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Biochar

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Biochar as a climate-smart strategy for restoring dryland soils and mitigating desertification

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Abstract

Arid and semi-arid regions are increasingly vulnerable to desertification, soil degradation, and water scarcity, which severely threaten agricultural productivity, food security, and ecosystem stability. This review explores biochar as a climate-smart, integrative, nature-based solution to address these critical challenges, enhance water use efficiency, and build resilience in fragile dryland ecosystems. We hypothesize that strategically designed biochar systems aligned with consistent feedstock logistics, economic viability, and site-specific hydrological and biogeochemical needs can serve as scalable, multi-functional interventions to restore degraded soils and mitigate climate-driven desertification. To test this hypothesis, we critically synthesize interdisciplinary literature, uncovering underexplored synergistic roles of biochar in hydrological regulation, microbial ecology, and renewable energy integration. By consolidating data on biochar's physicochemical properties, we examine its mechanisms for improving soil structure, boosting water retention, enhancing nutrient cycling, buffering pH, and supporting microbial communities in dryland soils. Field evidence further demonstrates biochar's capacity to rehabilitate soils, increase crop yields, and reduce erosion risks. We also highlight emerging opportunities at the intersection of biochar and precision agriculture, such as drone-assisted applications, co-composting to produce nutrient-rich biochar, and integration with solar-powered irrigation. Given the accelerating trends of land degradation and climate variability, there is an urgent need to optimize biochar systems for specific soil–climate contexts, quantify long-term carbon sequestration, and assess ecosystem-level impacts. Overcoming challenges related to high production costs, feedstock variability, and ecological uncertainties will require coordinated, multidisciplinary efforts. In conclusion, this review emphasizes biochar's multifaceted role as a transformative strategy for climate-resilient agriculture and sustainable land management in drylands.

Keywords Dryland soil fertility, Biochar applications, Desertification control, Climate change adaptation, Sustainable agriculture, Soil amendment strategies

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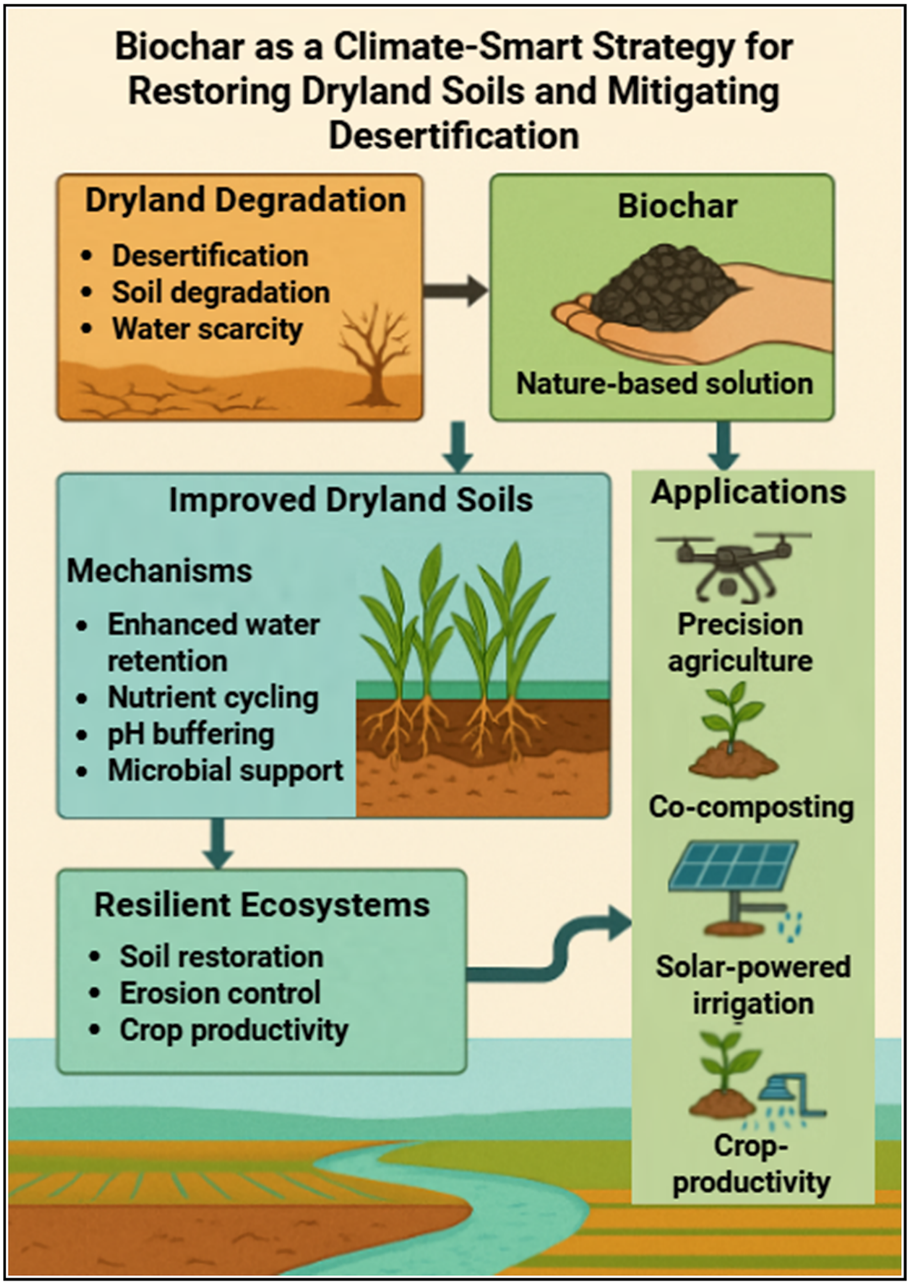
Graphical Abstract



1 Introduction

Arid and semi-arid regions account for nearly 40% of global land area and are defined by extremely low annual precipitation (< 250 mm year^{-1}), high evapotranspiration (> 1,000 mm yr^{-1}), and fragile soils prone to salinization and structural degradation (Abdelhak 2022; Jiménez-Bonilla et al. 2025). These inherent constraints, combined with rapid demographic growth and climate-driven desertification, have resulted in critically low soil organic matter (SOM < 0.5%) across many dryland zones, destabilizing soil aggregation and microbial habitats (Gunarathnea et al. 2022). Traditional measures such as mineral fertilizer intensification and non-optimized irrigation often exacerbate salinity and offer diminishing returns, failing to address subsoil structural decline (Lee et al. 2022).

Biochar, produced via pyrolysis under oxygen-limited conditions at 350–700 °C offers a technically viable pathway to mitigate these constraints. Its high specific surface area (150–400 m^2 g^{-1}) and cation exchange capacity (25–60 cmol kg^{-1}) can enhance soil water holding by 15–35% and stabilize microbial biomass by up to 50% (Wu et al. 2019; Wibowo et al. 2024; Luo et al. 2025). Moreover, biochar sequesters up to 80% of initial feedstock carbon into recalcitrant aromatic matrices, representing a global CO_2-equivalent mitigation potential of ~ 1.8 Gt yr^{-1} (de Oliveira et al. 2024; Yang et al. 2024).

However, for deployment at scale, biochar systems must achieve economic sustainability not merely environmental benefits. Production costs typically range from \$300–700 t^{-1}, with ~ 45% attributable to feedstock collection and transport, and ~ 35% to processing energy and maintenance (Maroušek 2014; Henke 2025). Critically, feedstock consistency drives process economics: while post-harvest residues or leaf litter are seasonally sporadic and highly variable in lignocellulosic composition, feedstocks such as wood waste, digestate, or brewery spent grains are available year-round with stable quality, reducing cost variability by ~ 20–30% (Maroušek and Trakal 2022; Maroušek et al. 2023). In Central Europe, studies reveal that producing biochar from microalgae without innovative cultivation remains economically prohibitive, underscoring the primacy of robust feedstock logistics (Marousek et al. 2024). Moreover, application to soil now competes with higher-margin uses. Incorporating biochar into cement matrices particularly via phosphate (PO_4^{3-}) enrichment from wastewater achieves internal rates of return exceeding 18%, far outstripping soil amendment pathways (de Carvalho Gomes 2020; Marousek et al. 2025). This aligns with investment portfolio models which demonstrate that land-based carbon technologies must secure stable demand profiles and risk-adjusted profitability to attract capital flows (Akbari et al. 2021; Pavolova et al. 2021).

Importantly, interpreting increases in total SOM after biochar application requires caution (Lorenz and Lal 2014). SOM quantity alone is insufficient; qualitative indicators such as carbon mineralization rates, labile fractions, C:N ratios, and microbial respiration indices are essential to determine bioavailability to soil consortia and long-term fertility impacts (Zhang et al. 2020). Technological advances support tailored biochar systems: mobile pyrolysis platforms reduce transport costs by ~ 25%, precision drone application enhances nutrient use efficiency by 10–15% (Kang et al. 2021; Mayadevi and Sandeep 2025), while nano-engineered biochars improve Na^+ and NO_3^- adsorption under saline stress (Hersh et al. 2019). Co-composted biochars enriched with microbial inoculants further improve soil aggregate stability and root colonization in semi-arid trials (Hejazi Mahabadi et al. 2025).

Recent syntheses and field trials clarify when and how biochar improves salt-affected soils (Wu et al. 2024a; Irfan et al. 2025). Meta-analyses show consistent EC reduction in saline soils, with variable pH responses, and identify effective windows for application rate and pyrolysis conditions (Gao et al. 2024; Wang et al. 2024). New critical reviews of modified biochars and co-amendments (for example, gypsum or microbe-enriched formulations) highlight mechanisms for lowering ESP/SAR and stabilizing structure under saline–sodic stress (Vuong et al. 2025). Given this backdrop, we hypothesize that biochar systems, when rigorously aligned with consistent feedstock supply chains, investor-driven profitability models, and site-specific hydrological–biogeochemical requirements, can simultaneously address ecological restoration and deliver economically competitive returns in arid landscapes. This review critically evaluates the technological, agronomic, and economic dimensions of biochar deployment, emphasizes overlooked facets such as SOM quality and investor risk-return frameworks, and identifies integrative pathways to upscale biochar within the intersecting imperatives of climate resilience and market viability.

2 Biochar: characteristics and mechanisms

2.1 Biochar composition and properties

Biochar is produced by pyrolysis of organic biomass under oxygen-limited conditions, typically at 350–700 °C (El-Fawal et al. 2025). Its structural and chemical properties including surface area (150–400 m^2 g^{-1}), pore volume, aromaticity, cation exchange capacity (25–60 cmol kg^{-1}), and pH (often 7–10) are highly sensitive to feedstock type and pyrolysis conditions (Beusch 2021; Murtaza et al. 2022). For instance, higher pyrolysis temperatures increase carbon aromaticity and stability but may reduce oxygenated functional groups important for nutrient interactions (Sun et al. 2025). The combined influences of pyrolysis temperature, feedstock variability, and resulting physicochemical propertiessuch as surface area, aromatic carbon fractions, and cation exchange capacity determine biochar's effectiveness in improving macroaggregate stability, regulating soil moisture dynamics, and supporting microbial biomass in arid soils (Fig. 1).

A high fraction of aromatic carbon makes biochar resistant to microbial decomposition, enabling sequestration of 60–80% of the original biomass carbon for decades to centuries (Shyam et al. 2025). However, recent studies indicate that this stability does not always translate into immediate benefits for soil fertility, which depends on labile carbon fractions and surface chemistry. In fact, biochars with very high C:N ratios (> 80) can initially immobilize N, slowing crop uptake, which is problematic in nutrient-poor arid soils (Alghamdi et al. 2020; Fatima et al. 2021).

Additionally, biochar's high surface area and pore network enable adsorption of heavy metals and organic pollutants, offering potential for soil detoxification (Xiang et al. 2022; Yuan et al. 2025). Yet this adsorption competes with nutrient binding, occasionally reducing availability of nitrate (NO_3^-) and PO_4^{3-} in the short term. Thus, the same chemical features that make biochar a long-lived carbon sink can also complicate its role as a fertility amendment, highlighting the need for tailored formulations depending on local soil constraints (Wang et al. 2025a).

2.2 Mechanisms in arid soils

Arid and semi-arid soils typically contain < 0.5% organic matter, exhibit low aggregate stability, and suffer from high infiltration losses coupled with limited moisture retention (Dalal and Bridge 2020). Biochar can improve particle connectivity, enhance aggregate stability, and reduce susceptibility to wind and water erosion (Naskar et al. 2025; Wang et al. 2025b). For example, studies report up to a 30% increase in macroaggregate formation after biochar addition. However, under coarse-textured sandy soils, biochar may fail to sufficiently bind particles, leading to negligible improvements (Wani et al. 2023). Variations in biochar aromaticity and labile carbon fractions, together with its high surface area and sorption capacity for both nutrients and contaminants, shape its role in enhancing aggregation, mitigating infiltration losses, and moderating microbial responses under arid conditions (Fig. 1).

In addition to these general constraints, it is important to distinguish among the major classes of salt-affected soils saline, sodic, and saline-sodic because they differ fundamentally in ion composition and the mechanisms by which biochar can alleviate degradation (Amini et al. 2016; Singh et al. 2023). Saline soils are dominated by soluble salts (high EC but normal ESP), where biochar improves leaching efficiency and mitigates osmotic stress (Kamal et al. 2024). Sodic soils exhibit high exchangeable sodium percentage (ESP) and poor structural stability; here, biochar's functional groups and Ca/Mg-rich

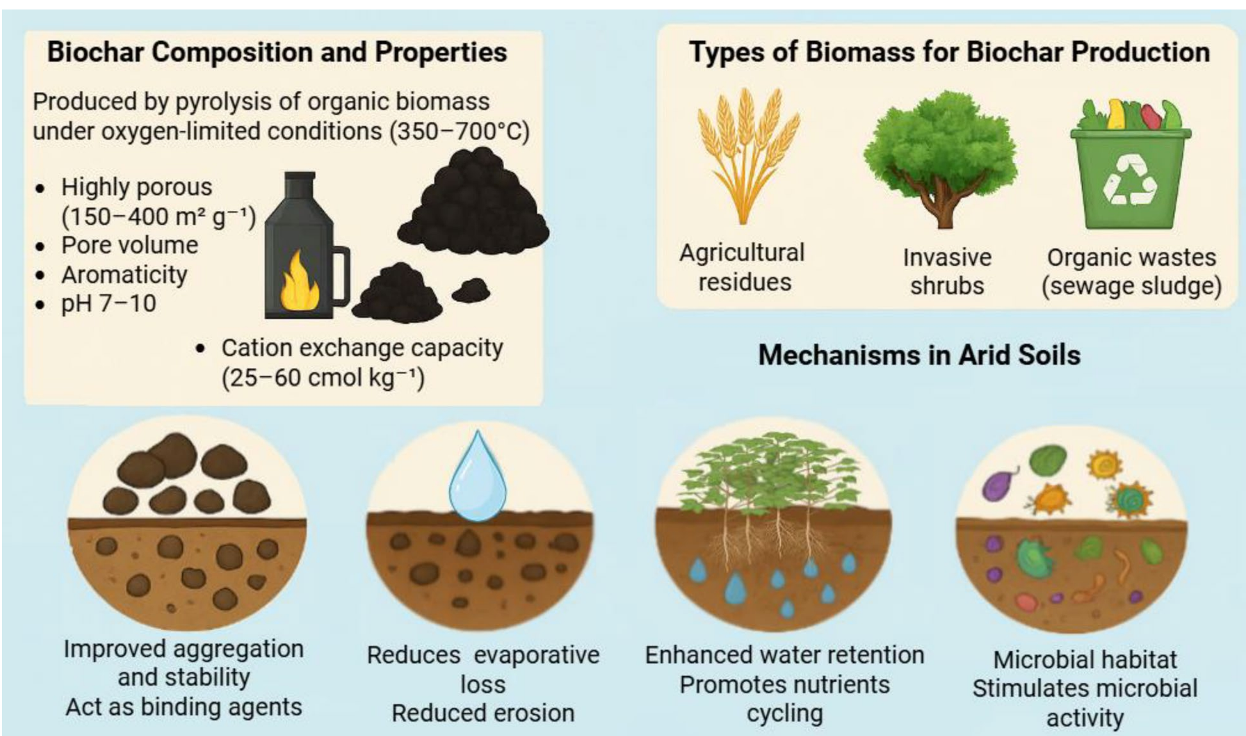


Fig. 1 Tructural and chemical attributes of biochar as influenced by pyrolysis conditions and feedstock types, and their combined roles in improving soil aggregation, water retention, and microbial habitats in arid and semi-arid regions. The figure also highlights pathways linking biomass sources such as crop residues, invasive species, and sewage sludge to biochar's physicochemical properties and subsequent impacts on soil processes, emphasizing implications for sustainable land restoration and carbon sequestration.

ashes can replace Na^+ on exchange sites and restore aggregation. Saline–sodic soils combine both challenges, requiring amendments that reduce both EC and ESP simultaneously (Farooqi et al. 2025). The effectiveness of biochar in these soils depends on feedstock traits: high ash or sludge-derived chars may elevate EC and worsen salinity, whereas wood-based or manure-based chars with balanced Ca/Mg content, moderate pH, and well-developed pore structure are more beneficial (Amesalu et al. 2020; Singh et al. 2025). Therefore, careful selection of feedstock and pyrolysis conditions, along with quality control of ash content and soluble ion concentrations, is essential for tailoring biochar to the specific constraints of salt-affected soils.

Claims that biochar universally enhances water retention are increasingly recognized as overly simplistic. The ability of biochar to retain plant-available water depends critically on matching its pore structure with soil texture; macroporous biochars may drain too rapidly to benefit sandy soils, while microporous chars could restrict capillary flow in silty matrices (Acharya et al. 2024). Field experiments show that improvements in soil water retention can vary from negligible to over 40%, largely based on this pore-size compatibility (Yang and Lu 2021).

Microbial dynamics in arid soils are equally nuanced (He et al. 2024). Biochar's porous surfaces offer microhabitats for fungi and bacteria, potentially increasing microbial biomass by 20–50% (Palansooriya et al. 2019). However, in extremely arid or saline environments, baseline microbial populations are sparse, and biochar alone may not suffice to catalyze substantial biotic recovery (Dey et al. 2024). This suggests that combined strategies (e.g., inoculation with beneficial microbes) may be needed to fully leverage biochar's habitat functions.

2.3 Types of biomass for biochar production

The selection of biomass feedstock is pivotal to the chemical and economic viability of biochar systems (Sahoo et al. 2021). Different types of biomass, including invasive shrubs, agricultural residues, and organic wastes, serve as feedstocks for biochar production, each influencing the resulting carbon dynamics (Altaf et al. 2025). Diverse biomass feedstocks from crop residues to sewage sludge impact the chemical attributes and nutrient profiles of resulting biochars, influencing not only soil structural and hydrological properties but also the economic feasibility of large-scale applications in arid regions (Fig. 1). Many studies emphasize crop residues, local shrubs, or invasive species, which can reduce waste and aid ecosystem restoration. For example, converting invasive mesquite or Prosopis into biochar not only provides a feedstock but also curtails biodiversity loss (Yang et al. 2022; Abhishek et al. 2025). However, reliance on seasonal or sporadically available biomass complicates supply chains, leading to process downtime, variable product quality, and cost increases of 20–30% (Graves et al. 2022).

Sewage sludge (biosolids) stands out as an underutilized alternative, available in large volumes year-round and often at no feedstock cost. Recent techno-economic analyses show sludge biochar can be produced at < $100 t^{-1}$, dramatically reducing cost barriers compared to lignocellulosic sources (Vochozka and Maroušková 2017; Zepeda et al. 2024). Moreover, sludge-derived biochar is naturally enriched with N and phosphorus (P), reducing reliance on external fertilizers (Qin et al. 2022). Yet heavy metal content and public perception pose significant obstacles that demand robust quality control and regulatory frameworks areas still underexplored in arid land applications.

Importantly, even though pyrolyzing crop residues or fruit peels can close local nutrient loops and reduce open burning emissions, the inconsistency in biomass supply remains a hurdle (Adak and Sengupta 2024). This underscores why pairing economic feasibility with environmental sustainability requires prioritizing year-round, stable feedstocks such as sludge, digestate, or wood byproducts (Vochozka et al. 2016a).

3 Impact of biochar on soil fertility in arid regions

3.1 Soil water retention

Water scarcity and rapid evaporative losses fundamentally constrain crop productivity in arid regions (Xing and Wang 2024). Biochar's role in enhancing soil moisture retention is well acknowledged, yet recent field evidence highlights that outcomes are strongly contingent on pore-size compatibility, soil texture, and aging processes (Acharya et al. 2024). For instance, Zhang et al. (2025a) showed that maize-stalk biochar ($5\ t\ ha^{-1}$) improved 0–20 cm water content by 12% under 350 mm rainfall in Xinjiang, while Yang et al. (2022) reported that wood-derived biochars with relatively large pore diameters increased soil water content by only ~ 2% in coarse sandy soils, highlighting a pore-matrix mismatch that limited water retention. By contrast, improvements in pore continuity and microstructural integration achieved through biochar amendments have been widely shown to mitigate evaporative losses and stabilize soil moisture profiles in arid environments.

Furthermore, micro-CT analyses have shown that biochar amendments facilitate the formation of interparticle "pore bridges," enhancing lateral water redistribution an effect particularly important under deficit irrigation practices common in water-limited regions (Heikkinen et al. 2019). Similarly, studies in Egypt's semi-arid wheat systems have shown that biochar application reduces saturated hydraulic conductivity by approximately 18%, thereby slowing percolation and extending water availability in the root zone of shallow-rooted cereals (Barnes et al. 2014). Modifications in pore architecture and capillary tension under biochar amendment enhance water holding capacity, buffering soils against episodic drought and irregular precipitation in semi-arid systems. Improvements in soil water retention under biochar amendment arise not only from modifications to pore architecture and capillary dynamics but also through reductions in evaporative losses and percolation, ultimately sustaining soil moisture availability even under irregular rainfall (Fig. 3).

3.2 Nutrient retention and cation exchange capacity (CEC)

Low native CEC (< 10 cmol kg^{-1}) in arid soils accelerates nutrient leaching, particularly of NH_4^+ and K^+. Biochars produced at 400–600 °C typically exhibit CECs of 30–60 cmol kg^{-1} (Fadl et al. 2024), improving retention by 30–50%. However, studies using ^{15}N isotope tracing have shown that while biochar can reduce NO_3^- leaching by approximately 30%, it also alters vertical N distribution by concentrating more NH_4^+ in the top 15 cm, which may disadvantage deeper-rooting species (Zhao et al. 2025). By increasing cation exchange capacity and reducing NO_3^- leaching, biochar sustains more stable nutrient pools under conditions that typically promote rapid depletion, thereby supporting plant productivity and mitigating nutrient losses common to low-CEC arid soils (Fig. 2).

Notably, the emerging practice of using biochar as a sorbent for nutrient recovery from wastes like anaerobic digestate or sludge adds a compelling economic dimension. Experiments have shown that rice-husk biochar enriched with P from digestate can reduce synthetic P-fertilizer requirements by 25% in millet cultivation, resulting in overall system cost savings of approximately 22% (Gamage et al. 2021; Chaudhary et al. 2025). Such integrated nutrient-biochar strategies represent a conceptual departure from earlier reviews that treated biochar solely as an in-field amendment without linking it to offsite waste valorization and circular nutrient economics. Such integrated nutrient–biochar strategies represent a conceptual departure from earlier reviews that treated biochar solely as an in-field amendment without linking it to offsite waste valorization and circular nutrient economics.

Field evidence further reinforces these nutrient-retentive benefits. As summarized in Table 1, multiple studies have reported substantial reductions in NO_3^- leaching, enhanced ammonium retention in surface layers, and improved nutrient-use efficiency following biochar

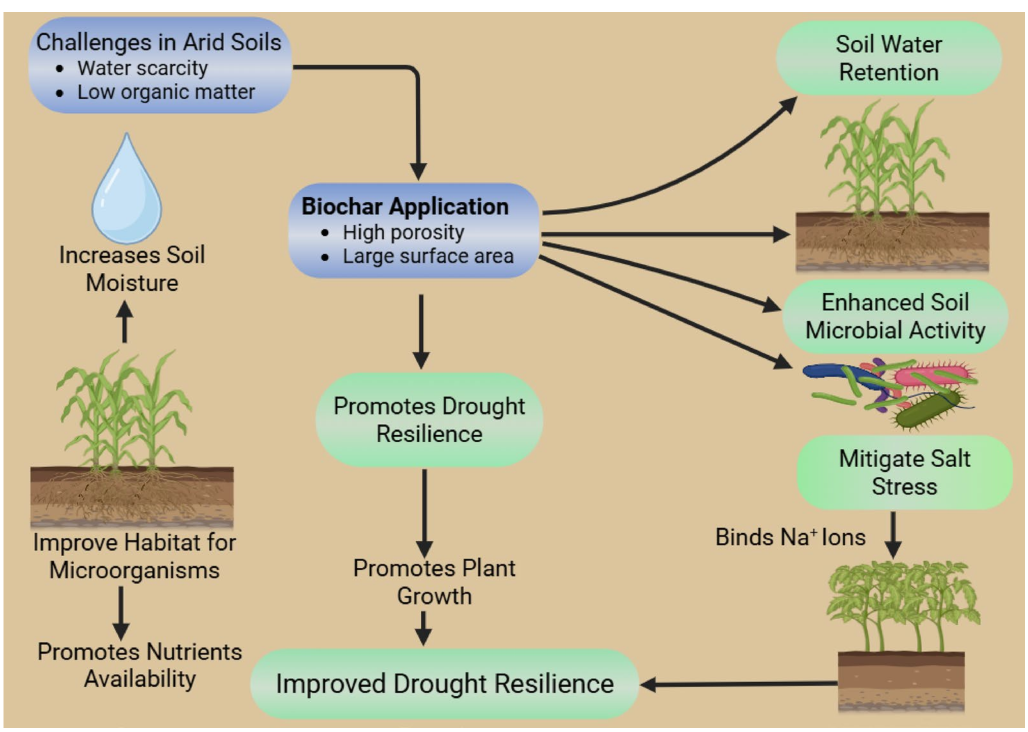


Fig. 2 Effects of biochar on key soil properties in arid regions, including enhanced water retention via pore architecture, increased cation exchange capacity reducing nutrient leaching, stimulation of microbial biomass and activity, and mitigation of salinity through selective ion adsorption

application in arid and semi-arid soils. These results underscore the dual hydrological and chemical roles of biochar in stabilizing nutrient dynamics, particularly under conditions of limited rainfall and rapid nutrient depletion.

3.3 Enhanced soil microbial activity

Biochar's micro-porosity creates refugia that can mitigate harsh microclimates in arid soils, raising total microbial biomass by 30–60% (Singh et al. 2022). Recent high-throughput sequencing studies have revealed more nuanced shifts in microbial community composition under biochar amendment (Cole et al. 2019; Bai et al. 2024). In dryland soils of northwest China, biochar application led to a pronounced enrichment of Actinobacteria and P-solubilizing taxa, enhancing nutrient mobilization (Sui et al. 2022). Concurrently, an increase in ammonia-oxidizing archaea was detected under prevailing alkaline conditions, potentially intensifying nitrification processes and resulting in episodic NO_3^- leaching (Ding et al. 2021). The creation of porous microhabitats under biochar enhances microbial biomass and functional diversity, reinforcing enzymatic transformations and nutrient mobilization pathways that underpin improved soil fertility in arid systems (Fig. 2).

These effects are corroborated by empirical findings summarized in Table 1, where studies report biochar-induced microbial biomass increases of up to 60%, delayed enzyme activity responses, and enhanced microbial-mediated nutrient stabilization. Such outcomes demonstrate that microbial gains under biochar application are not solely a result of improved habitat structure, but also reflect cascading influences on nutrient cycling and enzymatic processes in low-organic-matter dryland soils.

Furthermore, enzyme profiles show that while biomass often rises, key functions such as urease or phosphatase activities may not always keep pace. In West African semi-arid systems, enzyme activity increases have been found to lag behind biomass gains by 15–20%, indicating a functional decoupling that necessitates careful co-management of organic inputs (Okebalama and Marschner 2024). Enzyme activity and microbial biomass gains under biochar reflect not only greater habitat availability but also stabilization of labile carbon substrates, reinforcing nutrient transformations and microbial resilience (Fig. 2).

Adding another dimension, recent research has shown that biochar application reduced N_2O emissions by approximately 18% in semi-arid maize systems, linking its microbial-mediated effects to greenhouse gas mitigation and thereby strengthening climate resilience arguments alongside direct improvements in soil fertility (Ullah et al. 2024; Minofar et al. 2025). Enhancements

Table 1 Recent (2022–2025) empirical findings on biochar impacts in arid and semi-arid soils, highlighting quantitative effects, primary mechanisms, and key contextual drivers

Study and location	Soil and climate context	Biochar type and rate	Main finding (quantitative)	Dominant mechanism	Key controlling factor
(Jia et al. 2024; Jiang et al. 2024), China	Sandy loam, < 350 mm rain	Maize-stalk, 5 t ha^{-1}	↑0–20 cm soil moisture by 12%	Pore-size matching to sand capillarity	Fine pores aligned to low soil matric suction
(Wei et al. 2023), China	Coarse sand, similar rain	Hardwood, coarse pores	↑ soil water by only 2%	Large pores bypass capillarity	Texture mismatch, fast drainage
(Wang et al. 2025b), lab CT	Controlled arid sands	Various, 2–4 t ha^{-1}	Formed lateral "pore bridges"	New pore networks stabilize moisture	Micro-aggregation via biochar bridging
(Gence and Erdem 2024), Egypt	Sandy, arid	Generic biochar	↓ NO_3^- leaching 30%, ↑ ammonium (NH_4^+) top 15 cm	Strong NH_4^+ retention alters vertical profiles	Pyrolysis T & functional groups
(Liu et al. 2024), China	Semi-arid millet	Rice-husk + digestate P	↓ synthetic P by 25%, cost ↓22%	Dual role: adsorbs P, slow-release	Integration into nutrient recovery system
(Sundha et al. 2025), India	Arid loam, < 200 mm	Wheat-straw, 4 t ha^{-1}	↑ microbial biomass 30–60%	Pores as microbial refugia	Low initial OM boosted microbial colonization
(Okebalama and Marschner 2024), W. Africa	Semi-arid	Local residues	↑ biomass, enzyme lag ~ 15–20%	Delayed enzyme activation under stress	Needs organic co-input for full cycling
(Ayaz et al. 2025), Pakistan	Maize system	Generic biochar	↓ N_2O emissions ~ 18%	Immobilizes N, shifts micro-fluxes	Supports climate mitigation aspect
(Yan et al. 2023), China	Saline-sodic soils	Wood, 6 t ha^{-1}	↓ ESP by ~ 20%, ↑ stability by 33%	Selective Na^+ adsorption maintains structure	Effective under moderate irrigation salinity
(Gao et al. 2024), meta + lab	Various arid soils	Sludge vs. wood	Sludge ↑ EC 10–20%, wood ↓ EC 5–25%	Ash/soluble ions dictate salinity outcome	Highlights need for feedstock QA/QC

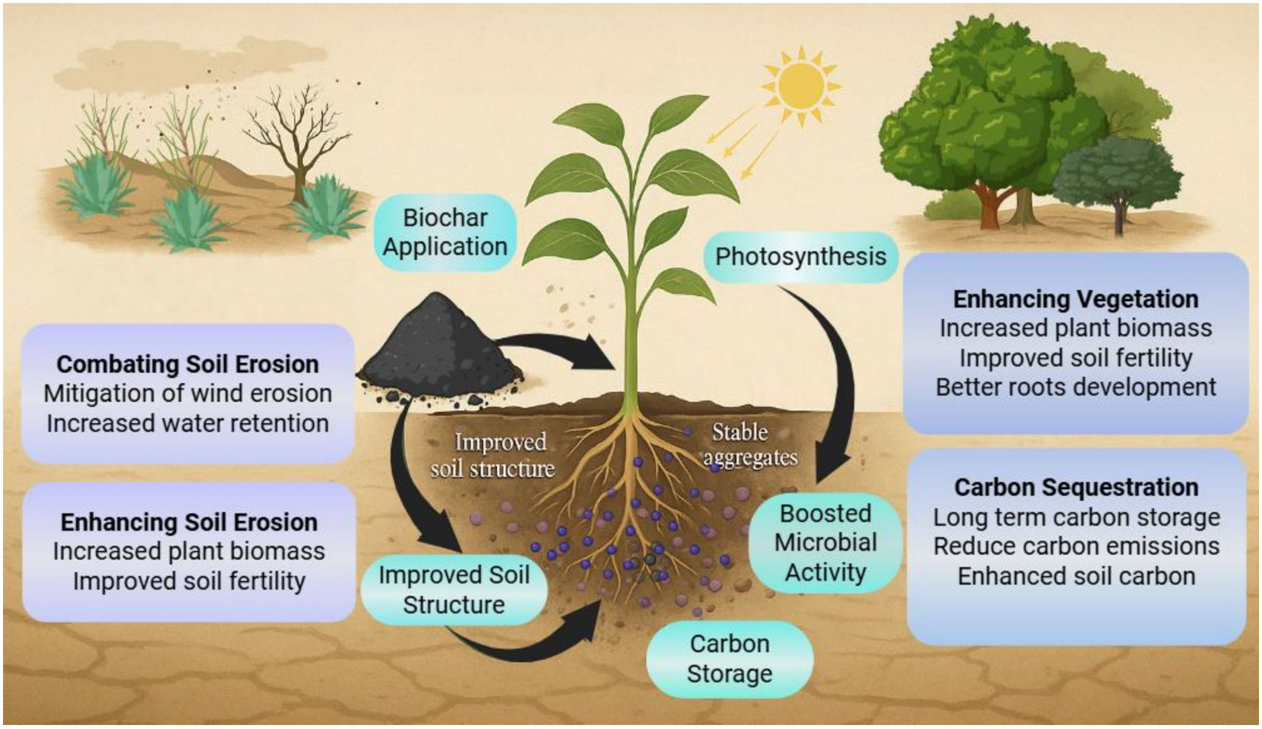


Fig. 3 Mechanisms by which biochar mitigates desertification in arid regions, including improved soil aggregation and surface stability reducing wind and water erosion, enhanced nutrient and water retention supporting vegetation establishment, and long-term carbon sequestration through stable aromatic structures

to the soil microbiome under biochar application extend beyond mere increases in microbial abundance, influencing broader enzymatic cycling and biogeochemical transformations (Parasar and Agarwala 2025). Recent findings from dual-inoculation approaches, where biochar is combined with plant growth-promoting rhizobacteria or mycorrhizal fungi, reveal synergistic outcomes that substantially surpass the effects of biochar alone on both microbial diversity and plant physiological performance (Phour and Sindhu 2024). Notably, the co-application of biochar with PO_4^{3-}-solubilizing bacteria resulted in a 55% increase in microbial respiration rates in arid Indian soils compared to sole biochar treatments, underscoring the role of biochar not merely as an amendment but as a functional matrix that promotes multi-microbial consortia establishment and activity (Malik et al. 2024). Enhanced habitat heterogeneity provided by biochar pores supports diverse bacterial and fungal assemblages that drive decomposition and mineralization processes in nutrient-poor arid soils.

3.4 Effects on soil pH and salinity

In salt-affected soils, biochar can decrease bulk EC through pore-mediated salt leaching and enhanced lateral water redistribution, lower ESP/SAR via Ca^{2+} exchange and Na^+ adsorption, and moderate rhizosphere osmotic stress through microhabitat and ion-transporter effects (Wu et al. 2025). These outcomes depend on feedstock ash and EC, surface functional groups, and co-amendments such as gypsum (Gao et al. 2024). Alkalinity and salinity frequently co-occur in arid soils, with pH often 7.5–9 and $EC > 4\ dS\ m^{-1}$. While biochar's alkaline pH (typically 8–10) can stabilize micro-fluctuations, longer trials reveal nuanced trajectories (Shi et al. 2021). Initial pH rises ($7.9 \rightarrow 8.5$) in saline-sodic soils with biochar, followed by multi-year stabilization to approximately 8.1 likely due to shifts in carbonate equilibria were reported, indicating that this transient overshoot could temporarily restrict micronutrient uptake (e.g., Fe, Zn) and thus warrants controlled application rates (De Vasconcelos 2020). Shifts in pH buffering capacity and selective ion adsorption mitigate alkalinity and sodicity stresses, maintaining ionic balance and fostering soil environments more conducive to plant and microbial function (Fig. 2). Meanwhile, biochar's selective Na^+ adsorption plays a pivotal role in mitigating sodicity, as wood biochar reduced ESP by approximately 20%, boosted aggregate stability by 33%, and maintained infiltration under saline irrigation (Tan et al. 2021). Biochar's selective Na^+ adsorption and impacts on rhizosphere ionic dynamics mitigate salinity stress, while pH buffering maintains conditions conducive to nutrient uptake and microbial activity (Fig. 2). Remarkably, metagenomic analyses further revealed that biochar altered rhizosphere genes linked to ion transporters, suggesting an indirect, microbiome-mediated enhancement of plant osmotic stress management (Ahmed et al. 2025).

3.4.1 Saline soils (high EC, normal ESP)

Saline soils are characterized by excessive concentrations of soluble salts, resulting in elevated electrical conductivity (EC) while maintaining a relatively normal exchangeable sodium percentage (ESP) (Admas et al. 2025). High osmotic potential reduces plant water uptake and suppresses microbial activity. Biochar application can mitigate these effects by increasing soil porosity, enhancing leaching of soluble salts, and providing microhabitats that alleviate osmotic stress (Murtaza et al. 2025). Meta-analyses indicate reductions of EC by 5–25% under biochar amendment, particularly when wood-derived or crop-residue biochars are used at moderate application rates (20–40 t ha^{-1}) (Schmidt et al. 2021; Wang et al. 2024). Moreover, neutral to slightly alkaline biochars with high surface area enhance Ca^{2+} and Mg^{2+} retention, thereby moderating Na^+ accumulation. Nevertheless, risk arises when using biochars derived from saline feedstocks or sewage sludge, which may introduce additional salts and increase EC (Schmidt et al. 2021). Thus, in saline soils, feedstock selection and pre-treatment are critical to avoid exacerbating salinity stress.

3.4.2 Sodic soils (high ESP/SAR)

Sodic soils, defined by excessive exchangeable sodium and high sodium adsorption ratio (SAR), exhibit poor structural stability, low infiltration, and surface crusting (Osman 2018). The mechanism of biochar action in sodic soils is primarily linked to ion exchange and structural restoration. Biochars rich in divalent cations (Ca^{2+}, Mg^{2+}) promote Na^+ displacement from exchange sites, lowering ESP and improving soil aggregation (Lin et al. 2024). Experimental evidence shows reductions of ESP by ~ 15–25% and increases in water-stable aggregates by 30–40% when biochar is combined with gypsum or lime (Sanga et al. 2024). Functional groups (–COOH, –OH) on biochar surfaces further enhance cation exchange and improve hydraulic conductivity. However, stand-alone applications of biochar in highly sodic soils may be insufficient, as exchangeable Na^+ often overwhelms natural amelioration processes (Liu et al. 2025). Consequently, synergistic strategies that combine biochar with gypsum, elemental sulfur, or organic manures are more effective, restoring structure and infiltration capacity while also supporting microbial recolonization.

3.4.3 Saline–sodic soils (high EC and high ESP)

Saline–sodic soils present the greatest challenge, as they combine the osmotic stress of high EC with the dispersive effects of high ESP (Zhang et al. 2025b). In such soils, biochar must simultaneously facilitate salt leaching and reduce exchangeable Na^+. Evidence from recent field trials shows that wood-derived biochars applied at 5–10 t ha^{-1} can lower ESP by 20% and increase structural stability by over 30%, especially when irrigation water quality is moderately improved (Zhang et al. 2025c). Mechanistically, the porous structure of biochar enhances infiltration and leaching of soluble salts, while Ca^{2+}-rich ash fractions contribute to Na^+ displacement (Lin et al. 2024). In addition, biochar–microbe interactions promote osmotic adjustment in plants, increasing root growth and stress tolerance. Nonetheless, the success of biochar in saline–sodic soils depends on careful integration with co-amendments such as gypsum or organic residues, as well as adequate drainage management (Chauhan et al. 2024). Without these complementary measures, improvements may be temporary or restricted to surface horizons.

4 Desertification control through biochar application

Desertification, the degradation of land in arid, semi-arid, and dry sub-humid areas due to climate variations and human activities, affects over two billion people worldwide (Malpede and Percoco 2025). The primary drivers of desertification are soil degradation, the loss of vegetation, and increased erosion, making sustainable land management strategies essential. As a result of its unique properties, biochar has emerged as an effective tool to combat desertification by improving soil structure, enhancing vegetation growth, and reducing carbon emissions (Solomon et al. 2024).

4.1 Combating soil erosion

In arid regions with sparse vegetation cover and loose soils, soil erosion by wind and water is a significant consequence of desertification (Alzahrani et al. 2024). In drylands, wind erosion is particularly prevalent, where strong winds can remove topsoil, resulting in nutrient loss, organic matter loss, and desert-like conditions. By improving soil aggregation and increasing soil stability, biochar can contribute to soil erosion mitigation (Islam et al. 2025). By promoting aggregate stability, increasing soil surface roughness, and reducing wind velocity near the ground, biochar substantially mitigates both wind and water erosion risks in degraded arid landscapes (Fig. 3). As a result of biochar's porous and granular structure, soil particles can bind together, forming more significant, more stable aggregates. Increased aggregation reduces soil erosion, especially in wind-prone areas, by preventing soil particles from detaching and transporting (Kayoumu et al. 2025). Adding biochar to sandy or degraded soils improves soil cohesion and minimizes water and air erosion risks. In addition to increasing soil surface roughness, biochar can decrease wind velocity near the ground, thus reducing the potential for wind erosion. In arid and semi-arid areas, it has been reported that biochar can reduce wind erosion by up to 30%, thereby reducing the movement of dust and sand particles, and maintaining soil health and reducing air pollution (Sharma et al. 2025; Wang et al. 2025c). Besides preventing topsoil erosion, biochar protects soil surfaces from dust storms, a common phenomenon in desertified areas. Moreover, biochar can retain water in the soil, enhancing its erosion-control effectiveness. Increasing soil moisture promotes better root development, stabilizing the soil and protecting it from wind and water erosion. In desertified areas, biochar provides a valuable tool for fighting soil erosion by improving soil structure, enhancing water retention, and increasing vegetation cover (Sharma 2024).

4.2 Enhancing vegetation growth

Restoring vegetation cover in degraded lands is one of the critical components of desertification control. Plants stabilize soil, reduce surface temperature, enhance water infiltration, and promote biodiversity by stabilizing the soil and reducing the surface temperature (Naskar et al. 2025). It is difficult to reestablish plant growth in desertified areas because of poor soil fertility and scarce water. Through its ability to improve soil fertility, water retention, and nutrient availability, biochar has been proven to be critical in supporting vegetation growth in such challenging environments (Waheed et al. 2025a).

In degraded and desertified lands, biochar amendments can significantly enhance plant growth. Research conducted in semi-arid regions of China has shown that biochar application increases grass species' biomass by 30–50% (Cen et al. 2021). It improves soil nutrient retention, optimizes N utilization, and boosts microbial populations, enhancing photosynthesis and carbohydrate production. Improvements in soil fertility, water-holding capacity, and nutrient availability associated with biochar amendments create favorable conditions for root proliferation and vegetative establishment under challenging desertified conditions (Fig. 3). These benefits help plants better withstand environmental stresses, promoting vegetative growth resilience and productivity even under water-limited conditions. Biochar amendments also increased crop yields and enhanced the establishment of native grasses for land restoration in degraded soils of sub-Saharan Africa (Faye et al. 2021). Desertified areas often benefit from cultivating native species that are drought-resistant and well-adapted to the harsh environment. By improving soil moisture retention and nutrient availability, biochar supports the establishment of these species. Biochar was used for desert restoration in the Negev desert of Israel to support the growth of *Acacia* species (Dzokom 2019; Kang et al. 2022). Optimizing photosynthetic performance, regulating cellular osmotic adjustments, and modulating antioxidant systems represent interconnected pathways through which biochar mediates plant adaptation to thermal and moisture stresses in dry environments (Fig. 3). Reforestation or afforestation projects in arid regions, where seedlings are often vulnerable to water stress and poor soil conditions, can also benefit from biochar. In desertified areas, biochar improves soil fertility and creates favorable conditions for plant roots (Wu et al. 2024b).

4.3 Carbon sequestration

A significant benefit of biochar for the environment is its ability to sequester carbon over the long term. Unlike organic matter, biochar is composed of highly stable carbon compounds resistant to microbial decomposition, allowing it to remain in the soil for hundreds to thousands of years (Ayaz et al. 2025). Biochar contributes to climate change mitigation by sequestering carbon, especially in arid and semi-arid regions where soil organic carbon levels are often low. Carbon stability in biochar is due to its aromatic structure, which resists microbial degradation. Incorporated into the soil, biochar acts as a stable carbon sink, keeping carbon in the soil for an extended period (Azim et al. 2024; Chen et al. 2024). Depending on the feedstock and pyrolysis conditions, biochar can sequester 50–70% of the carbon in the original biomass. The incorporation of biochar into arid soils contributes to long-term carbon stabilization while concurrently reducing greenhouse gas emissions from degraded lands, reinforcing its multifunctional role in combating desertification and climate change (Fig. 3).

The ability to store carbon is especially beneficial in arid areas, where soil carbon levels are naturally low, and traditional methods of storing organic carbon, such as composting, may not be as effective because organic matter decomposes rapidly at high temperatures and low moisture levels (Hernandez-Soriano et al. 2018). As well as sequestering carbon, biochar can mitigate climate change by reducing greenhouse gas emissions. The degradation and poor land management of arid soils often result in greenhouse gas emissions such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which contribute to global warming (Filonchyk et al. 2024). As a result of improving soil structure and nutrient retention, biochar reduces the need for chemical fertilizers, a significant source of N_2O emissions. By reducing soil erosion and enhancing vegetation cover, biochar can prevent soil degradation processes from releasing stored carbon into the atmosphere (Yang et al. 2020).

In desertified regions, large-scale biochar projects are needed to maximize the benefits of carbon sequestration and desertification control. Several initiatives have already integrated biochar into land restoration strategies, including Africa's "Great Green Wall" project and afforestation efforts in China's drylands (Liu et al. 2022; Smith et al. 2024). Besides restoring degraded lands, these projects also contribute to global efforts to offset carbon emissions by sequestering carbon in soils. As a result of the widespread adoption of biochar in land restoration projects, the global carbon sequestration effort could be enhanced while desertification could be combated simultaneously (Ascenzi et al. 2025).

5 Novel methods for biochar application in arid and semi-arid regions

Growing interest in sustainable land management and desertification control has spurred innovative biochar application strategies tailored to the harsh conditions of arid and semi-arid regions (Abdelhak 2022). Traditional broadcast or tillage incorporation methods often fail in these environments due to poor water and nutrient retention and high operational costs. Recent advances include subsurface banding, which in arid potato systems boosted soil water availability and yields by over 30%, and hydrochar combined with salt-tolerant microbes, doubling water retention and enhancing nutrient cycling (Mohanty et al. 2024; Mostafa et al. 2025). Additionally, layered biochar-mulch systems have reduced evaporation by 50%, increasing crop yields by up to 73% under severe drought (Canedo et al. 2025). Mobile, on-farm pyrolysis units using local residues further cut costs, improving the economic feasibility of precision biochar use in drylands. These emerging approaches collectively offer more effective, site-specific solutions to enhance soil resilience and support agricultural productivity in water-limited regions.

5.1 Precision biochar application

Precision agriculture technologies offer a transformative pathway to overcome the cost barriers of biochar by ensuring its targeted, efficient use. Using automated applicators and drone systems equipped with multispectral and thermal sensors, biochar can be applied exactly where soil organic matter, moisture content, or nutrient deficiencies are most acute (Khan and Babar 2024). (Pierson et al. 2024) demonstrated that precision placement can reduce total application rates by ~ 30% without compromising soil moisture gains, thereby directly improving the cost-effectiveness of biochar amendments.

As noted by Vochozka et al. (2016a), such precision approaches become even more essential given that broad-scale uniform applications often fail under the economic scrutiny. By concentrating investment only in the most degraded zones, these systems increase biochar profitability, aligning soil improvement with financial sustainability. Targeted delivery of biochar to microzones characterized by elevated root density and microbial turnover exploits spatial heterogeneity in soil hydraulic and chemical properties, optimizing amendment efficiency in arid landscapes (Fig. 4).

5.2 Biochar co-composting for nutrient-enriched soil amendments

A primary limitation hindering the widespread utilization of biochar as a soil amendment is its inherently low concentration of readily available macro- and micronutrients, which renders it insufficient to meet the demands of nutrient-deficient or degraded soils, particularly in arid and semi-arid regions (Bo et al. 2023). To overcome this constraint, substantial research has focused on the co-composting of biochar with organic waste materials. This strategy synergistically combines biochar's high surface area, porosity, and sorptive properties with the nutrient richness of compost, resulting in soil amendments that provide both immediate and sustained fertility benefits.

During the composting process, nutrients such as NH_4^+, NO_3^-, and PO_4^{3-} are physically adsorbed and chemically bound within the biochar's porous matrix, creating a nutrient-enriched biochar that acts as a slow-release fertilizer (Cui et al. 2025). For instance, Alarefee Ahmed et al. (2021) demonstrated that biochar co-composted with poultry manure increased the total N and available P content by 22% and 19%, respectively, compared to compost without biochar. Similarly, Naeem et al. (2024) reported that biochar-amended compost enhanced cation exchange capacity and nutrient retention, leading to a 15–30% improvement in maize biomass under water-limited conditions.

Recent investigations into the molecular ecology of these systems reveal that biochar surfaces provide microsites that selectively enrich denitrifying microbial taxa, thereby reducing N losses via N_2O emissions (Minofar et al. 2025). A study by Gao et al. (2023) employing metagenomic sequencing illustrated that co-composted biochar amendments reduced N_2O fluxes by approximately 35% relative to conventional compost, attributed to enhanced abundance of nosZ-harboring denitrifiers

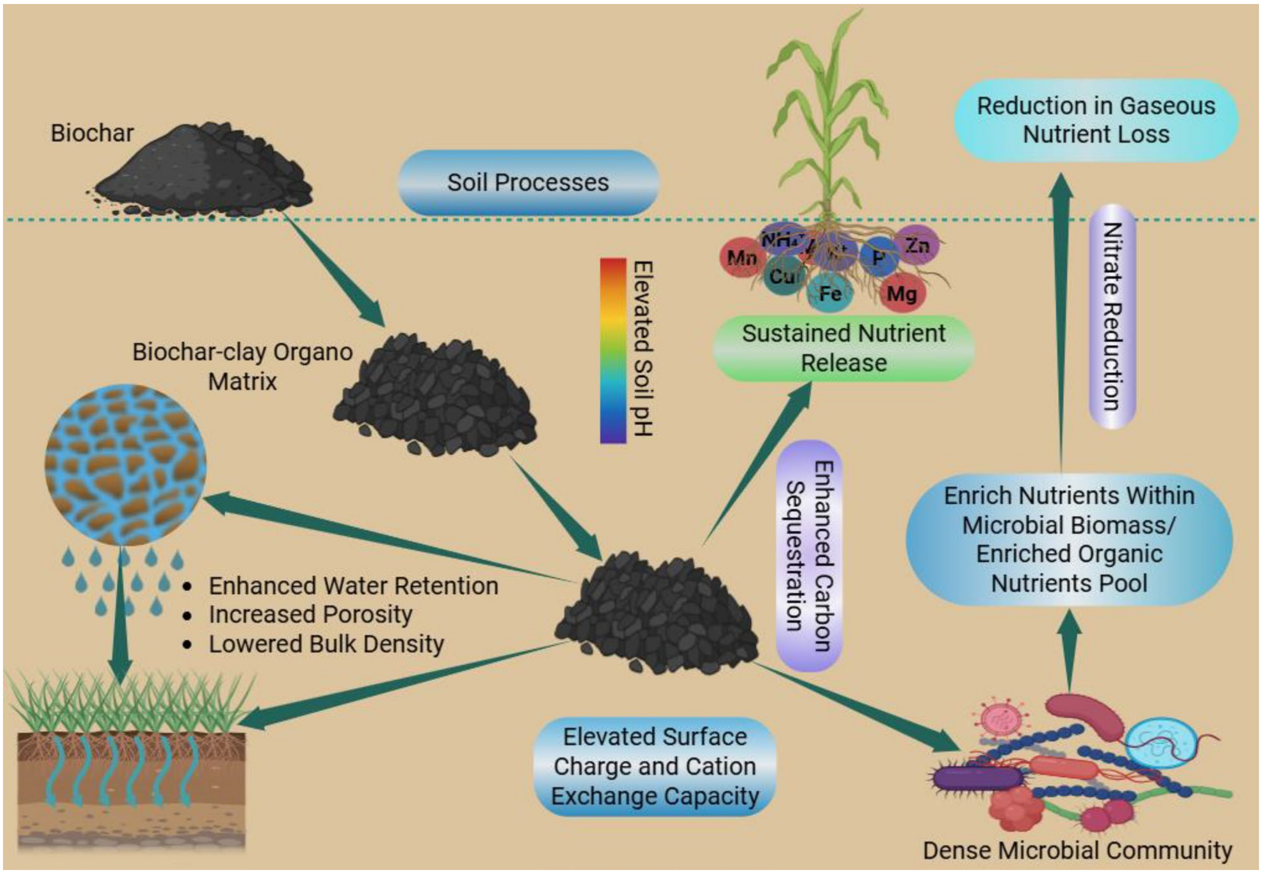


Fig. 4 Biochar influences soil processes by forming a biochar-clay organic matrix, which enhances water retention, increases porosity, and lowers bulk density. Adding biochar elevates soil pH and increases surface charge and cation exchange capacity, leading to sustained nutrient release and enhanced carbon sequestration. Biochar also supports the development of a dense microbial community, enriching the organic nutrient pool and microbial biomass. This microbial activity promotes NO_3^- reduction and reduces gaseous nutrient loss, further contributing to soil health and crop productivity

and improved soil redox conditions. Moreover, long-term field trials highlight the dual benefits of such amendments for carbon sequestration and soil organic carbon stabilization. For example, a five-year study by Adebayo et al. (2025) in semi-arid soils showed that biochar co-compost increased total soil organic carbon by 18% over standard compost applications, contributing significantly to the mitigation of atmospheric CO_2. Sustained carbon accrual and prolonged nutrient release from co-composted biochar systems outperform conventional organic amendments, supporting longer-term improvements in fertility management under moisture-limited conditions (Fig. 5).

5.3 Integration of biochar production with solar energy technologies

The high production costs of biochar remain a substantial barrier to its large-scale deployment, with fossil fuel-dependent pyrolysis systems accounting for a significant proportion of the final market price (Vochozka et al. 2016b). In arid and semi-arid regions characterized by abundant solar irradiance, coupling biochar production with renewable energy sources — particularly solar energy — represents a compelling pathway to enhance economic and environmental sustainability.

Recent advances in solar thermal engineering have demonstrated that concentrated solar energy systems can reliably achieve the temperatures required for biomass pyrolysis, typically in the range of 400–600 °C. Ullah et al. (2025) reported that a parabolic trough solar reactor efficiently converted agricultural residues into biochar, achieving energy yields comparable to conventional pyrolysis while virtually eliminating external fossil energy inputs. Similarly, Calise et al. (2022) optimized a solar-driven pyrolysis system using Fresnel lenses, reducing the specific energy demand by 45% relative to traditional gas-fired processes.

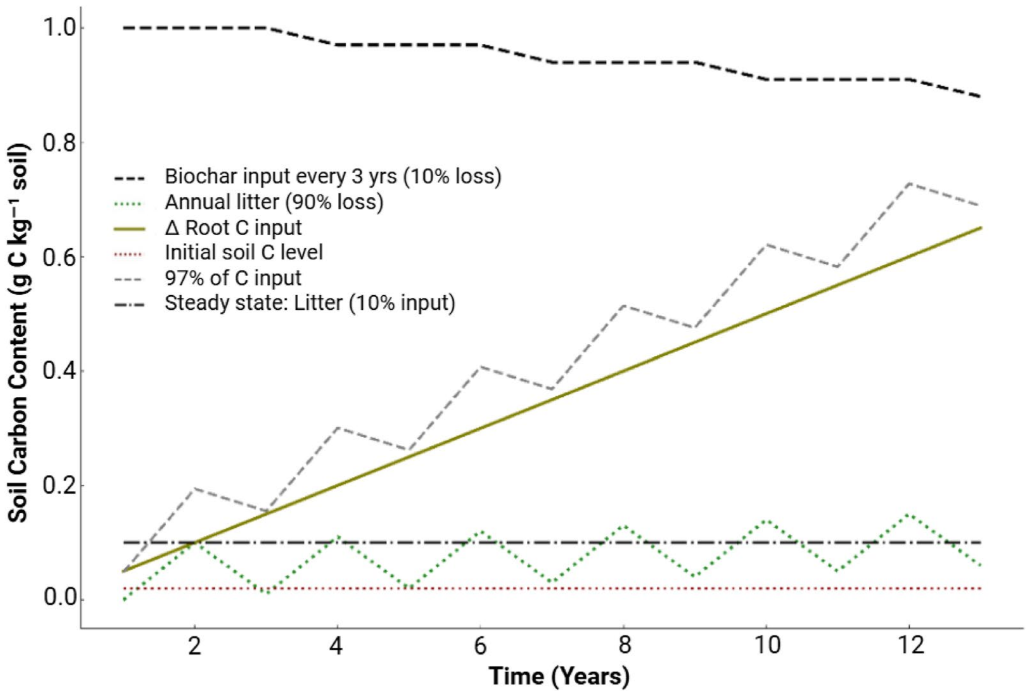


Fig. 5 Soil carbon content trajectories under sequential inputs from biochar, litter, and root biomass. The black dashed line indicates biochar additions applied triennially, undergoing a 10% decomposition rate, resulting in characteristic stepwise plateaus and subsequent gradual declines. The green dotted line reflects annual inputs of rapidly decomposing organic residues (litter, manure, compost) with a 90% turnover, approaching a steady state at approximately 10% of carbon input. A continuous linear accumulation of root-derived carbon is represented by the olive solid line. The brown dotted line denotes the initial baseline soil carbon content, while the grey dashed line delineates the cumulative retention at 97% of combined inputs, signifying near-steady-state equilibrium under these simulated dynamics

Decentralized applications of this technology have shown particular promise in remote or resource-limited settings. (Subbiah et al. 2025) developed a modular solar pyrolysis unit capable of processing on-farm crop residues directly at the point of generation. Lifecycle assessments indicated a reduction in greenhouse gas emissions exceeding 50% compared to diesel-based systems, alongside significant cost savings by avoiding the transportation of bulky, low-density biomass. Furthermore, this decentralized model fosters local circular economies by enabling farmers to valorize agricultural waste into high-value biochar, thus lowering the economic barriers to adoption and promoting entrepreneurship aligned with sustainable development goals (Smith 2025).

Integration of biochar production with solar energy systems not only addresses the pressing need to decarbonize the biochar supply chain but also provides a scalable, site-adapted solution particularly well-suited to sun-rich dryland regions (Zhou et al. 2025). This approach enhances the financial feasibility of biochar use in soil restoration and carbon sequestration programs, contributing simultaneously to climate mitigation and rural economic resilience. Renewable energy-driven pyrolysis, when aligned with local feedstock logistics, reduces operational costs and advances the feasibility of decentralized biochar production systems in energy-scarce arid regions (Fig. 6).

5.4 Biochar-infused irrigation systems for enhancing water and nutrient use efficiency

The incorporation of biochar into irrigation systems represents an emerging strategy to simultaneously improve water-use efficiency and nutrient management in arid and semi-arid agricultural landscapes (Alharbi et al. 2024). By integrating finely milled biochar into drip or micro-sprinkler irrigation delivery, it is possible to directly target the rhizosphere with biochar–water slurries, thereby aligning nutrient and moisture availability with crop uptake dynamics. This approach optimizes the synchrony between localized root absorption zones and micro-environmental distributions of both water and nutrients, advancing the principles of precision agriculture in resource-limited settings.

The porous architecture and high specific surface area of biochar facilitate substantial water retention within the soil matrix, enabling gradual release and extended availability in the root zone. Alfadil et al. (2021) demonstrated that soils amended with biochar exhibited a 20–30%

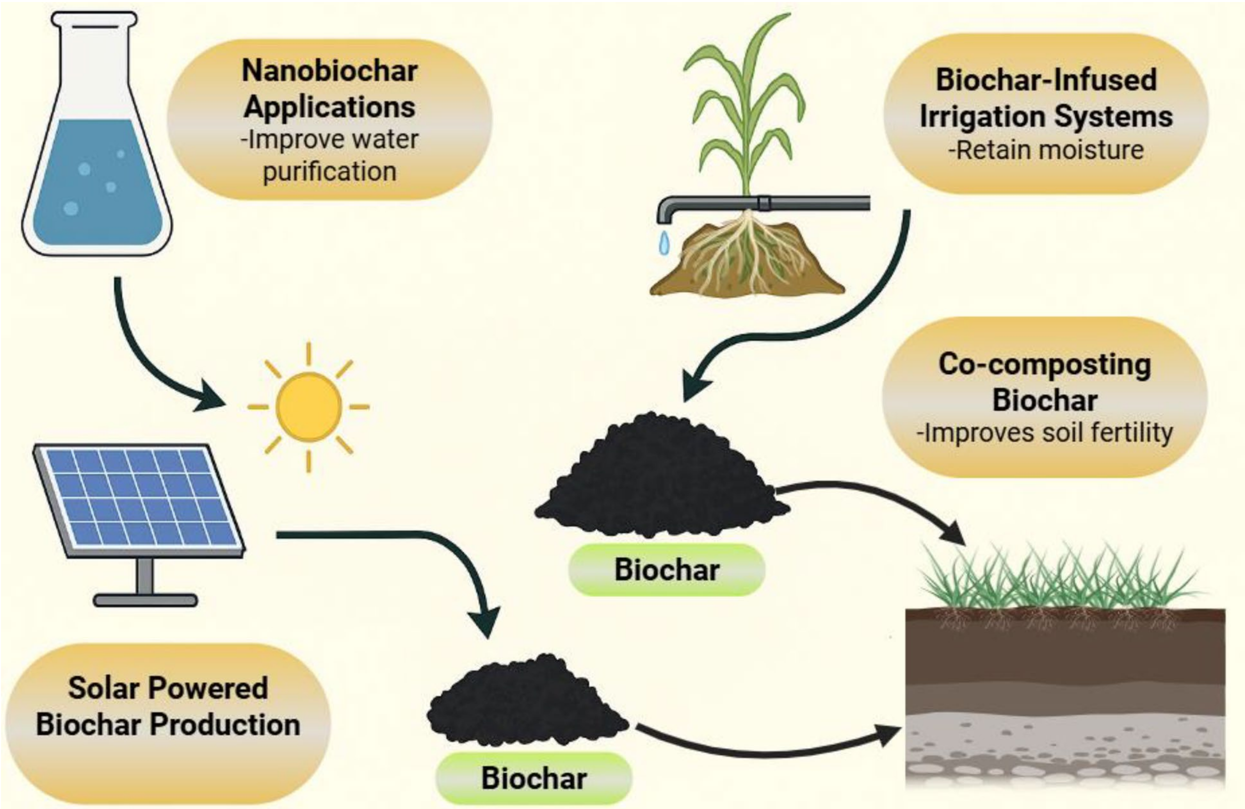


Fig. 6 Biochar application strategies tailored for arid regions. The diagram illustrates four innovative approaches to enhance sustainability and resource efficiency in dryland environments: (1) Nanobiochar applications improve water purification capabilities; (2) Biochar-infused irrigation systems enhance water-use efficiency by retaining moisture; (3) Co-composting biochar improves soil fertility through basic nutrient enrichment; and (4) Solar-powered biochar production incorporates renewable energy sources into biochar synthesis, though current methods remain inefficient. Each strategy addresses specific environmental challenges associated with arid ecosystems

increase in plant-available water capacity, effectively reducing irrigation frequency under water-deficit conditions. More recently, Ahmed et al. (2024a) highlighted that biochar-infused drip systems improved maize water productivity by 18%, attributable to reduced percolation losses and enhanced moisture conservation.

Beyond hydrological benefits, biochar's capacity to adsorb and slowly release macro- and micronutrients mitigates leaching and promotes sustained nutrient availability. Li et al. (2021) reported that biochar co-applied through fertigation systems decreased NO_3^- leaching by approximately 28% while improving N-use efficiency. Similarly, Schmidt et al. (2017) showed that biochar-enriched irrigation reduced potassium (K) and P runoff in vegetable cropping systems by up to 35%, underscoring its potential to safeguard limited soil fertility in drylands.

5.5 Hybrid Biochar-mulching techniques for enhanced soil moisture conservation and resilience

In arid and semi-arid agroecosystems, mulching is a widely adopted practice to suppress soil evaporation, buffer soil temperatures, and improve microclimatic conditions conducive to crop establishment and productivity (Yin et al. 2016). Recent advancements have explored hybrid biochar–mulching systems, which integrate the high water-holding and sorption capacities of biochar with the protective benefits of surface mulches, offering a synergistic solution to the multifaceted challenges of dryland farming (Das et al. 2024; Canedo et al. 2025).

This approach typically involves applying biochar either to the soil surface or lightly incorporating it into the upper soil layer, followed by the addition of an organic mulch such as straw, wood chips, or in some cases even biodegradable plastic films. Such combined strategies simultaneously enhance near-surface water retention and reduce direct soil moisture loss by limiting exposure to wind and solar radiation. For instance, Li et al. (2025) demonstrated that integrating biochar with rice straw mulch reduced cumulative evaporation by 28% compared to mulching alone, while also lowering peak soil temperatures by up to 4 °C under semi-arid conditions (Fig. 6).

Emerging studies have further extended this concept to multifunctional systems. Prats et al. (2021) reported that hybrid biochar-mulching not only moderated soil thermal regimes and improved water availability but also reduced the bioavailability of heavy metals in degraded soils, thus offering a holistic approach to land restoration. Similarly, novel combinations with nanoscale biochar composites or hydrogels have been shown to enhance the retention of both water and labile nutrients, providing a controlled release mechanism well-suited for moisture- and nutrient-stressed environments (Lu et al. 2020). Importantly, in severely desertified regions, the cumulative addition of organic matter from decomposing mulches further improves soil structure and nutrient cycling over time, amplifying the long-term fertility benefits initiated by biochar application. This makes hybrid biochar–mulching particularly valuable for ecological rehabilitation initiatives such as reforestation or pasture regeneration in hyper-arid landscapes.

5.6 Nanobiochar applications

Nanobiochar, produced by engineering biochar particles to the nanoscale (typically < 100 nm), represents a novel advancement that significantly amplifies the adsorption, catalytic, and reactive properties of traditional biochar (Fig. 6). This enhancement is principally attributed to the dramatic increase in specific surface area and the exposure of functional groups on nanobiochar surfaces, which collectively elevate its capacity to immobilize a wide range of contaminants (Sani et al. 2023).

Recent studies have demonstrated that nanobiochar exhibits superior affinity for heavy metals, persistent organic pollutants, and pesticide residues in both soil and aqueous environments (Moulick et al. 2025; Waheed et al. 2025b). For instance, Sani et al. (2023) reported that nanobiochar derived from oil palm biomass achieved removal efficiencies exceeding 90% for cadmium and lead in contaminated water systems, substantially outperforming bulk biochar counterparts.

In arid and desertified regions, where water resources are not only scarce but frequently compromised by salinity or anthropogenic contaminants, the integration of nanobiochar into water purification systems offers a promising intervention. Shiade et al. (2025) showcased the application of nanobiochar-modified sand filters, which effectively reduced electrical conductivity and removed NO_3^- and arsenic from saline groundwater used for irrigation, thereby improving water suitability for both agricultural and domestic use. While promising, nanobiochar applications in dryland field conditions remain largely experimental, requiring further long-term studies to establish agronomic benefits and environmental safety.

Beyond water treatment, the exceptionally small particle size of nanobiochar facilitates its deeper penetration into soil matrices. This characteristic enables it to amend Subsoil horizons, improving aggregate stability and enhancing nutrient and water retention even under low-moisture conditions. Gill et al. (2024) found that incorporating nanobiochar into saline-sodic soils reduced exchangeable sodium percentage by 18% and increased wheat biomass by 27%, illustrating its role in ameliorating soil structure and fertility in degraded dryland systems. Moreover, the high density of reactive sites on nanobiochar enables the adsorption of phytotoxic ions and organic toxins, thus contributing to the reclamation of marginal lands for agriculture and ecological restoration projects.

6 Case studies and recent advances

Biochar has gained considerable attention in recent years as a tool for improving soil fertility, controlling erosion, and mitigating desertification, particularly in arid and semi-arid regions. Multiple studies from diverse geographical contexts have demonstrated its potential to address land degradation challenges and enhance sustainable agricultural practices (Barbier and Hochard 2018; Smith et al. 2020). The following sections provide insights into specific case studies across different regions.

6.1 North Africa

The Sahara and Sahel regions of North Africa are among the most vulnerable to desertification, primarily due to extreme climatic conditions, low annual precipitation, and human activities such as overgrazing and deforestation (Ibrahim et al. 2022). These factors have led to substantial soil degradation, reduced agricultural productivity, and displacement of local communities. Biochar has emerged as a promising solution to combat desertification and enhance soil health in these areas (Gwenzi et al. 2015).

Recent studies in the Sahel have focused on using biochar derived from agricultural residues, such as crop waste and desert shrubs, to restore degraded soils. For instance, biochar has been applied to smallholder farms in Burkina Faso and Niger, leading to significant improvements in soil organic matter, water retention, and crop yields. Farmers in drought-prone regions have reported increases in millet and sorghum yields by up to 50% after the application of biochar (Abdelhak 2022). Additionally, biochar has been shown to improve the efficiency of water use in these regions, particularly for crops like millet, which are highly sensitive to water stress (Naseri-Minabi et al. 2025).

In the Sahara, biochar has been instrumental in dune stabilization and the prevention of wind erosion. By enhancing soil aggregation and increasing vegetation cover, biochar helps reduce soil erosion and the movement of desert sands, thus safeguarding nearby agricultural lands and settlements (Sharma et al. 2025). Moreover, the carbon sequestration potential of biochar is considered a long-term benefit for both land restoration and climate change mitigation. Despite its potential, the widespread adoption of biochar in North Africa faces challenges, including the high cost of production and limited biomass feedstock availability (Yin et al. 2022).

6.2 Central Asia

Soil erosion, salinity, and declining soil fertility are pressing challenges in Central Asia, particularly in Kazakhstan and Uzbekistan. These issues are exacerbated by the overexploitation of water resources from the Aral Sea, inefficient irrigation practices, and intensive agricultural activities (Qadir et al. 2009). Biochar has been identified as a potential solution for addressing these soil-related problems and improving agricultural productivity in the region (Shackley et al. 2010).

In Kazakhstan, biochar derived from agricultural waste such as wheat straw and livestock manure has been applied to degraded soils to improve nutrient retention and reduce salinity (Doszhanova et al. 2025). Recent studies have shown that biochar amendments lead to increased soil organic matter, enhanced soil structure, and improved nutrient availability, particularly for N and P (Hasan et al. 2024; Song et al. 2025). Additionally, biochar has been effective in reducing soil salinity and buffering soil pH, which is critical for restoring saline soils that have been subjected to decades of over-irrigation (Fernandez-Bou et al. 2025).

In Uzbekistan, biochar is used alongside conservation agriculture practices, including minimal tillage and mulching, to mitigate wind and water erosion (Doszhanova et al. 2025). Studies have demonstrated that biochar improves soil aggregation, reduces soil compaction, and enhances water infiltration, all of which are crucial for preventing soil erosion in semi-arid regions (Peter 2018; Imran 2025). Furthermore, biochar application has been linked to significant increases in crop productivity particularly for staple crops such as wheat and cotton ranging from 20% to 40% (Qayyum et al. 2020). Despite the promising results, challenges in biomass availability and the scalability of biochar production in rural areas remain significant obstacles to its broader application (Pierson et al. 2024).

6.3 Australian outback

The Australian Outback, characterized by its arid climate, low rainfall, and nutrient-poor soils, presents one of the most challenging agricultural environments (Dadzie et al. 2023). Dryland farming in this region is highly susceptible to land degradation, soil erosion, and declining productivity. Biochar, as a sustainable soil amendment, has shown potential in improving soil health and water retention under these harsh conditions (Yan et al. 2024).

Biochar produced from local biomass, such as eucalyptus wood and agricultural waste, has been applied to dryland farms across the Outback. Studies indicate that biochar significantly improves the water-holding capacity of soils, with observed increases in crop yields of 20–35%, particularly for crops such as wheat and barley, even under drought conditions (Larsen et al. 2024; Rahman et al. 2025). The improvement in soil organic carbon levels and nutrient cycling, particularly N and K, has helped reduce the reliance on chemical fertilizers, promoting more sustainable farming practices (Nandwa 2001).

In addition to supporting crop production, biochar has been used to enhance pasture quality and control soil erosion in the Outback. By improving soil aggregation and stabilizing surface soils, biochar helps prevent wind and water erosion, which is particularly important in areas heavily grazed by livestock. This has contributed to the restoration of degraded pastoral lands and the maintenance of biodiversity in arid rangelands (Sharma 2024). While biochar has shown promise in these applications, the high cost of production and limited biomass availability in remote areas remain barriers to its widespread adoption (Gwenzi et al. 2015).

7 Challenges and limitations

Biochar shows substantial promise for improving soil fertility, enhancing water retention, and mitigating land degradation in arid and semi-arid regions. However, as highlighted in Table 1, a range of technical, logistical, and economic barriers must still be addressed to enable its broader implementation.

7.1 Economic and logistical constraints in biochar deployment and emerging solutions

A key challenge for large-scale biochar deployment is the substantial cost associated with its production and transportation, particularly due to the energy-intensive pyrolysis processes required to produce stable, high-quality biochar (Su et al. 2024). Although innovations such as mobile and solar-powered pyrolysis units have emerged, achieving consistent, scalable biochar production in remote or marginal areas remains economically unfeasible (Caputo and Mašek 2021). Additionally, the low bulk density of biochar compounds this issue by increasing its volume-to-mass ratio, which escalates transportation costs an especially prohibitive factor in sparsely populated, infrastructure-poor drylands (Tardy et al. 2023).

Economic assessments suggest that conventional biochar initiatives often fail to meet economic viability thresholds unless higher-value co-products or on-site production strategies utilizing locally sourced biomass are incorporated (Zilberman et al. 2023). Decentralized, modular, or solar-powered systems could mitigate some of these issues by reducing the need for long-distance transportation and leveraging locally available energy resources. This approach can align biochar production economics more closely with the ecological needs of marginal landscapes (Fig. 6).

Recent studies on digital twin technologies and industrial metaverse platforms have demonstrated their potential to simulate production cost structures, optimize logistical configurations, and reduce investment risk through virtual testing of region-specific scenarios (Nagy et al. 2025; Singh 2025). These platforms allow stakeholders to evaluate the feasibility of biochar projects comprehensively, from feedstock logistics to the anticipated improvements in soil functionality. By combining localized production strategies with advanced digital modeling, this approach can effectively overcome many of the economic and logistical challenges of biochar deployment, enabling more resilient land management in severely degraded regions.

7.2 Regional suitability of biomass sources and evolving regulatory frameworks

The selection of biomass feedstock is crucial in determining the quality and agronomic effectiveness of biochar. In arid and semi-arid regions, limited vegetation cover restricts the availability of biomass, necessitating reliance on locally abundant sources such as native woody shrubs, invasive species like *Prosopis juliflora* and *Acacia tortilis*, or region-specific agricultural residues (Tardy et al. 2023). Recent research underscores the significant influence of feedstock type on key biochar attributes, such as nutrient content, surface chemistry, pH, and water-holding capacity, which directly affect soil amendment outcomes. For example, Azim et al. (2024) found that biochar derived from *Prosopis* biomass exhibited a higher cation exchange capacity and improved moisture retention compared to cereal straw-derived biochar, which enhanced wheat yield stability under saline soil conditions.

The compatibility of regional biomass streams with long-term carbon stabilization and nutrient management goals is essential for tailoring biochar strategies to specific ecological contexts. Lv et al. (2025) demonstrated that biochars produced from high-lignin biomass sources offer greater carbon persistence in soils, thus supporting climate mitigation objectives while enhancing soil physical properties. Furthermore, evolving regulatory frameworks are shaping the biochar landscape, particularly in Europe and North America. Policies are increasingly mandating the prioritization of nutrient recovery from biowaste streams before pyrolysis, aimed at closing nutrient cycles and reducing dependence on mined fertilizers. For instance, under the European Union's Circular Economy Action Plan, guidelines incentivize pre-treatment processes such as composting or digestate extraction prior to biochar production ((Bürgin 2023). This regulatory shift necessitates more complex, multi-component processing systems, which can alter the economic and logistical dimensions of biochar deployment. Oldfield et al. (2018) highlighted that coupled compost–biochar systems not only comply with regulatory requirements but also produce amendments with superior N retention and reduced greenhouse gas emissions compared to standalone biochar applications. Incorporating feedstock and regulatory considerations into biochar planning ensures the technical robustness and economic viability of biochar projects, aligning them with soil restoration goals and evolving policy landscapes.

7.3 Long-term stability and aging dynamics of biochar in soils

Biochar's persistence in soils has been extensively documented, with archaeological studies frequently recovering charcoal fragments that have remained intact for thousands of years (Mašek et al. 2024). However, contemporary research increasingly focuses on understanding the evolution of biochar's physical pore architecture and nutrient exchange capacity under specific environmental conditions, especially in arid systems. These properties are critical for determining its continued efficacy in improving soil water retention and supporting plant–soil interactions.

In arid environments, biochar's pore networks are prone to occlusion by fine soil particles and mineral precipitates, which can significantly reduce its water-holding capacity over time through repeated wetting and drying cycles (Yang et al. 2025). Although biochar is resistant to microbial decomposition, oxidative processes on its surface can alter its functional groups and surface charge, modifying its cation exchange capacity and overall sorptive behavior (Fan et al. 2018). These changes impact the retention and availability of essential nutrients, affecting long-term soil fertility.

Field studies underscore the importance of evaluating these dynamics under realistic environmental conditions. For instance, Cen et al. (2021) reported that after four years in semi-arid soils, biochar exhibited measurable shifts in surface chemistry and a decline in micropore volume, which corresponded to changes in moisture availability and crop growth patterns. The divergent stabilization pathways of organic matter and nutrient pools in biochar-amended soils across different soil-climate contexts further emphasize the necessity of conducting long-term, site-specific investigations to ensure the sustained functionality of biochar in arid landscapes.

7.4 Leveraging AI and CSR models for local-scale biochar planning

Advances in artificial intelligence (AI) and industrial digital twin technologies have introduced sophisticated capabilities for evaluating and optimizing biochar systems under real-world operational and economic constraints (Ali et al. 2024). Three-dimensional digital twin factories and cyber-physical production systems now facilitate comprehensive simulations of biochar supply chains, covering feedstock procurement, pyrolysis processing, transportation logistics, and field application under various economic scenarios. These platforms allow for in-depth assessments of how variations in parameters such as pyrolysis temperature, modular versus centralized processing, and transportation distances affect system costs, greenhouse gas emissions, and anticipated soil health outcomes, thereby reducing investment risks (Ghahramanieisalou and Sattarvand 2024). Furthermore, immersive extended reality systems and multi-sensory digital twins enhance these capabilities by modeling site-specific impacts of biochar interventions on soil water retention, N dynamics, and long-term carbon sequestration across multiple growing seasons. The integration of digital twin predictive analytics with diverse technological pathways positions biochar systems as integral components of next-generation land restoration frameworks, combining economic viability with climate resilience (Fig. 6).

Additionally, the inclusion of corporate social responsibility (CSR) and environmental, social, and governance (ESG) models in AI-driven frameworks is gaining traction (Rane et al. 2024). These data-centric models help quantify the contributions of localized biochar projects to employment generation, nutrient cycling efficiency, and carbon offset markets, effectively transforming sustainability metrics into measurable economic co-benefits. Recent studies have demonstrated that integrating biochar systems with regional nutrient recovery initiatives can simultaneously improve return on investment and support broader community development goals (Mohammed et al. 2024; Mbugua et al. 2025). By combining predictive digital simulations with rigorous socio-economic assessments, these approaches ensure that biochar initiatives are optimized for technical, environmental, and socio-economic outcomes, aligning with regional economic and social priorities.

8 Future perspectives and research gaps

Future research on biochar in arid and semi-arid regions must address several critical gaps to maximize its potential benefits. Long-term impact studies are essential to evaluate the sustained effects of biochar on soil health, crop productivity, and ecosystem services. In arid and semi-arid regions, biochar has been proven to enhance soil fertility, control desertification, and mitigate climate change effects (Abd El-Mageed et al. 2021). There are, however, many opportunities for improving biochar technology, understanding its long-term impact, and promoting its widespread adoption. Additionally, there is a need for the development of advanced pyrolysis technologies that are energy-efficient and capable of producing biochar at lower temperatures and optimizing its properties for specific soil types and climatic conditions. Exploring a wider variety of biomass feedstocks, including agricultural residues and invasive species, will help researchers understand their effects on biochar's characteristics and benefits. Investigating the synergistic effects of combining biochar with other soil amendments, such as compost and fertilizers, can enhance nutrient availability and improve soil quality.

8.1 Emerging biochar technologies

Biochar production innovations are essential to overcoming challenges related to cost, scalability, and environmental sustainability. In arid regions, emerging biochar technologies aim to enhance the efficiency and eco-friendliness of production processes while making biochar more widely available (Ahmed et al. 2024b). In remote or resource-scarce areas, biochar application is limited by the high cost and complexity of transporting biochar from production sites to end users. Biochar can be produced on-site using mobile pyrolysis units using locally available biomass. A portable unit can be transported to farms or reforestation projects, allowing decentralized biochar production (Sahoo et al. 2021). As biomass resources are dispersed and transportation infrastructure is limited in arid regions, mobile pyrolysis technologies are beneficial. By reducing the need for long-distance transportation and lowering overall costs, these units can process a variety of feedstocks, such as agricultural residues, desert shrubs, and invasive plants (Lin et al. 2016).

Thermal pyrolysis is a traditional method of producing biochar, which produces harmful emissions if not appropriately managed. Environmentally friendly biochar production systems aim to reduce the environmental impact of biochar production. By incorporating gas capture technologies into pyrolysis systems, emissions such as syngas can be captured and repurposed, making the pyrolysis process more energy-efficient and sustainable (Dunnigan et al. 2018). A solar-powered pyrolysis system, particularly well-suited for sun-abundant arid regions, provides a low-emission, renewable energy solution for biochar production. Composites of biochar and functionalized biochar are also being researched to improve biochar's performance in arid soils by combining it with compost, minerals, and fertilizers (Wang et al. 2022). As another innovation, functionalized biochar with specific chemical properties can help improve biochar's performance in degraded soils with low nutrient levels. Emerging technologies are critical to scaling up biochar production and enhancing its effectiveness in arid regions. To improve the accessibility and affordability of these technologies for small-scale farmers and local communities, continued research and development are needed.

8.2 Biochar in climate-resilient agriculture

Due to climate change, drought, extreme weather events, and soil degradation are becoming increasingly prevalent in arid and semi-arid regions. With its ability to enhance soil health, increase water-use efficiency, and improve crop yields under climate stress, biochar has the potential to play a vital role in climate-resilient agriculture (Sarma et al. 2024). Biochar can potentially mitigate the effects of drought by improving soil water retention. Using biochar in arid regions can help conserve soil moisture and reduce irrigation requirements, making agricultural systems more drought-resistant. During dry periods, biochar-amended soils can retain up to 50% more water than untreated soils, which can be vital for crop growth. As a result of climate change, biochar helps farmers adapt to increasingly erratic rainfall patterns (Kumar et al. 2022). Additionally, biochar increases nutrient availability and reduces the need for chemical fertilizers, contributing to more sustainable agricultural practices. With a high CEC, biochar can retain nutrients like nitrogen (N), P, and K, reducing nutrient leaching and increasing nutrient uptake (Šimanský et al. 2018). Especially in nutrient-poor soils, traditional farming practices can deplete soils and decrease crop productivity. In regions facing climate change and land degradation, biochar can contribute to food security by promoting sustainable soil management practices. A valuable tool for mitigating climate change is biochar's ability to sequester soil carbon. In addition to reducing atmospheric CO_2 levels, biochar can help offset greenhouse gas emissions by converting biomass into stable carbon (Smith et al. 2020). As well as improving soil health, biochar contributes to long-term climate change mitigation by locking carbon into the soil. In arid and semi-arid regions, biochar is a key component of sustainable land management strategies because of its co-benefits of crop productivity enhancement, improved water retention, and carbon sequestration (Srinivasarao et al. 2023).

8.3 Need for policy and incentives

Biochar's widespread adoption faces several barriers, including high production costs, limited infrastructure, and a lack of awareness among farmers and policymakers. As a tool for sustainable land management and desertification control, biochar needs support policies and incentives to overcome these challenges (Sharma et al. 2025). Governments and international organizations can play a crucial role in promoting biochar adoption by providing subsidies and financial incentives for biochar production and application. In low-resource settings, subsidies for purchasing biochar or biochar-producing equipment, such as mobile pyrolysis units, can reduce the initial costs for farmers and land managers. Carbon offset programs that recognize biochar's potential for carbon sequestration can also provide financial rewards to farmers and landowners who use biochar to improve soil health (Elias et al. 2024).

Continued research funding is essential to further explore biochar's long-term effects in arid and semi-arid regions, optimize biochar production methods, and identify biomass sources specific to the region. Governments and international bodies should prioritize funding for biochar research, especially in desertification-prone areas (Azim et al. 2024). The development of innovative biochar technologies and applications can be accelerated by collaborating with research institutions, private companies, and local communities. Integrating biochar into national and regional land management policies can help scale up its use to combat desertification and restore degraded lands. Biochar should be included in policies that promote sustainable land management practices, including agroforestry, reforestation, and soil conservation (Thengane et al. 2021). Furthermore, biochar should be integrated into global initiatives such as the United Nations Convention to Combat Desertification (UNCCD) and the Great Green Wall initiative in Africa, which aim to restore degraded lands and improve food security in arid regions (Sileshi et al. 2023). Educating farmers, land managers, and policymakers about biochar's benefits is essential to its widespread adoption. By providing farmers with training and education, they can produce and apply biochar effectively. Additionally, demonstration projects and field trials can demonstrate how biochar can improve soil fertility, water retention, and crop yields, encouraging more farmers to adopt biochar.

9 Conclusion

This comprehensive review partially validates the hypothesis that biochar can be an effective, scalable, and economically viable strategy for enhancing soil functions and mitigating land degradation in arid and semi-arid regions. The synthesis of multi-regional evidence highlights that biochar's functional versatility goes beyond incremental improvements; it fundamentally transforms dryland soil management by integrating hydrological regulation, nutrient buffering, microbial habitat enhancement, and long-term carbon sequestration into a unified amendment system. This review also emphasizes that the true industrial potential of biochar in arid environments lies not only in its traditional role as a passive soil amendment but in its integration with digital agriculture, advanced nutrient recovery, precision delivery systems, and renewable-energy-driven production methods. These innovations reposition biochar from a marginally economical, environmentally appealing input to a multifunctional agent within circular economies. The molecular-scale insights into N transformation dynamics and the techno-economic modeling made possible by AI-driven digital twin simulations provide a robust foundation for the future of biochar technologies. While case studies and field trials show substantial ecological and agronomic benefits, significant challenges remain in industrial deployment. The capital-intensive nature of high-quality biochar production and the reliance on multi-stream value capture such as reduced fertilizer requirements, carbon credit generation, and water-use efficiency remain key economic barriers. Furthermore, the growing regulatory emphasis in many developed economies to prioritize nutrient recovery from biowastes before pyrolysis marks a paradigm shift. Biochar systems are increasingly being integrated with waste valorization and precision nutrient recycling frameworks, enhancing their economic viability. This evolution underscores the complexity of biochar beyond its role as a simple soil amendment, positioning it as a data-driven, multi-sectoral technology with significant promise for land rehabilitation in arid regions, particularly when deployed through advanced, economically optimized systems. By linking molecular microbial interactions with digital metaverse-scale techno-economic projections, this review broadens the scope of biochar research. It lays the groundwork for future interdisciplinary industrial ecosystems that can leverage biochar not only for soil restoration but also to reconfigure agri-environmental production networks in an increasingly water- and nutrient-constrained global landscape.

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Data availability
No new data were generated or analyzed in this study. All information is derived from previously published sources cited in the article; therefore, data sharing is not applicable.

Declarations

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

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