2021.02.002>
- Li Y, Shang H, Cao Y, Yang C, Feng Y, Yu Y (2022b) Quantification of adsorption mechanisms distribution of sulfamethoxazole onto biochar by competition relationship in a wide pH range. *J Environ Chem Eng* 10(6):108755. <https://doi.org/10.1016/j.jece.2022.108755>
- Liang J, Tang S, Gong J, Zeng G, Tang W, Song B, Luo Y (2020) Responses of enzymatic activity and microbial communities to biochar/compost amendment in sulfamethoxazole polluted wetland soil. *J Hazard Mater* 385:121533. <https://doi.org/10.1016/j.jhazmat.2019.121533>
- Liao J, Hu A, Zhao Z, Liu X, Jiang C, Zhang Z (2021) Biochar with large specific surface area recruits N₂O-reducing microbes and mitigate N₂O emission. *Soil Biol Biochem* 156:108212. <https://doi.org/10.1016/j.soilbio.2021.108212>
- Liu C (2021) Antibiotic stewardship challenges in an evolving healthcare market in China. *Lancet Infect Dis* 21(6):753–754. [https://doi.org/10.1016/S1473-3099\(20\)30685-X](https://doi.org/10.1016/S1473-3099(20)30685-X)
- Liu C, Li H, Ni J-Q, Zhuo G, Chen W, Zheng Y, Zhen G (2023a) Effect of municipal sludge-based biochar produced at different pyrolysis temperatures on humification and oxytetracycline degradation of pig manure composting. *Sci Total Environ*. <https://doi.org/10.1016/j.scitotenv.2023.167816>
- Liu F, Liu H, Zhu H, Xie Y, Zhang D, Cheng Y, Yang S (2023b) Remediation of petroleum hydrocarbon-contaminated groundwater by biochar-based immobilized bacteria. *Biochem Eng J* 197:108987. <https://doi.org/10.1016/j.bej.2023.108987>
- Liu H-Y, Song C, Zhao S, Wang S-G (2020a) Biochar-induced migration of tetracycline and the alteration of microbial community in agricultural soils. *Sci Total Environ* 706:136086. <https://doi.org/10.1016/j.scitotenv.2019.136086>
- Liu H, Xu G, Li G (2020b) The characteristics of pharmaceutical sludge-derived biochar and its application for the adsorption of tetracycline. *Sci Total Environ* 747:141492. <https://doi.org/10.1016/j.scitotenv.2020.141492>
- Liu L, Yin Q, Hou Y, Ma R, Li Y, Wang Z, Wang H (2024) Fungus reduces tetracycline-resistant genes in manure treatment by predation of bacteria. *Sci Total Environ* 906:167462. <https://doi.org/10.1016/j.scitotenv.2023.167462>
- Liu N, Liao P, Zhang J, Zhou Y, Luo L, Huang H, Zhang L (2020c) Characteristics of denitrification genes and relevant enzyme activities in heavy-metal polluted soils remediated by biochar and compost. *Sci Total Environ* 739:139987. <https://doi.org/10.1016/j.scitotenv.2020.139987>
- Liu S, Yin M, Sun L, Jiao Y, Zheng Y, Yan L (2023c) Iron-loaded sludge biochar alleviates the inhibitory effect of tetracycline on anammox bacteria: performance and mechanism. *Chemosphere* 333:138987. <https://doi.org/10.1016/j.chemosphere.2023.138987>
- Liu Y, Ma R, Wang J, Wang G, Li G, Wuyun D, Yuan J (2023d) Effect of nano zero-valent iron, potassium persulphate, and biochar on maturity and gaseous emissions during multi-material co-composting. *Environ Technol Innov* 32:103309. <https://doi.org/10.1016/j.eti.2023.103309>
- Liu Z, Quek A, Hoekman SK, Balasubramanian R (2013) Production of solid biochar fuel from waste biomass by hydrothermal carbonization. *Fuel* 103:943–949. <https://doi.org/10.1016/j.fuel.2012.07.069>
- Lopez Penalver JJ, Gomez Pacheco CV, Sanchez Polo M, Rivera Utrilla J (2013) Degradation of tetracyclines in different water matrices by advanced oxidation/reduction processes based on gamma radiation. *J Chem Technol Biotechnol* 88(6):1096–1108. <https://doi.org/10.1002/jctb.3946>
- Ma D, Yang Y, Liu B, Xie G, Chen C, Ren N, Xing D (2021) Zero-valent iron and biochar composite with high specific surface area via K₂FeO₄ fabrication enhances sulfadiazine removal by persulfate activation. *Chem Eng J* 408:127992. <https://doi.org/10.1016/j.cej.2020.127992>
- Ma L, Li Z, Qiao M, Liu J, Jia B, Yang B, Liu Y (2023) Enhancing electrokinetic remediation of TPH-Cr (VI) co-contaminated soils with biochar-immobilized bacteria as biological permeable reactive barriers. *Chem Eng J* 478:147301. <https://doi.org/10.1016/j.cej.2023.147301>
- Massé DI, Cata Saady NM, Gilbert Y (2014) Potential of biological processes to eliminate antibiotics in livestock manure: an overview. *Animals* 4(2):146–163. <https://doi.org/10.3390/ani4020146>
- Mitchell CJ, Jayakaran AD, McIntyre JK (2023) Biochar and fungi as bioretention amendments for bacteria and PAH removal from stormwater. *J Environ Manage* 327:116915. <https://doi.org/10.1016/j.jenvman.2022.116915>
- Mong GR, Chong CT, Ng J-H, Chong WWF, Lam SS, Ong HC, Ani FN (2020) Microwave pyrolysis for valorisation of horse manure biowaste. *Energy Convers Manage* 220:113074. <https://doi.org/10.1016/j.enconman.2020.113074>

- Motasemi F, Afzal MT (2013) A review on the microwave-assisted pyrolysis technique. *Renew Sustain Energy Rev* 28:317–330. <https://doi.org/10.1016/j.rser.2013.08.008>
- Mukherjee A, Zimmerman A, Harris W (2011) Surface chemistry variations among a series of laboratory-produced biochars. *Geoderma* 163(3–4):247–255. <https://doi.org/10.1016/j.geoderma.2011.04.021>
- Mulla SI, Hu A, Sun Q, Li J, Suanon F, Ashfaq M, Yu C-P (2018) Biodegradation of sulfamethoxazole in bacteria from three different origins. *J Environ Manage* 206:93–102. <https://doi.org/10.1016/j.jenvman.2017.10.029>
- Muzyka R, Misztal E, Hrabak J, Banks SW, Sajdak M (2023) Various biomass pyrolysis conditions influence the porosity and pore size distribution of biochar. *Energy* 263:126128. <https://doi.org/10.1016/j.energy.2022.126128>
- Ni Z, Zhou L, Lin Z, Kuang B, Zhu G, Jia J, Wang T (2023) Iron-modified biochar boosts anaerobic digestion of sulfamethoxazole pharmaceutical wastewater: performance and microbial mechanism. *J Hazard Mater* 452:131314. <https://doi.org/10.1016/j.jhazmat.2023.131314>
- Nie Y, Zhao C, Zhou Z, Kong Y, Ma J (2023) Hydrochloric acid-modified fungi-microalgae biochar for adsorption of tetracycline hydrochloride: performance and mechanism. *Bioresour Technol* 383:129224. <https://doi.org/10.1016/j.biortech.2023.129224>
- Ok YS, Bhatnagar A, Hou D, Bhaskar T, Mašek O (2020) Advances in algal biochar: production, characterization and applications. *Biores Technol* 317:123982–123982. <https://doi.org/10.1016/j.biortech.2020.123982>
- Pandey AK, Gaur VK, Varjani S, Pandey A, Kumar S, Ngo HH, Wong JW (2023) Role of biochar in polyaromatic hydrocarbons remediation and environment management. In: *Current developments in biotechnology and bioengineering*, pp 365–385. <https://doi.org/10.1016/B978-0-323-91873-2.00004-2>
- Palansooriya KN, Wong JTF, Hashimoto Y, Huang L, Rinklebe J, Chang SX, Ok YS (2019) Response of microbial communities to biochar-amended soils: a critical review. *Biochar* 1:3–22. <https://doi.org/10.1007/s42773-019-00009-2>
- Pinheiro BB (2021) Immobilized laccase biocatalysts as a way to improve degradation of micropollutants from water. *J Environ Manage*. <https://doi.org/10.1016/j.jenvman.2024.120984>
- Qiu L, Li C, Zhang S, Wang S, Li B, Cui Z, Hu X (2024) Importance of oxygen-containing functionalities and pore structures of biochar in catalyzing pyrolysis of homologous poplar. *Chin J Chem Eng* 65:200–211. <https://doi.org/10.1016/j.cjche.2023.09.002>
- Qu J, Wang S, Jin L, Liu Y, Yin R, Jiang Z, Zhang Y (2021) Magnetic porous biochar with high specific surface area derived from microwave-assisted hydrothermal and pyrolysis treatments of water hyacinth for Cr (VI) and tetracycline adsorption from water. *Bioresour Technol* 340:125692. <https://doi.org/10.1016/j.biortech.2021.125692>
- Quilliam RS, Glanville HC, Wade SC, Jones DL (2013) Life in the ‘charosphere’—Does biochar in agricultural soil provide a significant habitat for microorganisms? *Soil Biol Biochem* 65:287–293. <https://doi.org/10.1016/j.soilbio.2013.06.004>
- Rodríguez-Vila A, Forján R, Guedes RS, Covelo EF (2016) Changes on the phytoavailability of nutrients in a mine soil reclaimed with compost and biochar. *Water Air Soil Pollut* 227:1–12. <https://doi.org/10.1007/s11270-016-3155-x>
- Saghir S, Pu C, Fu E, Wang Y, Xiao Z (2022) Synthesis of high surface area porous biochar obtained from pistachio shells for the efficient adsorption of organic dyes from polluted water. *Surf Interface Anal* 34:102357. <https://doi.org/10.1016/j.surfin.2022.102357>
- Sahoo SS, Vijay VK, Chandra R, Kumar H (2021) Production and characterization of biochar produced from slow pyrolysis of pigeon pea stalk and bamboo. *Clean Eng Technol* 3:100101. <https://doi.org/10.1016/j.clet.2021.100101>
- Salam S, Khaliq N, Hussain N, Baqar Z, Iqbal HM (2023) Microbially synthesized nanoparticles: application in health-care management. In: *Microbial biomolecules*, pp 53–76. Elsevier. <https://doi.org/10.1016/B978-0-323-99476-7.00016-8>
- Sanchez-Monedero M, Cayuela ML, Roig A, Jindo K, Mondini C, Bolan N (2018) Role of biochar as an additive in organic waste composting. *Bioresour Technol* 247:1155–1164. <https://doi.org/10.1016/j.biortech.2017.09.193>
- Sharma A, Maurya N, Singh SK, Sundaram S (2024) Investigation on synergetic strategy for the rejuvenation of Cr (VI) contaminated soil using biochar-immobilized bacteria and cyanobacteria consortia. *J Environ Chem Eng* 12(2):112034. <https://doi.org/10.1016/j.jece.2024.112034>
- Singh AK, Chaubey AK, Kaur I (2023) Remediation of water contaminated with antibiotics using biochar modified with layered double hydroxide: preparation and performance. *J Hazard Mater Adv* 10:100286. <https://doi.org/10.1016/j.jhazadv.2023.100286>
- Sun Y, Lyu H, Cheng Z, Wang Y, Tang J (2022) Insight into the mechanisms of ball-milled biochar addition on soil tetracycline degradation enhancement: physicochemical properties and microbial community structure. *Chemosphere* 291:132691. <https://doi.org/10.1016/j.chemosphere.2021.132691>
- Tan X, Liu Y, Zeng G, Wang X, Hu X, Gu Y, Yang Z (2015) Application of biochar for the removal of pollutants from aqueous solutions. *Chemosphere* 125:70–85. <https://doi.org/10.1016/j.chemosphere.2014.12.058>
- Tan X, Zhang C, Wei H, Shi P, Chang H, Ho S-H (2022) Versatile strategy of sulfanilamide antibiotics removal via microalgal biochar: role of oxygen-enriched functional groups. *Chemosphere* 304:135244. <https://doi.org/10.1016/j.chemosphere.2022.135244>
- 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>
- Tran NH, Chen H, Reinhard M, Mao F, Gin KY-H (2016) Occurrence and removal of multiple classes of antibiotics and antimicrobial agents in biological wastewater treatment processes. *Water Res* 104:461–472. <https://doi.org/10.1016/j.watres.2016.08.040>
- Van den Berg L, Peters C, Ashmore M, Roelofs J (2008) Reduced nitrogen has a greater effect than oxidised nitrogen on dry heathland vegetation. *Environ Pollut* 154(3):359–369. <https://doi.org/10.1016/j.envpol.2007.11.027>
- Wan Y, Chen P, Zhang B, Yang C, Liu Y, Lin X, Ruan R (2009) Microwave-assisted pyrolysis of biomass: catalysts to improve product selectivity. *J Anal Appl Pyrolysis* 86(1):161–167. <https://doi.org/10.1016/j.jaap.2009.05.006>
- Wang B, Li Y-N, Wang L (2019) Metal-free activation of persulfates by corn stalk biochar for the degradation of antibiotic norfloxacin: activation factors and degradation mechanism. *Chemosphere* 237:124454. <https://doi.org/10.1016/j.chemosphere.2019.124454>
- Wang C, Wang Y, Yan S, Li Y, Zhang P, Ren P, Kuang S (2023a) Biochar-amended composting of lincomycin fermentation dregs promoted microbial metabolism and reduced antibiotic resistance genes. *Bioresour Technol* 367:128253. <https://doi.org/10.1016/j.biortech.2022.128253>
- Wang G, Yong X, Luo L, Yan S, Wong JW, Zhou J (2022a) Structure-performance correlation of high surface area and hierarchical porous biochars as chloramphenicol adsorbents. *Sep Purif Technol* 296:121374. <https://doi.org/10.1016/j.seppur.2022.121374>
- Wang H, Lv Y, Bao J, Chen Y, Zhu L (2024) Petroleum-contaminated soil bioremediation and microbial community succession induced by application of co-pyrolysis biochar amendment: an investigation of performances and mechanisms. *J Hazard Mater* 466:133600. <https://doi.org/10.1016/j.jhazmat.2024.133600>

- Wang K, Sun Y, Chen D, Xu Q, Li N, Li H, Lu J (2023b) Enhanced remediation of phenanthrene in water and soil by novel biochar-immobilized bacterial microspheres. *Chem Eng J* 462:141932. <https://doi.org/10.1016/j.cej.2023.141932>
- Wang L, Zhao Y, Li Y, Yao B, Zhang C, Zhang W, Zhang H (2022b) Fe-loaded biochar facilitates simultaneous bisphenol A biodegradation and efficient nitrate reduction: physicochemical properties and biological mechanism. *J Clean Prod* 372:133814. <https://doi.org/10.1016/j.jclepro.2022.133814>
- Wang Q, Wang H, Lv M, Wang X, Chen L (2023c) Sulfamethoxazole degradation by *Aeromonas caviae* and co-metabolism by the mixed bacteria. *Chemosphere* 317:137882. <https://doi.org/10.1016/j.chemosphere.2023.137882>
- Wang S, Chen Y, Ge S, Liu Z, Meng J (2023d) Adsorption characterization of tetracycline antibiotics on alkali-functionalized rice husk biochar and its evaluation on phytotoxicity to seed germination. *Environ Sci Pollut Res* 30(58):122420–122436. <https://doi.org/10.1007/s11356-023-30900-2>
- Wang S, Zhou J, Zhang Y, He S, Esakkimuthu S, Zhu K, Hu X (2023e) Biochar assisted cultivation of *Chlorella protothecoides* for adsorption of tetracycline and electrochemical study on self-cultured *Chlorella protothecoides*. *Bioresour Technol* 389:129810. <https://doi.org/10.1016/j.biortech.2023.129810>
- Wang T, Lin Y-C, Hung C-J, Liao Y, Xu R-X (2023f) Adopting abundant seawater as green chemical activators for preparing high surface area biochar. *Bioresour Technol Rep* 21:101386. <https://doi.org/10.1016/j.biteb.2023.101386>
- Warnock DD, Lehmann J, Kuyper TW, Rillig MC (2007) Mycorrhizal responses to biochar in soil—concepts and mechanisms. *Plant Soil* 300:9–20. <https://doi.org/10.1007/s11104-007-9391-5>
- Wei B, Zhang D, Jeyakumar P, Trakal L, Wang H, Sun K, He S (2024) Iron-modified biochar effectively mitigates arsenic-cadmium pollution in paddy fields: a meta-analysis. *J Hazard Mater* 469:133866. <https://doi.org/10.1016/j.jhazmat.2024.133866>
- Wu C, Wang M, Wang C, Zhao X, Liu Y, Masoudi A, Liu J (2023) Reed biochar improved the soil functioning and bacterial interactions: a bagging experiment using the plantation forest soil (*Fraxinus chinensis*) in the Xiong' an new area, China. *J Clean Prod* 410:137316. <https://doi.org/10.1016/j.jclepro.2023.137316>
- Wu Z, Zhang L, Lin H, Zhou S (2024) Enhanced removal of antibiotic resistance genes during chicken manure composting after combined inoculation of *Bacillus subtilis* with biochar. *J Environ Sci* 135:274–284. <https://doi.org/10.1016/j.jes.2022.12.002>
- Xia Y, Lu D, Qi Y, Chen H, Zhao Y, Bai Y, Hua E (2022) Removal of nitrate from agricultural runoff in biochar electrode based biofilm reactor: performance and enhancement mechanisms. *Chemosphere* 301:134744. <https://doi.org/10.1016/j.chemosphere.2022.134744>
- Xiang W, Zhang X, Chen K, Fang J, He F, Hu X, Gao B (2020) Enhanced adsorption performance and governing mechanisms of ball-milled biochar for the removal of volatile organic compounds (VOCs). *Chem Eng J* 385:123842. <https://doi.org/10.1016/j.cej.2019.123842>
- Xu X, Xu Z, Huang J, Gao B, Zhao L, Qiu H, Cao X (2021) Sorption of reactive red by biochars ball milled in different atmospheres: co-effect of surface morphology and functional groups. *Chem Eng J* 413:127468. <https://doi.org/10.1016/j.cej.2020.127468>
- Yang F, Xue Y, Gao Y, Zhu Q, Wang C, Sun H (2023) Biochar-derived dissolved organic matters influencing bacterium characteristics during biodegradation of sulfamethoxazole and chloramphenicol under alternation of visible and avoiding light. *Biochar* 5(1):9. <https://doi.org/10.1007/s42773-023-00208-y>
- Yang L-H, Qiao B, Xu Q-M, Liu S, Yuan Y, Cheng J-S (2021) Biodegradation of sulfonamide antibiotics through the heterologous expression of laccases from bacteria and investigation of their potential degradation pathways. *J Hazard Mater* 416:125815. <https://doi.org/10.1016/j.jhazmat.2021.125815>
- Ye H, Wang Z, Li X, Sun Y, Zhao L, Bai M, Li Y (2023) Assessing the biodegradation efficiency and underlying molecular pathway of strain AEPI 0–0: a newly isolated tetracycline-degrading *Serratia marcescens*. *Environ Technol Innov*. <https://doi.org/10.1016/j.eti.2023.103383>
- Yu F, Guo Y, Yang J (2023) Mechanistic insights into removal of bisphenol A from activate peroxymonosulfate by Fe-C coupled biochar with the assistance of electric-field activation. *Mater Today Commun* 37:107296. <https://doi.org/10.1016/j.mtcomm.2023.107296>
- Yu T, Wang L, Ma F, Wang Y, Bai S (2020) A bio-functions integration microcosm: Self-immobilized biochar-pellets combined with two strains of bacteria to remove atrazine in water and mechanisms. *J Hazard Mater* 384:121326. <https://doi.org/10.1016/j.jhazmat.2019.121326>
- Yu X, Guo T, Liu X, Zhou B, Zhai X, Yang J, Yang Q (2022) Improving surface properties of cathode and increasing abundance of autotrophic bacteria for chromium reduction with amino functionalized carbon nanotubes. *J Environ Chem Eng* 10(3):108005. <https://doi.org/10.1016/j.jece.2022.108005>
- Yuan H, Lu T, Wang Y, Chen Y, Lei T (2016) Sewage sludge biochar: nutrient composition and its effect on the leaching of soil nutrients. *Geoderma* 267:17–23. <https://doi.org/10.1016/j.geoderma.2015.12.020>
- Yue Y, Liu Y-J, Wang J, Vukanti R, Ge Y (2021) Enrichment of potential degrading bacteria accelerates removal of tetracyclines and their epimers from cow manure biochar amended soil. *Chemosphere* 278:130358. <https://doi.org/10.1016/j.chemosphere.2021.130358>
- Yue Y, Shen C, Ge Y (2019) Biochar accelerates the removal of tetracyclines and their intermediates by altering soil properties. *J Hazard Mater* 380:120821. <https://doi.org/10.1016/j.jhazmat.2019.120821>
- Yustres JLM, Zapata-Restrepo LM, Garcia-Chaves MC, Gomez-Mendez LD (2025) Microplastics in rice-based farming systems and their connection to plastic waste management in the Chicalor district of Espinal-Tolima. *Chemosphere* 378:144423. <https://doi.org/10.1016/j.chemosphere.2025.144423>
- Zeng S, Xia X, Miao S, Zhang J, Li K (2024) Green synthesis of highly pyrrolic nitrogen-doped biochar for enhanced tetracycline degradation: new insights from endogenous mineral components and organic nitrogen synergy. *J Clean Prod*. <https://doi.org/10.1016/j.jclepro.2024.141177>
- Zhang F, Wang J, Tian Y, Liu C, Zhang S, Cao L, Zhang S (2023a) Effective removal of tetracycline antibiotics from water by magnetic functionalized biochar derived from rice waste. *Environ Pollut* 330:121681. <https://doi.org/10.1016/j.envpol.2023.121681>
- Zhang G, Zhao Z, Yin X-A, Zhu Y (2021a) Impacts of biochars on bacterial community shifts and biodegradation of antibiotics in an agricultural soil during short-term incubation. *Sci Total Environ* 771:144751. <https://doi.org/10.1016/j.scitotenv.2020.144751>
- Zhang L, Jing Y, Xiang Y, Zhang R, Lu H (2018) Responses of soil microbial community structure changes and activities to biochar addition: a meta-analysis. *Sci Total Environ* 643:926–935. <https://doi.org/10.1016/j.scitotenv.2018.06.231>
- Zhang S, Hou J, Zhang X, Cai T, Chen W, Zhang Q (2024) Potential mechanism of biochar enhanced degradation of oxytetracycline by *Pseudomonas aeruginosa* OTC-T. *Chemosphere* 351:141288. <https://doi.org/10.1016/j.chemosphere.2024.141288>
- Zhang S, Hou J, Zhang X, Cheng L, Hu W, Zhang Q (2023b) Biochar-assisted degradation of oxytetracycline by *Achromobacter denitrificans* and underlying mechanisms. *Bioresour Technol* 387:129673. <https://doi.org/10.1016/j.biortech.2023.129673>

- Zhang S, Wang J (2021) Removal of chlortetracycline from water by *Bacillus cereus* immobilized on Chinese medicine residues biochar. *Environ Technol Innov* 24:101930. <https://doi.org/10.1016/j.eti.2021.101930>
- Zhang S, Zhang Y, Wang Y, Liu X, Li M, Fang H, Kong M (2023c) Effect of antibiotics, antibiotic-resistant bacteria, and extracellular antibiotic resistance genes on the fate of ARGs in marine sediments. *Sci Total Environ* 891:164305. <https://doi.org/10.1016/j.scitotenv.2023.164305>
- Zhang Y, Chen K, Zhang J, Huang K, Liang Y, Hu H, Wang Y (2023d) Dense and uniform growth of TiO₂ nanoparticles on the pomelo-peel-derived biochar surface for efficient photocatalytic antibiotic degradation. *J Environ Chem Eng* 11(2):109358. <https://doi.org/10.1016/j.jece.2023.109358>
- Zhang Y, Xu M, Liu X, Wang M, Zhao J, Li S, Yin M (2021b) Regulation of biochar mediated catalytic degradation of quinolone antibiotics: important role of environmentally persistent free radicals. *Bioresour Technol* 326:124780. <https://doi.org/10.1016/j.biortech.2021.124780>
- Zhao Y, Li W, Chen L, Meng L, Zhang S (2023) Impacts of adding thermotolerant nitrifying bacteria on nitrogenous gas emissions and bacterial community structure during sewage sludge composting. *Bioresour Technol* 368:128359. <https://doi.org/10.1016/j.biortech.2022.128359>
- Zheng H, Wang Z, Zhao J, Herbert S, Xing B (2013) Sorption of antibiotic sulfamethoxazole varies with biochars produced at different temperatures. *Environ Pollut* 181:60–67. <https://doi.org/10.1016/j.envpol.2013.05.056>
- Zhou Z, Chen H (2024) Evaluating human exposure to antibiotic resistance genes. *Biosafety Health*. <https://doi.org/10.1016/j.bshealth.2024.02.005>
- Zhu Z, Zhao C, Lu B, Liu J, Zhao Y (2024) Application of carboxylated multi-walled carbon nanotubes in bacteria-microalgae-fungi consortium for efficient antibiotics removal. *J Water Process Eng* 58:104865. <https://doi.org/10.1016/j.jwpe.2024.104865>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Jinli Wang^{1,2} · Xueying Li^{1,2} · Minghan Li³ · Haibo Sun^{1,2} · Jingyi Hou^{1,2} · Yang Yang^{1,2} · Yunshan Liang^{1,2} · Pufeng Qin^{1,2} · Yuan Yang^{1,2} · Zhibin Wu^{1,2}

✉ Yunshan Liang
lyss3399@126.com

✉ Zhibin Wu
wzbaaa11@163.com; wzbaaa11@hunau.edu.cn

¹ College of Environment and Ecology, College of Resources and Environment, Hunan Agricultural University, Changsha 410128, People's Republic of China

² Key Laboratory for Rural Ecosystem Health in the Dongting Lake Area of Hunan Province, Changsha 410128, People's Republic of China

³ Changde No.1 Middle School of Hunan Province, Changde 415099, People's Republic of China