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Biochar raises soil health and reduces greenhouse gas emissions in arid lands

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Biochar is increasingly recognized as a multifunctional amendment capable of restoring soil health and mitigating greenhouse gas (GHG) emissions, particularly in arid and semi-arid regions, where fragile soils, high salinity, and erratic moisture regimes exacerbate climate vulnerability. Despite the growing global interest, only ~3% of biochar studies target arid lands, leaving a critical knowledge gap in understanding its mechanisms under harsh edaphoclimatic conditions. This review synthesizes over 120 studies and provides a meta-analysis on the interplay between soil and biochar properties affecting GHG fluxes in arid agroecosystems. Biochar reduces CO₂, CH₄, and N₂O emissions in non-arid climates by -18%, -38%, and -40%, respectively, relative to unamended control soils, though the effects are less pronounced in arid and semiarid lands (-8%, -21%, and -33%, respectively), modulated by soil and biochar physico-chemical properties, as well as application rates. The meta-analysis revealed that the reduction in CO₂ emissions by biochar was significantly different between non-arid and arid or semiarid climates ($P < 0.05$); however, this was not the case for CH₄ and N₂O. Specifically, biochars are characterized by a high surface area and large porosity, enhancing soil aeration and oxygen diffusion while buffering soil pH. Together, these properties create conditions that favor nitrification over denitrification, and suppress N₂O formation, reduce methanogenesis, and promote CH₄ oxidation. Similarly, increased aeration and redox modulation reduce methanogenesis and increase CH₄ oxidation, particularly in sandy and saline soils. The inherent long-term stability of biochar organic carbon (C) plays a central role in the long-term C retention in soils. Microbial responses, such as the expression of functional genes, enzyme activities, and the archaeal-to-bacterial ammonia oxidizer ratio, serve as key bioindicators for tracking the performance of biochar in reducing GHG emissions. Our synthesis provides a mechanistic and data-driven framework to inform biochar use in arid agroecosystems, supporting a shift toward circular, climate-smart land management in some of the world's most sensitive landscapes.

KEYWORDS

arid agroecosystems, arid soils, carbon sequestration, denitrification and methanogenesis, meta-analysis

1 Introduction

Arid and semi-arid areas, which comprise 41% of the Earth's land surface and produce 60% of the world's food, are characterized by scarce rainfall, high evapotranspiration, and saline and alkaline soil conditions (1, 2). Agricultural activities contribute to global climate change by emitting 21% of global anthropogenic greenhouse gas (GHG) emissions, primarily CO₂, CH₄, and N₂O (3, 4), with emissions of methane (CH₄) from livestock (5) and irrigated rice-based (6) systems. Although arid and semi-arid soils are often considered net CH₄ sinks, they remain active components of the global methane cycle. Carbon storage in these ecosystems reflects the balance between limited organic matter (7), slow decomposition under arid conditions (8, 9), and the vital role of microbial communities in regulating carbon dynamics (10). Delherbe et al. (11) introduced the “reverse chimney” concept, showing that vegetation–microbiome interactions in dryland soils increase atmospheric CH₄ uptake. These findings confirm that arid lands are dynamic systems that act mainly as sinks but also as localized CH₄ sources under certain management or hydrological conditions (e.g., livestock manure and irrigated niches).

Agriculture is the largest source of CH₄ and N₂O, accounting for 60% and 47% of the total emissions, respectively (12, 13). Despite these emissions, agricultural soils offer valuable climate mitigation potential and pathways. With the adoption of soil conservation practices (i.e., cover cropping, agroforestry, integrated nutrient management, biochar application, and integration of crops with trees and livestock), they have the potential to sequester an estimated 1.5–1.8 Gt CO₂-equivalent annually (14, 15). Ahlström et al. (16) showed that although tropical forests account for the largest mean CO₂ sink, semi-arid ecosystems contribute 57% of the positive global sink trend (≈ 0.04 Pg C yr⁻² of the global 0.07 Pg C yr⁻²) and approximately 39–47% of interannual variability in global net carbon uptake. This suggests that arid soils are not marginal but central in driving both the direction and intensity of the terrestrial CO₂ sink.

Arid and semiarid agricultural soils face water deficits, variable rainfall, low fertility, poor structure, limited water retention, and salinity–sodicity issues dominated by Ca and Mg salts. These stresses are projected to intensify with future aridity (17, 18).

One of the key constraints for sustaining plant growth in these fragile and harsh ecosystems is the low soil organic matter (SOM) content (19). In general, SOM content in arid and semi-arid regions is typically low, ranging from 0.1% to 3% (20); however, its biological activity is relatively high (21). Consequently, farming practices that reduce soil C losses or even increase soil C storage are fundamental for achieving sustainable production in arid agroecosystems (22).

High ambient temperatures and photochemical degradation further exacerbate SOM loss through accelerated microbial decomposition, especially during warmer and wet seasons, contributing to declining soil health (23, 24). Increasing soil organic C (SOC) content in dry environments can support both C sequestration and agricultural productivity, thereby addressing

the interlinked challenges of food security and climate change (15). Even slight increases in SOC content can trigger microbial decomposition under hot semiarid irrigated soils, leading to relatively high CO₂ losses per unit of C (25–27). These losses are primarily driven by increased microbial and enzymatic decomposition under fluctuating soil moisture and temperature conditions. However, increasing SOC content remains central to increasing soil fertility, achieving a negative C balance, and mitigating global warming (28).

Biochar, a C-rich material derived from pyrolyzed biomass, has emerged as a resilient soil amendment with the potential to sequester C in soils because of its aromatic C structures that resist microbial mineralization (29–32). Biochar application is especially promising in drylands, where it can increase soil moisture storage, support SOC retention, and reduce GHG emissions through mechanisms such as nitrate adsorption, pH buffering, and the inhibition of denitrification pathways (32–35).

The persistence of stable SOC results from a delicate balance between C inputs from autotrophs and losses through microbial respiration (36–38). In arid regions, this balance is skewed by limited biomass input and rapid mineralization. Soil properties and management practices further modulate these dynamics. Intensified land use and poor conservation have accelerated SOC losses, strongly contributing to atmospheric CO₂ and CH₄ concentrations (39). Since the industrial era, an estimated 78–133 Pg (billion tons) of soil C has been lost, raising atmospheric CO₂ levels by approximately 10–15% (36, 40).

Soil conservation practices can help reverse these trends. Global estimates suggest the potential to sequester 0.4–1.2 Pg of C per year through soil C-saving strategies, offsetting up to 20% of the current annual anthropogenic CO₂ emissions (15, 41). Agronomic practices such as conservation tillage, cover cropping, agroforestry, and organic amendments (e.g., compost and biochar) not only mitigate CH₄ emissions but also increase soil fertility, nutrient cycling, and climate resilience (42, 43). However, sequestration gains are finite and reversible if they are not sustained by long term adequate management or the use of less labile C sources, such as biochar.

In this context, there is a critical need for a focused review addressing arid and semi-arid ecosystems, regions uniquely vulnerable to degradation and climate stress. These landscapes often feature depleted SOC content but harbor large inorganic C stores, especially in calcareous and alkaline soils, complicating the assessment of net C sequestration (44). Episodic water availability and extreme evapotranspiration rates, leading to droughts, further disrupt microbial balance, often exacerbated by mismanaged fertilizer use, which increases N₂O emissions and degrades long-term soil health. In many arid cultivated regions, reliance on high-input fertilizer regimes has become the norm, reflecting an attempt to compensate for persistent deficiencies in both nutrients and SOC content.

This review synthesizes recent evidence on the potential of biochar for GHG mitigation, SOC stabilization, and fertility increase in arid and semiarid agroecosystems. It also considers

the specific context of arid regions, where soil degradation and high GHG emissions coincide with opportunities for waste valorization and energy diversification. Despite the abundance of biomass resources (untapped waste streams such as date palm waste and landscaping pruning), biochar remains underutilized in agriculture. By highlighting its multifunctional potential under regional constraints, this review supports circular economy pathways and climate-aligned land management.

The specific objective of this review synthesis is to (i) quantitatively evaluate the effects of biochar on CO₂, CH₄, and N₂O emissions in arid and semi-arid agroecosystems, (ii) mechanistically assess how soil properties, biochar characteristics, and microbial processes regulate soil organic carbon stabilization and fertility responses under dryland conditions, and (iii) integrate these biophysical outcomes within the regional context of arid lands, where soil degradation and GHG emissions intersect with underutilized biomass resources, thereby linking biochar-based mitigation to opportunities for waste valorization, energy diversification, and climate-aligned land management.

This review offers a distinct contribution by explicitly focusing on arid and semi-arid agroecosystems and integrating quantitative and mechanistic evidence to explain biochar-mediated GHG responses under dryland conditions. Unlike most previous reviews that predominantly synthesize global or temperate-region studies, this work specifically evaluates how the distinctive constraints of arid soils low organic carbon availability, alkaline and saline chemistry, and episodic moisture regimes modify both the magnitude and mechanisms of CO₂, CH₄, and N₂O fluxes. By combining climate-stratified meta-analyses with a mechanistic synthesis linking soil properties, biochar characteristics, and microbial functional controls, this review advances a process-based framework for understanding why biochar performance in drylands differs from that reported in more humid systems.

We hypothesized that biochar application in arid and semi-arid agroecosystems reduces GHG emissions to a lesser extent than in non-arid climates, but that this mitigation can be optimized by understanding the mechanistic relationships between oxygen diffusion, pH buffering, and microbial responses (nitrification/denitrification, methanogens/methanotrophs), particularly in the alkaline and saline soils of arid lands.

2 Materials and methods

Review approach and objective: This work was developed as a critical (narrative) review supported by a quantitative evidence synthesis to strengthen interpretation of patterns reported across the published literature. The quantitative component was used as an aid to discussion (e.g., trend summaries and multivariate grouping) rather than as a formal systematic-review meta-analysis with a complete PRISMA workflow and a risk-of-bias cannot be excluded.

Literature search strategy: Peer-reviewed studies were identified through targeted searches conducted in Google Scholar and Consensus AI. Searches were performed using combinations of keywords related to biochar and greenhouse gas emissions, including biochar, soil, arid, semi-arid, dryland, CO₂, CH₄, N₂O, greenhouse gas emissions, and flux. In addition, the reference lists of key relevant papers were screened to identify further eligible studies not captured in the initial search.

Study selection and eligibility criteria: Studies were included if they met the following criteria:

- i. biochar was applied as a soil amendment,
- ii. at least one soil GHG flux was measured (CO₂, CH₄, and/or N₂O), and
- iii. the study included an appropriate unamended control treatment enabling direct comparison with the biochar-amended condition.

Studies were excluded when GHG emissions were not measured directly, control treatments were absent or unclear, or data were not extractable in a comparable form.

Data extraction and database development: Data from eligible papers were manually extracted and compiled into a harmonized dataset using Microsoft Excel. Extracted information included experimental setting (field or laboratory), soil and site descriptors (where available), biochar characteristics (feedstock and production details when reported), application rate, measurement duration, and reported GHG emission outcomes. The compiled spreadsheet was used as the basis for cross-study synthesis and subsequent multivariate analysis.

Data synthesis and multivariate analysis: Quantitative synthesis was used to explore broad relationships between biochar application, environmental context, and GHG outcomes across studies. Multivariate analyses, including principal component analysis (PCA) and associated multivariate statistics, were conducted using JMP (SAS Institute). PCA outputs were used to support interpretation of clustering patterns and the relative contribution of key variables to the observed variability across the assembled literature dataset.

Handling of missing data (gap filling): Because the dataset was derived from heterogeneous studies with incomplete reporting across variables, some entries were missing. To allow inclusion of key variables in PCA and avoid excessive data loss, missing values were gap-filled using group-wise mean substitution rather than regression-based imputation. This approach is commonly applied in multivariate synthesis of literature-derived datasets. However, mean substitution can introduce discrepancies between individual study values and gap-filled entries, and may dilute statistical contrasts in multivariate space. Therefore, the interpretation focuses on aggregated patterns and robust trends rather than reliance on any single imputed value.

Figure preparation and visualization: All statistical figures and PCA outputs were generated in JMP. Final figure panels were refined for layout consistency and visual clarity using Adobe

Illustrator (Version 27.0) without altering the underlying statistical results.

3 Bibliographic trends on biochar research

Bibliographic analysis shows that scientific interest in biochar has risen sharply over the past decade, with publication output growing several-fold between 2015 and 2024 (Figure 1). Social media mentions have expanded even faster, underscoring biochar’s transition from an academic focus to a topic of broad public interest. Research-to-society trends highlight the growing attention to soil–microbial interactions, carbon residence time, and greenhouse gas reduction.

The bibliographic analysis of biochar research associated with arid or semiarid soil environments shows similar annual growth compared to other ecosystems, and accounts for approximately 3% of all biochar publications (Figure 1). Key research themes in related papers include soil fertility, irrigation and salinity management, crop productivity, C sequestration, and the overall influence of biochar on soil microbes. Manuscripts from countries with arid and semiarid regions, such as Egypt, China, Australia, India, Iran, and parts of the USA, are prevalent.

Among the emerging research trends is the need to address multiple ecosystem services (ESs) simultaneously, with an emphasis on climate resilience and C sequestration. Substantial gaps remain, particularly regarding the mechanistic feedback of biochar on microbial functions in alkaline soils in arid ecoregions. Addressing multiple challenges simultaneously is usually discussed as a future direction, including soil health and resilience, strengthening agricultural performance, increasing resource use efficiency where there is little available, restoring and rehabilitating degraded soils, and contributing to anthropogenic climate change (ACC) mitigation. This is especially important in

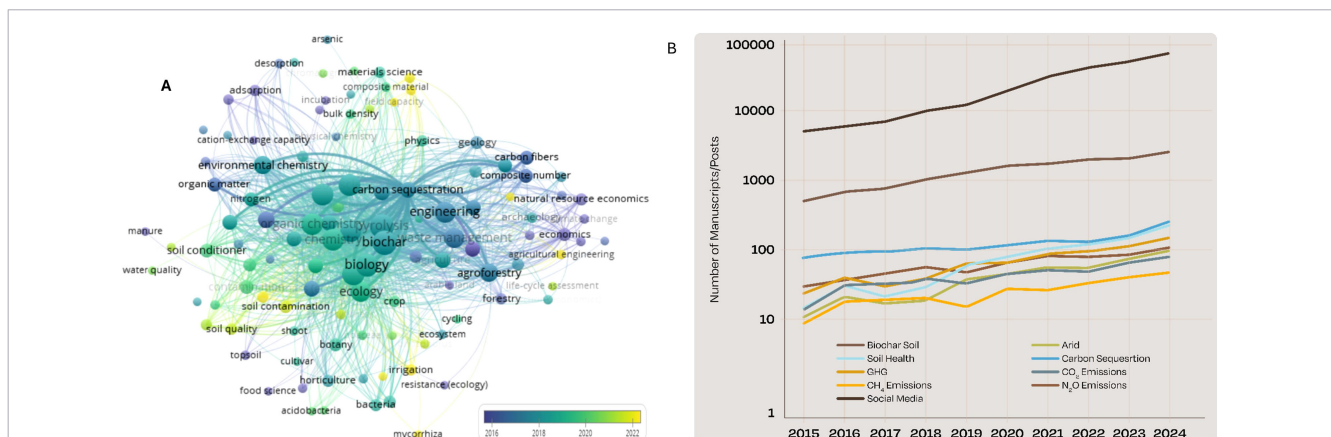
arid and semiarid alkaline soils, where fragile environmental conditions often pose risks to food security (45).

4 Biochar and soil health in arid regions: a microbial perspective

4.1 Biochar affects soil microbial constraints in arid regions

Sustaining soil health in arid and semi-arid regions remains a challenge because of fragile ecosystems and harsh environmental conditions, including salinity-induced osmotic stress, drought, oscillating evaporation rates, shallow water tables, and low SOC content, compounded by the intensive use of inorganic fertilizers (46–49). These conditions accelerate C turnover by drastically increasing microbial respiration per unit of biomass under increased C input (metabolic quotient; qCO_2), as well as reducing nutrient retention, and increasing GHG emissions (50–52). Microorganisms are central to these dynamics, playing critical roles in nutrient cycling, organic matter transformation, and GHG moderation (53).

Abrupt moisture changes, such as erratic rainfall or pulse irrigation, affect organic matter (OM) mineralization by reshaping microbial communities and enzyme-mediated decomposition processes (54–56). Therefore, enzyme assays are valuable tools for detecting microbial shifts in dry soils, where low organic matter and water content constrain microbial activity (57, 58). Pedologic processes such as microbial respiration, methanogenesis, nitrification, and denitrification govern CO_2 , CH_4 , and N_2O fluxes (59). The “Birch effect” (60), a short-lived pulse of CO_2 and N_2O emissions following rewetting, is particularly pronounced in drylands (48, 61). Additionally, high salinity and alkaline pH suppress methanogenic archaea while increasing ammonia-oxidizing bacteria, thereby increasing N_2O emissions (52).



Adaptation to low-C environments accelerates decomposition and limits long-term C storage (51). These microbial responses offer mechanistic insights into evaluating soil responses to biochar amendments (56, 58).

The influence of biochar on microbial activity is increasingly acknowledged, yet its effects remain underexplored in specific environments, such as arid agricultural systems. When studies are conducted across diverse soil types and climatic conditions, including arid regions, it becomes challenging to draw general conclusions regarding the direction and magnitude of its impact on soil microbial communities (62). Biochar's unique structure and composition shape microbial habitats by increasing water retention, buffering pH, and moderating temperature extremes (63, 64). These effects are most pronounced in the "charosphere," where the microbial biomass and enzyme activity are elevated (65). Biochar can create microbial niches through aeration, pH optimization, and moisture availability, thereby leading to beneficial microbes involved in nutrient cycling and C stabilization (66). These microhabitats foster colonization by bacteria and mycorrhizal fungi and support enzymatic activity by retaining C substrates and nutrients (67–70). Biochar surfaces offer refuge, substrates, and bioavailable nutrients, such as C, N, and phosphorus (P), supporting microbial metabolism and increasing microbial interactions (71). Increased cation exchange and water-holding capacity increase microbial activity and resilience (72, 73).

An increase in soil pH may also reduce N leaching and broaden microbial functional diversity (74, 75). Meta-analyses have shown that biochar increases microbial biomass C (MBC), lowers qCO_2 , and has no effect on respiration, indicating greater C-use efficiency and lower microbial CO_2 emissions (76). In arid ecosystems, the application of 10–30 Mg/ha of high-temperature biochar is most effective in minimizing emissions and increasing microbial functions, such as nutrient cycling, soil structure formation, and plant growth stimulation (77–79). Lower rates can help stabilize SOC and limit respiration due to reduced labile C inputs, whereas excessively high rates may temporarily increase CO_2 through positive priming, particularly in soils with low microbial activity (80). Although biochar generally increases microbial diversity and abundance, adverse effects can arise from excessive application or the use of low-quality biochars, such as those with high ash content or volatile organic compounds, which may disrupt microbial membranes or inhibit enzymatic functions (81, 82). In alkaline soils, mismatched biochar inputs may exacerbate P deficiency and suppress enzymatic activities (83). Furthermore, the sorption of enzymes and substrates onto biochar surfaces may impair the extracellular role of enzymes in C turnover. Therefore, optimizing biochar through feedstock choice and post-treatment is essential to maximize its benefits and minimize its risks (76).

4.2 Microbial function indicators for assessing biochar effects in arid soils

In arid-land environments, microbial indicators are often more responsive to environmental stress than chemical or physical indicators due to their sensitivity to moisture scarcity, salinity,

and temperature extremes (84, 85). For a start, the taxonomic diversity of functional microbial groups can provide useful indirect indicators of the effects of biochar on soil functions. Microbial groups, such as mycorrhizal fungi, nitrifying bacteria, and nematodes, are associated with nutrient efficiency and stress resilience (86, 87). Enzyme activities and the expression of related genes (e.g., ammonia monooxygenase) offer diagnostic tools to monitor C and N fluxes and N_2O emission potential (see Section 7; 88). Biochar usually increases these functions by enriching microbial habitat quality and resource availability.

In degraded drylands, biochar can stimulate nitrifying and denitrifying microbes, including shifts in archaeal-to-bacterial ammonia oxidizer ratios (89). In coastal saline-alkali soil, biochar alters the bacterial community structure and increases N cycling, as indicated by decreased NH_4^+ and increased NO_3^- content, indicating nitrification (90). Co-application with organic amendments further increases microbial biomass C (MBC) and its stabilization by providing additional nutrients and protective microsites that increase microbial necromass accumulation, which is an important mechanism of long-term C sequestration (91, 92). In arid soils with low SOC content (<1%), the co-application of sugarcane bagasse biochar (1% C ha^{-1}) and N fertilizers increased soil microbial and enzymatic activity (93). Microbial biomass C (MBC) and N increased by 19% and 50%, respectively, and urease and dehydrogenase activities increased by 15% and 18%, respectively.

These challenges are particularly pronounced in saline-alkaline soils, where unmodified biochar lowers microbial richness and exacerbates ionic imbalances (94, 95). The co-application of biochar and compost increases MBC and enzyme activities in saline-sodic soils by raising soil permeability and calcium (Ca) dynamics and reducing sodium (Na) stress (49). In saline-alkaline soils, alkaline biochars increase the microbial P demand, whereas acidic biochars increase N limitation (96). These changes in nutrient stoichiometry of saline-alkaline soils affect microbial functional guilds, leading to either P or N constraints, depending on the biochar's pH and elemental profile.

Microbial responses are not linear; moderate doses can increase diversity and enzyme activity, whereas excessive doses may suppress MBC and shift community structures. Microbial markers, such as elevated PLFA, N-acetyl- β -glucosaminidase activity, and increased gram-negative bacteria, are typical of well-functioning systems, but declines have been reported under suboptimal conditions (97, 98).

The time scale is also important. Long-term biochar application at moderate rates often increases microbial diversity and nutrient cycling. Because of its persistence, biochar accumulation gradually improves soil quality by increasing SOC content (direct augmentation of SOC by biochar), stimulating arbuscular mycorrhizal fungi (AMF), and increasing the AMF-to-saprotroph ratio, which are indicative of stronger symbiotic networks (99).

Overall, the impact of biochar on microbial ecology depends on its chemical composition, application rate, and the environmental setting. Although it can act as a catalyst for beneficial biological processes, careless application may yield counterproductive effects. Identifying the soil and biochar properties that impact microbial

responses, including GHG emissions, is essential to leverage biochar as a tool for sustainable soil management in arid lands.

5 Intrinsic and environmental drivers of biochar's soil health effects

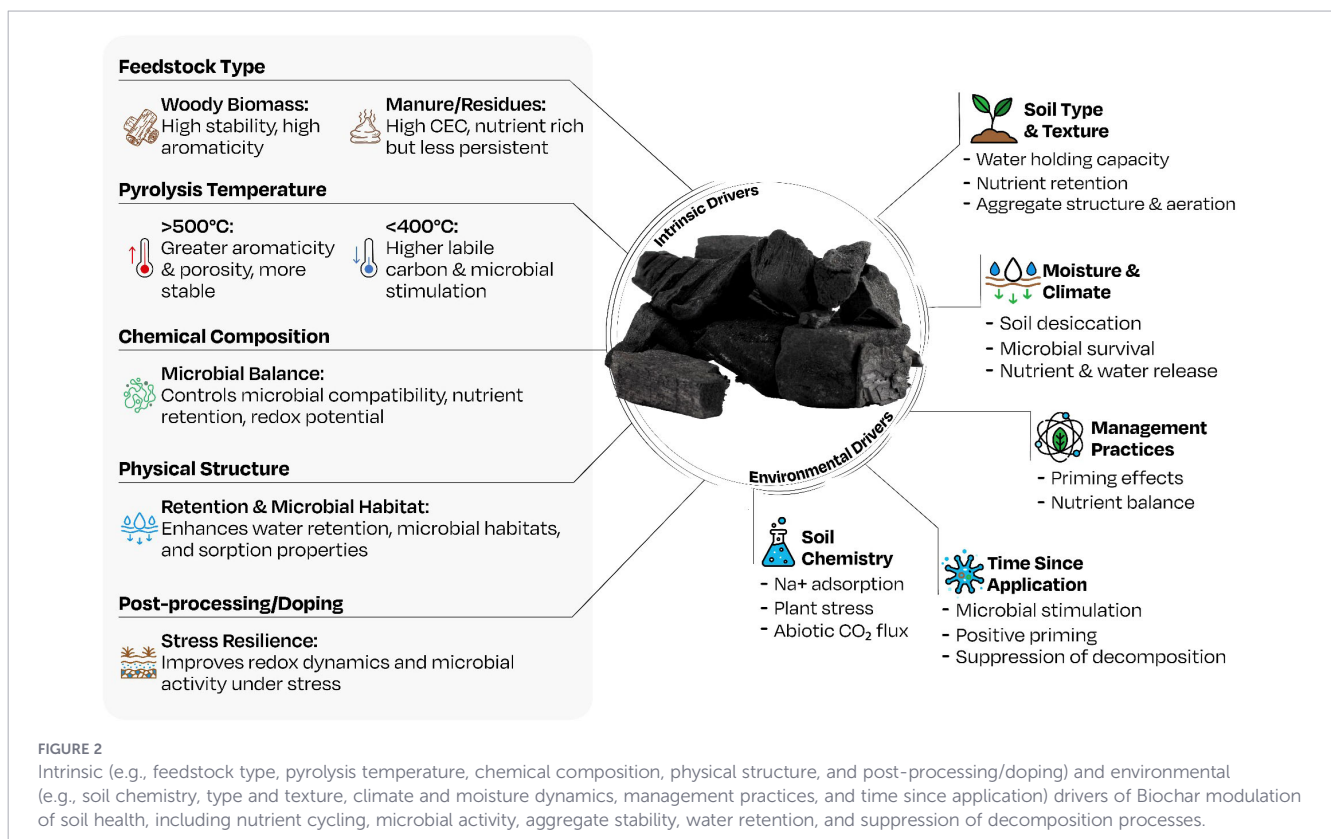
The performance of biochar in agricultural and environmental systems results from a complex interplay of intrinsic and extrinsic factors that influence soil health, GHG moderation, nutrient cycling, and microbial resilience (Figure 2). Effective biochar application across diverse edaphoclimatic contexts requires an understanding of its inherent characteristics and site-specific environmental conditions.

Among the intrinsic properties, the most influential are biochar's chemical composition, such as total C, N, soil salinity (EC), surface area, and pH, as well as its feedstock type and pyrolysis temperature (92). The feedstock origin and pyrolysis parameters shape the biochemical structure of biochars. For instance, woody biomass yields a high-aromatic C content and thermal stability, whereas biochars from animal manure or crop residues provide more nutrients but have lower persistence (100). High-temperature pyrolysis (>500 °C) enhances porosity and stability but reduces volatile compounds and functional groups needed for microbes (101). In contrast, rapid heating retains labile carbon, which boosts microbial activity but lowers long-term stability (102, 103). Field evidence indicates that low-temperature biochars (<400 °C) increase soil MBC, largely due to their higher content of bioactive compounds (92). Nutrient-rich biochars,

particularly those low in total C but high in N and ash, further stimulate SMBC under arid conditions, highlighting the role of nutrient density and mineral interfaces in supporting microbial activity. Notably, biochar properties alone explained 46.2% of the global variability in SMBC across trials (92). However, these low-temperature biochars degrade more rapidly and intensify the microbial decomposition of native C, triggering positive priming effects that compromise long-term C sequestration, particularly in low-SOC, arid ecoregions (104, 105).

The effect of biochar on SOC decomposition varies with time. Initially, it may stimulate the breakdown of both its own labile C and existing n-SOC through co-metabolic activities. However, over time, this effect can be reversed, with biochar suppressing n-SOC mineralization, likely due to the physical and chemical stabilization of SOM through sorption onto biochar surfaces. Some studies have reported suppression within the first year, whereas others have observed stimulation only after several years of application (106). Additionally, limited stability, hydrophobicity, and poor porosity reduce moisture retention and microbial functionality under hot, dry conditions (107).

The architecture of biochar (pore and particle size) also modulates water, nutrients, and microbial dynamics (108). Pore connectivity facilitates access to sequestered low-molecular-weight compounds, whereas feedstock-specific differences influence microbial compatibility. For instance, mesquite (*Prosopis* spp) biochar suppressed fungal activity in some arid soils of Oman, likely due to phytotoxic compounds, whereas date palm (*Phoenix dactylifera*) biochar increased microbial proliferation through higher organic content and surface area (83). Fast pyrolysis increases surface traits; in soybean (*Glycine max*)-derived biochar,



the surface area increased from 6 m²/g at 300 °C to 420 m²/g at 700 °C (109), enabling microbial proliferation in sandy soils (110). Under dry conditions, such porosity allows for gradual substrate release and sustains microbial functions (111). Post-pyrolysis doping with N, P, or sulfur (S) further increases microbial compatibility by changing redox dynamics (112).

Extrinsic factors, such as soil type, moisture availability, climate, and management practices, govern the effectiveness of biochar. In sandy soils typical of arid regions, biochar increases water and nutrient retention, whereas in clayey soils, it increases aeration and improves soil structure (113, 114). Biochar has the strongest impact on field moisture capacity (FC) and available water capacity (AWC) in coarse-textured soils, depending not only on soil texture but also on surface chemistry and its interactions with the soil matrix (115). Biochar increases saturated hydraulic conductivity (Ks), followed by a noticeable increase in the AWC content. Its influence on bulk density, porosity, and aggregate stability is comparatively modest (116). These processes affect microbial respiration and enzyme diffusion by modulating the Ks and pore structure.

In arid environments, biochar's high specific surface area and porosity buffer against desiccation and temperature stress, stabilizing MBC. Its porous architecture provides protective microhabitats that support microbial survival under stress (68). These physical traits also increase biochar's ability to adsorb sodium

ions (Na⁺) in saline-alkali soils, thereby limiting Na⁺ uptake by plants and alleviating salinity-induced stress (90, 117, 118). However, carbonate-rich calcareous soils, common in arid regions, may increase abiotic CO₂ release under transient acidification caused by amendments, such as N or S fertilizers (119), and biochar may mitigate this effect through its higher pH buffering capacity, aiding net C sequestration efforts (120, 121). For example, El-Mahrouky et al. (122) reported that the addition of raw OM led to 3–6 times higher CO₂ emissions than the input of biochar in calcareous soils due to rapid microbial respiration. The implications of these dynamics on GHG fluxes are further examined in Section 4.

6 Environmental and management modulators of biochar effects on GHG emission in arid agricultural soils

Emission of GHGs from soils of arid and semi-arid agricultural systems arise from the convergence of biophysical constraints, climate stressors, and land management practices (Figure 3). Overall, agrifood systems, including crop and livestock production, release ~7.8 Pg CO₂ eq (CO₂-equivalent including CH₄ and N₂O,

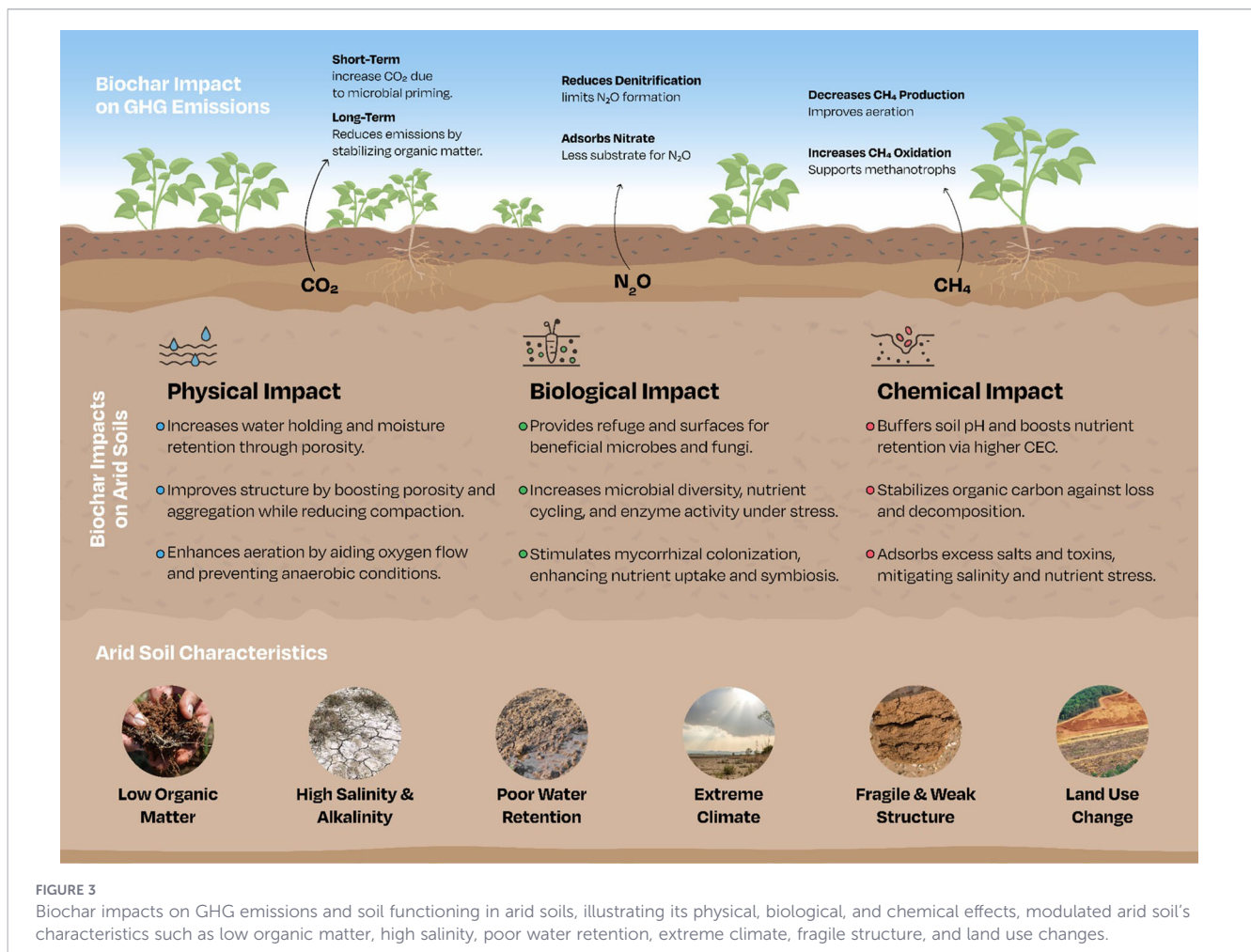


FIGURE 3

Biochar impacts on GHG emissions and soil functioning in arid soils, illustrating its physical, biological, and chemical effects, modulated arid soil's characteristics such as low organic matter, high salinity, poor water retention, extreme climate, fragile structure, and land use changes.

expressed as a single unit of CO₂ based on their global warming potential) from farm gate activities alone, contributing nearly one-third of global anthropogenic emissions (123). Meta-analyses have highlighted irrigation as a major GHG source in drylands, particularly CH₄ and N₂O, due to misaligned water management and redox imbalances (124, 125). In arid and sub-arid regions of sub-Saharan Africa (SSA), the Middle East (ME), and South Asia (SA), irrigation contributes to over 50% of the total on-farm CO₂ emissions intensity (125), not only due to increased energy use but also because of its effects on soil moisture, microbial respiration, and carbon turnover.

N₂O emissions strongly correlate with synthetic N fertilizer use (126), contributing to approximately 5% of the ACC while depleting stratospheric ozone (127). The major N₂O sources include natural soils (6 Tg a⁻¹), agricultural soils (4.2 Tg a⁻¹), and anthropogenic sources (128). Furthermore, N is the most widely applied fertilizer globally, reaching 190 Tg by 2020 (129, 130), and is crucial for crop production in soils with low SOM (130, 131). Reliance on synthetic N has intensified in the quest to close persistent yield gaps in arid agroecosystems (132). Although the Green Revolution narrowed these gaps, it also increased environmental costs, including soil degradation due to excessive fertilizer use (133). In arid wheat (*Triticum aestivum*) systems, prolonged N use supports yields but decreases soil structure and resilience (134), raising concerns as desert lands are increasingly being brought under cultivation.

However, the effectiveness of N fertilizers in arid soils is often constrained by low SOM content and irregular moisture availability. These limitations can impair N cycling processes, although the co-application of organic residues may increase microbial turnover and enhance nitrification and denitrification. However, in alkaline soils, which are common in arid zones, incomplete denitrification frequently limits the conversion of N₂O to N₂, thereby extending its atmospheric lifetime (135).

In pastoral drylands, enteric CH₄ emissions are common due to low-quality forage and slow digestion rates (126). Poor manure management, particularly under hot and semi-aerobic conditions, fosters the simultaneous production of CH₄ and N₂O (136), reflecting a misalignment between organic waste inputs and management controls.

Agricultural land preparation frequently involves land clearing and intensive tillage, which expose SOC to oxidation. Coupled with low residue return and limited microbial buffering, these practices accelerate long-term CO₂ emissions and degrade soil fertility. A global meta-analysis of 174 paired observations demonstrated that in arid, sandy soils with low SOC content (< 1 %), conventional tillage increased CO₂ emissions by approximately 29% compared to no-till (NT) systems (137). Additionally, high evapotranspiration and erratic rainfall increase irrigation demands, increasing indirect CO₂ emissions through elevated fossil energy consumption (138). The limited adoption of renewable energy systems further entrenches this dependency on fossil fuels in arid irrigated systems.

Microbial responses to moisture fluctuations are central to GHG dynamics in soils of arid regions. Extended dry periods followed by rewetting, typical of these environments, trigger short-lived but intense pulses of CO₂ and N₂O, a phenomenon

known as the Birch effect (48, 60). These pulses are driven by (i) the sudden availability of drought-accumulated metabolites, (ii) microbial die-off fueling surviving microbes, and (iii) disruption of soil aggregates that expose protected C (49). Soil moisture variability also increases microbial N demand and reduces C-use efficiency, leading to enhanced heterotrophic respiration (139). These episodic responses, although brief, can contribute disproportionately to total annual GHG fluxes and disrupt nutrient recycling (140). Recent evidence shows that although dry regions are receiving more annual rainfall than before, faster than wet regions, this gain is offset by increased evapotranspiration due to warming, leading to intensified soil water cycle extremes (141, 142).

Low soil water availability, rather than high temperatures, is the dominant regulator of microbial activity and respiration in arid regions (143). Microbial dormancy during drought is primarily due to the limited diffusion of substrates and not inherent biological inactivity. However, once rewetting occurs, microbial surges release large pulses of C and nutrients, alongside heightened GHG emissions (60).

Soil pH and cation exchange capacity (CEC) strongly influence microbial processes. Elevated pH inhibits the enzymatic reduction of N₂O to N₂, thereby prolonging emissions (144). Clay mineralogy further regulates CH₄ oxidation; smectite's expansive structure enhances moisture retention and creates microaerophilic niches favorable for methanotrophs, whereas the compact nature of kaolinite restricts O₂ diffusion and limits oxidation (145).

Emerging evidence from semiarid ecosystems highlights dissolved organic C (DOC) as a key regulator of CH₄ oxidation, particularly under variable moisture conditions (146). Studies of piñon-juniper woodlands in northern Arizona report CH₄ oxidation rates exceeding the global averages for deserts and temperate forests, yet dryland environments remain underrepresented in global assessments (147). Traditional soil predictors that are effective in humid regions often fail in arid settings, where DOC availability and episodic moisture events drive microbial activity. The oxidation rates are over five times higher in wet soils than in dry soils, with canopy-covered areas showing even greater DOC content (148). This trend suggests that CH₄ uptake in arid zones may be underestimated, particularly during wet periods. However, a high soil moisture content may hinder oxidation by limiting O₂ diffusion (149), underscoring the delicate balance between water, C, and GHG fluxes in drylands.

Irrigation strategies decisively influence both the quantity and type of GHG emissions. While irrigated agriculture covers only 22% of arable land, it contributes 40% of global food production and up to 15% of agricultural GHG emissions (125, 150). These emissions stem from energy inputs (diesel or electric pumps) and changes in soil moisture content, which alter redox conditions and nutrient cycling (151–153). For example, flood irrigation increase anaerobic zones conducive to CH₄ production, while pressurized systems reduce CH₄ but increase CO₂ emissions, creating a trade-off between water efficiency and emission profiles (124). Addressing these challenges requires integrated strategies that align soil and nutrient management with emission reduction goals, infrastructure efficiency, and long-term resource sustainability.

7 The impact of biochar on soil GHG emission

The influence of biochar amendments on GHG emissions is governed by complex interactions among biomass characteristics, pyrolysis parameters, soil properties, amendment rates, and environmental conditions (154–159). These interactions are discussed below, together with meta-analyses of data gathered from the available literature, reporting the mean effect size derived from multiple climatic zones aggregated from studies conducted in humid, sub-humid, temperate, subtropical, and tropical regions, which were collectively contrasted with arid and semi-arid systems (Figure 4).

7.1 Effects of biochar on soil carbon dioxide emissions

The transformation of biochar's C chemistry during pyrolysis, especially at lower temperatures, tends to increase the fraction of labile C, which readily fuels microbial metabolism and can elevate short-term CO₂ emissions. This occurs either through the decomposition of readily available C fractions (160) or via stimulation of microbial communities that accelerate the mineralization of native SOM, a process commonly referred to as the priming effect (104). These emissions are particularly pronounced when biochars are produced at low pyrolysis temperatures, which preserve volatile and degradable C forms.

In microbial terms, these emissions often reflect shifts in soil biotic activity. Enhanced respiration from heterotrophic communities, including actinomycetes and gram-negative bacteria, has been associated with increased C turnover following biochar incorporation (99). These microbial dynamics are sensitive to both the feedstock source and the soil texture, with finer soils such as silt loam often exhibiting stronger responses due to their capacity to retain moisture and organic compounds. The intensity of the thermal treatment directly alters the biochar recalcitrance, and as the pyrolysis temperature increases, the resulting material becomes more aromatic and resistant to microbial attack (161). This leads to a decline in biochar-derived CO₂ emissions over time. For example, increasing the pyrolysis temperature from 400 °C to 600 °C has been shown to substantially reduce CO₂ release from poultry litter and swine manure biochars applied to the same soil matrix (156).

In the long term, the interaction of biochar with mineral phases and its role in forming organo-mineral associations becomes critical in stabilizing SOC (162, 163). These protective mechanisms mitigate C losses by reducing the accessibility of OM to microbial decomposers, especially under conditions where physical aggregation and chemical sorption processes are active. Therefore, although the immediate impact of biochar on CO₂ emissions can be stimulatory, particularly under certain climatic and edaphic contexts, the trajectory over time often shifts toward C stabilization and GHG emission reduction as more stable C fractions predominate.

The pyrolysis temperature of biochar plays a pivotal role in shaping its influence on soil C dynamics, particularly regarding the

priming of native SOC and associated CO₂ emissions. Lower pyrolysis temperatures generally produce biochars rich in labile C compounds, which can intensify microbial respiration and stimulate positive priming effects. In clay loam soils, for instance, the increased C availability from low-temperature biochar increases the microbial mineralization of SOC, resulting in CO₂ emissions (155). This response is linked to the greater bioavailability of C substrates in less thermally altered biochar, which fuels microbial metabolism and leads to a high C turnover.

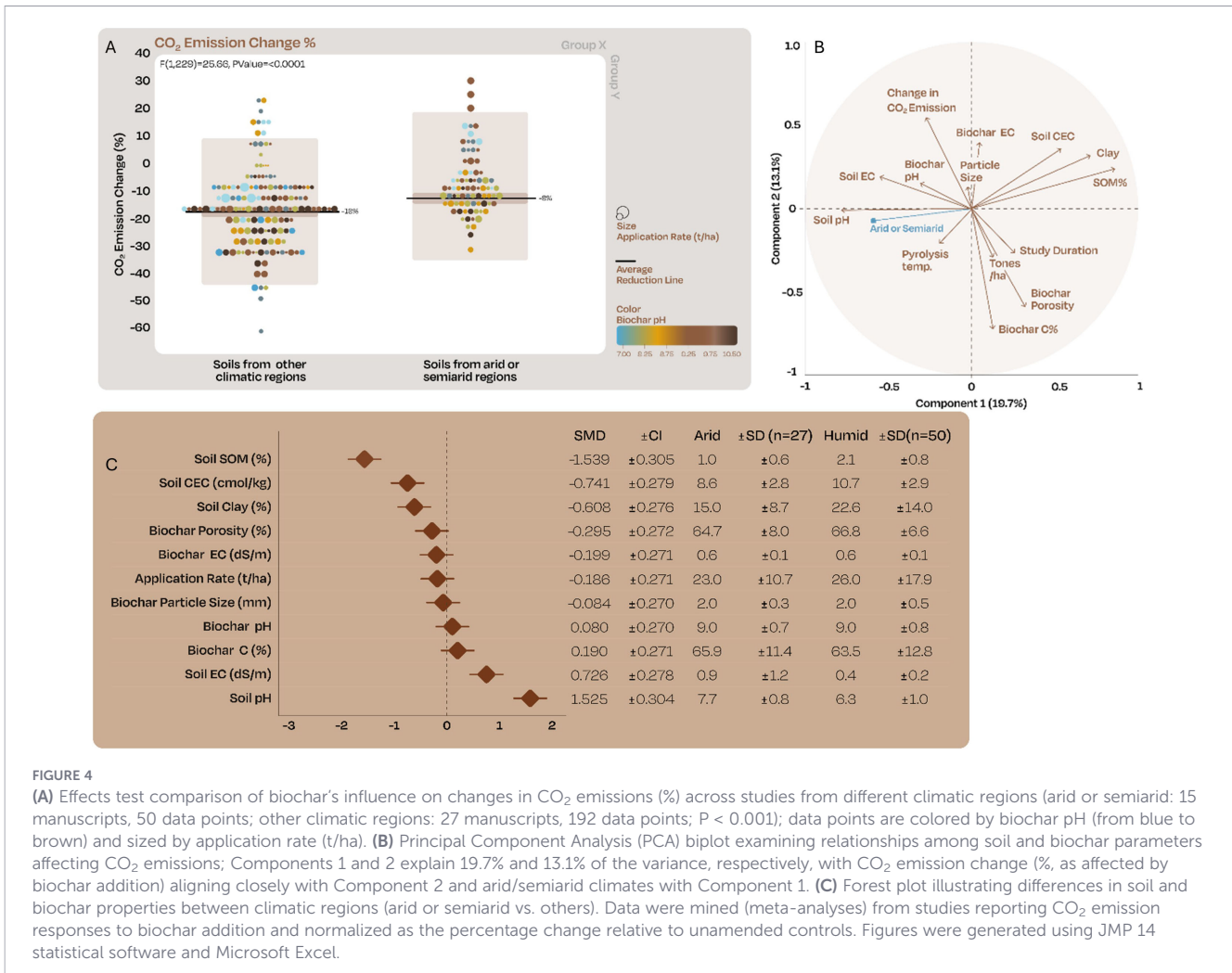
Conversely, biochars produced at higher pyrolysis temperatures tend to yield more condensed, aromatic C structures with limited microbial degradability. The suppression of CO₂ emissions under these conditions is often attributed to the reduced presence of volatile organic compounds and an increase in biochar's chemical recalcitrance (164–167). These chemical transformations limit microbial access to C, thereby curbing the extent of SOC decomposition and associated gas fluxes. This inverse relationship between pyrolysis temperature and CO₂ emissions underscores the central role of biochar's thermal history in determining its biogeochemical behavior in soil systems.

Empirical evidence supports this mechanism across diverse soil types and climatic zones in the world. In soils of temperate regions, for example, high-temperature biochars derived from swine manure have been shown to reduce cumulative CO₂ emissions, suggesting a diminished priming effect at elevated pyrolysis thresholds (168). Similar reductions have been observed in soils of sub-tropical regions amended with rice (*Oryza sativa*) husk biochar, where structural stabilization of OM may have offset microbial respiration (169). Even in arid regions, biochars produced from corn (*Zea mays*) straw at 400–500 °C consistently lowered CO₂ fluxes across consecutive growing seasons, indicating sustained suppression of mineralization rates under sandy loam conditions (170).

These variable outcomes reflect a suite of interactive controls, including soil type, soil moisture storage, microbial community structure, and management history. The modulation of soil pH and the increase in microbial activity following biochar addition can both stimulate or suppress CO₂ release, depending on the prevailing balance of C inputs and microbial demand (71, 171). Additionally, the favorable soil physical conditions induced by biochar (i.e., increased porosity, higher moisture retention, and reduced compaction) alter the soil environment in ways that can alter C storage and decomposition dynamics (71, 171–173). The combined chemical and structural modifications introduced by biochar thus act on multiple fronts to moderate SOC turnover, making their effect on CO₂ emissions highly context-dependent.

7.2 Methane emission from biochar amended soils

CH₄ is the second most important GHG driving the ACC. Although present at lower atmospheric concentrations than CO₂, it has a global warming potential (GWP) that is 25 times greater on a molar basis (174, 175). Figure 5A presents a meta-analysis comparison of the percentage change in CH₄ emissions between arid or semiarid regions (n=11) and other climatic regions (n = 49).



The average CH₄ emission was reduced by biochar by 20% in arid and semiarid soils, compared to an average 38% reduction in soils from other climatic regions. Unlike the observed for CO₂ emissions, the reduction in CH₄ emissions by biochar was not significant ($P \approx 0.09$) in arid or semiarid soils and other climatic conditions, probably due to the low number of studies (five) in arid or semiarid regions. Figure 5B shows the PCA biplot illustrating the relationships among background soil and biochar variables influencing the CH₄ emission percentage change. The PCA plot identifies groupings and aids in understanding multicollinearity and dominant influences in the meta-analysis of biochar's role in mitigating CH₄ emissions. Component 1 accounted for 24.6% of the variance, and Component 2 accounted for 19.3%. Although the PCA suggests that the physicochemical properties of biochar affect the reduction of CH₄ emissions, the factors that better explain CH₄ emissions include biochar pH, pyrolysis temperature, and application rate (t/ha), and are inversely related to biochar porosity and soil clay content. Interestingly, SOM was aligned with Component 1 and was unrelated to CH₄ emissions in this meta-analysis. Soil pH and sand content were aligned with the categorical indicator for arid or semiarid climates (highlighted in blue), diagonally aligned with Components 1 and 2, indicating that climate was a significant moderator of all the soil parameters.

Biochar application mitigates CH₄ emissions by improving soil aeration and the redox conditions. At 2% (g/g), it completely suppressed CH₄ emissions (176, 177) and increased CH₄ uptake by 96% (178). The porous structure and high surface area of biochar favorably affect soil physical properties, such as bulk density and porosity, thereby increasing O₂ diffusion throughout the soil matrix (179). The increased aeration creates conditions that are less favorable for methanogenic archaea, which rely on anaerobic environments, while simultaneously increasing aerobic microbial populations, including methanotrophs that oxidize CH₄. Such shifts in microbial community structure underpin many of the observed reductions in CH₄ emissions across different soil types and climates (Supplementary Table 1; see Supplementary File).

The suppression of CH₄ emissions is particularly evident in coarse-textured soils, such as sandy and silt loams, where biochar's physical amendments increase gaseous exchange. Studies have demonstrated that biochars derived from a variety of feedstocks and produced at different pyrolysis temperatures consistently reduce CH₄ emissions in these soils, a trend often magnified under alkaline conditions, where biochar exerts a stronger influence on soil aggregation and aeration (180, 181). Although comprehensive statistical comparisons across climatic zones are scant, especially for arid and semi-arid climates relative to other

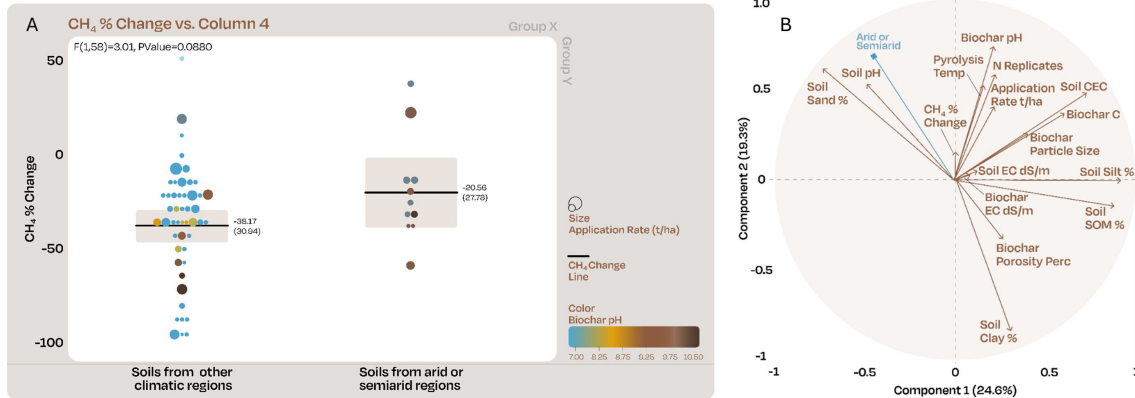


FIGURE 5

Results of the meta-analyses: (A) Effects test comparison of biochar's influence on changes in CH₄ emissions (%) across studies from different climatic regions (arid or semiarid: n=11; other climatic regions n=49; p = 0.0880); Data points are colored by biochar pH (from blue to brown) and sized by application rate (t/ha). (B) Principal Component Analysis (PCA) biplot examining relationships among soil and biochar parameters affecting CH₄ emissions; Components 1 and 2 explain 24.6% and 19.3% of the variance, respectively, with CH₄ emission change (% as affected by biochar addition) aligning closely with Component 2.

ecoregions, the available evidence supports a mechanistic link between favorable soil structure and reduced anaerobic microsite formation as a key pathway for CH₄ mitigation.

In fine-textured soils, however, the outcomes are variable, as the interaction between biochar and soil water retention may create microenvironments that differ in redox potential. In some cases, biochar addition to clay-rich soils has led to elevated CH₄ emissions, potentially due to moisture retention that prolongs anaerobic conditions favorable to methanogenesis (169). However, in other instances, even within clay loams, biochar produced from crop residues at moderate pyrolysis temperatures has reduced cumulative CH₄ emissions, probably due to shifts in the microbial community balance and C availability (182). These contrasting outcomes underscore the importance of considering both the intrinsic properties of biochar and the specific soil environment when evaluating its effects on CH₄ fluxes.

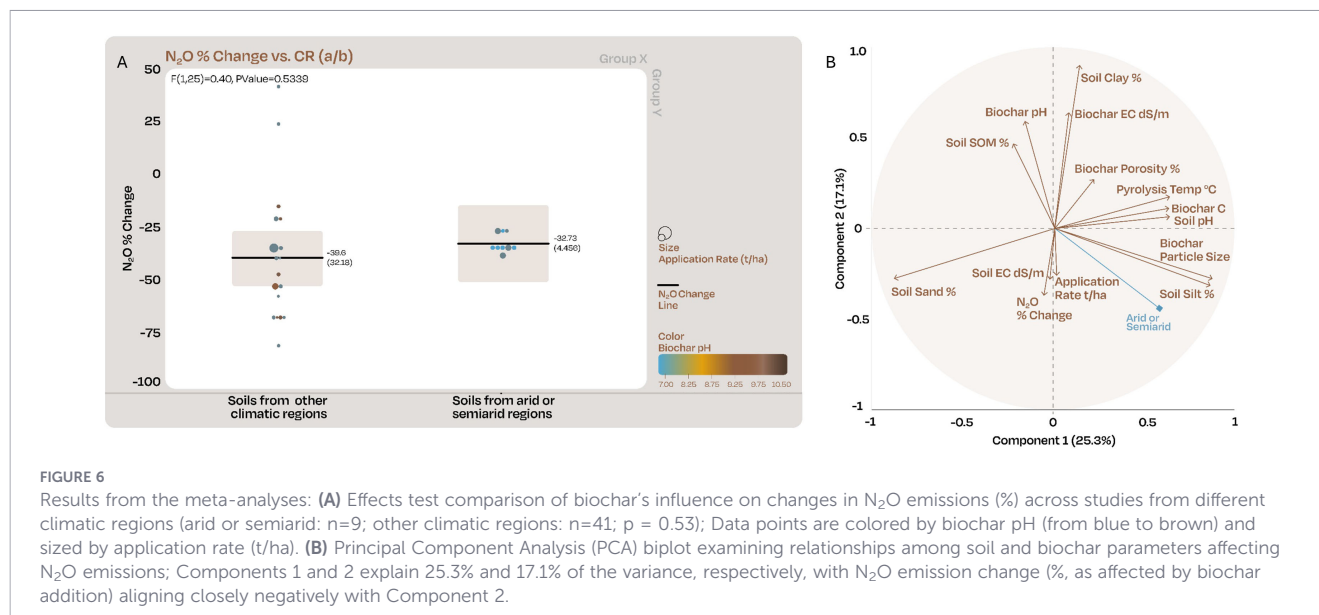
Microbial mechanisms are central to these processes. The balance between CH₄-producing archaea and CH₄-oxidizing bacteria determines net CH₄ fluxes in the soil. Biochar can influence this balance by altering the pH, nutrient availability, and redox potential, all of which mediate microbial activity. The resulting changes can lead to reduced CH₄ production and/or increased CH₄ oxidation, depending on how the microbial habitat is reshaped. In this context, biochar's indirect effects on microbial community composition and enzymatic function are just as critical as its direct effects on soil structure.

Given that CH₄ has a very high GWP, the ability of biochar to attenuate CH₄ emissions offers a powerful strategy for climate-resilient soil management. This is especially relevant for fine-textured soils that naturally support more anaerobic zones and are thus more susceptible to CH₄ release under conventional management practices (71, 183). The nuanced responses observed across different environments indicate the need for site-specific evaluations but also highlight the broad potential of biochar as a tool for CH₄ mitigation.

7.3 Nitrous oxide emission from soils amended with biochar

N₂O, a potent GHG with a GWP approximately 298 times that of CO₂, is primarily emitted from agricultural soils through the microbial processes of nitrification and denitrification, particularly after fertilizer application. Even at low concentrations, N₂O poses an important threat to climate stability due to its high GWP. The integration of biochar into soil systems has emerged as a promising strategy for mitigating these emissions. Figure 6A presents a meta-analysis effects test comparison of the effect of biochar on N₂O emissions between soils from arid and semiarid (34% reduction) and non-arid climates (40% reduction). Reductions in both groups were statistically equivalent (P > 0.5), likely due to the low number of studies (four) found for arid or semiarid climates. Figure 6B shows a PCA biplot of the multivariate relationships between environmental, soil, and biochar-related variables that potentially drive changes in N₂O emissions. This analysis revealed clusters of correlated variables (e.g., biochar pH and pyrolysis temperature), helping to identify primary drivers and collinearities in meta-analyzed studies on the impact of biochar on N₂O emissions. The first two components captured approximately 42.6% of the total variance, with Component 1 primarily separating factors such as the soil texture, pH, and biochar C content. Component 2 was negatively aligned with N₂O emissions and soil EC, which are key variables in arid and semiarid soils. Soil clay, SOM, and biochar pH were positively correlated with Component 2, in contrast to N₂O emissions.

Emissions of N₂O are affected by pH and its impact on microbial functional groups. Ammonia-oxidizing bacteria (AOB) thrive under neutral to alkaline conditions, whereas archaea (AOA) increase their abundance in acidic environments (184). Higher pH favor complete denitrification by increasing N₂O reductase activity and also the abundance of nosZ-carrying microbes (185–187). Biochar-mediated suppression of N₂O has been attributed to



better aeration, increased *nosZ* gene prevalence, NO₃⁻ adsorption, and increased substrate diffusion (188–192). High-temperature biochars (>600 °C) often exhibit a high suppression potential due to stronger alkalinity (193).

Numerous studies have demonstrated that biochar can suppress N₂O fluxes for soil systems both with and without synthetic N fertilizer additions (194–196). This mitigation effect is frequently attributed to the modification of soil biogeochemical processes, particularly those governing N transformation pathways.

One of the critical mechanisms by which biochar reduces N₂O emissions is through its influence on soil aeration and pH. The porous structure of biochar enhances O₂ diffusion into the soil matrix, thus inhibiting the anaerobic microsites required for complete denitrification, where N₂O is typically produced as an intermediate product. Additionally, biochar-induced increases in soil pH have been shown to shift microbial activity away from N₂O-producing pathways, promoting instead the complete reduction of N₂O to dinitrogen (N₂). In some soils, this effect is further strengthened by biochar's ability to adsorb nitrate (NO₃⁻), thereby reducing substrate availability for denitrifying bacteria (164, 165).

The efficacy of biochar in suppressing N₂O varies according to both its production characteristics and the soil context in which it is applied. Biochars produced at higher pyrolysis temperatures often exhibit higher aromaticity and stable C matrices, which increase their physical structure and chemical reactivity in ways conducive to N₂O mitigation. For instance, reductions in N₂O emissions have been attributed to biochars derived from feedstocks processed at 400 °C and above, which appear to inhibit denitrification more effectively under specific soil and climatic conditions. In some cases, emission reductions as high as 98% have been observed in sandy loam soils, depending on the application rate and biochar type (170,

191). However, the response of N₂O emissions to biochar is not uniform across all soil types or climatic conditions (Supplementary Table 2; see Supplementary File).

For example, in some soils of temperate and subtropical regions, biochar derived from swine manure or corn stalks did not produce substantial changes in N₂O fluxes, suggesting that specific combinations of biochar properties and soil characteristics may be pertinent to achieving consistent reductions (165, 197). In contrast, in silt loam soils, particularly under humid or temperate conditions, substantial decreases in N₂O emissions have been repeatedly documented, with observed reductions ranging from 53% to over 90%, depending on the pyrolysis temperature, biochar source, and fertilizer regime (169, 198, 199).

In finer-textured soils, such as clay loams, the effects of biochar appear to be mediated by a combination of physical and chemical interactions. Increased aeration through structural modification, coupled with the ability of biochar to buffer pH and retain N species, alters the microenvironment in ways that suppress N₂O production pathways. However, this response remains dependent on the specific biochar composition and soil hydrological behavior. In some instances, even within the same region and using similar feedstocks, contrasting emission outcomes have been observed depending on the soil moisture content and its seasonal variability (169).

Ultimately, the potential of biochar to mitigate N₂O emissions lies in its capacity to restructure the physical environment of the soil, moderate N cycling, and influence microbial ecology (200). Its multifunctionality, which ranges from NO₃⁻ retention to pH buffering and redox modulation, allows it to simultaneously target several core processes responsible for N₂O generation. These attributes support its broader application as a tool for climate-resilient soil management, especially in systems where synthetic N inputs and anaerobic conditions drive persistent GHG losses (165, 196).

8 Mechanistic interactions of management, climate, and soils in arid GHG emissions

Beyond the meta-analysis (Section 6), which delineates differences in GHG emissions between soils from arid and semiarid regions relative to those from humid regions, individual studies further identify and critically examine a range of direct and indirect mechanistic drivers. Soil application of biochar alters pH, with cascading effects on microbial communities and GHG fluxes (201). Typically, an alkaline amendment (pH 7.5–10.5), biochar raises soil pH through the presence of residual ash and proton-consuming surfaces (202). While this may benefit acidic soils, further alkalization in arid-alkaline regions may exacerbate microbial imbalances. Elevated pH (>7.5) generally reduce respiration (203), yet under high-temperature and variable soil moisture conditions, which are common in drylands, may increase microbial activity (204, 205) and aggravate GHG emissions (206).

Favorable soil structure created by biochar inputs (e.g., reduced bulk density, increased porosity, and a high aggregate stability) modifies O₂ diffusion and water retention (207–209). These changes influence microbial pathways associated with CO₂ emissions, particularly through enhanced oxidative enzyme activity under increased aeration (99, 210). In saline-alkaline soils, biochar also reduces salt stress, further amplifying microbial respiration (211).

Aeration shifts also affect the denitrification dynamics. In well-oxygenated soils, nitrification dominates, and the N₂O:NO₃⁻ ratio declines (212), while stable and well-developed soil structure limits anaerobic microsites (205). In clay-rich arid soils, re-aeration following irrigation interrupts denitrification cycles and reduces N₂O accumulation (90, 213). Increased aggregation and stratification from surface amendments further influence redox gradients and depth-specific emissions (214, 215).

Fluxes of CH₄ are determined by the balance between methanogenesis and methanotrophy, which are moderated by pH and O₂ availability. Methanogens favor pH 6.5–8.2 (216), whereas methanotrophs show broader pH tolerances (217). pH-driven microbial shifts can modulate CH₄ oxidation efficiency (218, 219). An increase in soil aeration suppresses methanogenesis and increases CH₄ oxidation (145, 147), although soil moisture content remains a limiting factor for methanotrophs in arid soils (220, 221). Structural improvements reduce methanogen diversity, particularly among hydrogenotrophic taxa (222), and lead to Type I methanotroph dominance in drier alkaline systems.

In soils of arid regions, enhanced drainage and soil structure mediate temporal GHG fluxes by altering wet-dry cycling and reducing salinity stress (223). High temperatures further intensify CH₄ turnover (220, 221), while limited OM restricts substrate availability for both methanogenesis and denitrification (224). Ultimately, biochar's role in reshaping the spatial arrangement of redox zones within soil aggregates intricately affect emission of CO₂, N₂O, and CH₄ across arid-alkaline landscapes.

9 Conclusions

Data gathered and synthesized in this review show that overall, biochar delivers measurable GHG mitigation and soil-function benefits in arid and semi-arid agroecosystems, though responses are strongly context dependent. Biochar application in arid and semi-arid agroecosystems mitigates CO₂ emissions less effectively than in non-arid climates, yet the meta-analysis could not statistically confirm this trend for CH₄ or N₂O, likely due to fewer observations for these gases. These attenuated responses reflect dryland constraints, including episodic moisture availability, alkaline-saline soil properties, and low organic carbon, which moderate microbial processes and can shift short-term microbial dynamics.

Mechanistically, biochar alters soil aeration, water retention, redox microsites, and substrate availability, thereby regulating methanogenesis versus methane oxidation and nitrification versus denitrification, including pathways linked to *nosZ*, *amoA*, and methanotroph-methanogen dynamics. Mitigation outcomes are most reliable when biochar properties and management are matched to dominant soil constraints and integrated with optimized fertilizer use and irrigation scheduling.

This review highlights biochar as a strategic soil amendment uniquely suited to address the intertwined challenges of soil degradation and GHG emissions in such dryland systems. The response of microbial communities and GHG fluxes to biochar is modulated by these site-specific constraints, and the outcomes are often nonlinear. For instance, although high-temperature biochars (>500 °C) show greater structural stability and suppress CO₂ and N₂O emissions in many settings, they may limit microbial colonization or lead to nutrient dilution effects if not properly matched to the concerning arid land soil conditions. Moreover, biochar may mitigate microbially driven GHG emission surges following soil moisture fluctuations arising from irregular irrigation of arid land soils, a dynamic that must be considered in mitigation strategies.

Bibliometric evidence indicates a growing recognition of these complexities, yet only a small fraction (~3%) of biochar studies explicitly target arid and semi-arid systems. This knowledge gap restricts the development of precision biochar strategies for these vulnerable agroecosystems. Despite increasing interest, biochar application in arid and semi-arid agroecosystems remains limited by gaps in empirical evidence, mechanistic understanding, and systems-level integration. Dryland soils are underrepresented in long-term, field-scale studies, constraining robust assessment of greenhouse gas responses and dryland-specific processes, including wet-dry pulse dynamics and the partitioning of organic and inorganic CO₂ in carbonate-rich soils. Mechanistic understanding of how soil-mediated biochar transformation influences microbial functional traits, enzyme activities, and carbon-use efficiency under extreme moisture variability remains limited. Moreover, integrated feasibility assessments are scarce, particularly in the world's most climate-stressed landscapes of Middle East and North Africa, where underutilized biomass resources could support coupled biochar-bioenergy strategies for climate mitigation and soil restoration. This review advocates for a systems-oriented and climate-smart framework for biochar use in arid lands,

integrating soil type, management history, microbial ecology, and socio-economic context.

Author contributions

SA-I: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft. RL: Validation, Writing – review & editing. YK: Validation, Writing – review & editing. JC: Validation, Writing – review & editing. FB: Writing – review & editing. BA: Writing – review & editing. DB: Data curation, Formal Analysis, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Supplementary material

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