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Biochar

REVIEW **Open Access**

Analyzing the trends and hotspots of biochar's applications in agriculture, environment, and energy: a bibliometrics study for 2022 and 2023

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Abstract

Biochar, produced from the thermochemical conversion of biomass waste, has various applications owing to its broad utility and advantageous properties. This study employs a scientometric approach to comprehensively assess the advancements in biochar application from 2022 to 2023. Utilizing 13,357 bibliographic records sourced from the Web of Science Core Collection with the search term "biochar", the analysis focuses on authorship, national contributions, and keyword trends. Findings demonstrate a continual rise in annual publications since 2009, albeit with a moderated growth rate in 2023. China leads in publication outputs, followed by USA and India, with Hailong Wang emerging as a prominent figure in biochar research. Keyword co-occurrence analyses identify key research themes such as biochar's role in climate change mitigation, easing salinity and drought stress, immobilizing toxic metals, degrading organic pollutants, serving as additives in anaerobic digestion, and functioning as electrodes in microbial fuel cells. Among these, biochar's application for global climate change mitigation gains significant attention, while its utilization as electrodes in microbial fuel cells emerges as a promising research frontier, indicating the growing need for sustainable energy sources. The study also outlines critical research gaps and future priorities for enhancing biochar application. Overall, it highlights the diverse applicability of biochar and offers valuable insight into research progression and forthcoming directions in biochar studies.

Highlights

- Utilization of bibliometric review for keyword analysis.
- Examination of recent developments in biochar application.
- The emerging focus on biochar's effectiveness as electrodes in microbial fuel cells (MFCs).
- Suggested future research directions and priorities for sustainable biochar application.

Keywords Bibliometric analysis, Research hotspots, Carbon neutrality, Microbial fuel cells, Sustainable application

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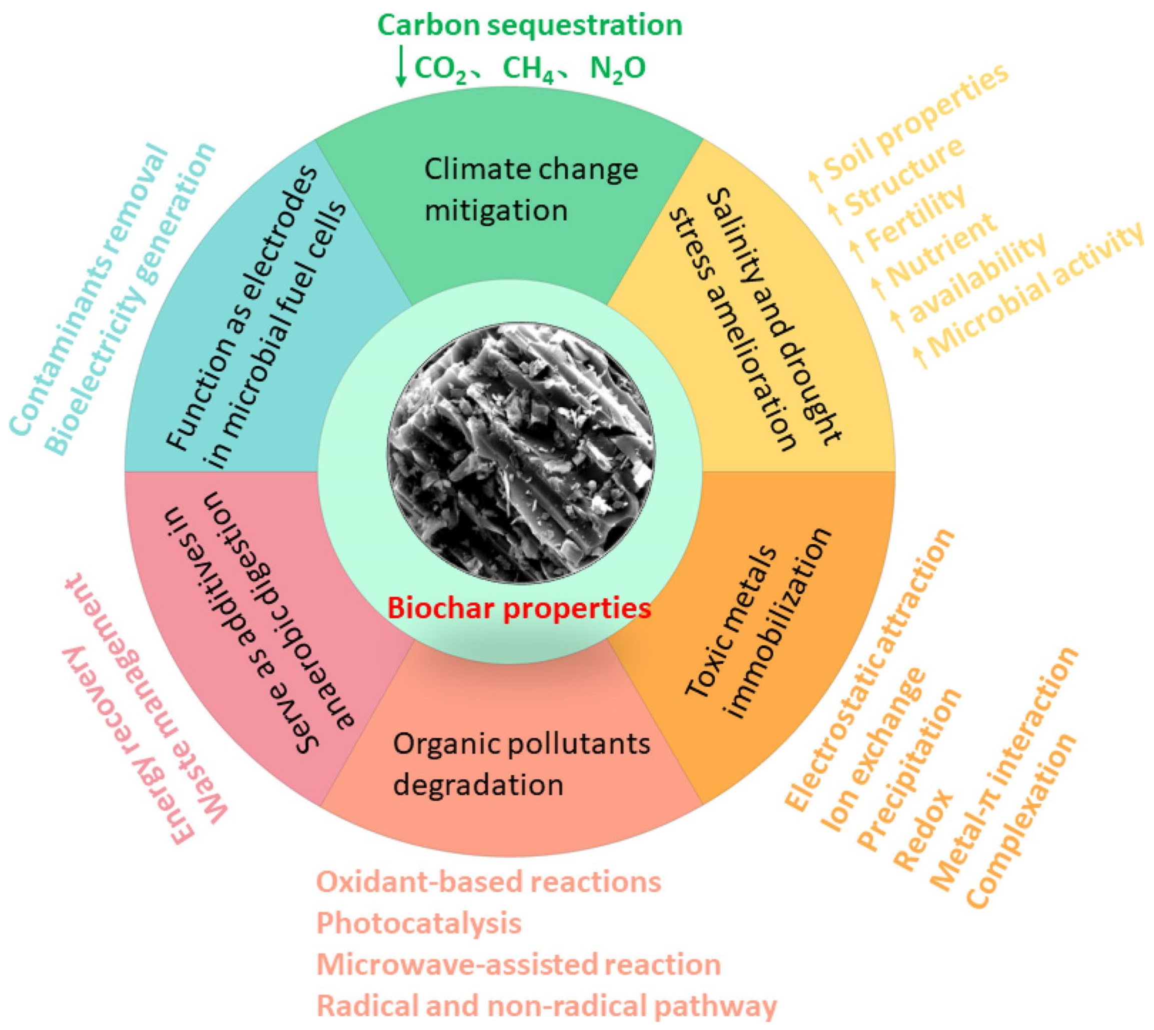
Graphical Abstract



1 Introduction

Biochar, a carbonaceous material resulting from the thermal decomposition of biomass under oxygen-limited conditions (Wang and Wang 2019; Woolf et al. 2021), stands as an eco-friendly strategy for managing waste biomass (Malyan et al. 2021; Roberts et al. 2010). Biochar feedstocks can be grouped into five categories: (1) agricultural waste (residues from wheat, corn, rice, legumes, and sugar cane); (2) lignocellulosic matter (fruit peels, nut shells, tree leaves, reeds, and weeds); (3) livestock manure (pig, cattle, or poultry manure); (4) sewage sludge (SS); (5) wood (hardwoods such as pine, bamboo, and oak) (Kerner et al. 2023; Wu et al. 2020). Multiple techniques like slow pyrolysis, fast pyrolysis, hydrothermal carbonization, gasification, microwave-assisted pyrolysis, flash carbonization, and torrefaction are available for biochar production (Wu et al. 2020), with slow pyrolysis being the most commonly adopted method due to its operational simplicity (Tripathi et al. 2016). The physicochemical properties of biochar are substantially influenced by the feedstock and thermochemical conditions, particularly temperature (Luo et al. 2015).

Biochar is a versatile material in agriculture, environment, and energy sectors (Liu et al. 2019; Rawat et al. 2023; Yin et al. 2023). Its fused aromatic structure facilitates carbon storage (Lee et al. 2010; Lehmann 2007) and aids in belowground carbon sequestration (including plant litter and rhizodeposits), while also mitigating greenhouse gases (GHG) emissions (Weng et al.

2017, 2022; Woolf et al. 2021). Consequently, biochar holds promise for soil carbon sequestration and achieving carbon neutrality (Wang et al. 2023b). Furthermore, it enhances nutrient use efficiency, moisture retention capacity, and root system development, thereby bolstering plant productivity and fostering sustainable farming practices (Mia et al. 2017; Zhang et al. 2020). Notably, biochar amendment demonstrates significant benefits for plant growth in saline–alkali soils, which otherwise hamper agricultural activities (Wang et al. 2024b). With its high sorption capacity and ability to facilitate oxidation processes, biochar emerges as a valuable material for environmental remediation efforts (Wang et al. 2023c; Yang et al. 2021b). Additionally, the syngas byproduct derived from biomass thermochemical conversion can be used for energy generation through combustion (Irfan et al. 2016). Moreover, biochar finds application in electrochemical energy storage, serving as electrode materials and templates (Cao et al. 2022).

However, some studies report that introducing biochar to soil may induce mineralization of soil recalcitrant components, potentially resulting in the loss of soil organic carbon (SOC) (Ling et al. 2022). Moreover, other studies have documented an increase in nitrous oxide (N_2O) emissions following biochar application (Lan et al. 2019; Lin et al. 2017; Saarnio et al. 2013). The variability in outcomes is largely attributed to the physicochemical properties of biochar and the heterogeneity of soil characteristics. Biochar application may also have adverse effects on soil health. For instance, polycyclic aromatic hydrocarbons (PAHs), heavy metals (HMs), and persistent free radicals (PFRs) in biochar pose risks to soil organisms (Godlewska et al. 2021; Xiang et al. 2021). Excessive biochar application may reduce nutrient use efficiency due to its strong nutrient sorption capability (Xiang et al. 2021). Hence, a critical assessment of the feasibility of biochar is warranted.

A systematic and comprehensive review of existing literature enables us to summarize knowledge on biochar applications and identify research gaps and future directions. Although many reviews highlight the broad applications of biochar in agriculture, environment, and energy, they often lack a macro-level overview of the current state and development trends in the field. Unlike traditional reviews, bibliometrics offers a more intuitive and systematic scientometric analysis of publications. More importantly, bibliometrics analysis can quantitatively evaluate emerging trends and shifts across multiple primary studies in an illustrative and logical manner (Qin et al. 2022). Currently, bibliometric analysis has been employed to investigate the efficacy of biochar in HMs remediation (Phiri et al. 2024), the evolving trends in biochar for carbon sequestration (Zhang et al. 2023b), advancements in biochar/hydrochar production and application (Agyekum and Nutakor 2024; Huang et al. 2023), and the development of biochar-based organic fertilizers (Wang et al. 2024a). The bibliometric analysis conducted on recent articles will play a crucial role in guiding future biochar research.

In this study, we employed bibliometric analysis using Citespace software to quantitatively synthesize recent findings on biochar applications. The interrelations among different countries, notable authors, and highly cited literature were visually examined. By visualizing keyword frequencies, major research focal points, emerging methodologies, and future research avenues were determined. We aim to provide valuable insights for improving the utilization of biochar.

2 Methods

2.1 Bibliometric analysis methods

Cite-space, an innovative data visualization and analysis software based on scientometric advancements, was utilized in this study (Li et al. 2020; Ren et al. 2021). Developed by Professor Chaomei Chen and his team at Drexel University, Cite-space is Java-based software (Chen 2004). Peer-reviewed articles were extracted from the "marked list" of the Web of Science (WoS) Core Collection and subjected to analysis using Cite-space software. Visually analyses of literature data encompassed contributing countries, authors, institutions, and keywords. This bibliometric approach facilitates comprehension of research hotspots and trends in biochar studies, offering new insights for future research endeavors (Qin et al. 2022). In the co-occurrence network maps generated, each node signifies an item, with lines connecting nodes. Node size corresponds to frequency, while line thickness reflects cooperation frequency between connected nodes.

2.2 Data extraction

A systematic literature search was conducted within the WoS Core Collection database using the keyword "biochar" to retrieve relevant peer-reviewed documents spanning 2022–2023. This yielded a total of 13,357 publications. To ensure data validity and accuracy, synonyms or closely related terms for keywords (e.g. "carbon dioxide" and "CO_2", "cadmium" and "Cd", "anaerobic digestion" and "AD", "microbial fuel cells" and "MFCs") were manually merged.

3 Results and discussion

3.1 Brief analysis of publications on biochar research

A total of 13,358 articles were published in the field of biochar during the period spanning 2022–2023. Notably, a substantial increase in annual publications has been evident since 2009, with a more pronounced growth trend observed over the last five years (2018–2022). However, this upward trend showed signs of moderation in 2023 (Fig. S1), indicating a growing interest and a substantial accumulation of scientific knowledge in this field.

3.2 Country network

The network map of country collaborations is depicted in Fig. S2. Notably, China, the USA, and India have emerged as leading contributors to biochar research, accounting for 3730 (27.92%), 587 (4.39%), and 517 (3.87%) publications, respectively. Additionally, significant scientific outputs were observed from Pakistan, Saudi Arabia, and Australia (Table S1). Particularly, China has established close collaboration ties with the USA and Pakistan (Fig. S2).

3.3 Author and institution analysis

Co-authorship analysis sheds light on scholarly communications within the biochar research community, serving as an important indicator of academic collaboration. Collaborative efforts among academics can foster subject area advancements and yield deeper insights into research areas. Table S2 lists the top 15 authors with the highest publication volumes. "Hailong Wang" (39 articles), "Ying Zhang" (36 articles), and "Yong Sik Ok" (35 articles) emerge as leading figures in driving biochar research forward. However, the collaborative relationships among the top 10 authors by publication volume appear relatively weak, underscoring the need for continual strengthening of author collaboration.

Table S3 presents the top 10 research institutions by published volume. Chinese Academy of Sciences recorded the highest publication count, with 454 papers, representing 4.42% of all publications. This was followed by the University of Chinese Academy of Sciences and Northwest Agriculture & Forestry University. Moreover, nine out of the top 10 research institutions with the highest publication volumes are in China (Table S3), reaffirming China's leadership role in biochar research.

3.4 Keyword co-occurrence network

Keyword co-occurrence analysis helps identify research hotspots, trends, and frontier shifts in biochar research. The analysis revealed six main areas of focus: (1) the potential of biochar to mitigate global climate change; (2) biochar for salinity and drought stress amelioration; (3) biochar for toxic metals immobilization; (4) biochar for organic pollutants removal; (5) the role of biochar in enhanced anaerobic digestion; (6) biochar as an electrode in microbial fuel cells (Fig. 1).

3.4.1 Potential of biochar to mitigate global climate change

Keyword co-occurrence analysis highlights the importance of biochar's role in mitigating global climate change (Fig. 1). China plays a significant role in climate governance, contributing substantially to research on carbon sequestration and greenhouse gas (GHG) emission reduction.

3.4.1.1 Biochar carbon sequestration potential Biochar is effective for long-term carbon sequestration due to its high content of stable carbon forms. The stability of biochar increases significantly with higher treatment temperatures (HTT) and retention times. Additionally, biochar produced from wood exhibits lower H/C_{org} ratios and greater stability compared to that from herbaceous biomass (Luo et al. 2023b).

Biochar's impact on SOC mineralization varies. It can reduce SOC mineralization (negative priming effect) by slowing down the turnover of both native SOM and newly added rhizodeposits (Liu et al. 2022b). However, some studies report that biochar amendment can also induce the mineralization of soil recalcitrant components (positive priming effect) due to the activation of specific bacterial groups associated with these components (Fig. 1A) (Ling et al. 2022; Tian et al. 2023). The priming effects depend largely on the available C/N ratio in biochar. Thus, optimizing the C/N ratio can mitigate positive priming effects (Luo et al. 2023b). Also, the priming effects induced by biochar vary with application rate and applied soil type. Advanced technologies like machine learning or artificial intelligence can elucidate biochar's C sequestration effects, considering biochar properties, soil characteristics, and management strategies. These technologies are expected to assist policymakers in promoting sustainable agriculture. Earthworms can enhance SOM content and stabilization in agricultural soils by facilitating the direct sorption of plant-derived substrates or microbial necromass onto mineral particles (Kellerová et al. 2024). A life-cycle assessment indicated that sustainable biochar production from various feedstocks could sequester 455.7 Mt CO_2-eq yr^{-1} in China. However, using SS as a feedstock may not be appropriate for agricultural carbon neutrality due to the high energy demands for sludge drying (Xia et al. 2023).

Biochar is a promising material for climate change mitigation through CO_2 capture due to its large specific surface area (SSA), microporous structure, abundant oxygen-containing functional groups (OFGs), and minerals (Zhang et al. 2022a). CO_2 capture by biochar can occur through physical and/or chemical adsorption. The

Fig. 1 Keyword co-occurrence map in the field of biochar research (2022–2023)

primary mechanism for CO_2 capture by pristine biochar is physisorption, which provides a relatively low adsorption capacity for CO_2 (Shafawi et al. 2021). However, engineered biochar demonstrates high performance in CO_2 uptake through both physisorption and chemisorption (Yuan et al. 2022b). The introduction of heteroatoms can enhance active sites for CO_2 uptake via chemical bonding. For instance, N/O co-doped porous biochar (NOBC) exhibits a high CO_2 adsorption capacity of 6.09 mol kg^{-1} due to the synergistic effects between N and O atoms, enhancing CO_2 affinity and electron transfer between CO_2 and NOBC (Luo et al. 2023a) (Fig. 2B). Similarly, N-doped biochar produced from corncob powder, potassium carbonate, and urea by one-step process showed effective CO_2 capture (5.69 mmol g^{-1}). Theoretical calculations indicate that increased dispersion and electrostatic interactions between biochar and CO_2 after N doping are the main mechanisms for this enhanced capacity. This biochar also demonstrates excellent thermal stability and reusability (Li et al. 2023). Additionally, lignin-treated biochar presents a superior CO_2 uptake capacity of 178.75 mg g^{-1} due to its super-microporous structure (Cao et al. 2023) (Fig. 2C).

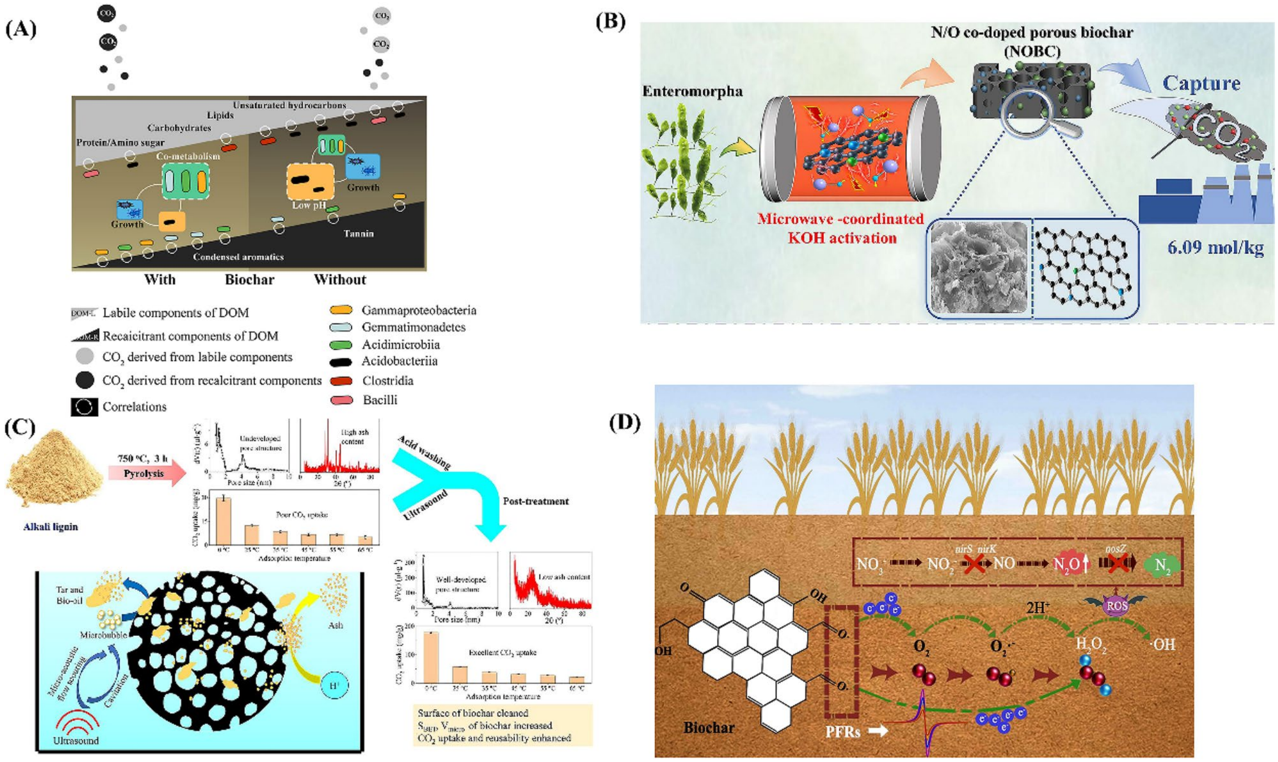


Fig. 2 Mechanisms underlying SOC mineralization induced by biochar (**A**) (Ling et al. 2022), CO_2 capture mechanism using N/O co-doped porous biochar (**B**) (Luo et al. 2023a), CO_2 adsorption performance and mechanisms of lignin-treated biochar (**C**) (Cao et al. 2023), and the effects of persistent free radicals within biochar on its capacity to mitigate soil N_2O emissions (**D**) (Wu et al. 2023)

3.4.1.2 Effects of biochar on other GHG fluxes from soils Biochar can also mitigate N_2O and methane (CH_4) emissions from croplands. The primary cause of N_2O emissions is the increasing use of N fertilizers with low use efficiency (Kerner et al. 2023). Numerous studies indicate that biochar has significant potential to reduce N_2O emissions by altering nitrification and denitrification processes (Yuan et al. 2022a; Zhu et al. 2022). A three-level meta-analysis observed a 12.7% decrease in cumulative N_2O emission due to biochar. However, fertilization can weaken biochar's potential to mitigate these emissions (Kerner et al. 2023).

Biochar aging was found to reduce its mitigation effect on soil N_2O emissions by accelerating N_2O production during the nitrification process (Feng et al. 2022). Persistent free radicals (PFRs) in biochar also decrease its potential to mitigate soil N_2O emissions by inhibiting the *nosZ* genes (N_2O reductases), which are crucial for the final step in the denitrification pathway that releases N_2 gas. Therefore, biochar with lower PFRs is more effective in reducing N_2O emissions (Wu et al. 2023) (Fig. 2D). Additionally, biochar's electron shuttle function can enhance the dissimilatory nitrate reduction to ammonium process in paddy soil, thus reducing N_2O emissions and improving N retention (Yuan et al. 2022a). Biochar has also been shown to mitigate N_2O emissions during composting by promoting the abundance of denitrifying bacteria harboring the *nosZ* genes (Wang et al. 2022b; Yin et al. 2024).

Biochar has also shown potential for mitigating CH_4 emissions from paddy soils. Wood-derived biochar can act as an electron acceptor, promoting the microbial anaerobic oxidation of organic substrates and thereby suppressing CH_4 production (Xin et al. 2023). A multi-task deep learning model was developed to investigate biochar's potential in CH_4 mitigation. The results indicated that biochar characteristics contributed to 62.5% of CH_4 mitigation, with the C/N ratio being the most influential factor, accounting for 67.9% of the overall CH_4 mitigation efficiency. Soil properties accounted for 26.7% of mitigation efficiency, while biochar dose had a limited impact (Yin et al. 2023). A moderate biochar application is essential to avoid ineffective or negative impacts on its CH_4 mitigation potential.

3.4.2 Biochar for salinity and drought stress amelioration

Soil salinization presents a significant challenge to agricultural productivity and farmland health. China has invested heavily in preventing and restoring saline-alkali land (Yang et al. 2021a). Current research indicates that biochar plays a crucial role in remediating saline-alkali soil (Alsamadany et al. 2022; Taheri et al. 2023). Amending salt-affected soils with biochar enhances soil physicochemical properties, structure, fertility, nutrient availability, and microbial activity (Hou et al. 2023). N leaching and ammonia (NH_3) volatilization are major constraints in saline-alkali soils (Zhu et al. 2020). Biochar application effectively mitigates these issues due to its high adsorption capacity for inorganic N (You et al. 2023). Innovative biochar modifications have shown greater effectiveness in saline-alkali soil amelioration. For instance, ball-milled red phosphorus-loaded biochar reduces soil salinity and alkalinity through phosphate precipitation with soluble salt ions and acid–base neutralization, while also improving soil quality, fertility, and microbial community structure, thereby enhancing maize germination and growth (Zhang et al. 2022b). Biochar can also modulate antioxidant defense systems, including superoxide dismutase, peroxidase, catalase, ascorbic acid, and malondialdehyde, which alleviates salt stress in plants (Abo Elyousr et al. 2022). Combining biochar with functional bacteria has gained attention for improving salt-affected soils. For example, integrating plant growth-promoting bacteria (PGPB) with biochar significantly increased soil phosphorus and nitrogen availability, enhancing maize growth (Liang et al. 2023b). Previous studies have reported that biochar application increases soil pH (Meng et al. 2023; Wang et al. 2023f). This increase may reduce the remediation effects of biochar in salt-affected soils. However, a recent meta-analysis showed that biochar had a negligible effect on pH (Wang et al. 2024c). Most salt-affected soils are alkaline with a high initial pH, which may limit biochar's liming effect. Additionally, biochar's high buffering capacity can resist soil pH changes (Wang et al. 2024c).

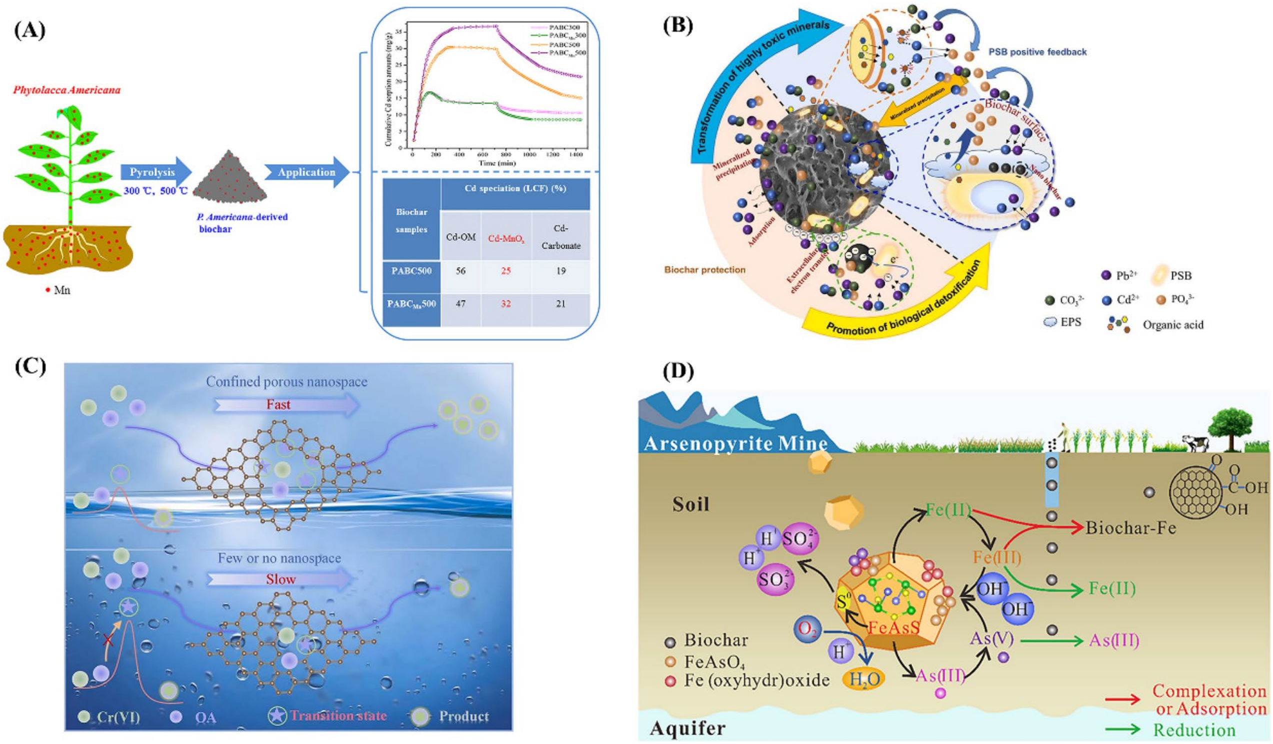
Drought is another common issue affecting agricultural productivity. Biochar application helps preserve soil moisture, enhance water holding capacity, and improve irrigation water use efficiency. The combined use of biochar and manure alleviated water stress in sugar beet, increasing sucrose content in tubers (Lebrun et al. 2022). Similarly, combining biochar with N fertilizer improved irrigation efficiency and effectiveness in Roselle cultivation under drought conditions (Albalsmeh and Piri 2023). Dual application of biochar and arbuscular mycorrhizal fungi benefited soybean cultivation and boosted soil enzyme activity under drought stress (Jabborova et al. 2022). Overall, biochar is an effective soil amendment with great potential for ameliorating soil salinity, alkalinity, and drought stress, thereby improving soil properties, structure, and agricultural productivity.

3.4.3 Biochar for toxic metals immobilization

Toxic metals are a significant concern due to their long residence time and tendency to accumulate in the food chain. Biochar has emerged as an effective material for immobilizing toxic metals, owing to its unique and excellent surface properties. The immobilization of toxic metals by biochar remains a "hot" topic (Fig. 1). Cadmium (Cd) is one of the most studied HMs because it is harmful even at low concentrations (Balali Mood et al. 2021; Genchi et al. 2020).

Converting SS into biochar via thermal treatment is a feasible strategy for the safe disposal of SS, as it reduces the bioavailability of HMs in SS (Zhang et al. 2023a). However, direct thermal treatment of high-moisture sludge requires significant energy. Hydrothermal treatment of SS before pyrolysis or calcination saves energy and decomposes organic pollutants in SS. Importantly, hydrothermal treatment coupled with pyrolysis or calcination significantly reduces the soluble fractions of HMs and their potential ecological risks (Li et al. 2022c). A similar study found that alkaline hydrothermal treatment combined with pyrolysis was more effective in stabilizing HMs compared to direct SS pyrolysis. This treatment significantly decreased the ecological risk of HMs in SS from 57.27 to 30.05, indicating a low potential ecological risk of SS-derived biochar (Li et al. 2022b). Biochar produced from the co-pyrolysis of SS and other biomass (e.g., coconut fiber and kitchen waste) demonstrated high sorption capacities for HMs and organic contaminants (Wang et al. 2024d; Yang et al. 2022).

Engineered biochar provides a feasible solution for producing specialized biochar suitable for the remediation of specific toxic metals. For instance, biochar prepared from Mn hyperaccumulators is a highly efficient sorbent for Cd, with maximum sorption capacities reaching up to 337 mg g^{-1}. The Cd maximum sorption capacity of Mn hyperaccumulator-derived biochar is significantly higher than that of other modified biochars, suggesting a high potential for metal hyperaccumulator-derived biochar in HMs removal. The main sorption mechanism involves the association of Cd with organic matter, carbonate, and MnO_x in the biochar (Wu et al. 2022b) (Fig. 3A). The sorption process is well described by pseudo-second-order and Langmuir models (Biswal and Balasubramanian 2023; Li et al. 2022a). Machine learning approaches have been used to predict biochar's efficiency in immobilizing HMs. The results indicated that the most important factors are the N content of biochar and its



Biochar samples	Cd speciation (LCF) (%)		
	Cd-OM	Cd-MnO$_2$	Cd-Carbonate
PABC500	56	25	19
PABC$_{Mn}$500	47	32	21

Fig. 3 The sorption capacity and mechanism of Cd by Mn-hyperaccumulator (**A**) (Wu et al. 2022b), the concurrent immobilization mechanisms of Cd and Pb by phosphorus-dissolving bacteria on biochar (**B**) (Chen et al. 2023a), the mechanism of Cr(VI) reduction by biochar-based microporous nanosheets (**C**) (Yang et al. 2023a), and the electrochemical mechanism of arsenopyrite weathering in soil by biochar (**D**) (Wang et al. 2023d)

application rate. Causal analysis showed that the importance of factors governing HMs immobilization capacity follows the order: biochar characteristics > experimental conditions > soil properties > HMs properties (Palansooriya et al. 2022) (Fig. 3B). It is necessary to note that earthworms can weaken the ability of biochar to immobilize HMs by reducing soil pH and gut digestion (Wang et al. 2023a).

Functional bacteria immobilized on biochar have frequently been used for HM bioremediation. Combining biochar with phosphate solubilizing bacteria (PSB) accelerates the immobilization of Cd and Pb by forming stable Cd/Pb-carbonate and Cd/Pb-phosphate complexes (Chen et al. 2023a). Similarly, a novel porous spherical PSB bead loaded with biochar and nano zero-valent iron (nZVI) enhanced Pb passivation in soil (Wang et al. 2022a). The synergistic application of biochar and *Bacillus spp.* also shows promise for HMs bioremediation (Schommer et al. 2023).

Biochar-based materials have been widely used to remove metal anions, primarily arsenic (As) and chromium (Cr). Engineered biochar exhibits enhanced performance in removing As and Cr. For example, Yang et al (2023a) developed biochar-based microporous nanosheets through one-step calcination. These materials, characterized by their developed micropore structures, demonstrated high efficiency in reducing Cr(VI) (Yang et al. 2023a). Chitosan-modified biochar improved Cr(VI) reduction by *Shewanella oneidensis* MR-1 by acting as an electron shuttle to enhance extracellular electron transfer (Yu et al. 2023). Similarly, inoculating arbuscular mycorrhizal fungi with biochar increased plant tolerance to Cr toxicity by promoting Cr immobilization and improving antioxidative response (Chen et al. 2022). Loading biochar with metal oxides or metals is a common method to boost As immobilization efficacy through electrostatic attraction and complexation. Magnetic high-loading ZVI-biochar composites, for example, effectively promote As(III, V) removal. For As(III), the possible removal mechanisms include As(III) oxidation to As(V) and the subsequent sorption of As(V) through surface complexation, co-precipitation, and electrostatic attraction and direct sorption of As(III) through complexation and electrostatic attraction (Xu et al. 2022a). However, biochar can also accelerate the oxidation dissolution of arsenopyrite (FeAsS), resulting in release of As(III). The abundance of quinoid and aromatic groups in biochar promotes the reduction of As(V) and Fe(III) as well as sorption with Fe(III). This hinders the generation of passivation films containing iron arsenate and iron (hydr)oxide, thus expediting the weathering of FeAsS and worsening soil contamination with As (Wang et al. 2023d). Consequently, the potential negative effects of biochar on soil should be carefully considered before large-scale applications.

3.4.4 Biochar for organic pollutants removal

3.4.4.1 Sorption removal The use of biochar for the sustainable removal of organic pollutants has remained a hot topic over the last two years. Adsorption offers cost-efficient and convenient advantages over other techniques for removing target contaminants. Per- and poly-fluoroalkyl substances (PFAS) are synthetic organic compounds with long-chain structures. They exhibit high stability, persistence, mobility, and bio-accumulation potential, raising significant concerns about their impacts on human health (Cousins et al. 2022). Utilizing biochar for the adsorption of PFAS has emerged as an effective approach for remediating PFAS-contaminated environments. Biochar derived from digested sewage sludge has been proven to be a cost-effective and efficient sorbent for PFAS under most environmental conditions, often showing sorption effectiveness comparable to or even better than activated carbons. The notable pore volume and carbon content of sludge-derived biochar are key factors contributing to its strong sorption capability (Krahn et al. 2023). The physicochemical properties of biochar play a crucial role in PFAS sorption. Recent research indicates that the pore diameter is the primary parameter influencing PFAS removal. Thus, tailoring biochar physicochemical properties to enhance PFAS sorption potential could significantly broaden its applicability in PFAS removal. An innovative porous Fe-doped graphitized biochar has demonstrated excellent sorption capacity for co-removal of various chain-length PFAS. Modifying the surface chemistry and pore structure of biochar represents a strategy to enhance PAFS sorption. Wang et al (2023e) reported that brief thermal oxidation of biochar greatly increased its surface area and porosity, thereby boosting PFAS sorption (Wang et al. 2023f). The Fe-doped biochar pyrolyzed at 900 °C exhibited a maximum sorption capacity of 10.1 mg g^{-1} for short-chain perfluorobutyric acid and 39.1 mg g^{-1} for perfluorooctanoic acid. The main sorption mechanisms involved pore-filling, electrostatic, and hydrophobic interactions (Liu et al. 2023d) (Fig. 4D).

Another engineered biochar produced from food waste through hydrothermal carbonization and high-temperature activation with $ZnCl_2$ demonstrated favorable sorption performance for various PFAS. The relatively high SSA and hydrophobic surface properties were key parameters influencing the greater sorption of PFAS

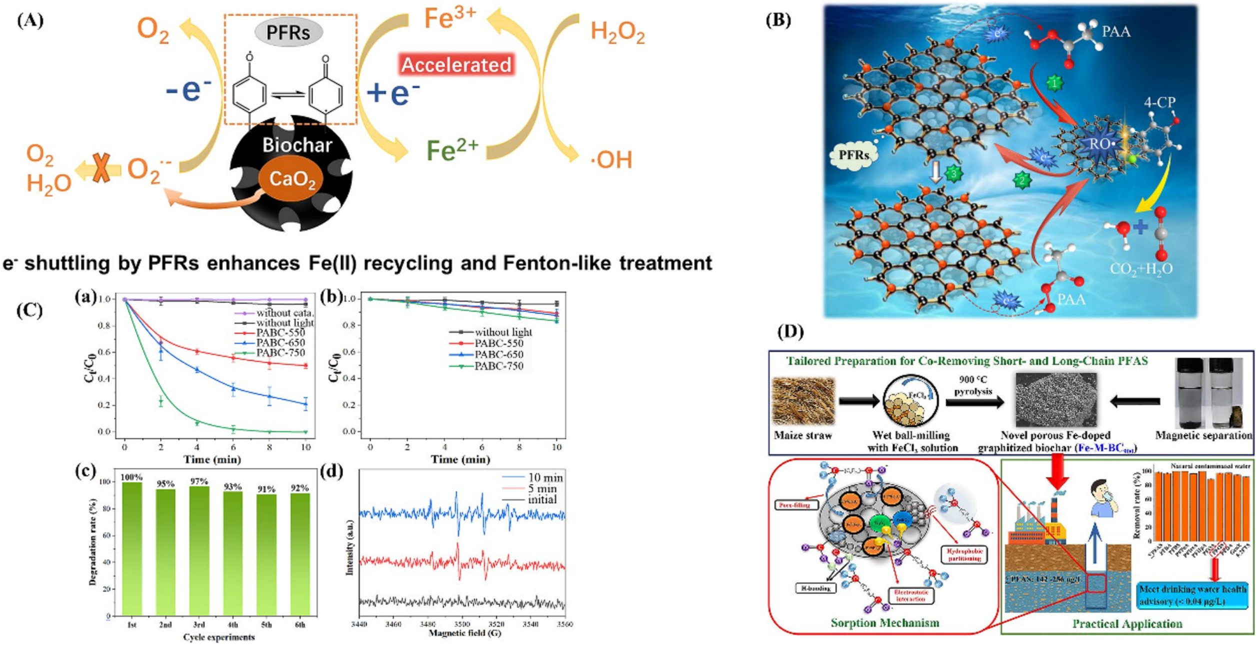


Fig. 4 The role of persistent free radicals in biochar for sulfamethoxazole degradation by accelerating Fe(III)/Fe(II) cycling (**A**) (Zhang et al. 2022c), the degradation mechanism of p-chlorophenol by biochar with activation of peracetic acid (**B**) (Wu et al. 2022a), the photodegradation efficiency of rhodamine B by biochar derived from Mn hyperaccumulator and the stability of this biochar (**C**) (Cui et al. 2022), and the preparation of porous Fe-doped graphitized biochar and the removal capacity for per-/polyfluoroalkyl substances by this biochar (**D**) (Liu et al. 2023d)

(Chen et al. 2024). However, the effectiveness of biochar in stabilizing PFAS in soils may change over time. Studies suggest that biochar's efficacy in stabilizing PFAS is generally brief due to aging effects in soils (Navarro et al. 2023). Thus, long-term assessments of PFAS stabilization performance in soils by biochar are warranted.

3.4.4.2 Advanced oxidation process Advanced oxidation processes (AOPs), including oxidant-based reactions, photocatalysis, and microwave-assisted reaction have been widely employed to degrade organic contaminants (Wang et al. 2023c). Biochar-based nanocomposites have gained extensive attention due to their high catalytic degradation properties. Incorporating metal oxides (e.g., Cu_2O, TiO_2, Fe_2O_3, and MnO_2) with biochar as a substrate to develop composite biochar-based photocatalysts has emerged as a promising approach to efficiently degrading organic pollutants. For example, Cu_2O-biochar composites exhibit superior photocatalytic degradation activity towards sulfamethoxazole (SMX), with $O_2^{\cdot-}$ together with h^+ being the dominant active species responsible for SMX photodegradation (Zheng et al. 2022). Biochar/MnO_2/g-C_3N_4 composites significantly enhance the generation of $^1O_2$, resulting in high photocatalytic degradation activity towards formaldehyde (Li et al. 2022d). Fe-based biochar commonly acts as a catalyst to activate a series of oxidants (e.g., O_2, H_2O_2, peroxymonosulfate (PMS), and peroxydisulfate (PDS)) to degrade organic pollutants. Fe/Mn bimetallic-supported biochar nanosheets can serve as PMS activator for efficient degradation of tetracycline (TC), working through both radical and non-radical pathways. This material is applicable across a wide pH range and various water environments, demonstrating broad-spectrum adaptability towards various organic contaminants (Liang et al. 2023a). Another example includes FeS/N-doped biochar prepared by pyrolyzing jute fibers pretreated with $(NH_4)_2Fe(SO_4)_2$, which enhances peroxydisulfate activation for triclosan degradation. This biochar-based catalyst can be regenerated through reheating to recover its catalytic activity completely (Chen et al. 2023b).

The PFRs within biochar can accelerate AOPs-driven organic pollutant removal. Zhang et al (2022c) demonstrated that PFRs within biochar act as active sites to enhance electron transfer from $O_2^{\bullet-}$ to Fe(III) in Fe-tartaric systems, generating Fe(II) and promoting •OH formation, thus speeding up SMX degradation (Zhang et al. 2022c) (Fig. 4A). Similarly, loading ZnO nanoparticles on biochar enhances the formation of oxygen-centered PFRs, which possess high catalytic ability. The resulting $SO_4^{\bullet-}$ and •OH from the electron transfer between PFRs and PS contributed to TC degradation (Xu et al. 2022b).

Peracetic acid (PAA)-based AOPs are increasingly recognized as effective for organic pollutants degradation. A novel mixed sludge-derived biochar (from primary and secondary sludge) exhibited excellent structure, abundant electron-donating groups, and massive electronic defects, promoting PFR formation. The active PFRs sites in sludge-derived biochar proved effective in activating PAA to produce organic radicals (RO•), which were dominant in degrading p-chlorophenol. These active PFR sites can be regenerated, facilitating the reuse of this biochar (Wu et al. 2022a) (Fig. 4B).

Recently, biochar-based single-atom catalysts have emerged as promising AOP catalysts. A novel Mn-biochar-based single-atom catalyst derived from a Mn hyperaccumulator (*Phytolacca americana*) demonstrated excellent stability and high photodegradation efficiency for rhodamine B, with dispersed Mn–N_4 as the active center critical for photocatalytic degradation (Cui et al. 2022) (Fig. 4C). Similarly, single-atom Mn catalysts from a Mn hyperaccumulator (*Phytolacca americana*) showed excellent catalytic activity for PMS activation, with Mn–N_4 sites on biochar being responsible for degrading chloroquine phosphate (Yang et al. 2023c).

3.4.5 The role of biochar in enhanced anaerobic digestion

Anaerobic digestion (AD) stands as a critical technology for renewable energy recovery and sustainable waste management (Wang et al. 2020). The integration of biochar into the AD process to strengthen its stability and sustainability remains a topic of great interest to researchers. Biochar's efficacy in enhancing the AD process stems from several mechanisms, including: (1) promoting the formation of granular sludge within AD reactors; (2) accelerating the decomposition of organic compounds; (3) mitigating the toxicity of inhibitors (e.g., ammonia, volatile fatty acids, HMs, and phenols); (4) enhancing *in-situ* CH_4 quality by acting as a sorbent for CO_2; (5) augmenting the activity of functional enzymes and abundance of beneficial microorganisms; and (6) facilitating direct interspecies electron transfer (DIET) (Bu et al. 2022; Deena et al. 2022; Ning et al. 2022). The physicochemical properties of biochar directly influence its role within AD systems. Parameters such as SSA, porosity, and surface charge govern microbial colonization and the bioavailability and ecotoxicity of harmful substances. Biochar characterized by high SSA and surface porosity enhances cell attachment and the adsorption of toxic substances (Zhang et al. 2023c). Moreover, the electrochemical properties of biochar, including electron-donating capacity (EDC) and electron-accepting capacity (EAC), significantly impact DIET. Among these, EDC plays a more important role in DIET (Ning et al. 2022; Sun et al. 2022). Surface functional groups of

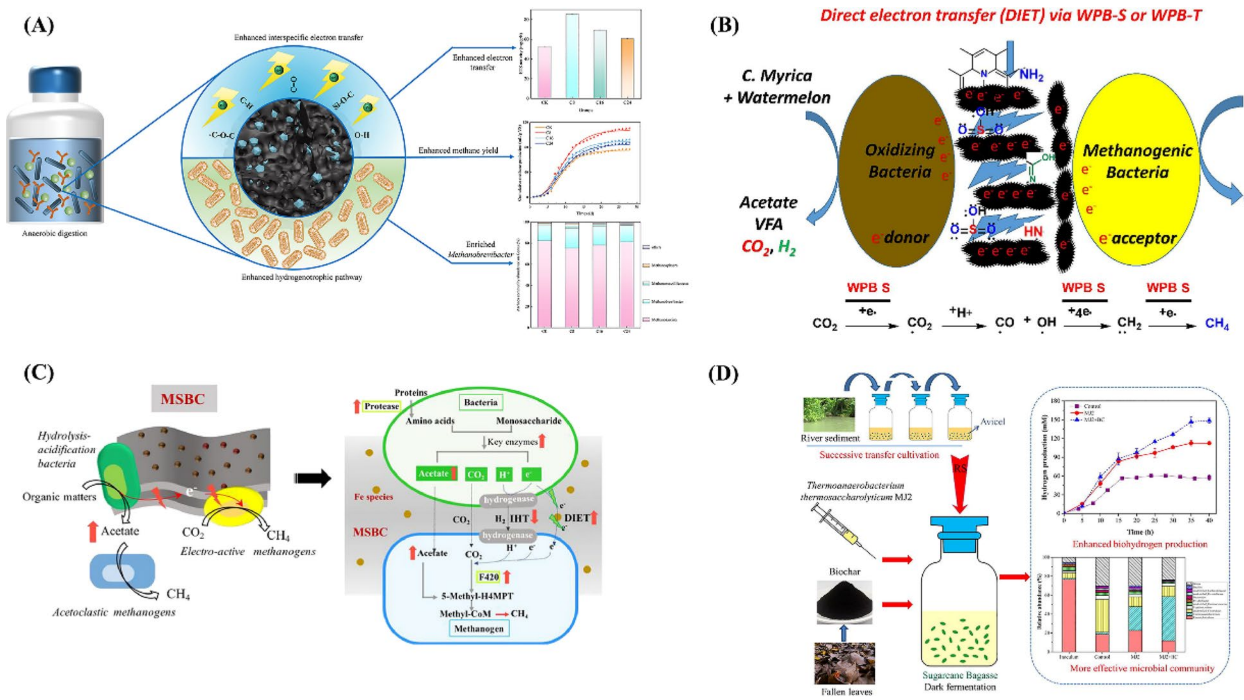


Fig. 5 The impacts of humic acid-loaded biochar on CH_4 production in AD system (**A**) (Liu et al. 2023c), the proposed mechanism of S-doped biochar for biogas production (**B**) (Hassaan et al. 2023), the specific promotion mechanisms of magnetic straw-based biochar in AD (**C**) (Liu et al. 2022a), and the synergistic effect of functional bacteria and biochar on H_2 production (**D**) (Huang et al. 2022)

biochar also play a crucial role in determining AD performance (Liu et al. 2023c) (Fig. 5A). The redox and electrochemical properties of biochar are closely linked with its OFGs. Furthermore, OFGs influence the adsorption capacities of toxic substances within AD systems (Cai et al. 2022). The physicochemical properties of biochar are largely HTT-dependent. Broadly speaking, the surface area and porosity increase with increasing HTT; while the OFGs decrease with increasing HHT, which would decrease DIET. Given the AD performance and cost, biochar produced at low HTT may be more suitable for AD.

The inherent features of pristine biochar limit its application in AD system. Engineered biochar, however, offers numerous advantages in the AD process. Hassaan et al (2023) discovered that both S-doped biochar and N-doped biochar enhance CH_4 production. S-doped biochar exhibits superior capabilities in improving biogas production (623 mL g^{-1} VS) compared to N-doped biochar, owing to the introduction of S-functional groups. The doping of S-functional groups increases the electrical conductivity and reduces pore volume of biochar, thereby playing a critical role in enhancing DIET (Hassaan et al. 2023) (Fig. 5B). A novel N-doped biochar supported with magnetite also promotes CH_4 production. Electron exchange capacity and electrical conductivity are two crucial physicochemical characteristics that facilitate DIET in this material (Zhong et al. 2023). Chemical treatments of biochar, including oxidation by oxidants, acid treatment, and alkali treatment, can improve the porosity, SSA, and redox properties of biochar, all of which are conducive to DIET and CH_4 yield (Li et al. 2022e; Lu et al. 2022; Sun et al. 2022). Optimal oxidation modification and acid treatment time can maximize biochar's performance in AD systems. Interestingly, prolonged H_2O_2 or HNO_3 treatment of biochar has either no significant effect or even inhibits the AD process (Li et al. 2022e; Sun et al. 2022).

The loading of functional materials such as metals, metallic compounds, enzymes, or microorganisms, further improves biochar's role in AD systems. For instance, incorporating a green magnetic-straw-based biochar synthesized by ball-milling and carbonization methods significantly increased CH_4 yield in AD systems by 45.36%. This enhancement is attributed to improved intracellular electron transfer and DIET within the anaerobic reactor (Liu et al. 2022a) (Fig. 5C). Additionally, nano zero-valent iron (nZVI) modification enhances the EDC of biochar, thereby facilitating the conversion of organic waste to biogas (Ning et al. 2022). Moreover, nZVI-modified biochar with its high OFGs exhibits great adsorption capacity for certain inhibitory substances (Lim et al. 2022). Overall, loading Fe-based materials onto biochar is a promising method for functionalization to enhance biochar's potential in AD systems. Immobilizing functional microorganisms on biochar promotes microbial growth and metabolism in AD systems, resulting in a synergistic effect on biogas production (Huang et al. 2022; Lee et al. 2022; Yan et al. 2022) (Fig. 5D). In conclusion, functional biochar with excellent characteristics, particularly higher EDC, electrical conductivity, and porosity exhibits greater potential for facilitating the AD process.

3.4.6 Biochar as an electrode in microbial fuel cells

Biochar's role as an electrode in microbial fuel cells (MFCs) has gained attention in recent years. MFCs technology offers an eco-friendly solution that can simultaneously remove contaminants from wastewater and generate bioelectricity as a renewable energy source (Ebrahimi et al. 2021). Biochar, with its exceptional characteristics, can function effectively as electrodes to support robust exoelectrogenic biofilm formation and improve electrochemical reactions within MFCs (Yang et al. 2023b). Of particular importance are the high porosity and SSA of biochar used in MFCs, which facilitate microbial colonization (Gao et al. 2023). Highly crystalline biochar produced via plasma-based processes with high electrical conductivity has shown promise in promoting microbial colonization and improving electrocatalytic performance in biochar-fabricated electrodes, thereby enhancing contaminant removal efficiency and electricity generation efficiency (Mittal et al. 2023) (Fig. 6A). Novel self-bonding 3D spherical biochar as anodes has also exhibited excellent electrocatalytic performance in MFCs, attributed to its high electrical conductivity and porous structure (Liu et al. 2023b).

Introducing metals such as Cu, Fe, and Co into biochar is recognized as an effective strategy to improve the performance of MFCs (Ramya et al. 2022). A newly

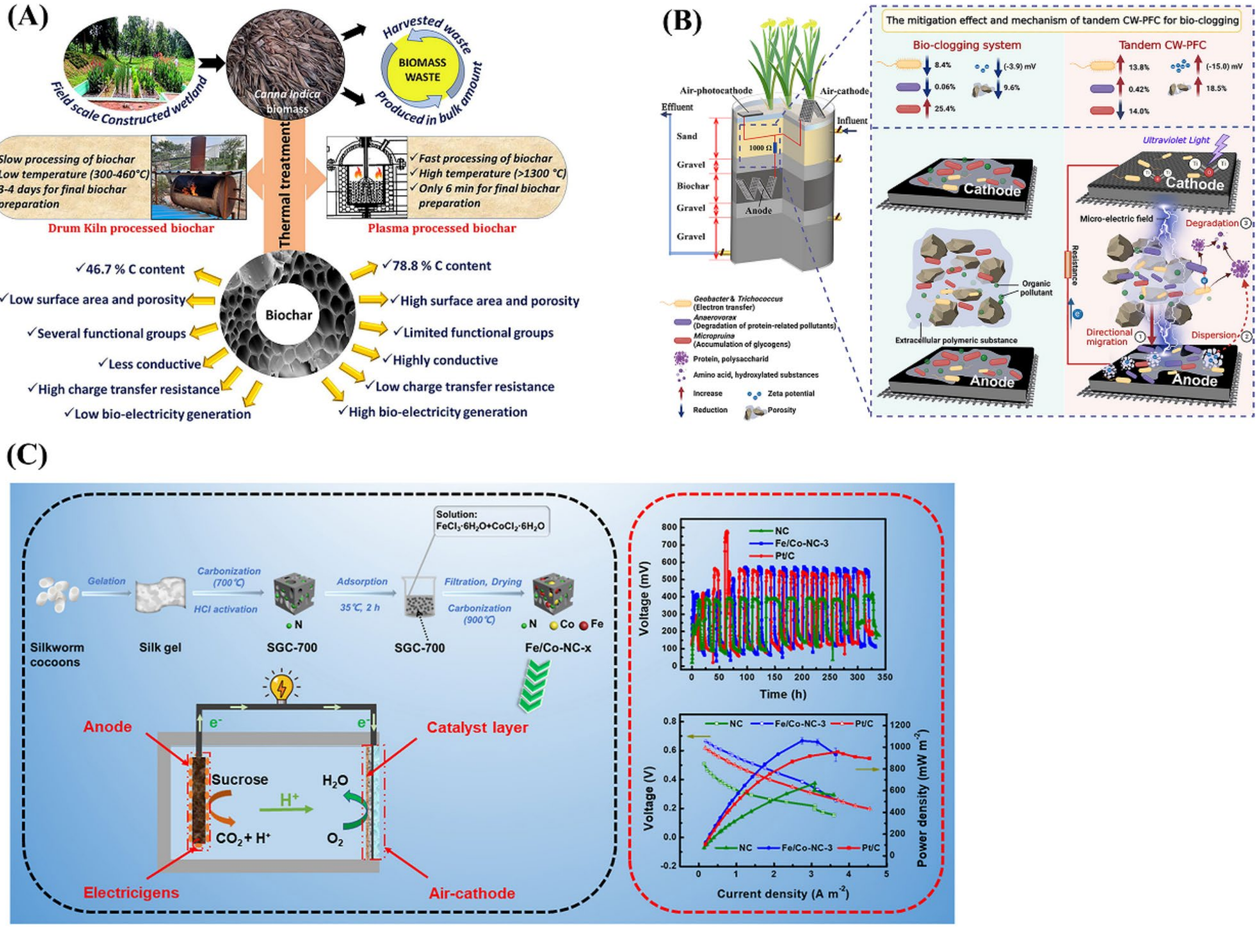


Fig. 6 The efficacy of biochar acting as a conductive electrode substrate in constructed wetlands coupled with MFCs (**A**) (Mittal et al. 2023), the performance and mechanism of Fe/Co-decorated biochar as an air–cathode catalyst in MFCs (**B**) (Liu et al. 2023a), and the mechanism of TiO_2-coated biochar as an air–photocathode in constructed wetlands coupled with MFCs (**C**) (Wang et al. 2023e)

developed Fe/Co-decorated N-rich porous biochar (Fe/Co-NC-3), synthesized through secondary carbonization of silk gel (N-rich biomass)-derived biochar initially adsorbed Fe and Co, has demonstrated remarkable performance as an air–cathode catalyst in MFCs. The presence of various N on Fe/Co-NC-3, including pyridinic N, graphitic N, and formed N–C structures, provides numerous active sites for oxygen reduction reactions (ORRs). Coating the air–cathode MFCs with Fe/Co-NC-3 enhances MFCs performance and electrical energy output (Liu et al. 2023a) (Fig. 6B). Beyond enhancing biochar's performance as electrodes in MFCs for wastewater treatment, its application can also meet the demands of constructed wetland (CW) MFCs. TiO_2/biochar-photocatalysts in the cathode accelerate ORRs and electricity generation in CW-photocatalytic fuel cells (CW-PFCs). The micro-electric field generated from CW-PFCs enhances the degradation of extracellular polymeric substances into small molecules (Wang et al. 2023e) (Fig. 6C). In conclusion, incorporating biochar into MFCs offers a promising approach for sustainable energy production and environmental remediation.

3.5 Conclusions and future expectations

This study offers a comprehensive scientometric analysis, encompassing 13,358 publications of biochar research retrieved from WoS core collection in 2022–2023. By outlining research trends and hotspots in the field of biochar, it sheds light on significantly important areas for future scientific inquiry and research directions. China emerged as the leading contributor to biochar research, with notable contributions from Hailong Wang. Keyword clustering analysis revealed prominent research focuses in 2022–2023, including "Biochar for global climate change mitigation", "Biochar for salinity and drought stress amelioration", "Biochar for toxic metals immobilization", "Biochar for organic pollutants degradation", "Biochar as additives in anaerobic digestion", and "Biochar as an electrode in microbial fuel cells". Notably, the application of biochar for global climate change mitigation gained increasing attention, while the role of biochar as electrodes in microbial fuel cells emerged as a recent focal point, highlighting the need for large renewable energy sources.

The efficacy of biochar for carbon sequestration is closely linked to soil properties, with the aging process potentially altering its physicochemical properties and thus affecting its carbon sequestration functions. Future studies are anticipated to focus on assessing the long-term carbon sequestration capability of biochar across different soil types and ecosystems. Given the growing concerns surrounding waste management, the conversion of waste biomass into biochar for safe disposal and waste recycling is expected to become more prevalent. Biochar amendment has great potential for crop pest and pathogen control. However, biochar applied at high doses may either have no effect or exacerbate crop pests or pathogens. Moreover, the efficacy of biochar in crop pest or pathogen control may vary with thermochemical conditions, feedstocks, and applied soil types. The application saturation threshold of biochar in soil for crop pest or pathogen control is still lacking and remains to be further revealed. Additionally, integrating nanotechnology into biochar production processes to enhance its role in environmental restoration, ecological sustainability, and energy efficiency is poised to be a hotspot for future research endeavors.

Although biochar applications in agriculture, environment, and energy show significant potential, there are some concerns about its feasibility. The contrasting behaviors and potential eco-environmental risks of biochar application restrict its widespread application in complex environments. More importantly, the preparation and practical application processes often lack economic viability. Biochar has great potential in soil remediation and C sequestration but does not significantly increase crop yield over conventional fertilizers, making it less appealing to farmers. Supportive regulations and subsidies for biochar application could encourage investors and adoption. Life cycle assessment (LCA) is frequently used to evaluate the feasibility of biochar applications in agriculture, environment, and energy. A comprehensive LCA on biochar as a soil amendment and energy fuel, considering economic feasibility and ecological effects, is needed to maximize biochar's benefits. For instance, LCA can assess the feasibility of converting biomass wastes into biochar for C sequestration. Biochar's incorporation into MFCs as an electrode material and catalyst for energy production and environmental remediation is a growing area of interest, requiring further investigation to improve its potential. A holistic LCA can estimate the net environmental advantages of biochar application in MFCs. Techno-economic evaluations are also vital for sustaining the commercial feasibility of biochar-based MFCs. To ensure sustainable use of biochar, future research should emphasize economic viability and LCA of biochar production and application.

Supplementary Information

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Supplementary Material 1.

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Availability of data and materials
All data generated during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

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

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