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Biochar

REVIEW

How much biochar should be used in global ecological restoration?

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Abstract

Biochar applied in ecological restoration shows a significant dose-dependent effect. Therefore, determining an appropriate rate for specific environments is essential in practical applications. To this end, we integrated soil profiles and biogeochemical and microbiome datasets from six major ecosystems (agricultural, grassland, forest, coastal wetlands, desert, and polar tundra), constructed a global biochar remediation threshold map, and investigated the driving mechanisms of threshold formation. Simultaneously, differentiated application frequency strategies tailored to each ecosystem are proposed. The results showed that the appropriate thresholds for different ecosystems were 5–30 t ha^{-1} (agricultural), 5–40 t ha^{-1} (grassland), 5–40 t ha^{-1} (forest), 10–50 t ha^{-1} (coastal wetlands), 10–40 t ha^{-1} (desert), and 20–60 t ha^{-1} (polar tundra). Within the threshold range, in combination with customized application frequency, biochar enhances ecological functions by increasing soil water-holding capacity (by approximately 10–14.3%), reducing greenhouse gas emissions (by approximately 16.4–31.5%), lowering soil heavy metal content, and increasing soil organic matter. Exceeding the threshold can cause sharp fluctuations in soil pH, increases in bioavailable polycyclic aromatic hydrocarbons, and decreases in microbial diversity, thereby inhibiting remediation. Inadequate application frequency also weakens the ecological restoration efficacy of biochar. The thresholds are environmentally dependent. The threshold window can be expanded or narrowed by the joint regulation of preparation parameters, soil characteristics, climate, and human management. Based on this, we propose a framework of "threshold identification–mechanism analysis–targeted intervention" and customized application paths for ecosystems (e.g., on-farm biochar + fertilizer single/strip application, low-dose staged application in grassland, forest low-dose dispersal single intervention, combination of wetland surface and spot combined with seasonal application, desert inter-root precision single application, and zoned management of medium and low doses in polar regions). The framework provides a quantitative and mechanistic basis for formulating standards for the production and application of biochar and for promoting precise remediation.

Highlights

- Establish a global biochar remediation threshold map to define applicable doses for six major ecosystems.
- Develop ecosystem-specific biochar application strategies based on biochar preparation, soil, and climatic conditions.
- Address the knowledge gap in biochar application doses across ecosystems, enabling precise ecological restoration and regional standard formulation.

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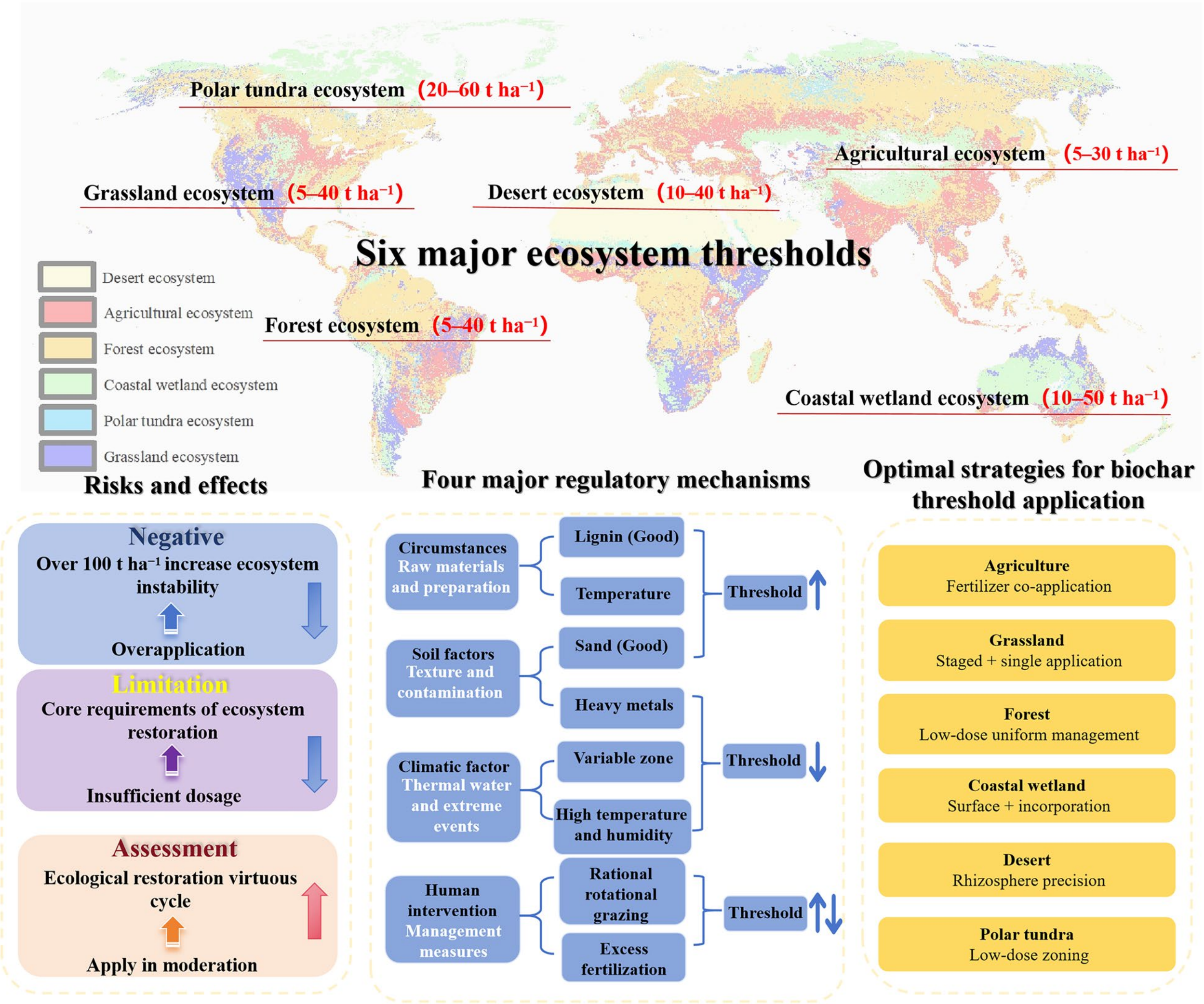
Keywords Biochar, Application threshold, Application frequency, Ecological restoration, Mechanism analysis, Precision regulation

Graphical Abstract



1 Introduction

With the intensification of global climate change and the growing problem of ecosystem degradation, biochar has become a key material in ecological restoration (Diatta et al. 2020; Lehmann et al. 2011). However, the large-scale application of biochar has shown that excessive application can inhibit plant growth, alter the soil microbial community structure, and trigger the risk of secondary pollution, while insufficient application cannot achieve the expected remediation effect, thereby causing resource waste and prolonging the ecological restoration cycle (Khan et al. 2022; Hu et al. 2025; Majewska and Hanaka 2025; Wang et al. 2024a, b, c, d).

The key to solving this problem lies in clarifying the precise application thresholds for biochar. However, current research faces several challenges. First, current research results on the application of biochar show heterogeneity across various ecosystems. Most studies have focused on agricultural ecosystems, and there are significant gaps in the research on ecosystems such as forests, grasslands, and wetlands (Li et al. 2024). This not only limits the cross-system migration of research conclusions but also hinders the development of a universal principle. The IPCC Special Report on Climate Change and Land (2019) of the Intergovernmental Panel on Climate Change noted that approximately one-quarter of the world's ice-free land has been degraded by human activities (Shukla et al. 2019), highlighting the urgent need to develop ecosystem restoration technologies such as biochar.

The application thresholds of biochar are not fixed values but rather dynamic ranges regulated by spatiotemporal factors. Long-term field observation data indicate that the core functions of biochar, such as carbon sequestration, will gradually decline over time (Gross et al. 2024; Li et al. 2025a, b). In addition, environmental disturbances, such as freeze–thaw cycles, can alter the physicochemical properties and environmental behavior of biochar, thereby shifting the effective application threshold (Siatecka and Oleszczuk 2023; Bai et al. 2026). Current research generally neglects this spatiotemporal dependence, making application suggestions based on static thresholds that are difficult to adapt to real ecological scenarios.

The above-mentioned knowledge gaps stem from the deep limitations of the current research paradigm. First, cognitive fragmentation, lacking cross-ecosystem comparative analysis, makes it difficult to distill universal laws. For example, in paddy field ecosystems, the application of biochar needs to balance the relationship between greenhouse gas emissions and crop yields, whereas the core goal in grassland ecosystems is to improve soil structure and promote the colonization of forage plants. There are significant differences in the criteria used to determine thresholds for the two (Liu et al. 2012; Zhang et al. 2024). Second, there are deficiencies in our understanding of the mechanisms of action. Existing studies focus on the surface level and have not yet clarified how the interrelationships among biochar properties, soil properties, and climatic conditions affect the application threshold (Lehmann et al. 2011). Third, there is a disconnect between theory and practice. Although the academic community has clearly demonstrated that the effect of biochar is habitat-dependent, most threshold suggestions are only numerical ranges and have not been combined with the management scenarios for different ecosystems, thus failing to form targeted ecosystem management plans (Joseph et al. 2021).

In response to these issues, this study aimed to: (1) integrate and map the application thresholds of biochar for six major ecosystems; (2) clarify the intrinsic mechanisms underlying the regulation of the interaction between biochar, soil, and climate; and (3) propose feasible implementation plans for each sub-ecosystem. To this end, we constructed a dynamic threshold framework based on the mechanism of action, bridging the gap between the general application recommendations for biochar and ecological restoration practice, thereby providing a basis for the standardized and sustainable application of biochar (Fig. 1).

2 Methodology

This review employed quantitative integrative analysis methods to examine the application thresholds and ecological restoration effects of biochar across six major ecosystems (agricultural, grassland, forest, coastal wetlands, desert, and polar tundra). To ensure rigor, reproducibility, and representativeness, a structured literature search and screening process was conducted using Web of Science and ScienceDirect, covering the period from January 2011 to December 2025. The search term coverage was as follows: ("biochar" and "ecosystem") or ("biochar" and "soil fertility") or ("biochar" and "soil water-holding capacity") or ("biochar" and "nutrient absorption") or ("biochar" and "carbon sequestration") or ("biochar" and "greenhouse gas emissions") or ("biochar" and "microbial activity") or ("biochar" and "crop yield") or ("biochar" and "soil remediation") or ("biochar" and "ecological remediation"). The initial query retrieved 1533 peer-reviewed articles based on the titles and abstracts.

The inclusion criteria were as follows: (1) original research or meta-analysis papers published in peer-reviewed journals, (2) research focusing on the application of biochar in the six ecosystems listed above, and (3) the presence of relevant data on the dosage of biochar application (such as t ha^{-1}) and the corresponding quantitative results of ecological effects (e.g., soil physical and chemical properties, microbial activity, vegetation productivity, and carbon sequestration efficiency). The exclusion criteria included the following: (1) conference abstracts, (2) editorial or opinion articles, and (3) studies lacking clear ecosystem type annotations or specific biochar dosages.

After screening, 178 studies were selected for a full-text review. Among these, 95 were included in the final analysis. The studies included field experiments, greenhouse experiments, meta-analyses, and review papers. The research topic encompassed six core areas: (1) soil physical properties (including bulk density, porosity, and aggregate stability), (2) nutrient absorption efficiency (nitrogen, phosphorus and potassium availability, and nutrient ratios), (3) microbial interactions

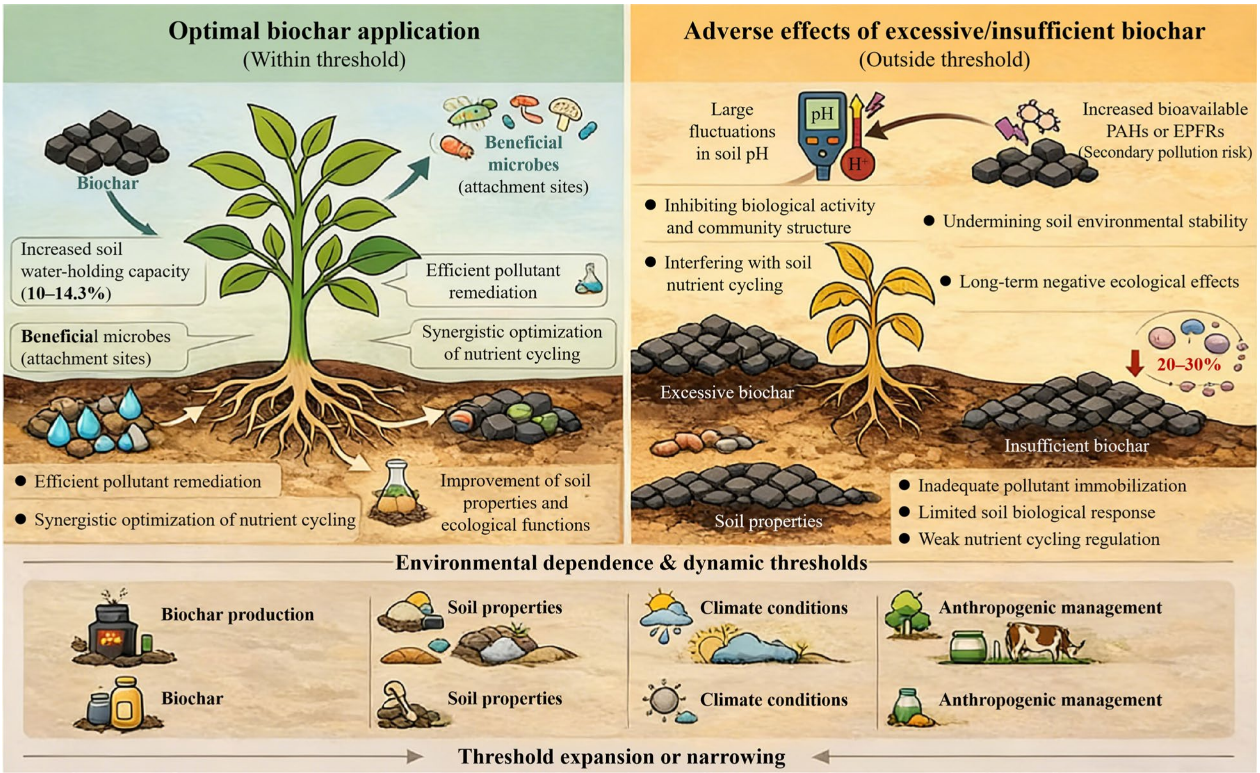


Fig. 1 Application and dilemma of biochar

(microbial activity, community structure, and functional diversity), (4) vegetation productivity (crop yield, forage biomass, and plant stress resistance), (5) pollutant remediation (reduction in salt, heavy metals, and petroleum pollutants), and (6) climate mitigation potential (carbon sequestration and reduction of greenhouse gas emissions). The six core areas are shown in Fig. 2, presenting a structured analytical framework for organizing the review of research findings. This framework was constructed based on recurring themes identified during the full-text review and included the soil structure, nutrient absorption efficiency, microbial interactions, crop yields, pollutant remediation, and climate change mitigation. This structured thematic approach enables the identification of recurring patterns, context-specific outcomes, and research gaps in the biochar literature.

Among the 95 included studies, 19 focused on improving the soil structure, 24 on nutrient absorption and efficiency, 18 on microbial interactions, 16 on crop productivity, 13 on pollutant remediation, and five on climate mitigation strategies. This classification supports a structured topic framework and enhances the clarity of the synthesis.

3 Threshold risks of biochar in ecosystem restoration

3.1 Risks of excessive application

(1) Undermining soil environmental stability: High dosages of biochar may cause large fluctuations in soil pH, disrupt the soil ion balance, and reduce the availability of key nutrients, such as nitrogen and phosphorus (Dong et al. 2025). Once endogenous pollutants (e.g., PAHs or environmentally persistent free radicals (EPFRs)) carried by biochar exceed the safety threshold, they may trigger secondary pollution through leaching or bioaccumulation (Dong et al. 2025).

(2) Inhibiting biological activity and community structure: Excessive biochar may be toxic to soil biota, reducing the activity and diversity of beneficial microorganisms by 30–60% and decreasing the abundance and biomass of soil macrofauna, such as earthworms, by approximately 70%, severely disrupting the soil food web (Lehmann et al. 2011). In addition, excess biochar can inhibit seed germination and root development; nanobiochar can even penetrate cell walls and cause cell death (Dong et al. 2025).

(3) Interfering with soil nutrient cycling: Excessive application overly immobilizes nitrogen compounds (e.g., ammonia and nitrite), causing nitrogen deficiency in plants, while reducing phosphorus use efficiency by

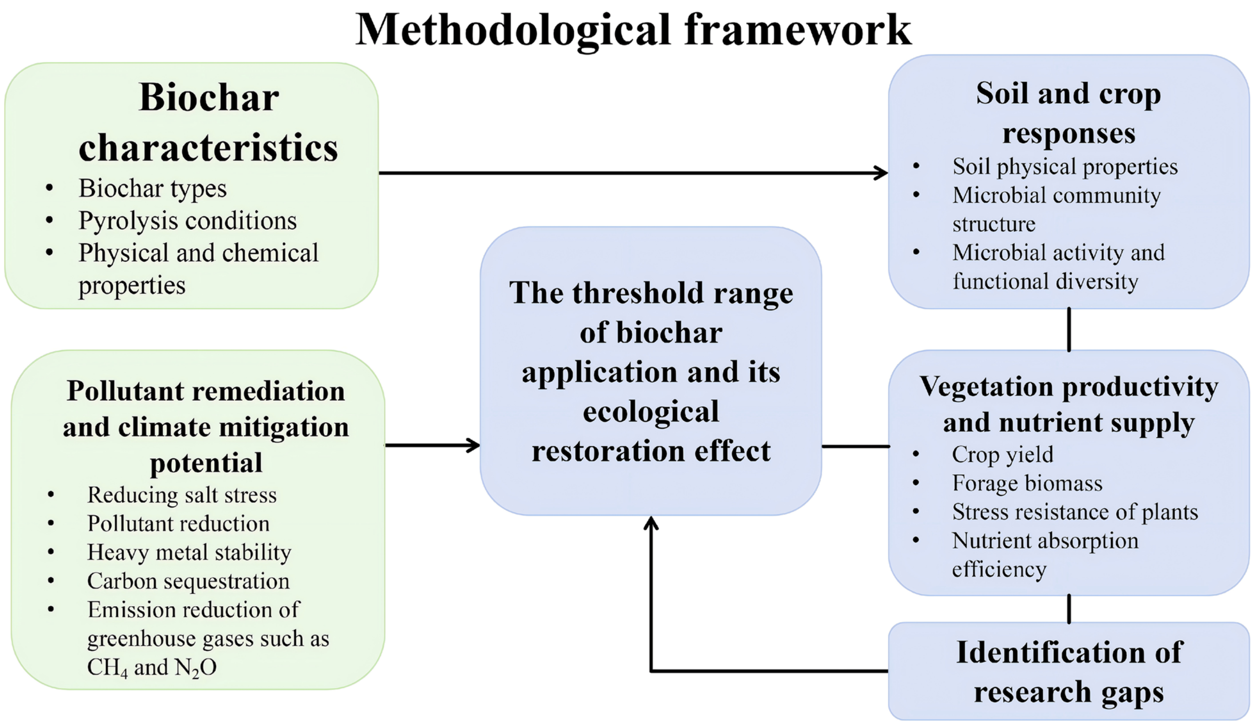


Fig. 2 Methodology core themes framework

20–30% and exacerbating existing soil nutrient imbalances (Chamoli et al. 2025; Glaser and Lehr 2019).

(4) Long-term negative ecological effects: Biochar may interfere with carbon sequestration in terrestrial ecosystems and cause abnormal soil carbon mineralization. For example, an application rate exceeding 100 t ha^{-1} can offset the original carbon sink benefits (Jeffery et al. 2011). Meanwhile, the excess biochar can disrupt the soil structure, reduce organic matter availability, and impair pollutant immobilization capacity (Cen et al. 2021).

3.2 Risks of insufficient application

(1) Inadequate pollutant immobilization: Low-dosage biochar may fail to provide sufficient adsorption sites and pore structures, resulting in low immobilization rates of heavy metals (e.g., Cd and Pb) and organic pollutants (e.g., antibiotics and PAHs), and thus cannot effectively alleviate the toxic effects on plant roots and soil microorganisms (Dong et al. 2025; Wang et al. 2025).

(2) Limited soil biological response: An insufficient dosage makes it difficult to construct a suitable microbial habitat and provide adequate carbon and nutrients for degrading bacteria, leading to limited optimization of the microbial community structure, low metabolic activity, and a 30–40% decrease in the efficiency of pollutant degradation (Lehmann et al. 2011).

(3) Weak nutrient cycling regulation: A low dosage can increase soil phosphorus use efficiency, making phosphorus solubilization and mineralization in saline-alkali soils difficult, thereby failing to alleviate phosphorus limitation. Meanwhile, the effect of a low dosage on nitrogen cycling may be insignificant, with ammonia immobilization rates as low as 15% and nitrite removal rates below 20% (Chamoli et al. 2025; Chang et al. 2025; Glaser and Lehr 2019; Liu et al. 2012).

(4) Limited improvement of soil physicochemistry and system stability: An insufficient application dosage may have minimal effects on improving the soil structure, the soil organic matter content, and the soil water/nutrient retention capacity. Especially in semi-arid regions, too low a dosage cannot balance carbon and nutrient levels, making it difficult to support long-term restoration of ecosystems (Cen et al. 2021; Jeffery et al. 2011; McCormack et al. 2019).

3.3 Effects of appropriate application

(1) Efficient pollutant remediation: An appropriate application of modified biochar (e.g., iron-modified or nitrogen-doped) can significantly immobilize heavy metals (e.g., Cd reduction by 29.45–45.80%) and remove over 80% of antibiotics from soil via pore adsorption and electrostatic interactions. An appropriate amount of biochar also provides attachment sites for functional

microorganisms, synergistically enhancing pollution control (Chang et al. 2025; Wang et al. 2025).

(2) Synergistic optimization of nutrient cycling: An appropriate biochar dosage can increase soil phosphorus use efficiency by 15–25%, accelerate phosphorus mineralization, and effectively immobilize ammonia and nitrite to reduce nitrogen loss, achieving synergistic improvement of nitrogen and phosphorus nutrients (Chamoli et al. 2025; Glaser and Lehr 2019; Wang et al. 2025).

(3) Improvement of soil properties and ecological functions: Biochar can adjust the soil pH to the suitable range of 6.5–7.8, protect plant chloroplasts, and improve photosynthetic efficiency, thereby reducing cumulative CO_2 emissions and promoting soil health and crop yields (Chang et al. 2025) (Fig. 3).

(4) Multi-ecosystem applicability and synergy: In various ecosystems, appropriate biochar application promotes vegetation restoration, improves the soil structure and organic matter content, and regulates biological communities and carbon cycling (Cen et al. 2021; Thomas and Gale 2015). When combined with modifiers such as zeolite and hydrochar, they can further enhance soil quality during restoration (Kravchenko et al. 2024; Kukowska and Szewczuk-Karpisz 2025).

4 Biochar application thresholds in global ecosystems

The effect of biochar, as an important environmental functional material, is highly dependent on the application amount, and there are clear thresholds for single application doses in different ecosystems. These threshold differences underscore the fact that the application of biochar should follow the principle of "tailored measures for local conditions", taking into account the interactions among multiple ecological factors to maximize benefits and avoid potential environmental risks (Fig. 4).

4.1 Agricultural ecosystems (5–30 t ha^{-1})

The application rate of biochar in agricultural ecosystems is influenced by multiple factors, and different application rates can have significant variation in their effects on crop productivity. In cropland ecosystems, an application rate of 20 t ha^{-1} can significantly promote the growth of wheat and maize, increasing crop biomass and yield (Adekiya et al. 2025). To reduce N_2O emissions while maintaining crop yields, application rates exceeding 20 t ha^{-1} have demonstrated favorable performance, reducing global N_2O emissions by 19% (Liu et al. 2012). Specifically, a rate of 30 t ha^{-1} can not only reduce greenhouse gas emissions but also decrease soil bulk density and increase soil porosity and soil buffer capacity. However, this application rate may also inhibit microbial activity and exacerbate physiological stress on crops (Dvořáčková and Dvořáček 2023; Nie et al. 2023; Xiaoli et al. 2019). At a rate of 20 t ha^{-1}, the emission factor for chemical nitrogen fertilizers decreased significantly from 0.61 ± 0.12% without biochar to 0.31 ± 0.13% and 0.2 ± 0.07% with biochar application (Liu et al. 2012). Furthermore, 10–30 t ha^{-1} can enhance microbial activity and increase the efficiency of antibiotic degradation, whereas exceeding 30 t ha^{-1} can inhibit microbial activity, leading to increased physiological stress on crops and reduced seed yield (Wang et al. 2025).

The effects of biochar are dose-dependent, and its threshold range varies according to crop physiology, soil microbial function, and biodiversity (Liu et al. 2012). For example, applying biochar-based organic fertilizer at 5 t ha^{-1} enhanced soil fertility, promoted the stabilization of recalcitrant organic carbon, increased plant vitamin C content by 12.8–29.9% and 7.0–26.8%, and simultaneously reduced electrical conductivity and available potassium (Zhang et al. 2025a, b). Additionally, 20–30 t ha^{-1} biochar protects crop chloroplast ultrastructure, increases stomatal density, and enhances photosynthetic rates. Below 20 t ha^{-1}, stress-relief effects are limited, while above 30 t ha^{-1}, toxic substances (e.g., PAHs) present in biochars may accumulate, thereby exacerbating physiological stress on crops (Wang et al. 2025). Optimal soil–crop systems can increase wildflower density, indirectly boosting the foraging frequency of pollinators such as bees, establishing a virtuous ecological chain linking biochar, microorganisms, soil animals, and insects (Wang et al. 2025). Therefore, a reasonable application range can promote the ecological restoration of agricultural ecosystems.

4.2 Grassland ecosystems (5–40 t ha^{-1})

The threshold dose of biochar is a key regulatory parameter for degraded grassland restoration, and its precise determination affects ecological recovery projects and functional maintenance. Research indicates that moderate application can enhance vegetation growth and optimize the plant community composition by improving soil physicochemical properties. For example, in tropical pasture grasslands in Brazil, 15–30 t ha^{-1} represented the optimal economic-ecological threshold, significantly improving soil properties, enhancing forage productivity, strengthening microbial activity and nutrient cycling, and reducing the dependence on chemical fertilizers. The effects are generally not significant below this range, while exceeding this rate can lead to diminishing marginal returns and ecological risks (Latawiec et al. 2023). In contrast, in natural grasslands in the Netherlands, an application of 10 t ha^{-1} of pruning-derived biochar facilitated soil carbon sequestration while causing minimal

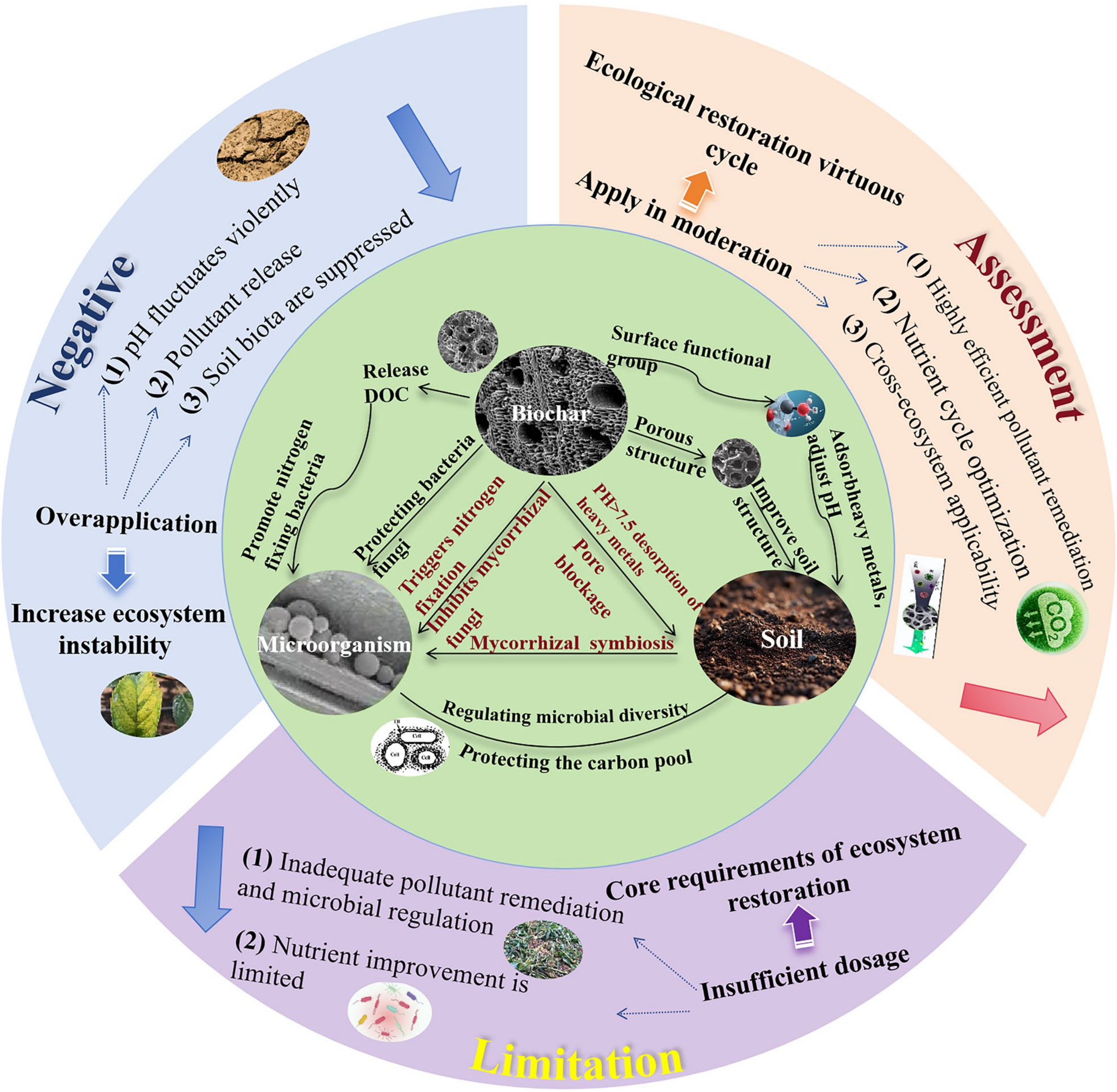


Fig. 3 Threshold risks of biochar in ecosystem restoration

disturbance to biodiversity and productivity (Jeffery et al. 2022). In Canadian grasslands, applying 17 t ha^{-1} of pine woodchip biochar significantly reduced cumulative N_2O emissions (Pokharel et al. 2018). Additionally, application rates of 20–30 t ha^{-1} can accelerate grassland humification, increase soil humic acid content, and enhance microbial activity. However, exceeding 30 t ha^{-1} can easily lead to excessively high soil pH, reducing the availability of trace elements such as iron and zinc (Cybulak et al. 2021).

It is important to emphasize that optimal thresholds exhibit significant regional dependence, stemming from the interaction between soil physicochemical properties and climatic conditions. For example, in degraded grasslands in Brazil, while 15 t ha^{-1} increased forage yield, regulated the soil pH, and reduced greenhouse gas emissions, this level also inhibited calcium and magnesium uptake, with unstable yield-increasing effects and relatively high costs (Latawiec et al. 2019). In alpine grassland regions of China, 10–40 t ha^{-1} can significantly improve soil quality in the 0–20 cm layer, enhancing soil

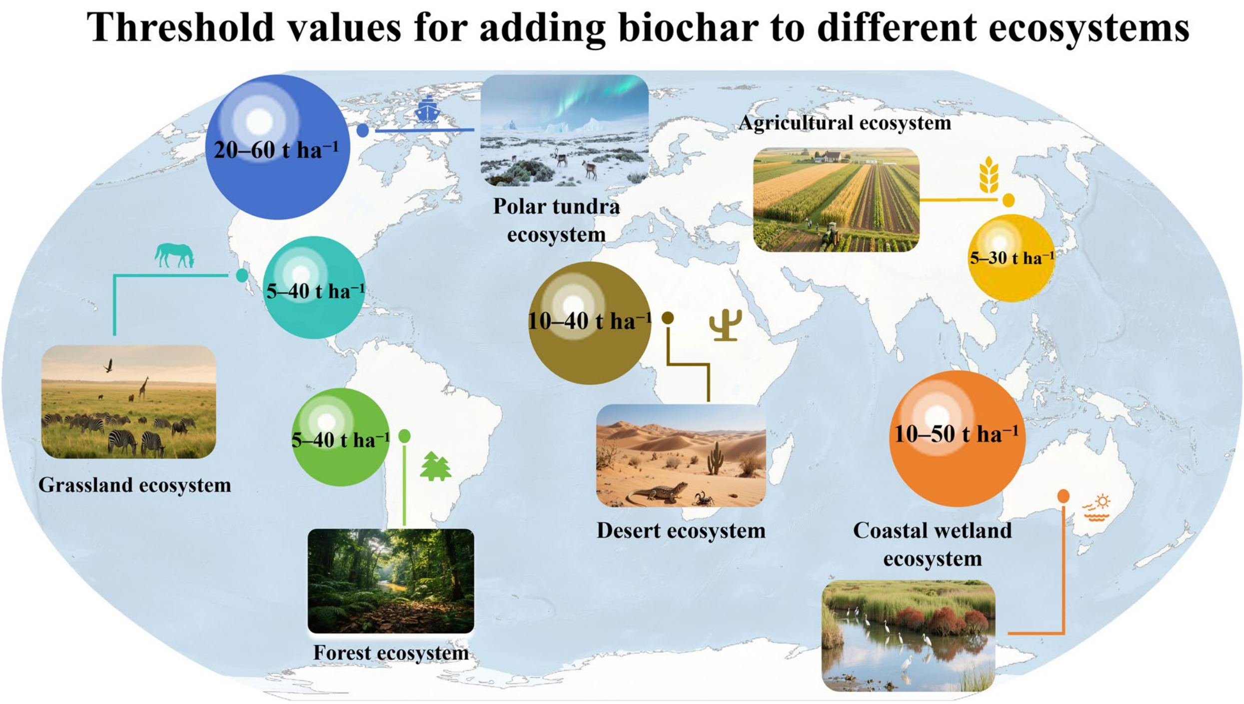


Fig. 4 Biochar application thresholds in six global ecosystems (The locations of the marked points correspond to representative areas within each ecosystem, with bubbles of varying colours indicating the threshold ranges for biochar application across different ecosystems)

fertility and microbial function (Li et al. 2022). In temperate seminatural pastures in the United States, 20–40 t ha^{-1} alleviated soil compaction, improved water use efficiency, and enhanced carbon sequestration; however, excessively high doses can reduce soil bulk density and inorganic phosphorus (Gao and DeLuca 2022). In summary, the application rate threshold for biochar is crucial for restoring degraded grasslands. Maintaining biochar application within the range of 5–30 t ha^{-1} can optimize ecological benefits.

4.3 Forest ecosystems (5–40 t ha^{-1})

Forest ecosystems show a high sensitivity to biochar dosage. Research has shown that in warm-temperate secondary deciduous forests, applying biochar at a rate of 10 t ha^{-1} increased litter decomposition by 8.6%, with significant effects on carbon sequestration, whereas the ecological benefits of a 5 t ha^{-1} dose were insignificant (Minamino et al. 2019). Similarly, studies in the Toohey Forest, Queensland, Australia, also found that while 5 t ha^{-1} could improve soil fertility and reduce nitrogen loss, its effects on water retention, carbon and nitrogen accumulation, and plant growth were limited. In contrast, a dose of 10 t ha^{-1} significantly increased the soil water content (by 14.3% and 13.8% in the 0–5 cm and 5–10 cm layers, respectively), effectively reduced nitrogen loss, enhanced the total soil carbon and nitrogen contents, and maximized plant growth (Sun et al. 2024). Furthermore, a study on greenhouse gas emissions indicated that a low biochar dose (~ 20.6 t ha^{-1}) reduced cumulative CO_2 emissions by 16.4%, cumulative N_2O emissions by 27.5–31.5%, and global warming potential by 17.2% compared with the control, whereas a high dose did not produce these effects (Hawthorne et al. 2017; Pokharel et al. 2018).

In contrast, the ecological restoration effects of biochar exhibit significant regional dependence over a reasonable application-rate range. For example, a global meta-analysis showed that woody plant biomass increased by an average of 41% under application rates of 20–40 t ha^{-1} (Thomas and Gale 2015). However, in a warm-temperate oak forest in Japan, while adding biochar at 10 t ha^{-1} significantly stimulated soil heterotrophic respiration (increasing by 31–37%) in the short term (2–3 years), this effect lasted for only 3 years and posed a higher long-term carbon loss risk (extra emissions accounted for 82% of the input carbon). The 5 t ha^{-1} dose did not have a short-term surge effect and had a lower risk of carbon loss, and both doses primarily promoted total long-term soil respiration by enhancing root respiration (Yoshitake et al. 2025). Similar regional differences were observed in Italian field experiments: While a 30 t ha^{-1} dose increased soil organic matter and cation exchange capacity, it significantly increased salinity and slightly inhibited microbial activity, showing no improvement in soil respiration or crop growth. In contrast, a 10 t ha^{-1} dose not only significantly increased soil heterotrophic respiration (+ 19.3%), organic matter content (+ 10.27%), and nutrient retention capacity but also effectively promoted microbial activity and crop growth (Curcio et al. 2025). Despite such regional variation, biochar application at rates of 5–40 t ha^{-1} can effectively promote the development of forest ecosystems.

4.4 Coastal wetlands (10–50 t ha^{-1})

In coastal wetland ecosystems, the regulatory function of biochar depends on salinity, with the optimal application dosage in the range of 10–50 t ha^{-1}. Within this range, biochar can effectively promote vegetation growth and improve soil properties. In terms of promoting growth and improving the soil, multiple studies have shown that applying 26–50 t ha^{-1} biochar can significantly increase alfalfa biomass, reduce soil salinity, and simultaneously enhance organic carbon, nitrogen availability, and microbial activity (Cui et al. 2022). In the Hetao Plain of Inner Mongolia, 40–50 t ha^{-1} biochar increased the soil water content and reduced the salinity and electrical conductivity of wetland soils, thereby positively regulating soil fertility and enzyme activity and increasing crop growth (Chen et al. 2024a, b). Research in the Yellow River Delta wetland, China, showed that 20–40 t ha^{-1} biochar could promote the growth of Suaeda salsa and regulate the rhizosphere microenvironment, although this effect may be weakened by persistent flooding (Cai et al. 2021). Other studies have demonstrated that 40–60 t ha^{-1} of Flaveria bidentis biochar could increase soil nutrients, reduce salinity, and affect plant functional diversity, but there are potential ecological risks in saline-alkali wetlands (Wang et al. 2024a, b, c, d). Application of 13–26 t ha^{-1} of phosphorus-magnesium-modified biochar can alleviate saline-alkali stress, optimize the composition of dissolved organic matter, and enhance bacterial diversity, whereas excessive application can exacerbate saline-alkali stress (Wang et al. 2024a, b, c, d).

In terms of pollution remediation, applying 52 t ha^{-1} Spartina alterniflora biochar adjusted the soil pH to 8.35–8.43, increased the organic matter and available phosphorus-potassium contents, and reduced cadmium accumulation in the aboveground parts of Suaeda salsa by 29.45%; however, there is the potential of vegetation niche loss (Shi et al. 2025). The combination of 20 t ha^{-1} biochar and $\leq 0.8\%$ rhamnolipid alleviated the inhibition of petroleum pollution on wetland algae and microbial communities, with algae biomass increasing by up to 30% (Wei et al. 2020). The impact on carbon cycling also exhibits a dose-dependent effect: Applying 10–44.4 t ha^{-1} peanut shell biochar increased soil organic carbon mineralization to 67.4 mg kg^{-1} while enhancing cation exchange capacity and water-holding capacity, thereby increasing carbon sequestration (Luo et al. 2016). Laboratory experiments confirm that 21–63 t ha^{-1} biochar can enhance organic carbon stability, but high doses will reduce the ratios of calcium-bound and iron/aluminum-bound organic carbon to total organic carbon (Chen et al. 2024a, b). In summary, the application of biochar in coastal wetlands must be strictly controlled, with a dosage of 10–50 t ha^{-1}, and should be combined with specific water conditions and remediation measures to maximize ecological benefits while avoiding potential risks.

4.5 Desert ecosystems (10–40 t ha^{-1})

Desert ecosystems are also highly sensitive to biochar dosage (Roy et al. 2022), and the restoration effects of biochar in deserts vary significantly by source and dosage (Chávez-García et al. 2023). Local plant-derived biochar (e.g., Artemisia desertorum) effectively increased the soil water-holding capacity by 10–11% and improved the dissolved organic carbon/nitrogen (DOC/DON) content, significantly outperforming exotic hardwood biochar and becoming a preferred material for desert restoration (Gebhardt et al. 2017). In terms of dosage response, threshold characteristics are particularly relevant in different desert systems. For example, applying 40 t ha^{-1} significantly increased the cation exchange capacity (CEC) of sandy soil (reaching 37–40 cmol kg^{-1}) and met plant nutrient demands for approximately 150 days, whereas exceeding 45 t ha^{-1} inhibited plant growth (Odokonyero et al. 2024). In the Thar Desert of India, an application dosage of 20 t ha^{-1} increased the soil water-holding capacity by 11–14% (Li et al. 2025a, b).

The nutrient regulation effects of biochar are highly dosage-dependent. In the Gurbantunggut Desert, 12.74 t ha^{-1} Artemisia desertorum biochar significantly increased the C, N, and P contents and nutrient ratios of the moss crust-soil system, and the crust system is particularly sensitive to low-dosage biochar (Chang et al. 2022). Additionally, biochar application demonstrated synergistic effects with other modifiers, significantly improving soil chemical properties, promoting tomato growth, increasing yield, and enhancing fruit quality. At the same time, biochar reduced levels of fat, ash, and carbohydrates, with these effects being most pronounced at the highest application rate of up to 40 t ha^{-1} (Adekiya et al. 2025). In contrast, excessively high biochar doses increase the risk of salinization in arid soils, thereby offsetting its ecological benefits (Alaboudi 2020). Therefore, the threshold range of 10–40 t ha^{-1} is capable of improving soil water retention, enhancing nutrient levels, and promoting ecological restoration.

4.6 Polar tundra (20–60 t ha^{-1})

In polar tundra ecosystems, the restoration, nutrient regulation, and greenhouse gas reduction effects of biochar all exhibit significant dose dependency. In terms of soil restoration, approximately 40.5 t ha^{-1} biochar was optimal for improving soil hydrothermal properties in seasonal frozen soil regions, resulting in an average significant increase of 22.03% in saturated hydraulic conductivity (Ksat) (He et al. 2023). Exceeding this dose produces negative effects. For example, in cotton cultivation in northern Xinjiang, applying approximately 60 t ha^{-1} cotton straw biochar after freeze–thaw significantly increased soil water storage (SWS) across all growth stages (by 14.88–59.5%) and improved cotton fiber quality; however, exceeding 60 t ha^{-1} disrupted the soil structure and decreased water absorption (Qi et al. 2022). A study in seasonal frozen soil regions of Northeast China showed that approximately 42.9 t ha^{-1} biochar increased the proportion of medium pores, improved aggregate stability (mean weight diameter (MWD) increased by 10.2%), and reduced soil permanent deformation by 81.19%, whereas a high dose of approximately 85.8 t ha^{-1} exacerbated deformation (Zuo et al. 2022).

In terms of nutrient regulation, an application rate of approximately 42.3 t ha^{-1} effectively maintained the stable basic carbon–nitrogen cycle of soil in frozen soil regions (Zhang et al. 2024). Further research found that in three types of freeze–thaw soils (black soil, albic soil, and meadow soil), adding biochar at approximately 39.9, 37.5, and 37.8 t ha^{-1}, respectively, combined with 0.5% straw, maintained a high dissolved organic carbon (DOC) content while balancing carbon sequestration and soil aeration (Xue et al. 2022). Dose thresholds are also crucial for regulating greenhouse gas emissions. Sole application of 20 t ha^{-1} biochar exhibited the strongest CH_4 uptake capacity during the freezing period; combined application reduced the global warming potential (GWP) of freeze–thaw agricultural soil and decreased CH_4 emissions by 8.25–30.75 μg kg^{-1} (Hou et al. 2020a, b). Experiments in the seasonal frozen soil region of Heilongjiang, China, showed that adding 30 t ha^{-1} biochar significantly improved the soil hydrothermal retention capacity and reduced global warming potential while slightly increasing soil CO_2 emissions and significantly inhibiting CH_4 and N_2O emissions (Xue et al. 2023). In summary, the application range of 20–60 t ha^{-1} is optimal for improving soil structure in polar tundra, reducing greenhouse gas emissions, and achieving effective restoration.

5 Factors affecting biochar application

The optimal application threshold of biochar is not a fixed value but rather a "guiding range" dynamically regulated by multiple factors. The physicochemical properties of biochar itself determine the initial path and intensity of its interaction with the surrounding medium. Soil properties are the fundamental physical framework that defines the threshold window. Regional climatic factors fundamentally influence the stability, aging rate, and spatiotemporal differentiation of the ecological effects of biochar by driving hydrothermal cycles. In addition, management measures can impose significant bidirectional disturbances on these natural processes, thereby further adjusting the threshold in practical applications. Therefore, the threshold ranges proposed in this paper should be regarded as dynamic references that must be calibrated in combination with specific soil-climate-biochar management combinations (Fig. 5).

5.1 Environmental factors

The ecological effects of biochar and the appropriate application amount depend on the degree of alignment between the biochar's physical and chemical properties and specific environmental requirements. The pyrolysis temperature is the core parameter that determines the function and applicable threshold of biochar. Biochar prepared at medium and low temperatures (400–500 °C) is rich in oxygen-containing functional groups and has a well-developed pore structure, making it suitable for systems with active microorganisms (such as forest topsoil and farmlands rich in organic matter). The threshold setting for this type of biochar needs to balance the promotion of microbial activity and the possible short-term competition for nutrients (Amirahmadi et al. 2025). High-temperature biochar (> 600 °C) has a high specific surface area, strong aromaticity, and high stability. Its application threshold is regulated by the nature of soil pollutants or the demand for acid–base buffering and thus is more suitable for the remediation of environments with low levels of organic matter or pollutants (Bolan et al. 2022). The selection of raw materials directly affects the role of biochar in balancing the system's nutrient levels. In nitrogen-deficient environments (such as barren farmland and degraded forest land), it is advisable to use biochar prepared from high-quality wood materials (such as hardwood), as it is less likely to cause nitrogen fixation and has a wider safety threshold (Bolan et al. 2022). In contrast, biochar made from herbaceous raw materials (such as straw) contains a relatively high amount of alkali-soluble organic carbon, which can induce nitrogen fixation in sandy soils or nitrogen-sensitive ecosystems, thereby significantly limiting the upper limit of safe application (Dadhich et al. 2025). In addition,

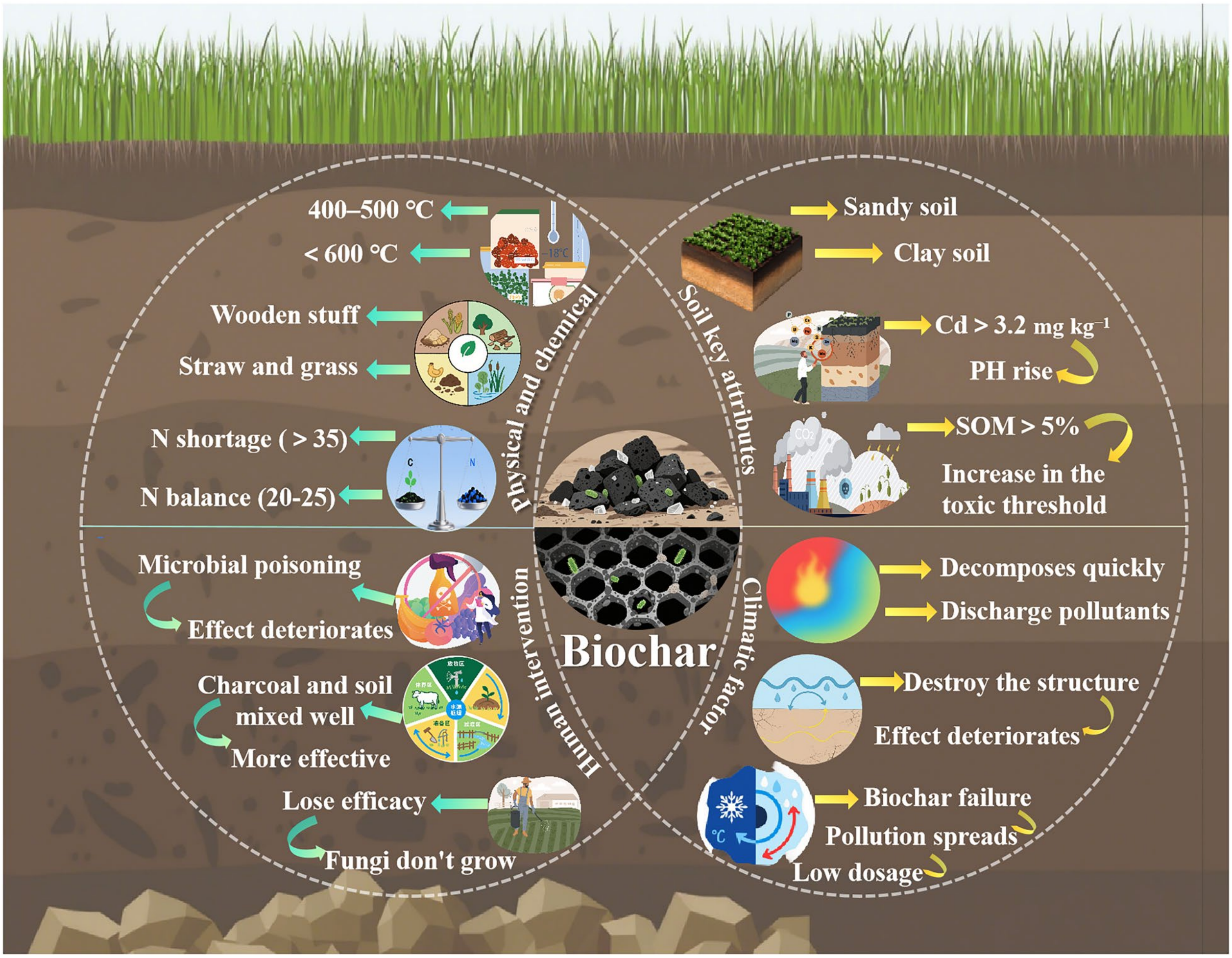


Fig. 5 The key influencing factors of the application threshold of biochar and their action paths (This figure comprehensively presents the regulatory mechanisms of the appropriate application amount of biochar by factors such as the physical and chemical properties of biochar, soil properties, climatic conditions, and human management measures. The yellow and green arrows in the figure indicate the interaction and influence directions among these factors)

the carbon-to-nitrogen ratio of biochar is a key indicator for predicting its nitrogen-fixing capacity. In ecosystems with severe nitrogen scarcity, biochar with a high C/N ratio (>35) will intensify the competition among microorganisms for nitrogen. Choosing biochar with a C/N ratio of 20–25, or combining it with organic fertilizer application (the BOF model), can help maintain the nitrogen-carbon balance, thereby increasing the application threshold while ensuring ecological security (Udomkun et al. 2025).

5.2 Soil factors

The physical structure, chemical composition, and biological activity of the soil matrix dynamically regulate the ecological threshold for biochar application through multiple feedback mechanisms. In sandy soils, a higher water conductivity and lower clay particle content are conducive to alleviating the pore blockage that may be caused by the addition of biochar, increasing the upper limit of its application threshold by approximately 20% compared with clayey soils (Acharya et al. 2024; Shin et al. 2025). In contrast, in clayey soils, when the coating rates of iron and aluminum oxides on the micropores of biochar exceed 40%, there is a significant steric hindrance effect, resulting in a reduction of up to 30% in the reaction efficiency at the microbiota-carbon interface, thereby narrowing the threshold window (Shi et al. 2022). At the fringes of urban areas, the toxic effects of heavy metals and the buffering capacity of soil organic matter jointly regulate the threshold stability of biochars. When the cadmium content in the soil exceeds 3.2 mg kg^{-1}, the pH increase caused by biochar input may promote cadmium desorption, reducing the application threshold by approximately 25% (Luo et al. 2023). In contrast, when the content of soil organic matter (SOM) is higher than 5%, the hydrophobic microdomain of biochar can increase the toxicity threshold of PAHs by 50% through strong adsorption, thereby significantly delaying the bioavailability of pollutants and maintaining the stability of the threshold (Schneckenburger and Thiele-Bruhn 2020).

5.3 Climatic factors

Climatic conditions drive the spatiotemporal differentiation of biochar environmental behavior and affect safety thresholds through hydrothermal coupling and extreme events, and their explanatory power for global threshold variation reached 41% (Wu et al. 2025). Specifically, in high-temperature and high-humidity environments, intense surface oxidation and the generation of hydroxyl radicals promote the desorption of fixed PAHs, resulting in the safety threshold of biochar in tropical regions generally being significantly lower than that in temperate regions (Han et al. 2025). In arid and semi-arid regions, frequent dry–wet cycles can easily damage the biochar–mineral complex, in one study increasing the pore closure rate by 37% and reducing the water-holding capacity to 1.8% (Zhang et al. 2025a, b). For example, in the desert areas of northwest China, due to such effects, the breakup of the biochar–montmorillonite complex and the rate of water permeation decreased by 28%, significantly narrowing the safe application window (Wang et al. 2024a, b, c, d; Wengang et al. 2022). In cold regions, the fragmentation of biochar particles caused by freeze–thaw action increases the longitudinal migration distance of PAHs by 1.8%, thereby strictly limiting its application range (Siatecka and Oleszczuk 2023). The CMIP6 model predicts that under a + 2 °C temperature rise scenario, the increase in freeze–thaw frequency will further reduce the safety threshold by disrupting the interface structure, promoting pollutant migration, and prolonging the half-life of PAHs (Gulfam-E-Jannat et al. 2025; Huang et al. 2023).

5.4 Human factors

Human intervention significantly disturbs and bidirectionally regulates the ecological threshold of biochar through two pathways: pollutant retention and application management. In terms of pollutant residue, organochlorine pesticides in intensively farmed land can reduce microbial diversity, thereby weakening the system's ecological adaptability to biochar and lowering its tolerance threshold by approximately 20% compared with natural ecosystems (Walder et al. 2022). In terms of management measures, human intervention has demonstrated a significant two-way regulatory effect. For example, implementing rotational grazing in degraded grasslands can increase the threshold for biochar application by approximately 25% by promoting the homogenization and mixing of charcoal and soil. In desert areas, the combination of drip irrigation and water-retaining agents can effectively reduce evapotranspiration, thereby increasing the threshold by approximately 40%. These measures broaden the safety margin of biochar by improving the hydraulic and physical structure of the system (Wang et al. 2024a, b, c, d; Zuo et al. 2022). However, excessive use of chemical fertilizers can reverse the surface potential of biochar, inhibit the colonization of ectomycorrhizal fungi, and reduce the biochar threshold in forest ecosystems by approximately 30%. This mechanism has been revealed at the microscopic scale through synchrotron radiation imaging (De la Sota Ricaldi et al. 2023).

6 Threshold application strategies for various global ecosystems

The application of biochar needs to be adapted to local environmental conditions to achieve optimal results. The application rate for the agricultural ecosystem should be controlled at 5–30 t ha^{-1}, and single strip- or hole-application should be adopted, depending on the crop type. The application rate for grassland ecosystems should be maintained at 5–40 t ha^{-1}, and the biochar can be mixed in at low doses in stages or through one-time rotary tillage before sowing. For forest systems, a concentration of 5–40 t ha^{-1} is ideal. Broadcasting or low-dose single application combined with organic fertilizers or microbial agents can be adopted. For coastal wetlands, the application rate should be between 10 and 50 t ha^{-1}, Seasonal surface application combined with shallow plowing, local deep application, or in combination with surfactants should be implemented. The optimal range for desert ecosystems is 10–40 t ha^{-1}, and the biochar should be applied in a coordinated manner through single rhizosphere fixed-point, strip covering, and drip irrigation. For the polar tundra ecosystem, the application rate is recommended to be in the range 20–60 t ha^{-1}. Low-frequency application of medium and low doses should be selected based on the target and combined with shallow mixing or straw application (Table 1).

6.1 Agricultural ecosystems

In agricultural ecosystems, determining the appropriate application amount of biochar requires careful consideration of its combined impact on crop productivity, soil properties, and environmental benefits. Studies have shown that an application dose of 5–30 t ha^{-1} can promote crop growth, improve the soil structure, and reduce

Table 1 Recommended biochar application dosage and strategies for different ecosystems

Ecosystems	Dosage	Type	Implementation path	Reference
Agricultural ecosystems	5–30 t ha^{-1}	High-nitrogen-fertilizer farmland Low-fertility farmland	The method of strip application or hole application Drip irrigation or carbon mixing method	Adekiya et al. (2025) Liu et al. (2012) Nie et al. (2023)
Grassland ecosystems	5–40 t ha^{-1}	Return grazing land to grassland Artificial improvement of farmland	Administer low doses in stages After applying a high threshold dose, crop rotation and mixed cropping were adopted	Latawiec et al. (2019) Li etal. (2022) Cybulak et al. (2021)
Forest ecosystems	5–40 t ha^{-1}	Northern coniferous forest Tropical and subtropical forests	Applied at approximately 10 t ha^{-1} after thinning operations Application controlled at around 5 t ha^{-1}, combined with organic fertilizers or microbial agents	Sun et al. (2024) Curcio et al. (2025)
Coastal wetland ecosystems	10–50 t ha^{-1}	Salt Marsh Polluted wetlands	Use a small dose of about 10–20 t ha^{-1} and surface broad casting combined with shallow tillage High application rates (e.g., 30–50 t ha^{-1}), combined with localized deep placement or co-application with surfactants	Cui et al. (2022) Wang et al. (2024a; b, c, d)
Desert ecosystems	10–40 t ha^{-1}	Shifting sand areas or sand-fixation engineering sites Severely nutrient-depleted degraded areas or artificial vegetation planting sites	Lower rates of 10–20t ha^{-1} and rhizosphere-targeted placement or strip coverage Rates near the upper limit (e.g., 30–40 t ha^{-1}) combination with drip irrigation, mulching, or other water-saving measures	Gebhardt et al. (2017) Li et al. (2025a; b) Odokonyero et al. (2024)
Polar tundra ecosystems	20–60 t ha^{-1}	To enhance soil resistance to freeze–thaw deformation and structural stability To promote CH_4 uptake during the freezing period and reduce global warming potential	A medium dosage of around 40 t ha^{-1} can be applied through shallow incorporation Lower dosages of 20–30 t ha^{-1} can be applied, potentially combined with straw or other organic materials	Zuo et al. (2022) Hou et al. (2020a; b) Qi et al. (2022)

N_2O emissions (Adekiya et al. 2025; Liu et al. 2012b). However, exceeding this range may inhibit microbial activity and intensify crop physiological stress (Nie et al. 2023). Therefore, it is recommended to control the application rate within the range of 5–30 t ha^{-1}. The formation of this threshold range is determined by both climatic conditions and soil properties. Climate factors such as temperature and precipitation determine the effective duration of biochar in farmland by influencing its aging rate and nutrient release ability (Long et al. 2024). Meanwhile, soil texture and pH further restrict the upper limit of safe application by regulating the fixation and activation of nitrogen and phosphorus (Dong et al. 2025). In practical applications, the dosage should be controlled, and a "biochar-chemical fertilizer" single strip/spot application frequency pattern should be developed based on crop type and the fertilization system. For example, in farmlands with high nitrogen fertilizer input, a lower threshold limit (approximately 5 t ha^{-1}) is preferred, and strip- or hole-application methods should be adopted to avoid nitrogen fixation caused by excessive carbon source input. In low-fertility farmland, the upper threshold (30 t ha^{-1}) should be approached, and drip irrigation or mixed carbon application should be combined to enhance water and nutrient retention. This way, the benefits of grain production can be maximized, and the risk of non-point source pollution can be reduced.

6.2 Grassland ecosystems

In grassland ecosystems, the threshold effect of biochar application is reflected in the coordinated improvement of soil conditions, water regulation, and community stability. Research has shown that controlling the application rate within 5–40 t ha^{-1} can effectively improve soil structure, enhance water-holding capacity, promote vegetation recovery, and reduce greenhouse gas emissions, with relatively low ecological risk levels (Latawiec et al. 2023; Li et al. 2022). However, exceeding this range may have negative effects, such as excessively high soil pH and decreased availability of trace elements (Cybulak et al. 2021). This relatively broad threshold range reflects the regulatory roles of precipitation gradients and soil structure differences in the grassland ecosystem on the function of biochar. In arid and semi-arid grasslands, water is the main limiting factor, while in areas with higher precipitation or weaker soil buffering capacity, high doses are more likely to cause ecological damage (Hou et al. 2024). Therefore, in grassland restoration, the dosage should be set within the range of 5–40 t ha^{-1} based on local soil and climatic conditions and the degree of degradation, and a differentiated application strategy should be implemented. In terms of the operational path, the grassland rotation grazing system can be combined with the application of biochar. Low-dose biochar (e.g., approximately 5–10 t ha^{-1}) can be applied in phases in areas that have been returned to grassland to enhance the community's recovery capacity. In artificially improved forage fields, a one-time application near the upper limit (approximately 30–40 t ha^{-1}) can be applied before sowing, and the soil can be rapidly improved by rotary tillage and mixing. This combined strategy of "low-limit phased + high-limit one-time" can enhance the grass yield and maintain ecological resilience.

6.3 Forest ecosystems

In forest ecosystems, precise control of biochar dosage is key to achieving soil improvement, optimizing the carbon cycle, and promoting the healthy growth of trees. Controlling the application rate within the range of 5–40 t ha^{-1} can increase soil moisture and nutrients and promote plant growth (Sun et al. 2024), while excessive doses may cause salt accumulation, inhibit microbial activity, and increase the risk of long-term carbon loss (Curcio et al. 2025). This threshold difference stems from the influence of climatic conditions on biochar stability and its nutrient-regulating effects. High-temperature and high-humidity environments accelerate the aging of biochar and the leaching of nutrients, thereby compressing its upper limit for safe application (Glaser and Lehr 2019). In cool or seasonally arid forests, the biochar is relatively stable, and the suitable dose range is relatively broad. Meanwhile, the common nitrogen limitation in forest soils further underscores the need for low- to medium-dose application (Thomas and Gale 2015). In the future, in forest management, application strategies can be differentiated according to different forest types and site conditions with low to medium frequency of single application. For example, in northern coniferous forests or warm-temperate secondary forests, a dose of around 10 t ha^{-1} can be applied after tending and thinning, and forest land operation can be used to promote the mixing of charcoal and soil, enhance the soil's ability to retain nutrients and water, and create a favorable environment for the growth of trees. In tropical and subtropical forests, due to the high-temperature, high-humidity environment, the oxidation and decomposition of biochar are relatively rapid. Therefore, the application rate should be strictly controlled at around 5 t ha^{-1}. At the same time, organic fertilizers or microbial agents should be combined to enhance stability. In the future, GIS and remote sensing technologies can be combined to monitor the threshold effect, and the application strategy can be dynamically adjusted to avoid long-term side effects.

6.4 Coastal wetland ecosystems

In coastal wetland ecosystems, the rational regulation of biochar dosage is key to balancing the mitigation of salt stress, pollution remediation, and ecosystem stability. Studies have shown that controlling the application rate within the range of 10–50 t ha^{-1} can effectively reduce soil salinity, enhance nutrient availability, promote the growth of salt-tolerant plants, and increase carbon sequestration (Cui et al. 2022; Wang et al. 2024a, b, c, d). However, excessive application may exacerbate saline-alkali stress or trigger ecological risks (Wang et al. 2024a, b, c, d). This threshold range is determined by precipitation, evaporation intensity, and tidal processes. These climate-hydrological factors determine the leaching and reenrichment patterns of salts, thereby affecting the effective window of biochar for alleviating salinization (Wang et al. 2024a, b, c, d). In practice, differentiated application should be implemented within this range based on specific remediation goals (salinization improvement or pollution remediation) and site conditions. For example, in the ecological restoration of wetlands with mild to moderate salinization, a dosage close to the lower limit (such as 10–20 t ha^{-1}) can be adopted, and methods such as seasonal surface + spotting frequency through surface spreading, combined with shallow plowing can be used to promote vegetation establishment and soil salt leaching. In wetlands contaminated by oil or heavy metals, medium to high doses (such as 30–50 t ha^{-1}) can be used, applied locally via deep injection or in combination with surfactants to enhance pollutant fixation and degradation. In the future, a joint restoration system of "biochar–microorganisms–plants" can be established by integrating clean energy, such as tidal and wind power. The application strategy can be dynamically adjusted through regular monitoring of the salt content, pollutant levels, and vegetation conditions to ensure the stability and sustainable development of the ecosystem.

6.5 Desert ecosystems

In desert ecosystems, the core determinant of biochar thresholds lies in improving soil water and nutrient retention. Studies have shown that controlling the application rate within the threshold range of 10–40 t ha^{-1} can effectively enhance the soil water retention capacity, improve the soil nutrient status, and support plant growth (Gebhardt et al. 2017; Li et al. 2025a, b), while excessive application may inhibit plant growth or increase salt levels (Odokonyero et al. 2024). The relatively high upper application limit in this ecosystem derives from the joint effects of an extreme arid climate and sandy soil on the aging and structural stability of biochar. Low precipitation and high evaporation delay the decomposition of biochar, while highly permeable soil reduces the risk of pore blockage (Fu et al. 2021). Based on the above mechanism, a lower dose of 10–20 t ha^{-1} should be adopted in mobile sandy land or sand barrier sand fixation projects. Through targeted application at the root zone or strip cover, the water-holding capacity of sandy soil can be rapidly enhanced, and the survival of pioneer plants can be promoted. In extremely nutrient-deficient degraded areas or artificial vegetation establishment sites, a dosage near the upper limit (such as 30–40 t ha^{-1}) can be selected and applied simultaneously with water-saving measures such as drip irrigation and mulching to continuously improve soil chemical properties and support long-term plant growth. Through this differentiated application model of "low-volume water retention for activation and high-volume soil improvement for stable nourishment," the efficiency of single inter-root application can enhance the efficiency of vegetation restoration under extreme drought conditions, and synergistically realize multiple ecological benefits such as soil and water conservation and carbon sinks and emission reductions.

6.6 Polar tundra ecosystems

In the polar tundra ecosystem, the determination of the biochar threshold hinges on soil structural stability, hydrothermal characteristics, and the balance of greenhouse gas emissions under freeze–thaw conditions. Studies have shown that controlling the application rate within the range of 20–60 t ha^{-1} can effectively improve the soil water-holding capacity, enhance soil aggregate stability, suppress greenhouse gas emissions, and support ecological restoration (Hou et al. 2020a; Zuo et al. 2022). Excessive application, however, may lead to destruction of the soil structure, hinder water absorption, and increase the risk of carbon loss (Qi et al. 2022). This threshold range reflects the dual constraints of a low-temperature climate and high-frequency freeze–thaw cycles on the physical stability of the soil. Long-term low temperature significantly slows decomposition of biochar, while frequent freeze–thaw cycles continuously destroy the soil aggregate structure, making a higher application rate to some extent a necessary condition for maintaining soil functioning (Hou et al. 2020a, b; Zuo et al. 2022). Therefore, in applications under extreme environments, the principle of "medium and low doses, regulation based on local conditions" should be adhered to, and the appropriate dose should be selected within this range. For example, to enhance the soil's resistance to freeze–thaw deformation and structural stability, a medium dose of around 40 t ha^{-1} can be adopted and applied through shallow mixing. If the main goal is to promote the absorption of CH_4 during the freezing period and thereby reduce the global warming potential, a lower dose of 20–30 t ha^{-1} can be selected, and it can be applied in combination with materials such as straw to synergistically enhance carbon sequestration and soil aeration. Synergies between soil function enhancement and climate mitigation can be achieved in the vulnerable high tundra by zoning the frequency of supplemental application at low frequency, combined with a sub-targeting strategy of "medium for structural improvement and low for gas regulation".

7 Conclusion

Based on multiple reports, the results of mechanistic experiments, and regulatory practices across six global ecosystems, this study has clarified the differentiation patterns, formation mechanisms, and regulatory pathways of biochar restoration application thresholds.

Biochar's ecological restoration thresholds vary significantly by ecosystem, being closely tied to each system's core functional needs: farmlands prioritize "yield–emission balance" (5–30 t ha^{-1}); grasslands focus on "water retention–community stability" (5–40 t ha^{-1}); forests emphasize "carbon sequestration–greenhouse gas control" (5–40 t ha^{-1}); coastal wetlands aim for "salinity regulation–pollution immobilization" (10–50 t ha^{-1}); deserts target a "water retention–aeration balance" (10–40 t ha^{-1}); and polar tundra ecosystems address "freeze-thaw stress and nutrient loss mitigation" (20–60 t ha^{-1}). These thresholds reflect the "functional matching" principle of biochar application.

Thresholds are determined by the triple interaction of biochar physicochemical properties (pyrolysis temperature determines adaptability: medium-low temperature for agriculture/grasslands and high temperature for adsorption), environmental factors (soil texture and organic matter affect upper thresholds via steric hindrance/buffering; climatic dynamics such as dry-wet/freeze-thaw narrow ranges), and biological responses (biochar provides habitats for beneficial microorganisms within thresholds, while excess biochar can trigger microbial community imbalance). The frequency of application further affects the threshold effect by regulating the interaction rhythms of biochar with soil and organisms, and inappropriate frequency can lead to accelerated biochar aging or increased nutrient competition.

Ecosystem-specific strategies maximize the benefits of biochar: "biochar + fertilizer + single/strip application" for agriculture; "staged + one-time application" for grasslands; "low-dosage single broadcast + remote sensing" for forests; seasonal differentiated surface/targeted burial for wetlands; "single rhizosphere precision + water-saving" for deserts; and "low-frequency topdressing" for polar regions.

This study cautions against the "one-size-fits-all" perception of biochar use, establishing a system-specific, operable, mechanism-clear threshold framework. The study provides a basis for large-scale biochar-based restoration, connects "material properties-ecological functions-global restoration" across scales, and supports biochar as a key technology for addressing global ecological degradation and achieving the UN SDGs of terrestrial ecosystem protection and climate action.

Supplementary Information

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Additional file1 (XLS 133 KB)

Author contributions

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Data and materials availability

All data needed to evaluate the conclusions in the paper are present in the paper and/or the materials cited herein.

Declarations

Competing interests

The authors declare that they have no competing interests.

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