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Biochar

REVIEW

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Bibliometric analysis of biochar research in 2021: a critical review for development, hotspots and trend directions

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Abstract

As a bioproduct from the thermal decomposition of biomass, biochar has various applications in diversified field. In this study, a bibliometric analysis was conducted to visualize the current research status and trends of biochar research. A total of 5535 documents were collected from the Web of Science Core Collection and subjected to visualization analysis for the biochar field's development in 2021 with CiteSpace software. The visual analysis results demonstrate that the number of publications expanded dramatically in 2021, and the growth trend would continue. China and USA were the most contributing countries in biochar research in terms of the number of publications. Based on the keyword co-occurrence analyses, "Biochar for toxic metal immobilization", "Biochar-based catalyst for biofuel production", "Biochar for global climate change mitigation", "Biochar for salinity and drought stress amelioration", "Biochar amendment in composting", and "Biochar as additives in anaerobic digestion" were the main research trends and hotspots in this field in 2021. This indicates that the biochar research was multidisciplinary. Regarding the research hotspots, the employment of biochar as heterogeneous catalysts for biofuel production gained great attention in 2021. On the contrary, bioremediation using functional bacteria immobilized on biochar and biochar-assisted advanced oxidation process were well-studied but with less frequency than other topics in 2021. Furthermore, the future research was proposed for green and sustainable applications of biochar. This review provides a comprehensive

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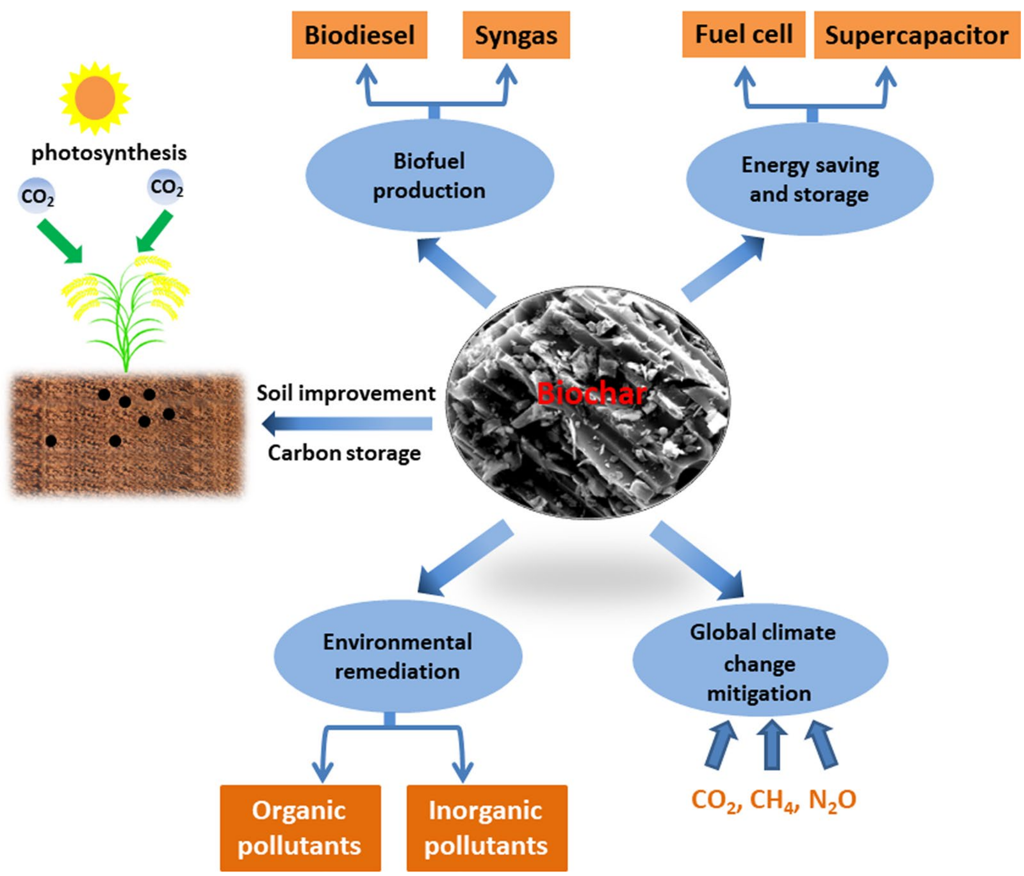
overview of the research frontiers, the evolution of research hotspots, and potential future research directions in the biochar field.

Highlights

- A total of 5535 publications were retrieved and evaluated by bibliometric analysis in 2021.
- Research frontiers and the evolution of research hotspots of biochar were identified.
- Future research outlooks were suggested for sustainable applications of biochar.

Keywords Bibliometric analysis, Citespace, Research hotspots, Toxic metal immobilization, Sustainable application

Graphical Abstract



1 Introduction

Biochar is a pyrogenic carbon-rich material formed through the thermal decomposition of biomass feedstock under an oxygen-limited condition (Hagemann et al. 2017; Inyang et al. 2015; Woolf et al. 2021). It has been established that different biomass materials have been utilized to produce biochar which entails agricultural waste, forestry waste, garden waste, food waste, livestock manure, sewage sludge, and aquatic organisms (Woolf et al. 2010; Wu et al. 2021a). Many processes can be used to produce biochar such as slow and fast pyrolysis, microwave-assisted pyrolysis, hydrothermal carbonization, gasification, flash carbonization, and torrefaction (Kostas et al. 2020; Wu et al. 2020; Wu et al. 2021a; Xiao et al. 2018) (Fig. 1). Slow pyrolysis and hydrothermal carbonization are the most frequently used methods for the preparation of biochar (Dutta et al. 2021; Lian and Xing 2017). Biochar is a heterogeneous mixture containing both amorphous less-carbonized fractions and microcrystalline graphite-like aromatic structures. It has special properties, such as highly developed porosity, high specific surface area (SSA), abundant surface functional groups, and high content of mineral components. Biochar properties are mainly regulated by feedstock composition and preparation procedures (Ahmad et al. 2014; Cha et al. 2016; Lian and Xing 2017).

Biochar has received increasing attention for its potential benefits in carbon sequestration, climate change mitigation, waste management, bioenergy production, soil improvement, and pollution control due to its unique properties (Nidheesh et al. 2021; Xiao et al. 2018; Yang et al. 2021e). Biochar has a high recalcitrant carbon (C) content and the strong adsorption capacity to carbon dioxide (CO_2). Its sustainable production and field applications enable its great potential for long-term carbon storage and carbon emission reduction, thereby mitigating climate change (Feng et al. 2021b; Yang et al. 2021e; Zhang et al. 2022). The conversion of biowaste, especially sewage sludge, into biochar through pyrolysis provides an alternative and promising way of managing waste biomass (Chen et al. 2020). The produced biochar can act as a catalyst for bioenergy production (Malyan et al. 2021). Again, biochar positively affects plant productivity and crop yields by improving soil quality and fertility levels (Farkas et al. 2020).

Meanwhile, the improvement in soil functions after biochar application is beneficial to alleviate the salinity and drought stress on plants (Mansoor et al. 2021; Zhu et al. 2020). Finally, the multifunctional characteristic of biochar makes it an effective material for environmental pollution (Ahmad et al. 2014; Nidheesh et al. 2021). The biochar's multiple functions are connected to its physicochemical properties (Manya 2012; Zhang et al. 2021g). Considering the striking heterogeneity in physicochemical properties of biochar, an in-depth understanding of the developments of biochar regarding its multifunctional applications is urgently required.

Although several meta-analyses and review studies have been carried out to evaluate biochar's multifunctional applications systematically, very few have investigated current trends and scientific developments in this field. A conclusive study was performed here and could help us to identify the main subject fields, the current research frontiers, and hotspots of biochar research (Wu et al. 2019; Wu et al. 2021a). Because new biochar applications emerge, the main signs of progress and insights associated with this field will change over time. Additionally, the unintended consequences of biochar application are likely to emerge after long-term biochar application. Therefore, it is necessary to provide an analytical overview of the main signs of progress and insights into biochar research in 2021.

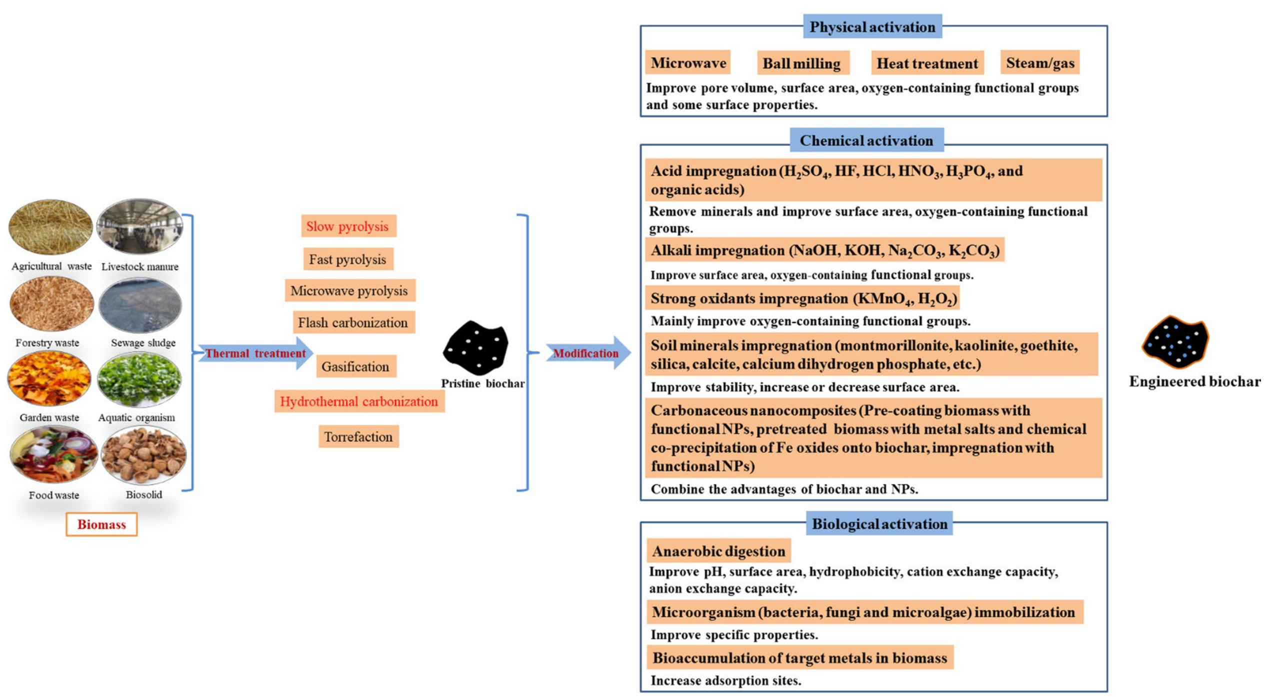


Fig. 1 Biochar production and modification. Modified from Wu et al. (2020)

Bibliometric analysis proceeded by Citespace software has gained rising interest in many fields due to its mathematical statistics and visual analytic functions (Chen 2004, 2017; Ren et al. 2021). It is believed to be an effective tool for quantitatively evaluating a given field's current situation and emerging trends (Kamali et al. 2020). In this study, a combined bibliometric analysis and critical appraisal of the related documents were utilized to quantitatively identify the research status and trend of biochar in 2021. The aims of this review are to: (1) analyze the primary authors, countries, and keyword frequency and hotspot trend of the publications; (2) identify the current trends and hot topics in the biochar field; (3) provide perspectives on full-scale applications of biochar.

2 Methods

2.1 Literature search

A systematic literature search was conducted from the Web of Science (WoS) Core Collection database using the keyword of "Biochar" in the title, keywords, and abstract (Ren et al. 2021). A total of 5533 documents were collected from the database in 2021. To guarantee the validity of data collected, the synonyms associated with biochar research, such as "Cadmium" and "Cd", "carbon dioxide" and "CO_2", "anaerobic digestion" and "AD", "nanoscale zero-valent iron" and "nZVI", and "polycyclic aromatic hydrocarbon" and "PAHs" were manually merged.

2.2 Scientometrics analysis tools

Cite-space is a new statistical analysis tool widely used for bibliometric analysis and visualization (Li et al. 2020; Ren et al. 2021). It is a Java-based software first developed by Professor Chaomei Chen and his team in 2004 (Chen 2004). Relevant documents were exported from the "marked list" (with "plain text" format) of WoS Core Collection and then inserted in Cite-space (5.3.R4) to analyze their specific characteristics. The visual analysis of cooperation networks of authors, contributing countries, institutions, categories, and keywords helps to reveal the clustering, knowledge structure, and emerging trends of biochar research. In the co-occurrence network maps, each node corresponds to one item (e.g., author, institution, keyword), and lines link the nodes. The higher the node's frequency, the larger the node's size. The thickness of the line indicates the cooperation degree between the two nodes.

3 Results and discussion

3.1 Publications about biochar research

A total of 5533 documents were extracted from WoS Core Collection in 2021 (Additional file 1: Fig. S1). It can be seen that the annual number of publications increased sharply, and this growth trend will continue, which indicates the huge and increasing attention as well as the increased amount of scientific knowledge of biochar research.

3.2 Contributing country analysis

As can be realized from Additional file 1: Fig. S2 and Table S1, China is the highest contributing country, accounting for 43.99% of the total publications. This is most likely because China is a great agricultural country with a large population, where agriculture occupies a significant and strategic position in the national economy. China was followed by the USA, with 504 publications, accounting for 9.11%. Besides China and USA, India, Pakistan, South Korea, Australia, Canada, Brazil, Saudi Arabia, and Germany also have many scientific documents. Many connections between countries indicate robust global cooperation and communication in this field.

3.3 Research institution analysis

The top 10 institutions with the most publications in the field of biochar research are summarized in Additional file 1: Table S2. Chinese Academy of Sciences published the largest number of papers in this field, followed by the University of Chinese Academy of Sciences and Zhejiang University. The Chinese Academy of Sciences is expected to be the leading institution in many fields. It can also be found that 8 institutions were from China among the top 10 productive institutions.

3.4 Keyword analysis

3.4.1 Biochar for toxic metal immobilization

Biochar utilized for immobilizing toxic metals has caused the interest of researchers in 2021 (Fig. 2). Keyword co-occurrence analysis suggested that the most studied toxic metal was Cd (Table 1). Such heightened research interest in Cd was due to its being highly toxic and carcinogenic even at low concentrations (Purkayastha et al. 2014; Rai et al. 2019).

The transformation of sewage sludge to biochar via pyrolysis provides a feasible approach for the safe disposal of the sludge (Buss 2021; Zhang et al. 2021f). The sewage sludge-derived biochar had a much lower leaching potential of heavy metals than the sewage sludge itself (Wang et al. 2021d; Xiong et al. 2021). Recently, co-pyrolysis of sewage sludge and waste biomass (e.g., rice straw, rice husk, cotton stalk, and sawdust) has been proven to improve the porous structure and reduce the leaching toxicity of heavy metals in sewage sludge-derived biochar (Tong et al. 2021; Wang et al. 2021d, 2021f, 2021g; Xiong et al. 2021). Another study also reported that co-pyrolysis of sewage sludge and calcium sulfate was conducive to

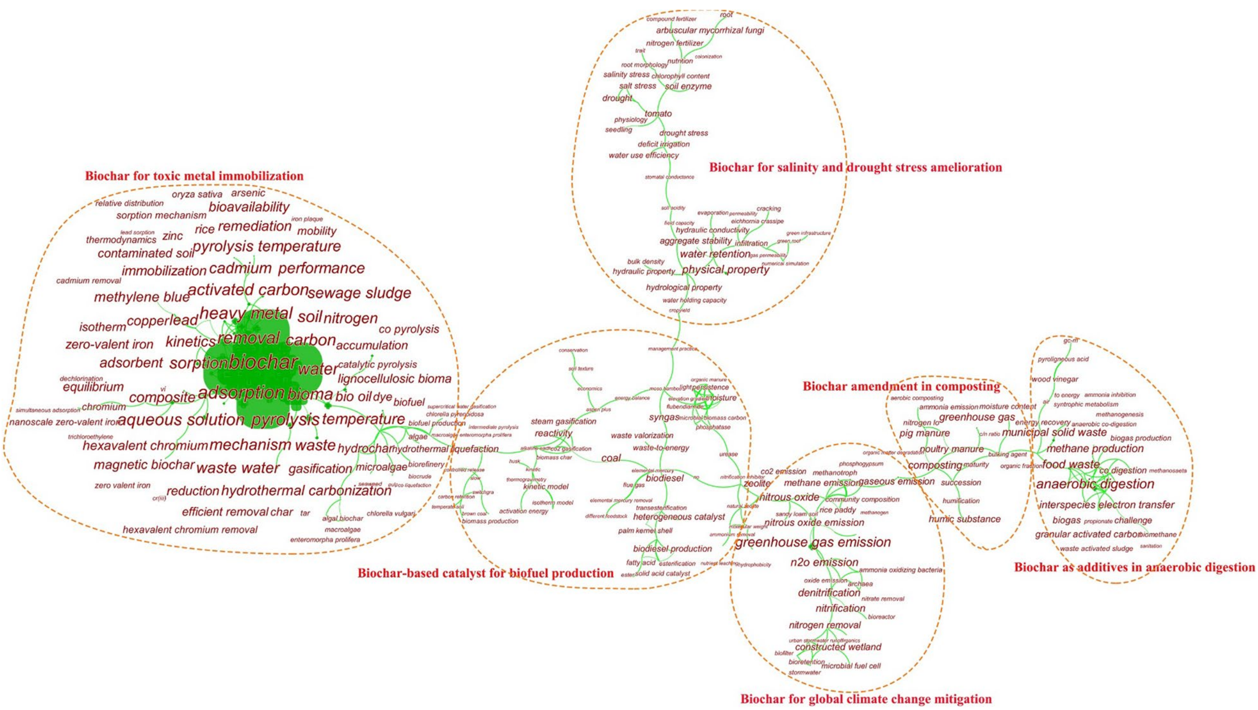


Fig. 2 Keyword co-occurrence map of biochar research in 2021

Table 1 The top 20 keywords related to biochar research in 2021

Rank	Keyword	Frequency
1	Biochar	2774
2	Adsorption	1064
3	Removal	716
4	Pyrolysis	668
5	Heavy metal	605
6	Aqueous solution	573
7	Bioma	545
8	Carbon	486
9	Activated carbon	484
10	Sorption	449
11	Water	448
12	Soil	439
13	Mechanism	419
14	Waste	327
15	Cadmium	325
16	Pyrolysis temperature	312
17	Performance	311
18	Sewage sludge	303
19	Waste water	297
20	Temperature	294

immobilizing heavy metals in sewage sludge-derived biochar (Liu et al. 2021a). The application of sewage sludge-derived biochar as a sorbent for toxic metal removal has shown promising results. The abundant mineral constituents in sewage sludge-derived biochar, such as Si, Al, Fe, and Ca, greatly participated in cationic metal removal via cation exchange, complexation, and precipitation (Gopinath et al. 2021; Islam et al. 2021; Jellali et al. 2021).

Engineered biochar has gained much attention in terms of immobilizing toxic metals in 2021. Modification may improve the carbon content, SSA, porous structure, functional groups, and stability of biochar. Recently, metal oxides and salts have been widely used for biochar modification. Magnetic or metal-based biochar synthesized by using the transition metals (e.g., Fe, Co, Ni) and their oxides (e.g., Fe_2O_3 and Fe_3O_4) with waste biomass exhibits advantages over pristine biochar in heavy metal immobilization. For instance, a novel functional colloid-like magnetic biochar with high dispersibility synthesized via impregnation of Fe(II)/Fe(III)/artificial humic acid onto corn stalk-derived biochar followed by torrefaction activation exhibited superior removal performance for Cd (the maximum adsorption capacity of 170 mg g^{-1}) (Yang et al. 2021c). The removal mechanisms included ion exchange, Cd–π interaction, complexation, and precipitation (Fig. 3a). Hierarchically porous magnetic biochar produced from K_2FeO_4 pre-treated wheat straw at 700 °C effectively removed Cd by 80 mg g^{-1} (Fu et al. 2021b). The pre- and post-heat treatment modification with Fe could produce Fe-loaded biochar with different properties. Generally, the Fe pre-modification

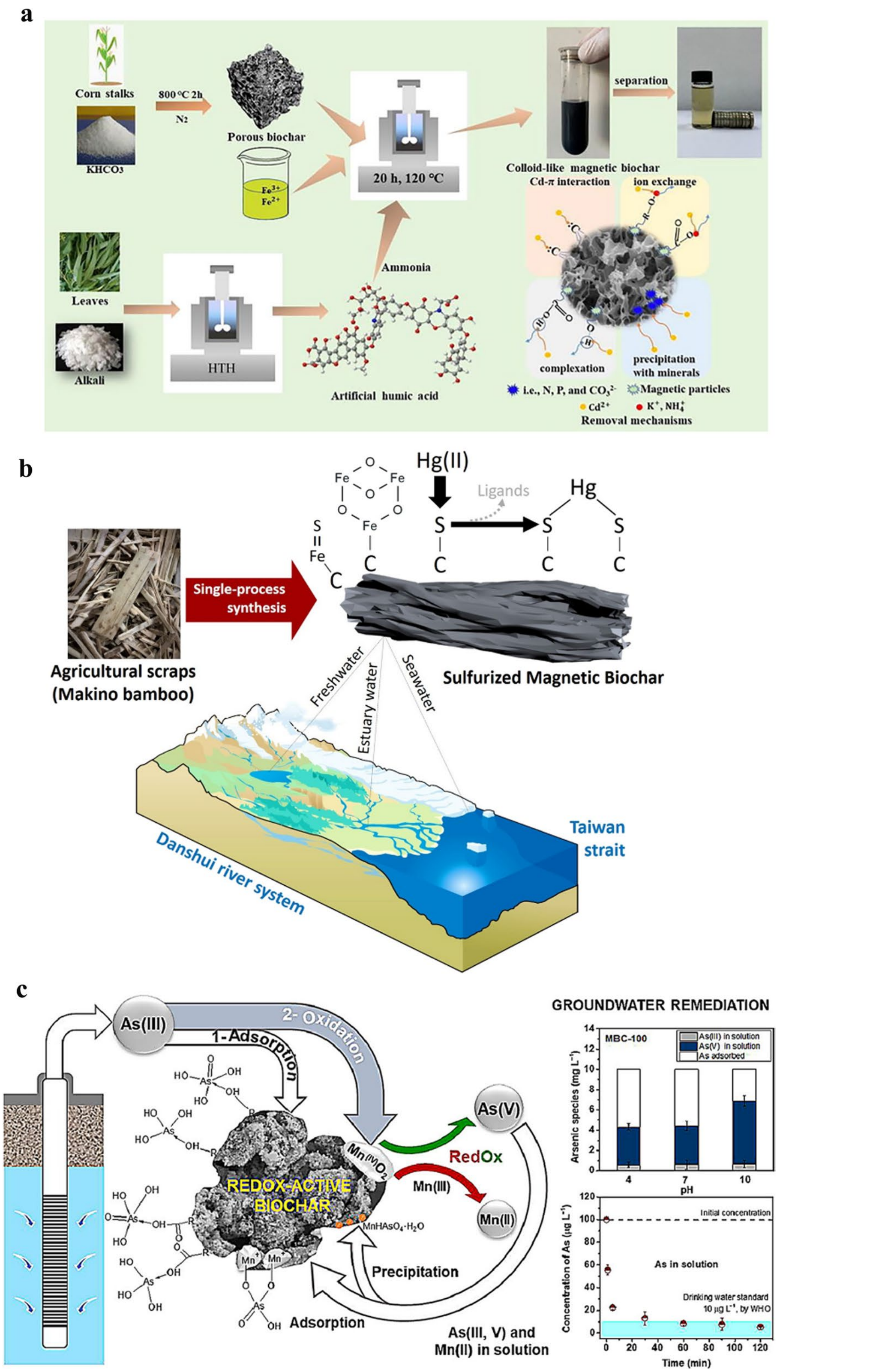


Fig. 3 Possible pathways for the removal of toxic metals by biochar. Cd removal mechanisms by functional colloid-like magnetic biochar (**a**) (Yang et al. 2021c); Hg(II) removal mechanisms by sulfurized magnetic biochar (**b**) (Hsu et al. 2021); As(III) removal mechanisms by MnO_2-biochar composite (**c**) (Cuong et al. 2021)

loaded greater Fe_3O_4 micro-/nanoparticles on biochar and achieved greater surface area, while the Fe post-modification enriched oxygen-containing functional groups on biochar (Reynel-Ávila et al. 2021; Zhao et al. 2021b). Hsu et al. (2021) synthesized sulfurized magnetic biochar via a single heating step. The product had high adsorption for Hg(II) (the maximum adsorption capacity of 8.93 mg g^{-1}), and C-S functional groups were the vital adsorptive sites for Hg(II) (Fig. 3b).

For metal anions (mainly As and Cr), biochar-based composites are effective sorbents for Cr and As. An active MnO_2-biochar composite was prepared to enhance As(III) removal from the aqueous solution. The removal mechanisms involved partial As(III) adsorption and the oxidation of As(III) to As(V) by MnO_2. The generated As(V) could be removed by forming MnHAsO4·H2O precipitation with Mn(II), complexation with Mn-OH groups on the MnO_2 surface, and O-containing functional groups on the biochar surface (Fig. 3c) (Cuong et al. 2021). Nano zero-valent iron (nZVI) modified biochar has been proven to be a promising remediation material for Cr removal (Zhou et al. 2021b; Zhuang et al. 2021). For instance, Zhuang et al. (2021) synthesized sulfidated nZVI-supported biochar for Cr(VI) removal. The porous structure of biochar and sulfidated nZVI dispersed on biochar surface could provide adsorption sites for Cr(VI). Then, Fe^0 and generated Fe(II) acted as electron donors to reduce Cr(VI). The generated Cr(III) would form co-precipitation with Fe(III) and be removed from the aqueous solution.

The employment of biochar in reducing the bioavailability and phytotoxicity of toxic metals in soil has attracted growing interest. However, pristine biochar has a limited effect on the remediation of toxic metal-contaminated soils (Arabi et al. 2021; El-Naggar et al. 2021). It was found that biochar, especially rice straw-derived biochar application contributed to the reduction of As(V) to As(III), which increased the potential mobility of As in soils (El-Naggar et al. 2021). Heat treatment temperature (HTT) is a predominant parameter influencing As mobility in soil. A meta-analysis indicated that biochar produced under low HTT ($\leq$450 °C) did not affect As mobility in soil, but high-temperature biochar (>450 °C) exhibited high As mobilization in soil (Arabi et al. 2021). Fe-modified biochar exhibited efficient removal of As from soil and reduced its mobility in paddy soil (Wen et al. 2021). Similarly, Fe/Al/Zn (hydr)oxides modified biochar significantly reduced As uptake by arugula (Sun et al. 2021b). More importantly, Fe-modified biochar could be considered an efficient remediation material for moderately and highly Cd- and As-co-contaminated farmland (Wen et al. 2021; Yang et al. 2021a, b).

Although most of the positive results are achieved for acidic heavy metal-contaminated soil amended with biochar, there needs to be more research on the remediation effect of biochar on alkaline heavy metal-contaminated soil. Previous studies showed that conventional biochar showed no significant remediation effect in alkaline soil. Meanwhile, biochar amendment might reduce soil fertility and cause soil alkalization. Fe- and Fe/Zn-modified biochar application promoted the transformation of exchangeable Cd into oxidizable and residual Cd (Sun et al. 2021c; Yang et al. 2021g). Moreover, Fe-modified biochar increased the richness and diversity of bacterial communities in the alkaline contaminated soil (Sun et al. 2021c). The combination of biochar with ferrous sulfate and pig manure is also reported to effectively immobilize Cd and reduce Cd uptake by wheat in the alkaline contaminated soil (Chen et al. 2021b).

3.4.2 Biochar-based catalyst for biofuel production

The employment of biochar as heterogeneous catalysts for biofuel production gained much attention in 2021. Biochar-based catalyst possesses sustainable feedstock availability, abundant surface functional groups and inorganic species, a hierarchical and well-developed porous structure, and tunable surface functionality (Chi et al. 2021; Low and Yee 2021).

Using biochar-based heterogeneous catalysts for biodiesel production is still a great research hotspot in 2021. The presence of biochar-based catalyst promoted the transesterification or esterification of waste cooking oil, vegetable oil, animal oil, or fats (Chi et al. 2021; Cho et al. 2021; Low and Yee 2021). Swine manure-derived biochar could act as an alkaline catalyst for the transesterification lipid fraction extracted from the swine manure (Fig. 4a). A high yield of biodiesel ($\geq$94%) was achieved with the application of the catalyst (Cho et al. 2021). A maximum biodiesel yield of 96.4% was obtained with methanol: oil ratio of 9:1 at 70 °C for 2 h using $K_2CO_3+Cu(NO_3)_2$-treated hydrochar-derived catalyst (Fig. 4b) (Abdullah et al. 2021). Likewise, Nazir et al. (2021) obtained a biodiesel yield of 89.19% at 60 °C for 15 min in the transesterification of oil with methanol at a molar ratio of 1:18, catalyzed by H_2SO_4-modified biochar. Moreover, the biochar-based catalyst exhibited high reusability and stability with a minor loss in its activity after being reused for six cycles. Microwave-assisted biofuel production has recently gained great attention due to the advantages of microwave heating (i.e., quick heating rate and energy efficiency) (Nazir et al. 2021; Zailan et al. 2021).

Syngas, produced through biomass gasification, usually consists of H_2, CO, CH_4, CO_2, and other hydrocarbons such as bio-oil or tar (Low and Yee 2021; Sun et al. 2021a). The addition of biochar as a catalyst for syngas

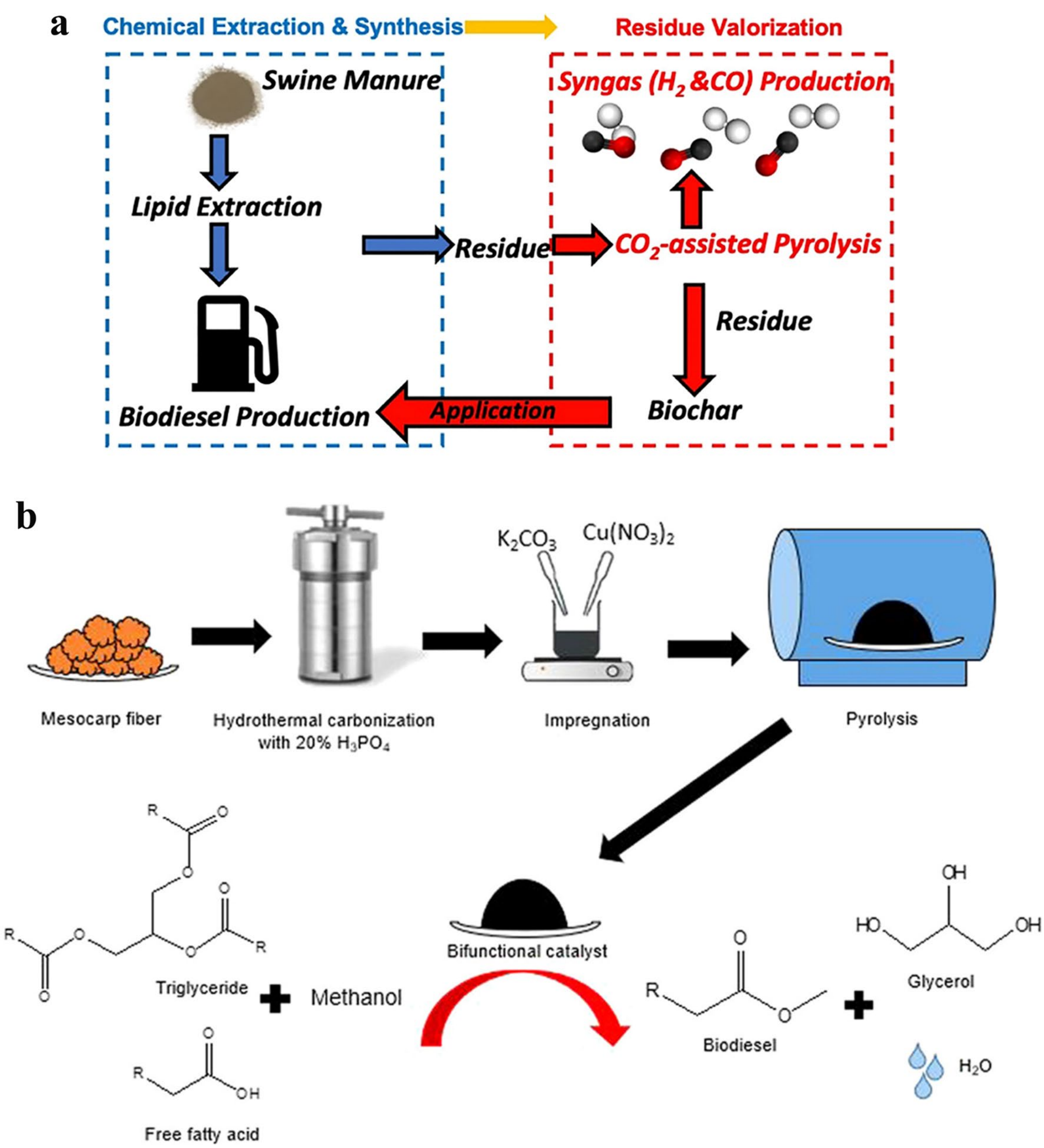


Fig. 4 Employment of biochar as heterogeneous catalysts for biofuel production. Biodiesel production through biochar-catalyzed transesterification of lipid fraction extracted from the swine manure (**a**) (Cho et al. 2021); Biodiesel production with $K_2CO_3 + Cu(NO_3)_2$-treated hydrochar as a catalyst (**b**) (Abdullah et al. 2021)

production and upgrading has been largely reported recently. Biochar-based catalysts have several advantages in tar reforming and syngas cleaning: (1) the highly porous structure and large SSA are conducive to prolonging the retention time of the reactants and improving their conversion efficiency; (2) the abundant functional groups favor the reforming of volatiles from biomass heat treatment; and (3) the alkali and alkali earth metals and other inorganic species present in biochar can provide a catalytic effect on tar removal (Feng et al. 2021a; Hu et al. 2021a; Liu et al. 2021c). By using walnut shell biochar with high contents of K_2O and CaO as a catalyst, the conversion efficiency of tar and H_2-rich gas production increased (Mazhkoo et al. 2021). Anniwaer et al. (2021) reported that biochar derived from Japanese cedarwood possessed a highly porous structure and contained high contents of alkali and alkaline earth metals, which might provide high catalytic activity for tar reforming. In this study, 99% of the remaining tar was cracked/reformed, yielding H_2-rich syngas. Metal-supported biochar exhibited excellent catalytic activity in syngas upgrading. Hu et al. (2021a) loaded Fe–Ni on pine wood biochar as a catalyst for syngas production; their results indicated that Fe–Ni-supported biochar significantly increased H_2/CO ratio to 1.97 in syngas. In addition, Fe–Ni-supported biochar still exhibited excellent catalytic activity after five times of reuse. Similarly, an H_2 concentration of 67.35% in syngas and a gasification efficiency of 96.93% could achieve by using Fe/Ca/Al-loaded biochar as a catalyst (Hu et al. 2021b). In short, engineered biochar has tremendous promise as a catalyst in syngas upgrading.

3.4.3 Biochar for global climate change mitigation

Biochar production and amendment have been increasingly adopted to mitigate global climate change (Woolf et al. 2021). China's rising influence on global climate change mitigation advances biochar's role in climate governance. The functionality of biochar to achieve carbon–neutral goals is mainly through carbon sequestration and emission reduction (Cao et al. 2021; Nan et al. 2021). The high content of aromatic carbon within biochar is the basis of its carbon sequestration benefits (Xu et al. 2021). Biochar storage in soil via agricultural soil management can also realize carbon sequestration (Guenet et al. 2021). Therefore, converting biomass waste into biochar and storing the produced biochar in soil has excellent potential for carbon sequestration. Yang et al. (2021d) used a life cycle assessment at the country level to evaluate the carbon sequestration potential of biochar produced from various crop residues. It was found that over 920 kg CO_{2e} t^{-1} (CO_2-equivalent) sequestration could be achieved in China, demonstrating great carbon sequestration potential through biochar that was incorporated into soil (Fig. 5a). Similarly, Leppäkoski et al. (2021) calculated the carbon footprint of willow biochar production and application in marginal lands by conducting a cradle-to-grave LCA. Their results found that the carbon footprint of willow biochar was − 1875 kg CO_{2e} t^{-1}, in which carbon sequestration (− 1704 kg CO_{2e} t^{-1}) dominated the carbon footprint. It is estimated that 63 − 82% of initial carbon in biochar was stably sequestered in soil after 100 years of using a greenhouse gas inventory model (Woolf et al. 2021). These results indicate the long-term sequestration of carbon by biochar storage in soil.

Biochar also has a high potential for CO_2 capture and storage (Shafawi et al. 2021). It has been reported that a large surface area, high micro-porosity, and abundant mineral contents of biochar contributed to CO_2 capture (Feng et al. 2021b; Shafawi et al. 2021). To highlight, N-doped biochar showed a superior CO_2 uptake capacity. The N-doped biochar prepared by urea phosphate impregnation-pyrolysis had a superior CO_2 adsorption capacity of 1.34 mmol g^{-1} (Ma et al. 2021). The excellent adsorption property of CO_2 was attributed to the enhanced microporous structure and various N-containing functional groups on the biochar (Fig. 5b). A related study by Feng et al. (2021b) showed that $NH_3·H_2O$ activation was beneficial to forming micropores and

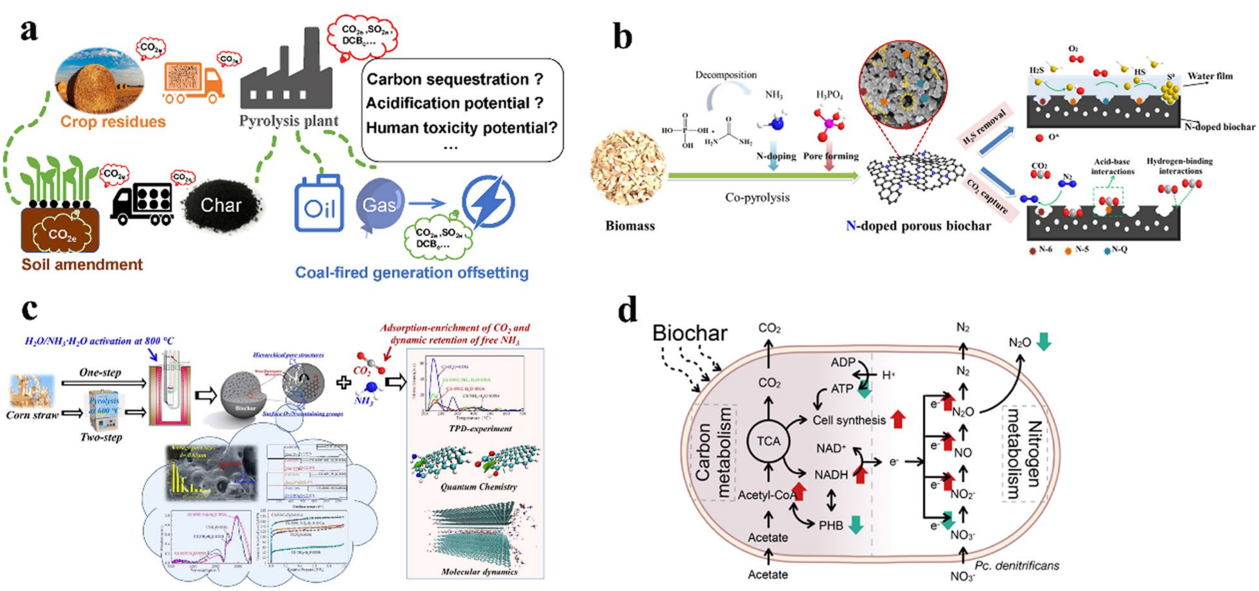


Fig. 5 Country-level potential of carbon sequestration for biochar implementation (**a**) (Yang et al. 2021d); The removal mechanisms of CO_2 by N-doped biochar (**b**) (Ma et al. 2021); The removal mechanisms of CO_2 by $NH_3·H_2O$-activated biochar (**c**) (Feng et al. 2021b); The mitigation mechanisms of N_2O Emission by biochar at the cellular level (**d**) (Zhang et al. 2021 g)

introducing N-containing functional groups on biochar surfaces. The N-containing functional groups dominated the adsorption of CO_2 (Fig. 5c).

Nitrous oxide (N_2O) has a global warming potential of 298 times that of CO_2, which plays an essential role in global warming (Zhang et al. 2021g). Excessive application of N fertilization and low N use efficiency are the primary sources of soil N_2O emissions (Reay et al. 2012; Tian et al. 2019). Numerous studies have demonstrated the effectiveness of biochar in mitigating N_2O emissions (Deng et al. 2021a; Jiang et al. 2021; Shin et al. 2021). Lower N_2O emissions involved several mechanisms, which included abiotic N retention mechanisms and microbial N immobilization mechanisms (Guenet et al. 2021; Lehmann et al. 2021; Liao et al. 2021). The promoted microbial reduction of N_2O to N_2 by biochar amendment was believed to be a permanent mitigation benefit as the transformation could not be reversed, and N had left the soil system. The microbial reduction of N_2O to N_2 could result from an increased expression of denitrification-associated functional genes (e.g., *nosZ, nirK, nirK*, and *narG*) (Deng et al. 2021a; Liao et al. 2021; Wu et al. 2021b). Additionally, biochar could act as an electron shuttle to facilitate electron transfer and N_2O reduction through biochar's O-containing functional groups and carbon matrices (Yuan et al. 2021; Zhao et al. 2021c). It is important to note that the positive effects of biochar on denitrification metabolism could be elucidated at the cellular level by integrating physiological and multi-omics (proteomic and metabolomics) analyses (Zhang et al. 2021g). It was observed that biochar could directly modulate carbon metabolism and allocate the produced reducing power, thereby promoting N_2O reduction (Fig. 5d). ^{15}N stable isotope tracing techniques have been widely used to gain insight into N_2O emissions in biochar-amended soils (Craswell et al. 2021). Zhang et al. (2021c) utilized a dual isotope (^{15}N–^{18}O) labeling technique to differentiate the contribution of nitrifier nitrification, nitrifier denitrification, nitrification-coupled denitrification, and heterotrophic denitrification to soil N_2O emissions amended with biochar. Their results indicated that biochar reduced N_2O emissions derived from nitrifier denitrification by 45–94%, nitrification-coupled denitrification by 30–64%, and heterotrophic denitrification by 35–46%. Biochar application for N_2O emission mitigation was due to the decrease of nitrite concentration while increasing N_2O reduction (Zhang et al. 2021c). A long-term field study also used a dual isotope (^{15}N–^{18}O) labeling technique to measure the effects of biochar on N_2O emissions; the results showed that biochar decreased N_2O emissions by 48% and 22% in acidic and alkaline soils, respectively. Lower N_2O emissions resulted from the decrease in nitrifier denitrification (by 74%) and heterotrophic denitrification (by 58%) (Zhang et al. 2021e). The ^{15}N stable isotope tracing techniques may help to fully understand N_2O emission mitigation mechanisms by biochar.

Biochar has been well-reported to mitigate CH_4 emissions from paddy soil (Dong et al. 2021; Jiang et al. 2021; Qi et al. 2021b). The mechanisms of CH_4 emission mitigation by biochar mainly included: (i) biochar inhibited the activity and abundance of methanogens but stimulated those of methanotrophs (Nan et al. 2021); (ii) biochar increased the adsorption of CH_4 in soil (Zhao et al. 2021a). Contrastingly, other studies have found that biochar amendment increased CH_4 emissions from paddy soils (Cao et al. 2021; Yang et al. 2021h). The unintended consequence of an increase in CH_4 emissions may result from the improved aeration condition after biochar application (Cao et al. 2021). Moreover, biochar's geoconductor function could directly transfer electrons to methanogens, stimulating CH_4 production (Yang et al. 2021h). The contradictory studies could be due to the differences in biochar and soil properties (Malyan et al. 2021; Yang et al. 2021h). Based on the discussions, biochar has great potential in mitigating CH_4 emissions from paddy soils. However, scientific soil management and proper biochar are necessary to avoid the unintended consequence of increased CH_4 production.

3.4.4 Biochar for salinity and drought stress amelioration

Biochar has the potential to enhance salinity tolerance to plants by improving soil physical (porosity, water holding capacity, hydraulic conductivity, pH, SOC), chemical (Na^+ bioavailability, cation–anion exchange capacity, nutrients, enzymatic activities), and biological (microbial activities, symbiotic N_2-fixation) properties (Farhangi-Abriz and Ghassemi-Golezani 2021; Singh et al. 2021). Incorporating biochar in salt-affected soil improved soluble cation (Ca^{2+}, Mg^{2+}) contents but decreased Na^+ concentration through its high sorption capacity. The higher Ca^{2+} concentration and lower Na^+ concentration facilitated K and P uptake by plants and thus promoted plant productivity (Zhou et al. 2021d). It was also found that biochar amendment in saline soil increased photosynthetic rate, leaf water content, stomatal conductance, pigment contents, nutrient uptake, and root and shoot growth (Cui et al. 2021a; Farhangi-Abriz and Ghassemi-Golezani 2021; Liang et al. 2021c; Singh et al. 2021). In some cases, toxic metal contamination and soil salinity may cause a more serious environmental concern. Soil salinity may aggravate the stress caused by toxic metals on plants (Azadi and Raiesi 2021; Shabbir et al. 2021). Biochar has been reported to mitigate the potential pressures of the co-occurrence of toxic metal contamination and salinity (Azadi and Raiesi 2021; Shabbir et al. 2021). The salt stress could also be alleviated by supplementing biochar with other additives. In addition, combining biochar with compost has increased plant productivity (Liang et al. 2021b).

Drought stress has been considered a major challenge for sustainable agricultural productivity (Mansoor et al. 2021). It has been discovered that biochar amendment improved the retention and availability of soil water, which led to enhanced stomatal conductance, photosynthetic rate, and productivity under drought stress (Fu et al. 2021a; Kim et al. 2021; Safahani Langeroodi et al. 2021). Biochar played a positive role in nutrient supply and improved plant performance in the clay soil under drought conditions (Mannan et al. 2021). The biochar amendment could also alleviate the oxidative damage of plants induced by drought stress (Khan et al. 2021; Safahani Langeroodi et al. 2021). Overall, biochar is an efficient soil amendment to ameliorate soil salinity/drought stress, improve soil functions, and promote plant productivity in salt/drought-affected soil.

3.4.5 Biochar amendment in composting

Composting is a promising technology to convert organic waste into stable and humus-like products for use as organic fertilizer (Lu et al. 2021; Shan et al. 2021; Yin et al. 2021). Composting is a cost-effective way to manage agricultural and breeding industry waste in China. However, some issues such as greenhouse gases (CH_4, CO_2, and N_2O) and odorous emissions (NH_3 and H_2S), and nitrogen loss during composting impede the development of these practices (Yin et al. 2021; Zhou et al. 2021c). The functionality of biochar as a bulking agent for composting has been proven to be a promising strategy for solving the environmental trade-offs of composting. Biochar as additives could enhance the aeration rate and provide main shelters for microorganisms to enhance their activity, thus improving the humification process and composting performance as well as minimizing GHGs and odor emissions. These capabilities are mainly attributed to its unique properties, including porous structure, large SSA, and abundant functional groups (Awasthi et al. 2021; Guo et al. 2021; Wang et al. 2021c). HHT is a critical parameter in assessing biochar's function in mitigating GHGs emissions during composting (Yin et al. 2021). It is concluded that biochar pyrolyzed at high temperatures (500–900 °C) is more effective in mitigating CH_4 and N_2O emissions; in comparison, biochar produced at low temperatures (< 500 °C) has a greater effect on reducing NH_3 emissions (Yin et al. 2021).

Toxic metals and antibiotics/antibiotic resistance genes (ARGs) are the main contaminants in composting products (Lu et al. 2021; Zhou et al. 2021a). It has been reported that biochar amendment aerobic composting is an efficient technology for reducing ARGs abundance in livestock manure and sewage sludge (Fu et al. 2021c; Zhou et al. 2021a). Qiu et al. (2021) found that biochar reduced the total abundance of ARGs by 17.6% during sewage sludge composting. The analysis revealed that biochar reduced the abundance of bacterial pathogens such as *Bacteroides and Pseudomonas*. It is suggested that change in the bacterial community by biochar amendment dominated the reduction in the risk of ARGs in manure/sludge composting (Mazhar et al. 2021; Qiu et al. 2021). Composting livestock manure or sewage sludge with biochar has also been reported to reduce the mobility and bioavailability of toxic metals. In sheep manure composting, 10% biochar dose passivated copper (Cu) and zinc (Zn) by 46.95% and 56.27%, respectively.

Additionally, microbial diversity was improved, and *Firmicutes* was the dominant bacterial phylum in biochar-based composting (Duan et al. 2021). In similar studies, biochar amendment had a positive impact on the diversity of toxic metal-resistant bacteria and toxic metals (Cu, Zn, Pb, Ni, Cr, As) passivation during livestock manure/sewage sludge composting (Liu et al. 2021b; Song et al. 2021; Zhang et al. 2021a). More importantly, reducing the bioavailability of toxic metals was responsible for lowering ARGs abundance (Qiu et al. 2021).

No more than 10% biochar dose was recommended because excess biochar addition could cause severe water loss and heat dissipation, thus negatively affecting the composting process (Wang et al. 2021c). Moreover, the cost of biochar may also be a limiting factor (Wang et al. 2021e).

3.4.6 Biochar as additives in anaerobic digestion

Anaerobic digestion (AD) is a biological treatment method to convert organic wastes into renewable biogas and biofertilizer and to sustain waste management (Ambaye et al. 2021; Su et al. 2021). Particularly, organic wet wastes, including livestock manure, food waste, and sewage sludge, are the most commonly used wastes for AD. However, several key challenges persisted thoroughly, including low methane efficiency, operational instability, unsatisfactory substrate degradation, and generation of toxic metabolic intermediates and gaseous pollutants (Zhang and Wang 2021).

Biochar has been identified as an effective additive to boost and improve AD performance (Qi et al. 2021c; Shi et al. 2021b; Sugiarto et al. 2021a). It could significantly assist in shortening the lag phase of organic

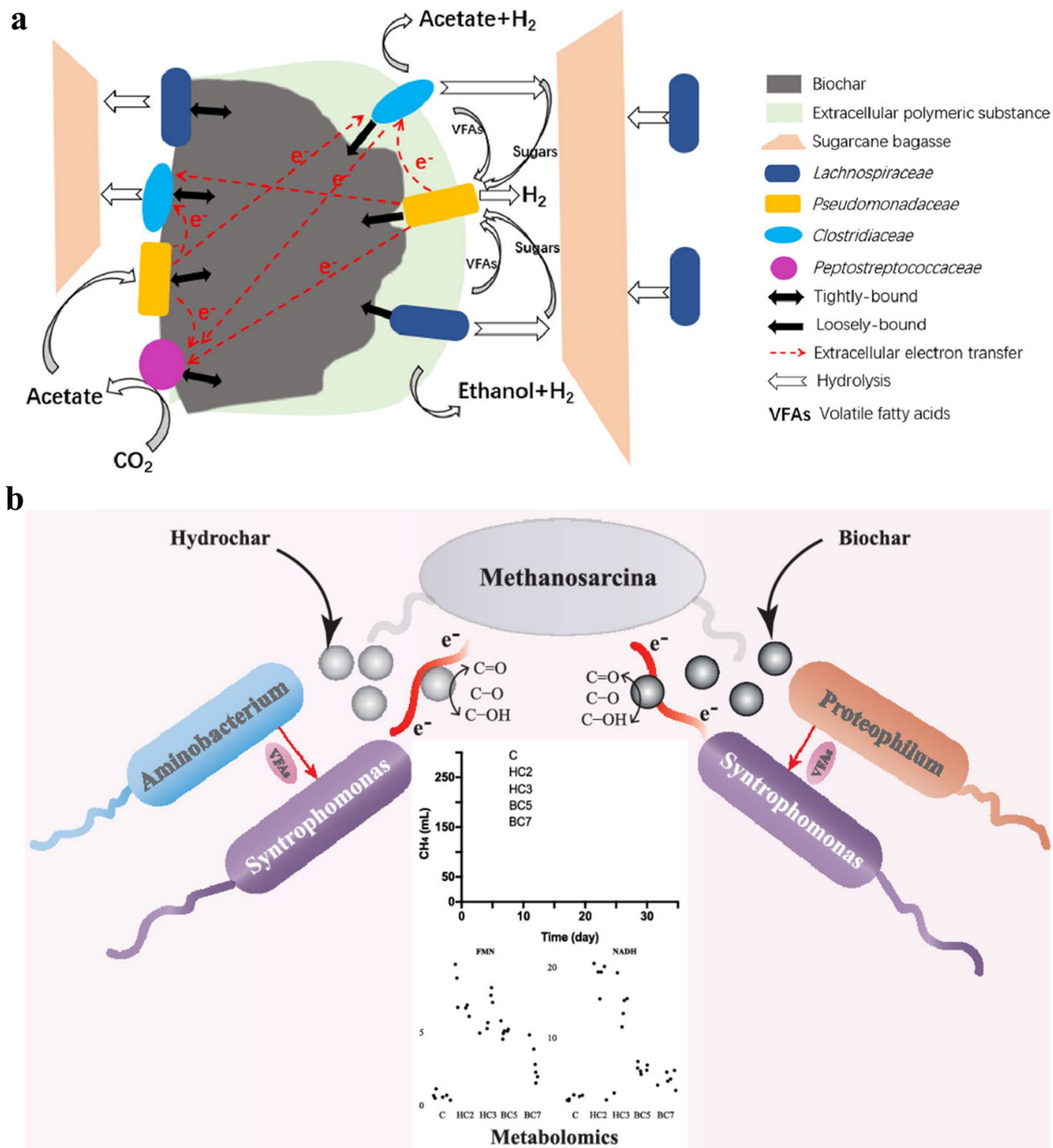


Fig. 6 Proposed schematic of dark fermentative hydrogen enhanced with biochar (**a**) (Bu et al. 2021); The anaerobic digestion of waste activated sludge promoted by hydrochar and biochar (**b**) (Shi et al. 2021b)

biodegradation, improving the production of methane (CH_4) and hydrogen (H_2). Such improvement in AD process efficiency with biochar amendment could be attributed to buffering capacity, adsorption of inhibitory substances (e.g., ammonia nitrogen (NH_4^+-N) and volatile fatty acids)), and accelerated direct interspecies electron transfer (DIET) (Ambaye et al. 2021; Bu et al. 2021; Qi et al. 2021c). Bu et al. (2021) reported that biochar significantly boosted H_2 production from pretreated sugarcane bagasse by implementing efficient enrichment

Table 2 Biochar performance in anaerobic digestion (AD) for the treatment of organic wet wastes

Feedstock	HTT (°C)	Substrate in AD	Dosage	Performance	References
Wood chip	700, 800, 900	Seed sludge	12 g L^{-1}	900 °C HTT enhanced specific CH_4 production to 742 mL g^{-1} ethanol	Qi et al. (2021d)
Fenton sludge	200, 400, 600, 800	Seed sludge + feeding substrate	–	400 °C HTT increased CH_4 production by 38.1%	Wang et al. (2021b)
Pine sawdust	650, 900	Food waste	15 g L^{-1}	900 °C HTT increased cumulative CH_4 production by 46.9%	Sugiarto et al. (2021a)
Corn straw	300, 400, 500	Kitchen waste	10 g L^{-1}	400 °C HTT enhanced CH_4 production rate by 152%	Wang et al. (2021a)
Horticultural waste	< 500	Seed sludge + food waste	50 g L^{-1}	Enhanced accumulative CH_4 production to 126.7 mL g^{-1} volatile solid	Zhang et al. (2021b)
RIce husk	550	Corn stover + chicken manure	10 g L^{-1}	Enhanced specific CH_4 production by 18.5%	Yu et al. (2021)
Waste apple tree branch	550	Potato pulp waste + dairy manure	2% TS content	Potato pulp waste/dairy manure enhanced maximum CH_4 yield of 200 mL g^{-1} TS	Chen et al. (2021a)
Rice husk	300	Swine manure	5% TS_{waste}	Increased accumulative CH_4 yield by 23.6%	Yang et al. (2021f)
Waste wood pellet	800	Food waste	25 g L^{-1}	Enhanced the ultimate accumulative CH_4 yield by 214%	Cui et al. (2021b)
Corn stover	300, 400, 500	Waste activated sludge	1.0 g g^{-1}	300 °C HTT increased the maximum CH_4 production rate by 181.6%	Shen et al. (2021)
Hickory wood chip	400, 900	Seed sludge	12 g L^{-1}	900 °C HTT increased specific CH_4 production to 725 mL CH_4/g ethanol	Qi et al. (2021c)
Corn straw	Hydrochar (260, 320); Biochar (500, 700)	Waste activated sludge	10 g L^{-1}	Hydrochar (260 °C) increased the CH_4 methane yield by 25.6%	Shi et al. (2021b)
Corn stover	500, HNO_3-modification	Food waste	10 g L^{-1}	Increased CH_4 production by 90%	Gao et al. (2021)
Corn straw	550, nZVI-modification	Sewage sludge + food waste	3.0 g g^{-1}	Increased the maximum CH_4 production rate by 49.87%	Zhang and Wang (2021)

and colonization of functional bacteria and activating extracellular electron transfer between functional bacteria (Fig. 6a). Moreover, biochar amendment could also advance the removal of key contaminants during the AD treatment of organic wet wastes, such as heavy metals, antibiotics, polycyclic aromatic hydrocarbons (PAHs), and microplastics (MPs). Biochar has been considered a passivator to reduce the bioavailability of heavy metals by electrostatic adsorption, physical adsorption, complexation, precipitation, and redox effect in AD (Qi et al. 2021a). Adsorption and promotion of biodegradation are critical pathways for removing antibiotics with biochar amendment in AD (Cheng et al. 2021). Biochar has high-effective performance in promoting the biodegradation of PAHs in AD. The enhancement was attributed to the increased DIET between syntrophic microorganisms and the activity of microorganisms (Qi et al. 2021a). Biochar could advance MPs removal in AD through direct adsorption. In addition, biochar amendment could promote microbial activity in AD, thus enhancing the biodegradation of MPs (Qi et al. 2021d). Table 2 summarizes the effects of biochar on AD performance.

The mineral contents (e.g., Fe, Ca, K, Na) present in biochar play a crucial role in promoting CH_4 and hydrogen production. It was reported that the addition of leached biochar in the AD system resulted in lower CH_4 and hydrogen production compared to unleached biochar treatment (Sugiarto et al. 2021b). The role of iron (Fe) within biochar in boosting CH_4 production in the AD system was largely reported in 2021. Wang et al.

(2021b) showed that magnetite-contained biochar prepared from Fenton sludge pyrolyzed at 400 °C significantly improved AD performance due to magnetite's high conductivity. Fe-modified biochar could act as a catalytic medium for substrate hydrolysis and accelerating methanogenesis. The generated Fe oxides on the biochar surface contributed to the interspecies electron transfer in syntrophic metabolism (Deng et al. 2021b). Therefore, introducing Fe oxides into biochar has great potential to improve AD performance.

Hydrochar has also been demonstrated to enhance AD performance. He et al. (2021) showed that hydrochar promoted methane production rates by 36.4–237% in AD of organic wastes via DIET mediated through surface oxygen-containing functional groups. Hydrochar prepared at lower temperatures had greater surface oxygen-containing functional groups, which were related to the facilitated DIET. Similarly, Shi et al. (2021a) found that hydrochar increased the methane yield and production rate by 31.4% and 30.8%, respectively. Genome-centric metatranscriptomics analysis revealed that hydrochar behaved as an electron shuttle to promote DIET between *Syntrophomonas* sp. FDU0164 and *Methanosarcina* sp. FDU0106. It should be noted that hydrochar exhibited a superior ability to promote methane yield and production rate than biochar. Hydrochar had greater surface oxygen-containing functional groups, which were related to facilitated DIET and enhanced methane yield and production rate. The metabolomic analysis also showed that the alterations of metabolites associated with fatty acids and amino acids metabolism induced by hydrochar were stronger than those of biochar (Fig. 6b) (Shi et al. 2021b).

The addition of biochar in the anaerobic co-digestion of food waste or livestock manure with sewage sludge has recently aroused considerable attention. It has highly synergistic effects on hydrolysis acidification and methane production compared with digestion alone (Johnravindar et al. 2021; Liang et al. 2021a; Zhang et al. 2021d). A recent study indicated that the anaerobic co-digestion of pig manure with municipal sludge enhanced methane yield by 83.0–136.5% and 31.3–68.0% at mesophilic and thermophilic temperatures, respectively (Zhang et al. 2021d). Notably, certain disadvantages of incompatible inoculum-to-substrate ratio, excessive acidification, and organic overloading may lead to the inhibition of biogas production (Liang et al. 2021a).

It is noted that biochar/hydrochar addition, exceeding a certain amount, could negatively affect AD performance. In some cases, the negative effect was due to the high sorption capacities of biochar, which might reduce the contact between microbes and substrates. Another potential explanation is that a high dose of biochar accelerated the hydrolysis and acidogenesis-acetogenesis, resulting in the accumulation of toxic metabolic intermediates that could delay methane production (Ambaye et al. 2021).

4 Conclusions and perspectives

CiteSpace-based scientometric analysis was used to analyze the research trends and hotspots in the biochar field based on 5535 publications collected from WoS core collection in 2021. The number of publications has expanded dramatically in 2021 and the growth trend may continue. China and USA were pioneers in this field. The keyword clustering analysis indicated that "Biochar for toxic metal immobilization", "Biochar-based catalyst for biofuel production", "Biochar for global climate change mitigation", "Biochar for salinity and drought stress amelioration", "Biochar amendment in composting", and "Biochar as additives in anaerobic digestion" were the main research trends and hotspots in biochar research in 2021. The employment of biochar as heterogeneous catalysts for biofuel production became the focus of biochar research in 2021. Biochar's applications for heavy metal immobilization, global climate mitigation, salinity and drought stress amelioration, biofuel production, and anaerobic digestion promotion represent sustainable growing topics in 2021. However, bioremediation using functional bacteria immobilized on biochar and biochar-assisted advanced oxidation process were well-studied but with less frequency in 2021 than in 2020. In short, the present review provides a comprehensive overview of the research and the evolution of research hotspots in biochar research.

Although biochar has multifunctional applications in agriculture, environment, and energy, its potential ecological risks, and long-term safety and implications are of great concern. Previous studies have confirmed that biochar contained several toxic components, including polycyclic aromatic hydrocarbon (PAHs), volatile organic compounds (VOCs), polychlorinated dibenzo-*p*-dioxins (PCDDs), persistent free radicals (PFRs), toxic metals, and water-soluble organic compounds (WSOCs) (Brtnicky et al. 2021; Godlewska et al. 2021). The detrimental effects of these harmful substances were correlated with their bioavailable fraction, which depended on the feedstock and preparation methods (Godlewska et al. 2021; Wang et al. 2019). PAHs are mostly formed during the incomplete combustion of biowaste (Wang et al. 2017). It is suggested that biochar produced by slow pyrolysis had lower PAHs than by fast pyrolysis (Wang et al. 2017). Biochar produced under medium temperatures (400–600 °C) often contained higher contents of bioavailable PAHs. In general, the majority of biochars contained a low bioavailable fraction of PAHs (Tomczyk et al. 2020). PCDD/Fs are mainly formed on the surface of biochar during the thermal treatment of feedstock, especially food waste (El-Naggar et al. 2019). It is reported that low temperatures (200–400 °C) and short residence time favored the formation of PCDDs on biochar surface (Lyu et al. 2016). It is accepted that PCDDs always existed in low quantities in biochar and posed a relatively marginal risk to organisms (Godlewska et al. 2021; Weidemann et al. 2018). VOCs are mainly formed on biochar surfaces or/and inside biochar pores by the thermal decomposition of biomass. The contents of VOCs in biochar decreased with increasing HTTs (Buss et al. 2015). Numerous studies have reported the stable and large molecular PFRs in biochar during the biomass carbonization process (Liao et al. 2014; Lieke et al. 2018; Yang et al. 2016; Zhen et al. 2021). It was found that the electron paramagnetic resonance (EPR) signals in lignin-derived biochar were higher than those in cellulose-derived biochar. The EPR signals increased with increasing HTT for the majority of biochar (Liao et al. 2014). Besides organic compounds, heavy metals (e.g., Cd, Cu, and Pb) in biochar are highly concerned with their toxicity. Heavy metal contaminants are mainly originated from feedstock rich in heavy metals, especially sewage sludge, animal manure, and plants grown on heavy metal-contaminated soils. The conversion of biomass abundant with heavy metals to biochar is considered a promising method for safely disposing of biomass and significantly reducing the bioavailability and leaching of heavy metals (Devi and Saroha 2014; Wang et al. 2019; Zhang et al. 2020). The contents of certain heavy metals increased with increasing HTTs, which may be attributed mainly to the 'concentration effect' resulting from a decrease in biochar yield (Zhang et al. 2020). The bioavailability of heavy metals depends on heavy metal contents in raw biomass and the transformation and dissolution of heavy metals in biochar (Godlewska et al. 2021). The release of water-soluble organic compounds (WSOCs) from hydrochar was higher than from biochar. With the increase in HTT, the contents of phenols and organic acids in WSOCs increased (Hao et al. 2018).

Despite the ecologically acceptable levels of these harmful substances for most biochar, it may pose an ecological risk to soil biota (Fig. 7). For example, it is

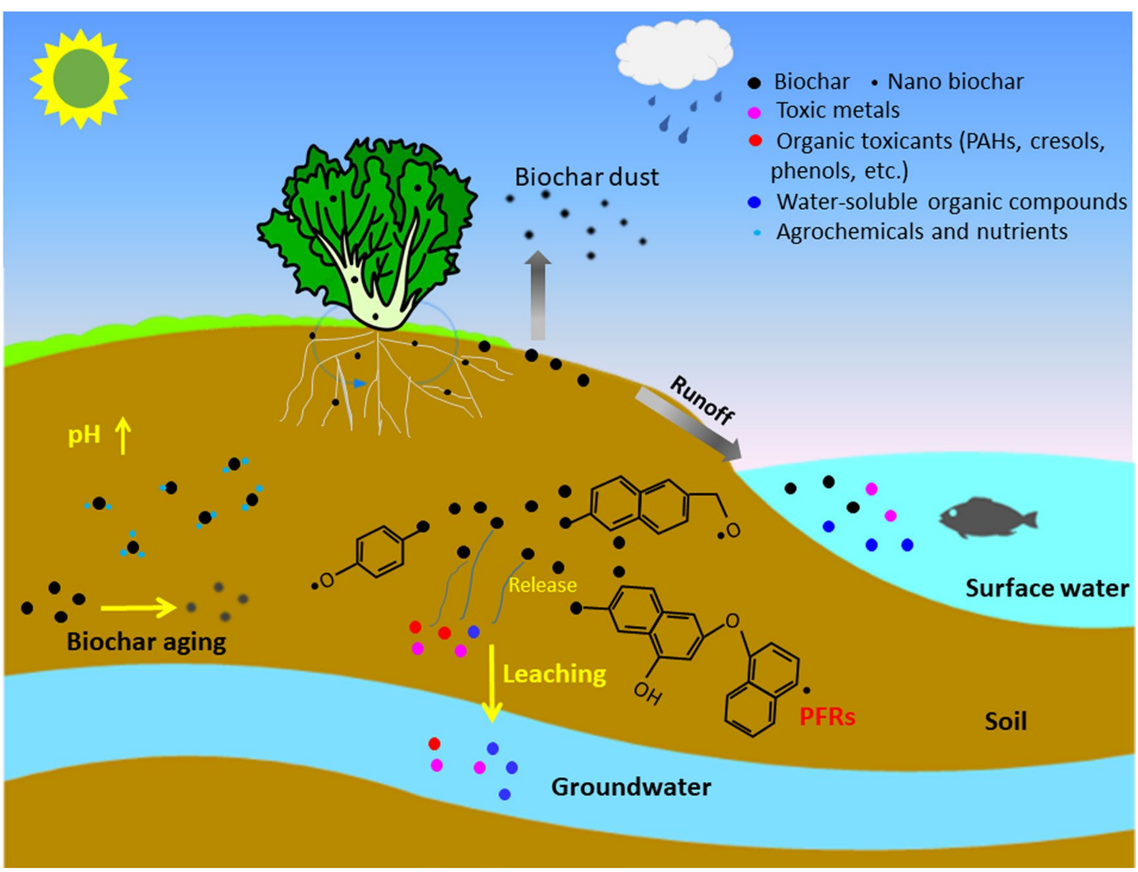


Fig. 7 Potential risks associated with biochar application to soils

revealed that the attendance of some contaminants (e.g., PAHs, cresols, methylated phenols) in biochar might cause direct toxicity to soil microorganisms (Oleszczuk and Koltowski 2018; Yang et al. 2019), for example, significant germination inhibition, plasma membrane disruption, and plant growth retardation (Liao et al. 2014). When incorporated into agricultural soils, dust emissions from biochar may cause a health hazard for farmers (Li et al. 2018). The nano biochar after ball milling had a higher potential ecological risk than pristine biochar due to its unique nanotoxicity (Huang et al. 2021). Moreover, soil physicochemical changes caused by biochar amendment may indirectly induce ecotoxicity to soil organisms. The increase in soil pH after biochar addition may negatively affect earthworm reproductions (Van Zwieten et al. 2009). The strong adsorption of nutrients by biochar would reduce the bioavailability of nutrients, thus inhibiting plant growth. Similarly, the accessibility of water to plants would decrease due to biochar's strong water retention capacity (Brtnicky et al. 2021). It has to be noted that an appropriate biochar application rate may not have unintended adverse effects on soil organisms. Still, excess biochar addition is likely to generate unintended consequences.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s42773-023-00204-2.

Additional file 1. **Table S1** The top 10 most productive countries in biochararea in 2021. **Table S2** The top 10 institutions in the field of biocharresearch in 2021. **Fig. S1** The number of published documents on biocharresearch. **Fig. S2** Countries performing biochar research in 2021.

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

Declarations

Ethics approval and consent to participate
No 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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