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Biochar

REVIEW **Open Access**

Challenges in safe environmental applications of biochar: identifying risks and unintended consequence

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Abstract

Over the past 10–15 years, biochar has garnered significant global attention in agriculture and environmental science. While most research has focused on the benefits of biochar application in soil enhancement, water quality improvement, and climate change mitigation, the potential risks associated with its use have often been overlooked. This oversight is critical, as the environmental fate of biochar is contingent upon understanding these risks. Once released into the environment, biochar can interact with environmental media, potentially releasing associated pollutants and threatening ecosystems. Therefore, it is essential to evaluate the unintended environmental and health risks associated with biochar during its production and application to select appropriate types for sustainable development. This review was conducted by systematically analyzing and synthesizing relevant studies from Web of Science, focusing on recent advancements and key debates in the field. It categorizes biochar risks into endogenous and exogenous risks based on the source of pollutants carried by biochar. The review analyzes in detail the impacts of raw materials, preparation processes, and application scenarios on the unintended environmental risks of biochar. Furthermore, it provides a thorough overview of the adverse effects on animals, plants, microorganisms, and human health, elucidating the mechanisms of pollutant release, aging, and nano-effects from environmental geochemical processes involving biochar. Additionally, this review summarizes the environmental risk assessment methods of biochar, providing a reference for its safe application and the sustainable development of biochar-related research.

Highlights

- The risks associated with the production and application of biochar are categorized into endogenous and exogenous risks.
- Factors affecting the environmental risk of biochar include raw materials, preparation conditions and application processes.
- Adverse effects of biochar on animals, plants, microorganisms and humans and related mechanisms were elucidated.
- The environmental risk assessment methodology for biochar proposed in this study provides a basis for the safe application of biochar.

Keywords Biochar, Endogenous and exogenous pollutants, Nanobiochar, Bioreporter, Environmental risk assessment

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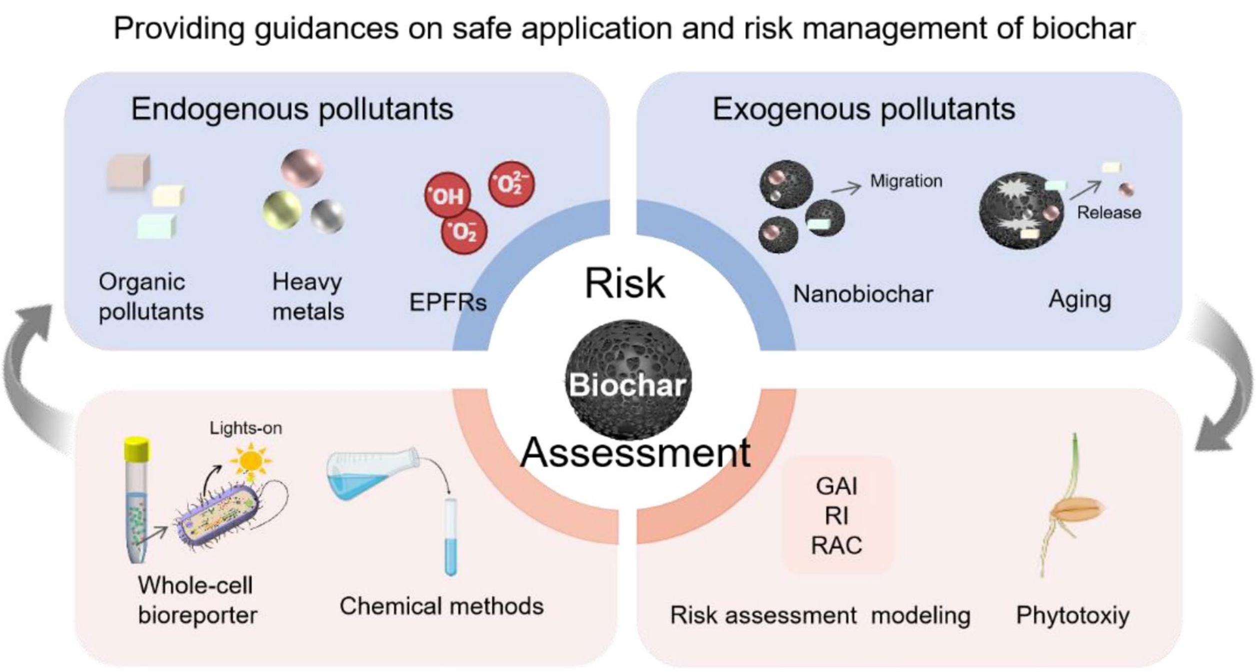
Graphical Abstract



1 Introduction

Biochar is an environmentally friendly and economically feasible carbonaceous material made from the pyrolysis of waste biomass at low to high temperatures (250–800 °C) under complete or partial anoxic conditions (Malabadi et al. 2023; Wang et al. 2023a). Over the 10–15 years, biochar has gained significant attention globally for its applications in soil health improvement (Hossain et al. 2020; Majumder et al. 2019; Zhang et al. 2021a), environmental remediation (Dong et al. 2023), carbon sequestration and emission reduction (Tan 2019) and energy (Liu et al. 2019). A search for the keyword "biochar" in the Web of Science (WoS) database reveals a sharp increase in publications from 2014 to 2023. The literature can be classified into four fields: functional materials, energy, agriculture, and pollution remediation. A chord diagram was plotted to summarize the publication trend on biochar in these four fields over different years (see Fig. 1A). According to the choropleth chart, biochar research is most prevalent in the environmental field, accounting for 46% of total publications and 20% in materials. Applied research in agriculture and energy fields accounts for 12% (Fig. 1A). This is mainly due to the fact that large specific surface area, rich surface functional groups, high mineral content, and high stability of biochar make it a powerful material for environmental remediation. For instance, many studies have shown that the application of biochar can effectively adsorb organic pollutants and heavy metals in the environment and reduce the environmental risk of the pollutants (Jagadeesh et al. 2023; Wang et al. 2021d). However, very few studies have been conducted on the potential risks involved in the environmental application of biochar.

The WoS database was used as the source of information, the keywords "biochar" and "biochar AND risk" were selected for the search to ensure that all relevant literature related to biochar and its potential risks were captured. Articles from 2014 to 2023 were retrieved to ensure the relevance and currency of the literature. After the retrieval, we reviewed each article to remove irrelevant articles and ensure that each article was relevant to biochar risk. Five key journals were selected based on impact and relevance within the field, including *Environmental Science & Technology*, *Environmental Pollution*, *Journal of Hazardous Materials*, *Biochar*, and *Science of the Total Environment*. The number of articles published in these journals per year was recorded (Fig. 1B). A three-dimensional bar chart, created by searching the number of articles published from 2014 to 2023 using the keywords "biochar" and "biochar AND risk" in WoS,

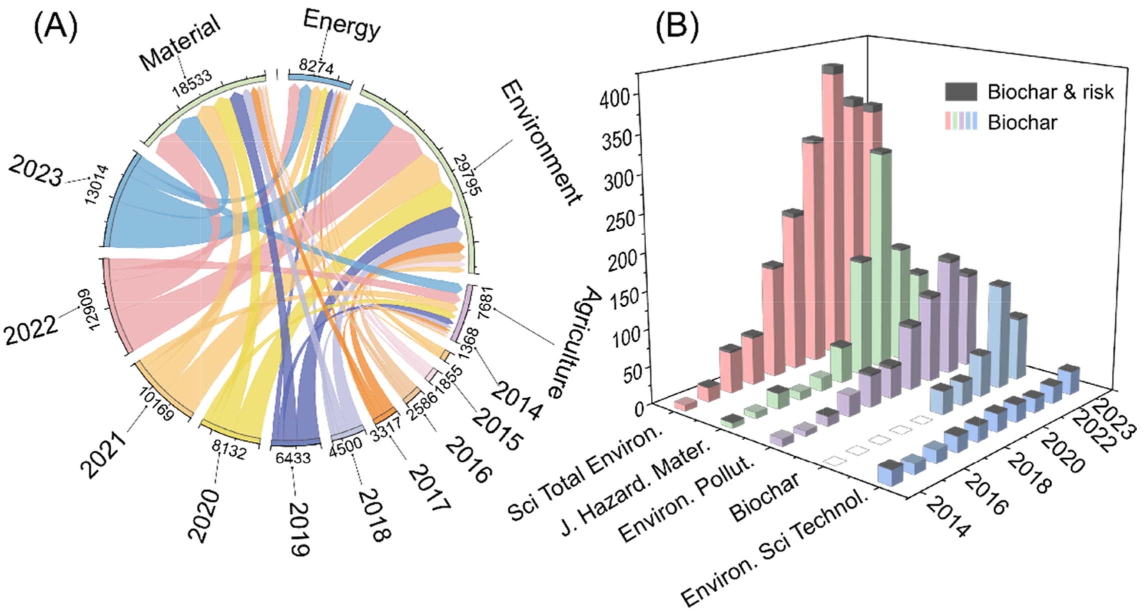


Fig. 1 The keyword "biochar" in the retrieved journals relates to the number of articles published in each of the four fields "energy, material, agriculture, pollution remediation" from 2014 to 2023 (**A**). The results of searches in mainstream journals in the environmental field using "biochar", and " biochar" AND "risk" as keywords, respectively, from 2014 to 2023 (**B**).The data were obtained from the Web of Science

illustrates a year-on-year increase in biochar publications across these five journals, followed by a slight decline after 2021 (Fig. 1B). This decline may be due to the emergence of new journals, leading to the publication of some articles elsewhere. Notably, the number of articles on biochar risks remains very low, indicating a research gap in this area.

Biochar is typically applied as small particles, rendering it mobile in the environment (El-Naggar et al. 2019). Figure 2 illustrates the primary processes governing the transportation and translocation of biochar across various environmental media. Within the soil, biochar particles can be mobilized through decomposition, runoff, drainage, or irrigation, subsequently infiltrating groundwater and potentially contaminating it (Chen et al. 2022b). They may enter the atmosphere via turbulent transport, undergo long-range transport with air currents, and eventually deposit back into the environment (Ravi et al. 2016). Additionally, biochar (mainly colloidal and nanobiochar) in the soil can be taken up by plant root systems, consumed by soil fauna, and transported through the food chain (Gu et al. 2022; Madžarić et al. 2018). Hu et al. (2022a) reported that biochar can enter the human body through dietary intake and inhalation during its preparation, with particles subsequently adhering to the respiratory tract.

The transport of biochar significantly increases its environmental risk once it becomes polluted or immobilizes environmental pollutants. With the development of the biochar industry, many wastes containing pollutants are used as feedstocks to produce biochar (Liang et al. 2021). When applied to soil, such biochar may release pollutants, posing potential threats to soil and water environments. Released heavy metals can be toxic to animals, plants, and microorganisms and can bioaccumulate in the food chain, threatening human health. Organic pollutants, such as polycyclic aromatic hydrocarbons (PAHs), generated during biochar preparation, pose potential environmental and health risks (Zhao et al. 2022). Environmental persistent free radicals (EPFRs) on biochar can induce reactive oxygen species (ROS), destabilizing cell membranes and leading to apoptosis, thus inhibiting seed germination and growth (Odinga et al. 2020). As biochar ages, it can degrade into nanoparticles, and nanobiochar can transport pollutants with it more quickly in the environment, increasing its environmental risk (Xu et al. 2023).

Zhao et al. (2022) found that biochar is an important source of organic and inorganic pollutants in soil. Murtaza et al. (2023) demonstrated the ecotoxicological risks of organic pollutants in biochar to plants and soil microorganisms. The larval population of *Collembola* was significantly suppressed in soil with 25% pine biochar addition, with a reduction of about 70% compared to the control (Gruss et al. 2019). In addition, the exchangeable acid soluble and reducible fractions of Zn were as high

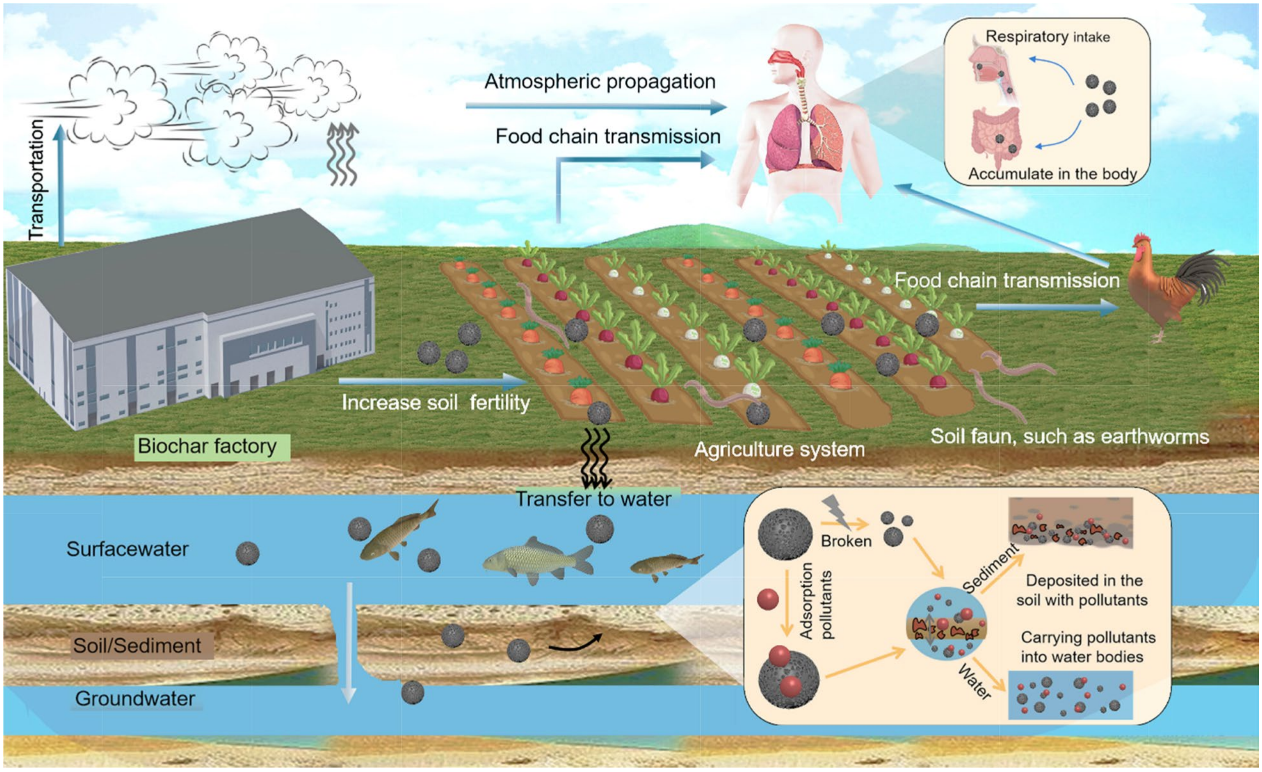


Fig. 2 Schematic diagram of biochar transport in the soil/water/atmosphere system

as 84.9% in the food waste biochar prepared at 300 °C (Xu et al. 2021). Although some studies have reviewed the environmental risks associated with biochar (Natasha et al. 2022; Xiang et al. 2021), they mainly provide an overview of the risks without a detailed discussion or summary of environmental risk modeling or chemical assessment methods. Biochar is considered a cost-effective remediation or pollution mitigation tool, yet its dual role as both a pollutant source and sink presents limitations. Therefore, during the preparation of this review, a total of thousands of articles in relevant literature were collected and after a rigorous screening process, 164 high-quality research articles were finally analyzed. This review critically assesses the risks of endogenous and exogenous pollutants in biochar and their negative effects on the environment, plants, animals, microorganisms, and human health. It outlines various risk assessment methods to predict potential environmental risks associated with biochar application, providing a theoretical basis for understanding the environmental risks of different biochars and advancing the industries associated with biochar to grow safely and sustainably.

2 Environmental risks of pollutants in biochar

2.1 Endogenous pollutants

Endogenous pollutants in biochar mainly originate from its raw parent materials (Ji et al. 2022). Studies have shown that the properties of biochar are significantly affected by the type of raw material and preparation conditions (Li and Skelly 2023; Joshi et al. 2022; Racek et al. 2020; Zhang et al. 2019a). For instance, municipal solid waste contains organic pollutants such as PAHs and polystyrene, while sewage sludge typically contains heavy metals such as Pb, chrome (Cr), and cadmium (Cd) (Ndirangu et al. 2019). During pyrolysis, heavy metals in the biomass either volatilize into the air as gases (e.g., PbO) or remain within the biochar as toxic substances (e.g., Cr) (Perendija et al. 2024). Additionally, free radicals, cellulose, and lignin in woody biomass can generate volatile organic compounds (VOCs), PAHs, and EPFRs at high temperatures. These pollutants can diffuse into the environment during the manufacturing process and application of biochar, threatening the environmental health (Hu et al. 2022b).

2.1.1 PAHs

The content of PAHs in biochar is significantly influenced by pyrolysis temperature. Lyu et al. (2016)

showed that the content of PAHs in biochar produced at 250 and 400 °C increased from 1.9×10^2 mg kg^{-1} to 8.6×10^2 mg kg^{-1}. Similarly, the PAHs content in biochar produced from chicken manure, date pomace, and sewage sludge was much higher at 700 °C than at 300 °C (Alharbi et al. 2023). It has also been found that the concentration of PAHs in biochar pyrolyzed at 600–800 °C is higher than that produced at 800 °C and 200 °C (Wang et al. 2019b). Biochar produced at lower temperatures (≤200 °C) contains less PAHs and is less toxic (Wang et al. 2019b). This is because lower temperature biochars are dominated by lower molecular weight PAHs (2–3 rings), while higher pyrolysis temperatures and longer pyrolysis times are required to form PAHs with more rings and higher concentrations (Sørmo et al. 2024). However, when the temperature reaches or exceeds 800 °C, high molecular weight PAHs can cleave into smaller PAHs and further into low molecular compounds such as CO, CO_2, and CH_4, leading to a decrease in PAH production under high-temperature conditions (José et al. 2019; Krzyszczak et al. 2021). PAHs with high ring numbers are more easily transported and transformed in soil, possess higher toxicity, and pose relatively greater environmental risks (Zhang et al. 2019b). Moreover, the concentration of PAHs in biochar is closely related to the type of raw material. Biochar produced from biomass with higher pectin and cellulose content tends to have higher concentrations of PAHs compared to biochar produced from biomass with higher lignin content (Hong et al. 2021a). This is because lignin, the main reactant in the pyrolysis process, is highly cross-linked and refractory at elevated temperatures, making it more difficult to produce PAHs (Torres et al. 2020). The binding effect of lignin on cellulose and hemicellulose makes these components less susceptible to degradation to low molecular weight organic matter, resulting in the formation of PAHs. Lignin can decompose more completely at higher temperatures and over longer periods (Wang et al. 2021b). Therefore, biomass containing more cellulose is prone to producing higher concentrations of PAHs compared to raw materials with high lignin content (Zhang et al. 2021b).

2.1.2 Heavy metal

Heavy metal enrichment is another factor affecting the environmental risk of biochar. This is controlled by pyrolysis temperature, raw materials, and the chemical forms of heavy metals (Jin et al. 2017). The loss of organic matter contained in the biomass during pyrolysis promotes the enrichment of heavy metals. As pyrolysis temperature increases, the concentration of heavy metals in biochar may increase or decrease due to the different nature of the metals (Table 1). The content of non-volatile metals (e.g., iron (Fe) and copper (Cu)) increases continuously with increasing pyrolysis temperature. Some volatile heavy metals and metalloids (e.g., Cd, mercury (Hg), and arsenic (As)) may volatilize as methylated species or in gas form at high temperatures, causing their concentrations to first increase and then decrease with rising pyrolysis temperature (Lu et al. 2016; Liu et al. 2016; Zhang

Table 1 The content of heavy metals in biochar prepared from different raw materials

Raw material	Heavy metal content in raw material	Pyrolysis temperature	Heavy metals content in biochar	References
Sewage sludge	Chromium (Cr) 124 mg kg^{-1} Copper (Cu) 134 mg kg^{-1} Lead (Pb) 121 mg kg^{-1} Zinc (Zn) 1341 mg kg^{-1}	700 ℃	Cr 225 mg kg^{-1} Cu 248 mg kg^{-1} Pb 204 mg kg^{-1} Zn 2355 mg kg^{-1}	Li et al. (2021)
Sewage sludge	Cu 251.7 mg kg^{-1} Zn 987.4 mg kg^{-1} Nickel (Ni) 53.6 mg kg^{-1} Pb 185.8 mg kg^{-1} Cr 237.6 mg kg^{-1}	700 ℃	Cu 300 mg kg^{-1} Zn 1425 mg kg^{-1} Ni 108.8 mg kg^{-1} Pb 238.6 mg kg^{-1} Cr 360 mg kg^{-1}	Xiong et al. (2021)
Swine manure	Cadmium (Cd) 0.52 mg kg^{-1} Cr 12.60 mg kg^{-1} Zn 686.78 mg kg^{-1} Cu 614.59 mg kg^{-1}	800 ℃	Cd 1.10 mg kg^{-1} Cr 30.83 mg kg^{-1} Zn 1457.69 mg kg^{-1} Cu 1335.06 mg kg^{-1}	Zeng et al. (2018)
Goat manure	Cd 1.21 mg kg^{-1} Cr 12.92 mg kg^{-1} Zn 98.69 mg kg^{-1} Cu 16.65 mg kg^{-1}	800 ℃	Cd 2.62 mg kg^{-1} Cr 31.98 mg kg^{-1} Zn 228.78 mg kg^{-1} Cu 40.43 mg kg^{-1}	Zeng et al. (2018)
Brassica napus L	Cd 0.140 mg kg^{-1}	400 ℃	Cd 0.30 mg kg^{-1}	Zhang et al. (2020c)
Pennisetum sinese	Cd 1.88 mg kg^{-1}	400 ℃	Cd 4.88 mg kg^{-1}	
Lolium perenne L	Cd 3.86 mg kg^{-1}	400 ℃	Cd 8.91 mg kg^{-1}	

et al. 2020c). For example, the total content of Cd in the biochar from textile dyeing sludge gradually increased from 0.793 mg kg^{-1} to 0.928 mg kg^{-1} as the pyrolysis temperature increased from 300 °C to 500 °C. However, when the pyrolysis temperature reached 600 °C, the Cd content in the biochar decreased to 0.139 mg kg^{-1} (Wang et al. 2019c). This is because Cd in biomass forms highly volatile compounds (e.g., $CdCl_2$) that readily volatilize as gases at certain temperatures (Wang et al. 2021a). Apart from pyrolysis temperature, the type of raw material strongly influences the accumulation of heavy metals in biochar (Wang et al. 2018b). Studies have shown that biochar derived from heavy metal-containing crops (e.g., corn stover, rice husk, wheat straw), livestock manure (e.g., cow dung, pig manure, chicken manure), and industrial waste (e.g., sewage sludge) can contain significant levels of heavy metals (Wang et al. 2022b, c; Zhang et al. 2020b) (see Table 1).

The environmental risk of heavy metals depends on their bioavailability rather than their total concentration, which is primarily influenced by their chemical form. Therefore, the speciation of heavy metals is a crucial factor affecting its environmental risk (Vuong et al. 2023). Huang and Yuan (2016) demonstrated that the exchangeable/acid-soluble fractions of heavy metals are the most bioavailable and toxic, being directly bioavailable with high bioavailability. The reducible and oxidizable fractions are also bioavailable under certain conditions. These fractions, known as bioavailable states, increase the likelihood of heavy metal released and secondary contamination (Gujre et al. 2021). In contrast, the residual fractions are not readily taken up biologically, have the weakest toxicity, and are considered stable and non-toxic (Li et al. 2018b). For example, compared to raw cow dung, the exchangeable/acid-soluble and reducible fractions of Cd and zinc (Zn) in cow dung biochar were lowered by 15% and 10%, respectively, while the relatively stable residual fractions were increased by 70 times (Cd) and 51.31 times (Zn), respectively (Zhang et al. 2020b). This suggests that Cd and Zn bioavailability and environmental risks are reduced when cattle manure is converted to biochar.

2.1.3 EPFRs

EPFRs are classified as emerging pollutants because of their ability to generate ROS and pose a significant risk to the agricultural environment and human health (Liu et al. 2018b; Vinayak et al. 2022; Zhang et al. 2023). Studies have shown that the concentration of EPFRs depends on the pyrolysis temperature and the raw material of the biochar (Ruan et al. 2019). Yang et al. (2017) found that the concentration of EPFRs gradually increased when pine trees were pyrolyzed up to 500 °C and significantly decreased at 700 °C. Fang et al. (2015a) showed that at relatively low temperatures (300 and 400 °C), the EPFR content increased with pyrolysis time, peaking at 12 h. At higher temperatures, the EPFR content reached a maximum at 1 h of pyrolysis and then gradually decreased; phenolic compounds continue to decompose with increasing pyrolysis temperature and time (Fang et al. 2015a; Ruan et al. 2019). The amount of EPFRs produced also varies significantly with different raw materials. Lignin, cellulose, and hemicellulose are the major precursors for EPFR generation during biochar production, with cellulose and hemicellulose contributing more than lignin. Cellulose and hemicellulose decompose at lower temperatures to form various free radicals, whereas lignin, with its complex structure, requires higher energy for free radical production through a series of complex decomposition processes (Ruan et al. 2019).

Metal modification also affects the EPFR content in biochar due to the electron transfer from phenolic compounds in biomass to metal oxides, forming free radicals (Huang et al. 2019). The addition of metal cations increases the aromaticity and strength of the aromatic structure. For example, adding Fe(III) promotes decarboxylation reactions, increases lactone groups and phenolic hydroxyl content, and facilitates the formation of EPFRs like semiquinone-type and phenoxylate-type free radicals (Ruan et al. 2018). However, excessive metal ions can deplete EPFRs and reduce their concentration because EPFRs in biochar promote the reduction of metals, which depletes EPFRs (Fang et al. 2015a; Ruan et al. 2019). In summary, the environmental risks of organic pollutants, heavy metals, and EPFRs in biochar are dependent on the selection of raw materials, preparation processes, and modification methods. Establishing a screening system to guide the production of biochar with low-risk biochar is essential to ensure its safe application in the environment.

2.2 Exogenous pollutants

Although the hazards of endogenous pollutants in biochar can be mitigated by the selection of suitable biomass, it is important to note that exogenous pollutants (e.g., heavy metals, PAHs, etc.) in environmental media can be adsorbed during migration due to the favorable adsorptive properties of biochar, which has the potential to increase the environmental risk of biochar (due to carrying large amounts of pollutants). Biochar does not remove pollutants from the environment but rather reduces their mobility through immobilization. Therefore, pollutants adsorbed by biochar may remain toxic. Wang et al. (2020a) showed that some fractions of tetracycline adsorbed by biochar are still bioavailable, and tetracycline adsorbed in high-temperature biochar was

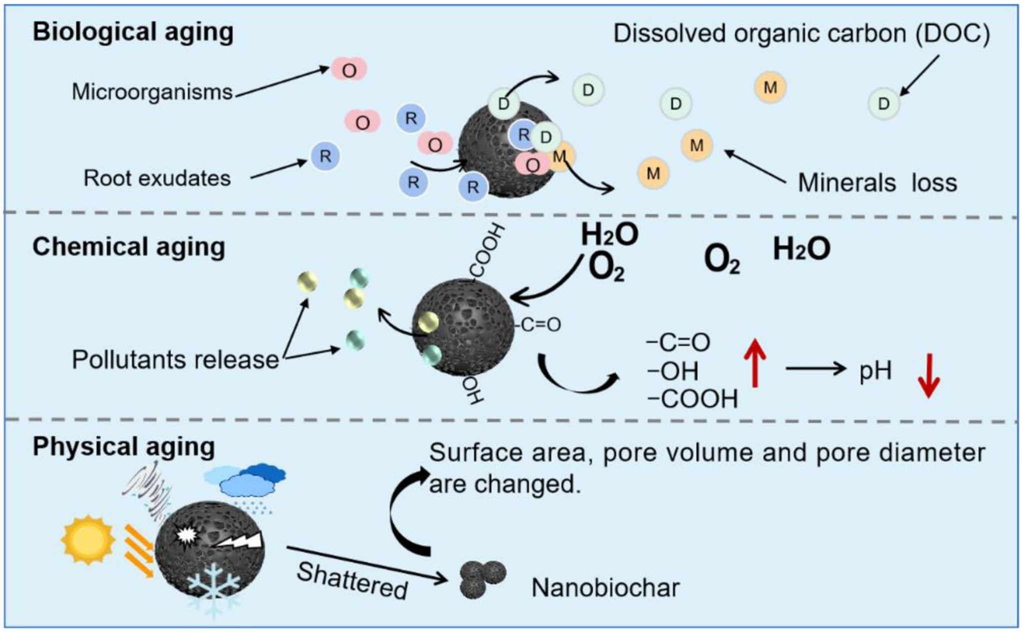


Fig. 3 Schematic diagram of the mechanistic reactions of the biochar aging process

more bioavailable than that in low-temperature biochar. Ke et al. (2023) found that the amount of Cd that remained bioavailable ranged from 40.83 to 78.99% of the total amount adsorbed by biochar. These exogenous pollutants are mainly introduced from the environment and are not generated by the biochar itself. Therefore, the risk of exogenous pollutants is influenced by the type of pollutant, the properties of the biochar and the environmental conditions.

2.2.1 Aging

When exposed to the environment, biochar goes through physical, chemical, and biological interactions that promote aging and clearly change its properties (Cao et al. 2019, see Fig. 3). Biochar carrying adsorbed pollutants may deteriorate under external environmental and climatic conditions such as extreme weather, sun exposure, rain, snow, and acid rain. These conditions can significantly alter its surface morphology, pH, elemental composition, degree of oxidation, and other properties, affecting its ability to adsorb pollutants and potentially triggering the secondary release of pollutants (Laghari et al. 2015; Meng et al. 2021). Studies have shown that biochar aging can lead to significant changes in its surface morphology, including an increase in roughness (Yao et al. 2023), extensive oxidation of the surface (He et al. 2019), and collapse of the surface structure (Cao et al. 2019; Weber and Quicker 2018).

During rainfall or freeze–thaw cycles, the expansion and volatilization of water molecules within the biochar lead to internal structural expansion and fragmentation, increasing the specific surface area and the number of pores (Sorrenti et al. 2016; Xie et al. 2022). In the aging process, the leaching of dissolved organic carbon (DOC) and mineralization of organic carbon, as well as the utilization of unstable aliphatic carbon in biochar by microorganisms, may lead to carbon loss (Wang et al. 2020a). Plant root secretions can bind DOC to minerals, resulting in the loss of mineral content from biochar (Wang et al. 2020b). Furthermore, it has been found that the increase of the specific surface area and porosity of the biochar, as well as the oxidation of aromatic ring π–π electrons, promote the release of adsorbed heavy metals, leading to secondary environmental pollution (Liu et al. 2021; Xiang et al. 2021). It has been found that the application of biochar reduces the content of exchangeable heavy metals, which indirectly reduces the mobility of heavy metals (Wang et al. 2018b). However, aging process may change the biochar properties and speciation of heavy metals adsorbed by biochar. Cui et al. (2021b) reported that the aging process decreased the pH of biochar and accelerated the loss of alkaline elements, weakening its ion-exchange capacity for heavy metals. Another study reported that the pH of biochar decreases as acid functional groups increase during aging, contributing to the reactivation of Cd passivated by the biochar, thus increasing the bioavailability of Cd (Gao et al. 2019). In term of organic pollutants, Zhang et al. (2016) reported that the adsorption capacity of bamboo biochar for phthalates decreased significantly after aging. They speculated that the change in the nature of biochar further increases the risk of secondary release of pollutants. Thus, aging can lead to changes in the properties of the biochar that would make the adsorbed pollutants unstable, and thus this portion of the pollutants may still be bioavailable (Cui et al. 2021a; Zhang et al. 2016).

2.2.2 Nanobiochar

Several studies have shown that weathering and aging can degrade biochar to nanobiochar (Ramanayaka et al. 2020; Zhang et al. 2020b), resulting in an increased proportion of nanobiochar in soil. Nanobiochar can also artificially prepared through ball milling, ultrasonication, and centrifugation to remove pollutants, increase agricultural yields, and enhance materials. With the increasing application of biochar in the environment issue, the nanoeffect on the environment could be produced by the accumulation of nanobiochar. Due to its smaller particle size (usually below 100 nm) and higher mobility (Chen et al. 2017; Liu et al. 2018a), nanobiochar can rapidly migrate into soil and even into groundwater, impacting groundwater quality (Chausali et al. 2021; Ramanayaka et al. 2020). Nanobiochar, usually in a colloidal or soluble state, exhibits a high photoconversion/degradation rate and a high yield of ROS (Gu et al. 2022). Li et al. (2023) demonstrated that nanobiochar was readily absorbed and transported into aboveground tissues through wheat and cabbage roots and accumulated in the edible parts of cabbage, raising concerns about the safety of the food chain. However, the migratory transformation process of nanobiochar in plants and animals is crucial for understanding its environmental risks. Therefore, more research is needed to understand the effects of nanobiochar on plants, animals, and soil microorganisms.

The migration and transformation of nanobiochar in the soil–plant system can have various effects on plants (Fig. 4). In recent studies, nanomaterials such as nanobiochar have been sprayed onto plant leaves to improve plant resistance and growth. However, nanobiochar sprayed on crop leaves can block stomata, preventing plant respiration (Hong et al. 2021b). The large specific surface area, hydrophobic surface of biochar, and abundance of polar and non-polar surface sites make it effective at adsorbing phosphorus (P) (Chen et al. 2018a). The co-migration of nanobiochar with P in the soil environment is highly susceptible to leaching, leading to nutrient loss and potentially carrying pollutants into groundwater or soil, generating environmental risks (Xiang et al. 2021). Aliphatic carbon, as well as phenolic substance, is dominant ingredients of bio-oils deposited on biochar during pyrolysis, with nanobiochar being a significant site for such deposits (Wang et al. 2018a; Zhang et al. 2020a). Phenolic compounds threaten plant growth and cause phytotoxic effects (Bai et al. 2022), and their presence on nanobiochar can have toxic effects on plants and animals during application and transfer. Lignin-rich nanobiochar has a high potential environmental hazard due to the formation of phenolic compounds during lignin pyrolysis (Chen et al. 2022a). Sigmund et al. (2017) showed that nanobiochar induces oxidative stress on fibroblasts, causing changes in cell morphology and inhibiting cell membrane translocation by reducing the accessible extracellular surface, resulting in toxic effects. Biochar nanoparticles easily and firmly adhere to the root surface of rice plants and adhere tightly, directly contacting roots during growth (Yue et al. 2019). Free radicals generated and stored on nanobiochar particles during charring may induce ROS production, significantly inhibiting germination and retarding growth in rice seedlings (Alfei et al. 2024; Fang et al. 2015b).

3 Risks of biochar to organisms

As mentioned above, biochar can diffuse into the environment during application through weathering, decomposition, leaching, and runoff processes. This diffusion can negatively affect plants, animals, and microorganisms, as well as human health, either directly or indirectly (e.g., through adsorption of pollutants) (Wang et al. 2023b). Due to its mobility in the environment, biochar may compete with plant nutrients, thus impacting the soil environment and plant growth (Kołtowski et al. 2017; Ndirangu et al. 2019). This section systematically describes the risks biochar poses to different organisms, including the species affected, damage sites, adverse symptoms, and mechanisms of harm (Fig. 5).

3.1 Animals

Earthworms are important bioindicators for assessing soil health, as they are often the first to sense changes in the soil environment when biochar is applied. Generally, biochar application increases the levels of organic matter, trace elements, and minerals in the soil, and it is favorable for earthworms (Hale et al. 2013). However, Llovet et al. (2021) found that high biochar concentrations (50 t ha^{-1}) negatively impacted soil earthworms by slowing growth and decreasing abundance. Gomez-Eyles et al. (2011) observed significant weight loss in earthworms exposed to hardwood biochar. Similarly, Briones et al. (2020) reported that a 50 t ha^{-1} biochar addition significantly reduced earthworm abundance and biomass, as well as population size and species richness. Biochar treatments also significantly affect nematode abundance. At a 50 t ha^{-1} biochar addition rate, nematodes were disturbed and had a reduced presence (Llovet et al. 2021). The concentration of PAHs from biochar is negatively

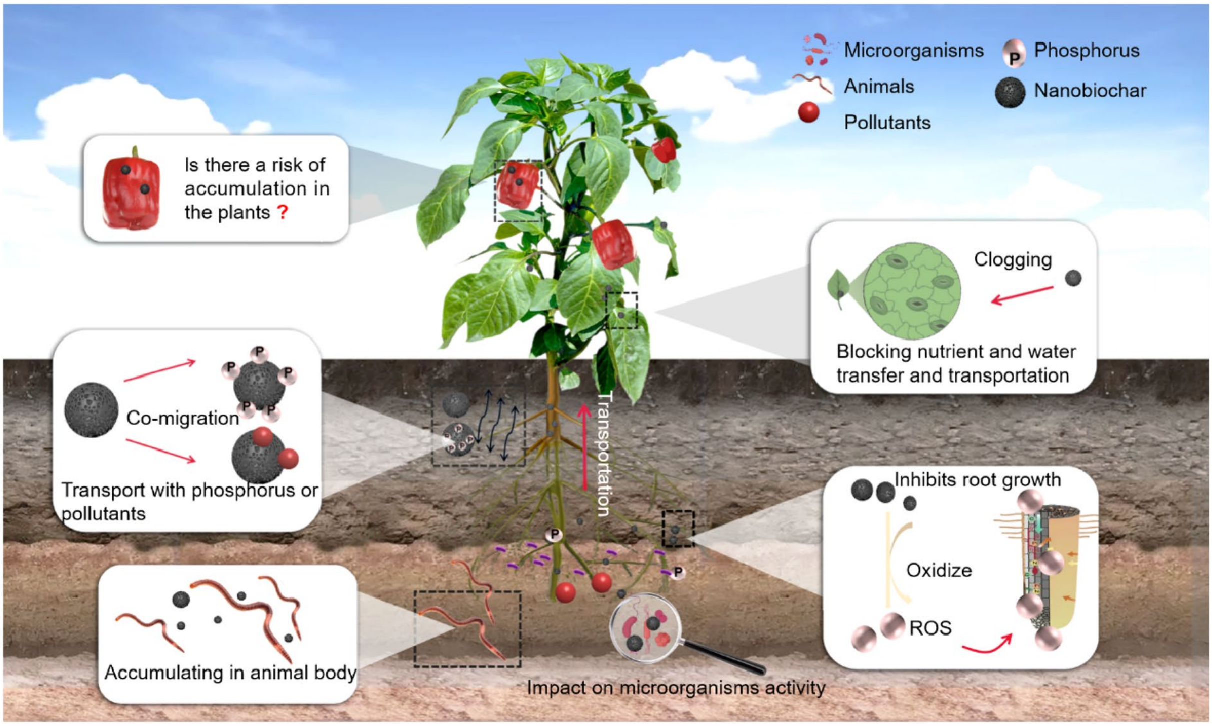


Fig. 4 Possible risks of migration and transformation of nanobiochar in soil–plant

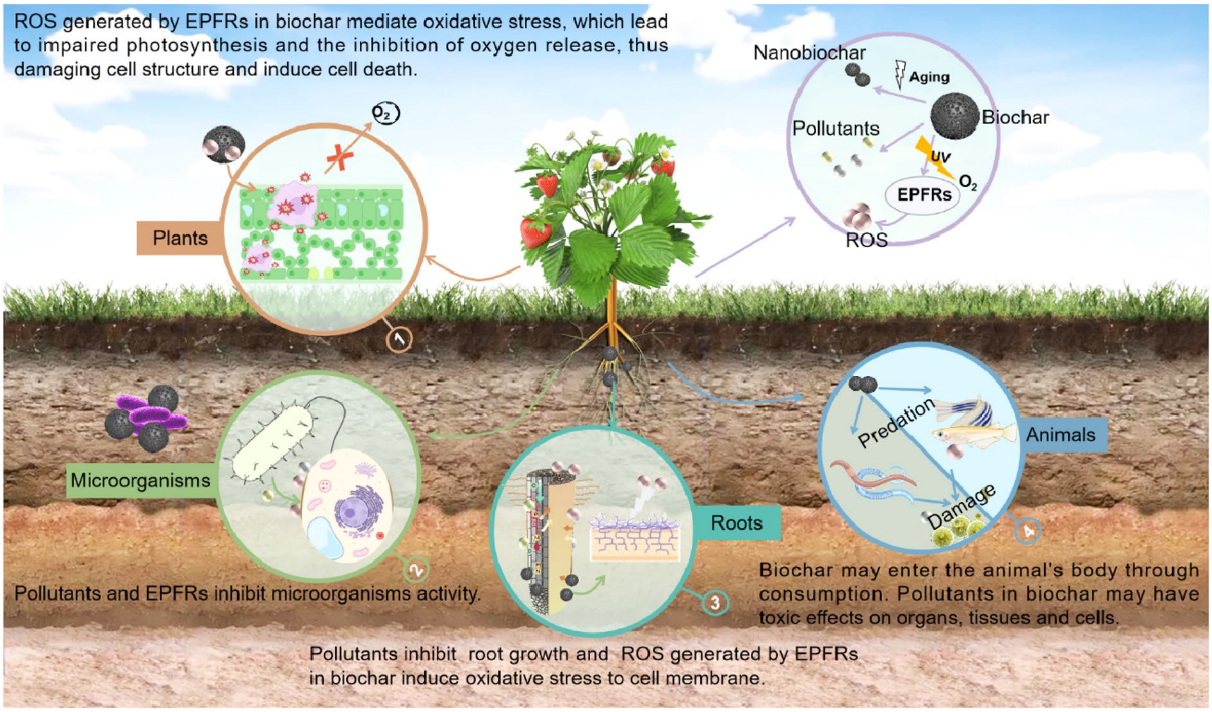
correlated with the relative abundance of nematodes, which are very sensitive to disturbance. PAHs in biochar cause disturbances to nematodes, leading to decreased abundance and indirectly increasing fungal and herbivore populations. This imbalance can result in the loss of function of the higher-level food web in the soil, increasing the risk to the soil environment (Llovet et al. 2021). Nanobiochar readily adheres to cell membranes, generating oxidative stress and inducing ROS that disrupt cell membrane integrity (Ouyang et al. 2022). Additionally, algae cells containing nanobiochar can be harmful to fish if they are consumed by fish (Huang et al. 2021; Lv et al. 2019). Therefore, more studies are demanded to clarify the implications of biochar on animals.

3.2 Plant growth

Biochar as a soil additive improves the soil environment (Häring et al. 2017), reduces plant damage from pollutants, and promotes crop growth (Fang et al. 2014; Hussain et al. 2017). However, biochar with high levels of pollutants (PAHs, VOCs, heavy metals, etc.) can cause adverse effects such as inhibited crop growth, reduced yields, and slow root growth. Biochar surface cations may also bind to nitrogen and trace elements (Cu, Fe, manganese (Mn)) in soil by electrostatic interactions (Hale et al. 2013; Laghari et al. 2015), thereby affecting nutrient uptake by plants (Subedi et al. 2017). The negative effects of metals in biochar on plants have received attention. For example, a study by Visioli et al. (2016) showed that Cu in biochar adversely affected plant germination and root elongation in cucumber, bean curd, and sorghum. This may be due to the sensitivity of cell division and elongation at root tips to metal pollutants. Additionally, organic contaminants (e.g., PAHs, polychlorinated biphenyls (PCBs)) in biochar can inhibit the efficiency of microbial utilization of soil nitrogen sources, affecting plant uptake of active nitrogen (Laghari et al. 2015).

The existence of EPFRs from biochar also inhibits plant growth and germination (Lian and Xing 2017). Rice straw-derived biochar (500 °C) exhibited growth retardation in root and stem length and significant inhibition of seed germination in maize, wheat, and rice. This effect is mainly due to severe disruption of the plasma membrane of the plant root system by EPFRs (Alfei et al. 2024).

Particle size affects the degree of plant stress from biochar, with smaller particle sizes typically having a greater specific surface area, promoting interaction with plants and resulting in greater growth inhibition (Huang et al. 2020). Nanobiochar showed a significant suppressive effect on grass height and biomass of rice plants compared to conventional biochar (Shen et al. 2020; Wang



ROS generated by EPFRs in biochar mediate oxidative stress, which lead to impaired photosynthesis and the inhibition of oxygen release, thus damaging cell structure and induce cell death.

Pollutants and EPFRs inhibit microorganisms activity.

Biochar may enter the animal's body through consumption. Pollutants in biochar may have toxic effects on organs, tissues and cells.

Pollutants inhibit root growth and ROS generated by EPFRs in biochar induce oxidative stress to cell membrane.

Fig. 5 Possible health risks arising from the application of biochar to different organisms

et al. 2018c). The accumulation of nanobiochar in plant root tissues contributed to slow growth, attributed to its good penetration into plant cell walls and membranes. ROS production induced an oxidative stress response, causing plant cell death and growth inhibition (Verma et al. 2019).

3.3 Microorganisms

Microorganisms are widespread in the environment and significantly impact ecosystem functioning, making them available for evaluation and analysis of the risks associated with biochar applications. Adding biochar to soil can have a direct or indirect adverse impact on soil microorganisms (Fan et al. 2020). The direct effects of biochar on microorganisms are more pronounced. Anjum et al. (2014) observed that high concentrations of PAHs in biochar have high mutagenicity sites and cause code-switching mutations in the G-C base pair locus of *Salmonella typhimurium* strains. Mutagenicity experimental studies conducted on swine manure biochar showed that biochar produced at 400 and 600 °C exhibited 54% mutagenicity against *Salmonella typhimurium*. Heavy metals or organic pollutants in biochar directly affect microbial activity. For example, the growth of bacterial and *actinomycetes* populations may be inhibited by Cd in biochar, while organic pollutants, for instance, PAHs, carboxylic acids, furans, phenols, benzene, and ketones, may inhibit microbial activity at high concentrations (Ding et al. 2013; Du et al. 2023). Biochar can also adsorb signaling molecules used by microorganisms for communication. Intraspecies and interspecies communication in bacteria is achieved by transmitting signaling molecules such as flavonoids, indoles, and quinolones (Brtnicky et al. 2021; Masiello et al. 2013). Adsorption of these signaling molecules by biochar may disrupt communication between microorganisms, inhibiting gene expression and the transmission of related processes (e.g., nitrogen and carbon fixation) (Masiello et al. 2013; Ren et al. 2021). Furthermore, EPFRs in biochar show an acute biological response to the marine luminescent bacterium *V. fischeri*, inhibiting bacterial activity (Bastos et al. 2014). ROS produced by EPFRs in biochar induced upregulation of SOD activity, disrupted redox homeostasis in *Streptococcus obliquus* and caused oxidative damage toxicity (Zhang et al. 2019c). In summary, biochar may adversely affect plants, animals, and microorganisms directly or indirectly through various pathways. Effectively assessing and minimizing these risks requires careful study and consideration.

3.4 Human health

The particle size of biochar is usually reduced before application by grinding to increase the contact area, leading to the diffusion of some biochar in the form of dust during application. This is the most significant way biochar can impact human health. For instance, biochar made from rice husk pyrolyzed at high temperatures contains toxic crystalline substances (silica) that may cause respiratory damage if inhaled by humans (Hussain et al. 2017; Li et al. 2022). Pollutants in biochar may accumulate and transport in plant roots, and these toxic substances are difficult to degrade, which can spread to the food chain and eventually threaten human health. Studies on the health risks of biochar are scarce and mainly limited to the assessment of the carcinogenic risk of PAHs, with the health risks of other pollutants in biochar not being systematically studied (Wang et al. 2019a). Therefore, a systematic assessment of the health risks of biochar is important for its safe production and utilization.

EPFRs are produced during biomass pyrolysis and can induce ROS formation, and according to various reports on the risks of EPFRs, these compounds have potentially adverse effects on humans and may pose a significant risk. The potential hazards to humans that may result from EPFRs from biochar are summarized in Fig. 6. EPFRs are strongly associated with declines in human metabolic health (Odinga et al. 2020). They markedly reduce the content of cellular enzymes, such as superoxide dismutase, glutathione, and glutathione peroxidase. Reactive oxygen species jeopardize the integrity of healthy cell membranes (Ruan et al. 2019) and accelerate cellular aging (Zhu et al. 2020). EPFRs are harmful to human health by generating ROS and causing oxidative stress in human lung cells when interacting with oxygen molecules (Chen et al. 2018b). EPFRs produced by oxidants, primarily metal oxides, can damage lung cells and DNA, further leading to pneumonia and cardiovascular diseases (Chen et al. 2018b; Liu et al. 2022). Nevertheless, the extent to which EPFR in biochar could affect human health requires further investigation.

The differences in risk to organisms of different types of biochar mainly depend on factors such as the degree of contamination of its raw materials, pyrolysis temperature and biochar particle size. Raw materials with a high content of heavy metals or organic pollutants for the production of biochar may increase the risk of endogenous pollutants to organisms. These risks can be significantly reduced by selecting suitable raw materials and adjusting the preparation conditions. Furthermore, long-term aging of biochar in the natural environment leads to changes in its properties, which not only weaken its original adsorption capacity, but may also induce the release of previously adsorbed pollutants (exogenous pollutants). In this case, adding catalysts or introducing functional groups through modification during the preparation of biochar, may improve the chemical stability and aging

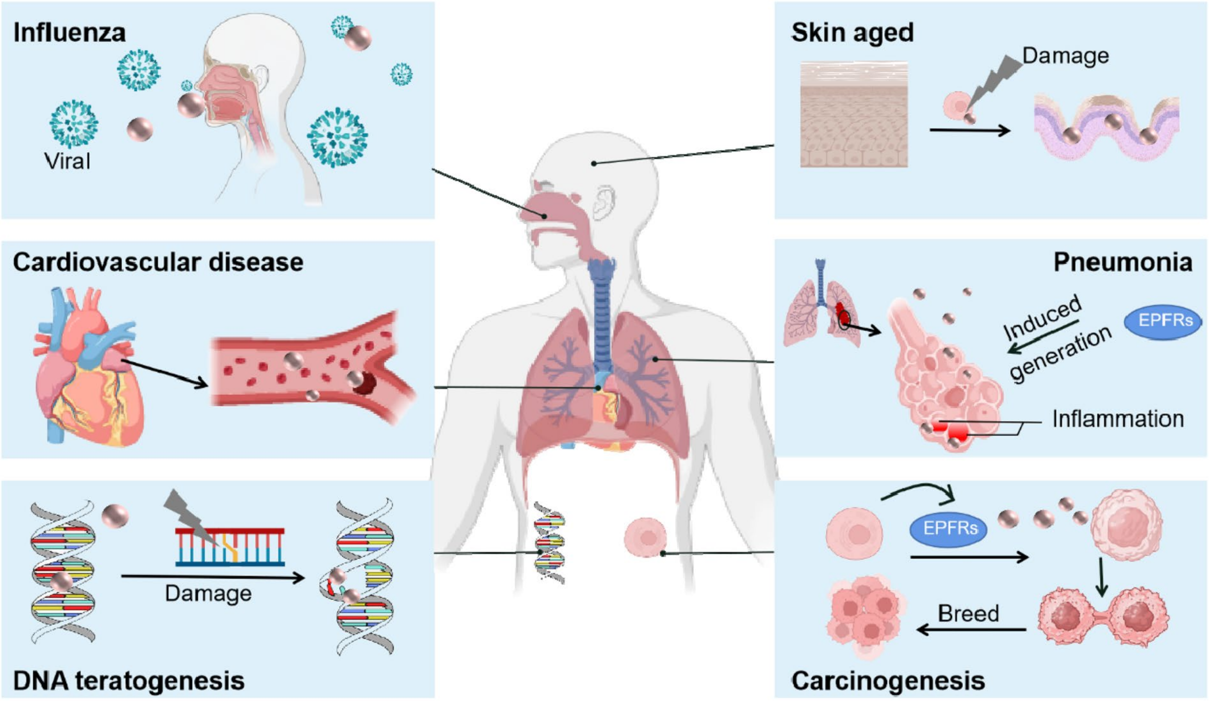


Fig. 6 Schematic representation of the possible damage to human health caused by the formation of EPFRs in biochar

resistance of biochar reducing the risk of exogenous pollutants (Wang and Wang 2019).

4 Environmental risk assessment of biochar

Environmental risk assessment of biochar is essential to ensure its sustainable use and minimize negative impacts. Understanding the possible environmental impacts of biochar can guide the development of effective management strategies, including preventing pollution of water bodies and soils, protecting ecosystem health, maintaining biodiversity balance, and reducing risks associated with its application. Risk assessment modeling, chemical assays, and bioassays are the main tools used to evaluate the environmental impact of biochar, providing varying degrees of qualitative or quantitative assessment by evaluating environmental matrices (soil, water bodies, and sediments), exposed objects (animals, plants, and microorganisms), toxic substances (organic and inorganic pollutants) carried or released by biochar, and biochar itself. Proposed risk assessment models and biochemical methods are prospective and predictive for biochar in practical production and application, offering guidance for effective environmental risk control and quality screening of biochar, and ensuring its safe and beneficial use in various environmental applications.

4.1 Risk assessment models

4.1.1 Phytotoxicity

The germination rate of plants can directly and effectively reflect the toxic effect of biochar on the initial growth of plants, making germination experiments a commonly used method for environmental risk assessment of biochar (Shen et al. 2022). PAHs, salinity, volatile fatty acids, pH, and heavy metals in biochar are the main pollutants that inhibit plant germination and growth (Huang et al. 2018). Analyzing the degree of inhibition of these pollutants on seed germination through the germination index (GI) is a simple and direct means of evaluating the environmental risk of biochar. The formula for calculating GI is as follows:

$$\mathrm{GI} = \frac{(\text{Seed germination number of treatment}) \times (\text{root length in treatment})}{(\text{Seed germination number of control}) \times (\text{root length in control})}.$$

However, this method primarily investigates the phytotoxicity of biochar through germination experiments, which means some drawbacks, for instance, long experimental times, unclear internal mechanisms, and other factors beyond control, are present during the experiment process. The environmental factors (temperature, humidity, light conditions, pH) can affect seed germination and these factors may change the toxic effects of biochar on plants (Wang et al. 2022a). The toxicity or pharmacological effects of certain plants may also vary seasonally (Carvalho et al. 2020). To mitigate the effects of external factors, environmental factors such as temperature, humidity and light should be controlled under laboratory conditions to ensure that conditions are consistent across all treatments (Visioli et al. 2016). In addition, replications of the experiment should be conducted to verify the reliability of the results.

Therefore, it can only qualitatively analyze the toxicity risk of biochar based on the GI value. For example, a GI value of less than 50% for corn stover biochar indicates high phytotoxicity (Shen et al. 2022). The GI value of biochar at 350 °C was found to be 46.7%, which significantly inhibited root length growth, indicating ecotoxicity (Huang et al. 2018).

4.1.2 Heavy metal risk assessment modeling

Public health and ecosystems have long-term been threatened by heavy metals due to their toxicity and inability to biodegrade (Min et al. 2022; Zhang et al. 2020b). Therefore, three analytical models were proposed to assess the risk of heavy metals in biochar (Liu et al. 2016). The Geological Accumulation Index (GAI) is a geochemical standard used to assess the extent of soil or sediment contamination (Li et al. 2018a).

$$I_{\text{geo}} = \log_2 \frac{C_n}{1.5 \times B_n},$$

where C_n is the amount of heavy metals in the sludge or biochar, and B_n is the amount of localized heavy metals in the soil, with a factor of 1.5 used to minimize the effects of possible localized soil changes. The I_{geo} is divided into seven intervals: uncontaminated (UC), uncontaminated to moderately contaminated (UMC), moderately contaminated (MC), moderately to heavily contaminated (MHC), heavily contaminated (HC), heavily to extremely contaminated (HEC) and extremely contaminated (EC).

Risk Assessment Codes (RACs) are used for quantifying the bioavailability of heavy metals in sediment, ash, soil, and the potential risk of heavy metals in biomass and biochar (Liu et al. 2016). The higher the RAC value, the greater the ecological risk of heavy metals (Mukherjee et al. 2022). The biological risk of toxic metals is assessed

Table 2 Models used for the risk assessment of heavy metals in biochar

Raw material	Model	Heavy metal						References
		Cadmium (Cd)	**Chrome (Cr)**	**Lead (Pb)**	**Copper (Cu)**	**Zinc (Zn)**	**Nickel (Ni)**	
Sludge	RAC	18.7 (MR)	2.2 (LR)	12.2 (MR)	0.9 (LR)	1.6 (LR)	0.5 (LR)	Liu et al. (2016)
	GAI	2.8 (MC-HC)	1.0 (MC)	-0.5 (UC)	2.8 (MC-HC)	3.5 (HC)	0.3 (UC)	
	E_r	154.74 (VHR)	0.49 (LR)	10.41 (CR)	0.9 (LR)	0.95 (LR)	11.08 (CR)	
Sludge	RI	491.6 (CR)						Wu et al. (2023)
Pokeweed	RI	67.51 (MR)						Yang et al. (2021b)
Swine manure	RAC	33.5 (HR)	–	–	4.34 (LR)	43.7 (HR)	–	Li et al. (2020)
	E_r	394 (VHR)	–	–	3.57 (LR)	5.25 (LR)	–	
	RI	403 (HR)						
Chicken manure	RAC	0.72 (LR)	5.29 (LR)	–	5.06 (LR)	5.91 (LR)	2.77 (LR)	Wang et al. (2021a)
Swine manure	RAC	15.61 (MR)	1.62 (LR)	–	5.72 (LR)	25.91 (MR)	5.91 (LR)	
Swine manure	E_r	MR	LR	LR	LR	LR	LR	Xu et al. (2020)
	RI	88(MR)						
Sludge rice husk	E_r	–	–	8.24 (LR)	–	43.4 (MR)	2.2 (LR)	Xiong et al. (2021)
Cow manure	GAI	– 0.84 (UC)	– 10.54 (UC)	– 5.76 (UC)	– 4.65 (UC)	2.24 (HC)	– 4.64 (UC)	Zhang et al. (2020b)
	RAC	4.54 (LR)	0.06 (NR)	1.93 (LR)	0.36 (NR)	17.97 (MR)	3.23 (LR)	
	E_r	170.1 (VHR)	0.86 (LR)	6.6 (MR)	2.15 (LR)	10.59 (CR)	21.24 (HR)	
	RI	211.54 (VH)						

Geological accumulation index (GAI, represented by I_{geo}) < 0 denotes uncontaminated (UC), 0–1 denotes uncontaminated to moderate contamination (UC-MC), 1–2 denotes moderate contamination (MC), 2–3 moderate contamination to heavy contamination (MC-HC), 3–4 denotes heavy contamination (HC), 4–5 denotes heavy to extreme contamination (HE-EC), > 5 denotes extreme contamination (EC). Risk assessment codes (RAC): denotes no risk (NR) < 1, 1–10 denotes low risk (LR), 11–30 denotes moderate risk (MR), 31–50 denotes high risk (HR), and > 50 denotes very high risk (VHR). Ecological risk (Er): ≤ 5 denotes LR, 5–10 MR, 10–20 considerable risk (CR), 20–40 HR, > 40 VHR. Potential ecological risk index (RI): < 30 denotes LR, 30–60 denotes MR, 60–120 denotes CR, > 120 denotes VHR

quantitatively on the basis of the RAC value, which also assesses the risk of bioaccumulation of heavy metals (Wu et al. 2022).

$$\mathrm{RAC} = \frac{F_1}{C_n} \times 100\%,$$

where F_1 means the content of exchangeable and carbonate fractions, and C_n means the content of heavy metals. Based on the values of the RAC, five risk levels are classified: no risk (NR), low risk (LR), moderate risk (MR), high risk (HR), and very high risk (VHR).

The potential ecological risk index (RI) assesses ecological risk based on the intensity, sensitivity, and toxicity of heavy metals (Bing et al. 2016).

$$C_f = \frac{C_D}{C_R},$$

$$E_r = T_r \times C_f,$$

$$\mathrm{RI} = \sum_{i=1}^{n} E_r,$$

where C_D means the concentration of the measured metal, C_R means the background concentration, and T_r means the toxicity response factor for each heavy metal. T_r is 1, 2, 5, 5, 5, 10, and 30 for Zn, Cd, Cu, nickel (Ni), Pb, As, and Cr, respectively. E_r represents the potential ecological risk of a single heavy metal, which can be divided into five components: LR, MR, considerable risk (CR), HR, and VHR. RI represents the potential ecological risk of all measured heavy metals and can be categorized into LR, MR, considerable risk (CR), and VHR. Wang et al. (2019a) assessed the environmental risk of heavy metals in swine and sheep manure biochar based on these three models. They showed that the GAI values of Cu and Zn in swine manure decreased from 200 °C to 800 °C, with the GAI value of Cd peaking at 2.45 (MHC) at 350 °C before decreasing. The GAI values of Cd in sheep manure biochar approached 0 (UC) at pyrolysis temperatures from 500 °C to 800 °C. Thus, the heavy metal pollution levels of pig and sheep manure biochar can be effectively reduced during high-temperature pyrolysis. This is because at high pyrolysis temperatures, the degree of thermal cracking of biomass gradually increased and the organic matter continued to decompose, leading to the deposition of more heavy metals in the biochar (Zhang et al. 2022b). However, at the same time, the elevated temperature leads to the fixation of metals in the carbon matrix, which promotes the transformation of unstable components to relatively stable ones, forming metal oxides, sulphide phases, or crystalline minerals (CuO and CuS) (Li et al. 2020), which reduces environmental and ecological risks. Based on the RI of heavy metals from biochar, 650 °C and above are considered the optimal pyrolysis conditions, with Cd being the main cause of risk. According to RAC-based assessments, pyrolysis temperatures higher than 650 °C are optimal (Wang et al. 2019a).

The assessment results based on GAI, RI, and RAC values showed some inconsistencies when assessing heavy metal contamination in livestock manure-derived biochar. GAI considers only the accumulation levels of individual heavy metals, while RI can describe either the ecological risk of a single contaminant or the combined risk of multiple contaminants. RAC considers only the F_1 fraction (the content of exchangeable and carbonate fractions) of each pollutant, ignoring the percentage in the reducible fraction (F_2) (Wang et al. 2019a). Therefore, comparing the results of multiple risk assessment methods ensures comprehensiveness and accuracy. Several studies have combined these three risk assessment models for a more holistic evaluation (see Table 2). Also, when assessing the environmental risk of biochar based on GAI, RI and RAC, the concentration of heavy metals in plant roots, stems and leaves is measured to assess their accumulation. Samples were collected from each part of the plant and the heavy metal content was determined using analytical tools such as Inductively Coupled Plasma Mass Spectrometer combining with data from GAI and RI. This approach ensured a comprehensive assessment of heavy metal accumulation during biochar application and its impact on plant growth.

4.1.3 Risk assessment of organic pollutant residues in biochar

Since PAHs are the main organic pollutant present in biochar, assessing the environmental toxicity of organic contaminants in biochar often involves analyzing the risk value of PAHs. The release and transfer of PAHs from biochar pose a toxicity risk to soil animals, plants, and humans; assessing PAH environmental risk in biochar should be considered a top priority. PAHs carried by biochar are extracted using Soxhlet extraction first, and then the toxicity equivalent quotient (TEQ) is calculated based on the toxicity equivalent factor (TEF) and individual PAH concentrations (Ni et al. 2021).

$$\mathrm{TEQ} = \sum_{i=1}^{n} C_{PAHi} TEF_i,$$

where C_{PAHi} is the concentration of PAHs in biochar (μg kg^{-1}), and TEF_i is the toxicity equivalence factor of PAHs.

Wang et al. (2019b) calculated TEQ data for 16 USEPA-prioritized PAHs in biochar produced at different pyrolysis temperatures. The PAH-TEQ values of biochar pyrolyzed at ≤ 200 °C, 200–400 °C, 400–600 °C,

Table 3 Methods of extraction and determination of organic pollutants in biochar

Raw materials	Method	Pollutant	References
Paper mill sludge	Soxhlet extraction	Polycyclic aromatic hydrocarbons (PAHs)	Devi and Saroha (2015)
Wheat straw	Liquid extraction	PAHs	Weidemann et al. (2018)
Corn stalk	Solid-phase microextraction	Volatile organic compounds (VOCs)	Ghidotti et al. (2017)
Chicken manure	Solid-phase microextraction	PAHs	Rombolà et al. (2015)
		Volatile fatty acids (VFAs)	
Coconut Shell	Soxhlet extraction	PAHs	Hale et al. (2012)
		Dioxin	
Sewage sludge	Soxhlet extraction	PAHs	Tomczyk et al. (2020)
Sawdust	Soxhlet extraction	Furans	Lyu et al. (2016)
–	Solvent extraction	PAHs	Sørmo et al. (2024)
–	Thermal analysis	VOCs	Dutta et al. (2017)
Textile dyeing sludge	Bureau community of reference (BCR) sequential extraction	Zn, Mn, Cu, Cr, Ni and Cd	Wang et al. (2019c)
Sewage sludge	Microwave digestion	Pb, Zn, Cu, Cd, Cr, Ni and As	Lu et al. (2016)
Sludge	Microwave digestion	Cr, Ni, Zn, Cd, As, Pb and Cu	Liu et al. (2016)
Cow manure	Microwave digestion and three-step BCR sequential extraction	Cd, Cr, Cu, Ni, Pb, and Zn	Zhang et al. (2020b)
Brassica napus L., Pennisetum sinese and, *Lolium perenne L*	Toxicity characteristic leaching procedure	Cd	Zhang et al. (2020c)
Rice straw	Microwave digestion	Cu, Zn, Cd, and Pb	Yang et al. (2021a)

600–800 °C, and ≥ 800 °C ranged from 37–3,341 μg kg^{-1}, 12–64,640 μg kg^{-1}, 195–78,387 μg kg^{-1}, 101–355,295 μg kg^{-1}, and 3,800–169,300 μg kg^{-1}, respectively. Approximately 0%, 23%, 40%, 53%, and 83% of the biochar produced at these temperature ranges exceeded the criteria for basic grade biochar (≤ 12,000 μg kg^{-1}), respectively.

4.2 Chemical methods

Chemical extraction methods can be used to accurately understand the levels of contaminants in biochar to determine the environmental risk it may pose. The commonly used quantitative methods for the determination of organic pollutants/heavy metals in biochar are soxhlet extraction (Ghidotti et al. 2017), solid-phase microextraction (Devi and Saroha 2015), liquid extraction (Weidemann et al. 2018), bureau community of reference (BCR) sequential extraction (Wang et al. 2019c) and microwave digestion (see Table 3). However, these chemical methods mainly measured the total concentration of organic pollutants/heavy metals in biochar rather than the bioavailability content. In addition, different organic solvents have different solubility for different types of pollutants, and improper selection may lead to incomplete extraction of pollutants, affecting detection accuracy. The physicochemical properties of the biochar itself (e.g., specific surface area and amount of pore structure) may affect the extraction efficiency and, consequently, the qualitative and quantitative accuracy. Therefore, whether chemical methods can accurately assess the toxicity risk of pollutants in biochar is debatable.

4.3 Whole-cell bioreporter technology

In the past few years, the application of whole-cell bioreporters in assessing the environmental risk of contaminants has been gaining attention. Whole-cell bioreporters are active microorganisms that are genetically designed to detect physical and chemical matters in the environment and generate electrochemical or optical signals through the action of reporter genes (Fig. 7A) (Zhu et al. 2022). Specific whole-cell bioreporters are typically constructed from promoters involved in specific genetic regulatory mechanisms and output signals through the expression of reporter proteins upon recognition of a specific target sample (Huang et al. 2024). Thus, they can recognize specific chemicals (e.g., heavy metals, antibiotics, and organics) and determine their bioavailability (Huang et al. 2024).

Studies have shown that whole-cell bioreporter technology can detect various types of heavy metals (e.g., Cd, Pb, Cr, Cu, As, and Zn) and organics (e.g., tetracyclines, PAHs, and PCBs) in the environment. By using this technology, Wang et al. (2020a) evaluated the environmental risk of tetracyclines on biochar, and Zhu et al. (2024) assessed the environmental risk of Pb on biochar. These studies confirmed that the pollutants in biochar are still bioavailable, demonstrating the good specificity and sensitivity of whole-cell bioreporters to these pollutants. This indicates that whole-cell bioreporters are suitable for the environmental risk assessment of biochar. However, assessing the bioavailability of contaminants in solid materials (e.g., biochar) using whole-cell bioreporters is more challenging than in aqueous phases because solid particles strongly affect the transmittance of the bioluminescent signal of the

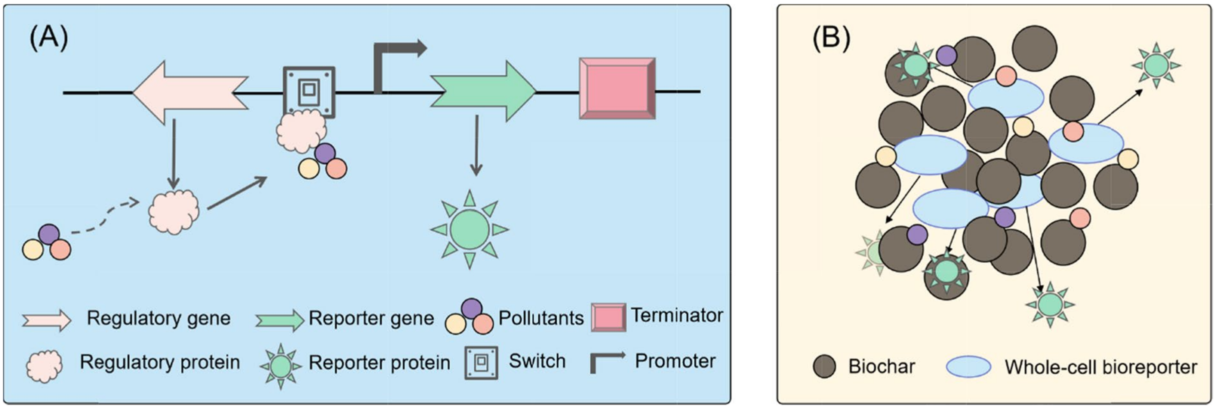


Fig. 7 Schematic diagram of environmental risk assessment of contaminants in biochar by whole-cell bioreporter. **A** Principles of whole-cell bioreporter for contaminants detection. When regulatory proteins recognize pollutants, a switch on the bacterial chromosome immediately adjacent to the promoter activates a reporter gene, which begins the synthesis of the reporter protein. **B** How whole-cell bioreporter recognizes contaminants in biochar and the effect of biochar on the light signal it delivers

whole-cell bioreporter (Fig. 7B), resulting in a weaker measured signal compared to the true value (Zhang et al. 2022a). Consequently, many assessments of the bioavailability of contaminants in solid particles have focused on measuring contaminants in easily extractable aqueous phases rather than suspensions of solid particles (Ji et al. 2023). However, it has been shown that whole-cell bioreporters can detect higher concentrations of contaminants in direct contact with suspensions of soil and sediment rather than in extractable aqueous phases (Chen et al. 2023). Therefore, measuring only the extractable aqueous phases in solid particles is insufficient to reflect the actual bioavailability of contaminants in samples. Zhang et al. (2022a, b) quantified the effects of suspensions of soil, sediment, and biochar on the blockage of the bioluminescent signal of a whole-cell bioreporter and developed a method to correct the optical signal blockage. This correction is crucial for using whole-cell bioreporters to assess the environmental risk of pollutants in biochar. Although studies quantifying the environmental risk of biochar based on whole-cell bioreporters are limited, it is feasible to quantify the bioavailability of contaminants in biochar through well-defined bioluminescence blockage correction methods for whole-cell bioreporters.

5 Conclusions and outlooks

Biochar may pose unintended environmental and health risks due to its specific physical properties and chemical interactions, which can have various potential adverse effects. The purpose of this review is not to downplay the benefits or magnify the potential drawbacks of biochar, but to more accurately assess the environmental and health risks of biochar by distinguishing between sources of pollutants. Understanding endogenous pollutants can help in the selection of cleaner feedstocks, resulting in safer biochar products. In contrast, knowledge of exogenous pollutants allows preventive measures to be taken during the application process of biochar. It provides a rational understanding and assessment of its potential risks through a combination of risk assessment methods. Such an approach is necessary for the sustainable development and safe use of biochar.

- Biochar has been increasingly utilized to remediate environmental pollution, but the environmental risks of pollutants adsorbed by biochar remain poorly understood. Moreover, existing environmental risk assessment methods focus on liquid-phase biochar extracts, overlooking the need to directly evaluate biochar itself.
- A standardized methodology for assessing the environmental risk of biochar is currently lacking. Using diverse assessment methods can yield substantially disparate results, underscoring the necessity for standardized approaches in future environmental risk assessments.
- To ensure the safe and sustainable use of biochar, unpolluted biomass with high lignin content should be preferred as feedstock to reduce the risk of endogenous pollutants in biochar. At the same time, pyrolysis temperatures should be controlled to decrease the formation of hazardous substances and to facilitate the volatilization or conversion of pollutants into more stable forms. In addition, biochar with excessively fine particles should be avoided to minimize diffusion and its potential environmental risk.
- Typically, toxicological studies on biochar are limited to short-term periods, with a lack of research on the long-term consequences of biochar exposure on living organisms. Furthermore, existing studies are predominantly concerned with the effects of biochar on terrestrial organisms, such as plants and animals, in soil ecosystems, with relatively little attention devoted to its toxicological impacts in aquatic environments.

Author contributions

Mingying Dong: conceptualization, data curation, investigation, visualization, writing—original draft. Mengyuan Jiang: writing—review and editing. Zirun Zhang: writing—review and editing. Williamson Gustave: writing—review and editing. Meththika Vithanage: writing—review and editing. Nabeel Khan Niazi: writing—review and editing. Bo Chen: writing—review and editing. Xiaokai Zhang: conceptualization, supervision, writing—review and editing. Hailong Wang: writing—review and editing. Feng He: writing—review and editing.

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Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

Hailong Wang is an Executive Editor of the journal Biochar, and he was not involved in the peer-review or handling of the manuscript. Nabeel Khan Niazi is an AE of the journal Biochar, he was not involved in the peer-review or handling of the manuscript. Meththika Vithanage is an EBM of the journal Biochar, she was not involved in the peer-review or handling of the manuscript. The authors have no other competing interests to disclose.

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