Emirati Journal of Civil Engineering and Applications
Vol 4 Issue 1 (2026)
Pages 45 - 59
Available at
www.emiratesscholar.com

Desert Soil Ecology, Biochar, and Mycorrhiza for Sustainable Agroforestry in Arid Regions - Agroeconomics

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ARTICLE INFO

KEYWORDS
Carbon; Dune sand; Mycorrhiza; biochar; circular economy; argo-economy; carbon sequestration

HOW TO CITE
Alnuaimi, M. (2026). Desert Soil Ecology, Biochar, and Mycorrhiza for Sustainable Agroforestry in Arid Regions - Agroeconomics. Emirati Journal of Civil Engineering and Applications, 4(1), 45-59.
https://doi.org/10.54878/r0g1jb56

ABSTRACT

Arid and semi-arid lands are frequently framed as marginal or degradable spaces, yet drylands cover a substantial fraction of the terrestrial surface and support diverse biota, cultural landscapes, and livelihoods. This article redrafts and substantially expands an attached narrative review addressing desert soil ecology, biochar amendments, and mycorrhizal symbioses as foundations for sustainable agroforestry and restoration in arid regions. We synthesise evidence across Earth-system dust biogeochemistry, dryland soil pulse dynamics, biological soil crust functioning, biochar agronomy and stability, and arbuscular mycorrhizal fungi (AMF) mechanisms for drought and salinity tolerance. The synthesis highlights three overarching conclusions. First, dust and surface biocrusts are not peripheral phenomena but core regulators of desert nutrient and microbial connectivity, and therefore require protection within any land-management intervention. Second, biochar can improve water retention in sandy soils and ameliorate salinity in salt-affected soils, yet outcomes are heterogeneous and contingent on feedstock chemistry, production conditions, soil properties, and time since application, demanding context-specific design and monitoring. Third, AMF are credible biological tools for enhancing plant stress resilience—including in date palm systems—but inoculation success in deserts depends on compatibility with native communities and on co-management with soil physical amendments and irrigation practices. We integrate these findings into a systems framework for desert agroforestry that prioritises native species, water-harvesting microinfrastructure, and, where warranted, the co-application of biochar with tailored microbial inoculate. We also evaluate the climate-mitigation framing of dryland forestation, noting that albedo feedbacks can offset much of the cooling benefit of carbon sequestration, reinforcing the need for locally grounded objectives and rigorous monitoring, reporting, and verification. Permanently enhanced soil directly creates an agricultural economy and food security.

Double-blind peer review by independent reviewers.
Received: 02 Feb 2026, Accepted: 03 May 2026, Published: 24 Jun 2026
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Definitional clarifications

Drylands encompass hyper-arid, arid, semi-arid, and dry sub-humid zones; within the Intergovernmental Panel on Climate Change [1] framing, drylands cover approximately 45–47% of global land area and host around 3 billion people, providing "unique, rich biodiversity" and ecosystem services while being subject to poverty and governance challenges in many regions. [2] Aridity is commonly quantified with the aridity index (AI), defined as the ratio of precipitation to potential evapotranspiration, with drylands typically AI < 0.65 (UNEP/UNESCO-derived classifications reported in IPCC materials). [20] Desertification, in contrast, is a process definition: land degradation in arid, semi-arid, and dry sub-humid areas rather than "deserts spreading," and assessment work highlights that when desertification occurs in arid/hyper-arid contexts it is often associated with oases and irrigated cultivated land uses. [14] This matters for agroforestry: interventions frequently target exactly those irrigated margins where salinity, waterlogging, groundwater depletion, and soil structural decline become the binding constraints.

Geographic emphasis and topic inference

The user's prompt left the "topic" unspecified; therefore, the operative topic for this redraft is inferred from the attached manuscript as: desert soil ecology and management pathways integrating biochar amendments and mycorrhizal symbioses to support sustainable agroforestry/restoration in arid regions, with particular attention to the Arabian Peninsula[21] and the Sahara Desert[22]. Where region-specific claims cannot be substantiated with high-quality sources within the accessible literature, they are flagged as hypotheses or research needs rather than treated as established fact.

Why "reforesting deserts" is not a neutral objective

The seed manuscript's conservation-versus-reforestation framing aligns with a substantial scientific debate: tree planting can be beneficial in degraded forest landscapes, but indiscriminate afforestation in non-forest biomes (including savannas, grasslands, and deserts) can misclassify intact ecosystems as "degraded" and generate biodiversity and climate trade-offs. [23] Critiques of global tree restoration potential estimates emphasise methodological inflation (especially soil carbon assumptions) and the failure to account for albedo and biome-appropriate restoration. [24] Dryland-specific modelling further indicates that even large-scale dryland forestation may provide limited net climate mitigation once albedo warming is integrated, reinforcing that desert land management should be justified by local adaptation and livelihood outcomes unless full Earth-system accounting is explicit. [13]

Methods

Approach and transparency about constraints

This redraft is a structured, citation-driven synthesis rather than a de novo experimental or fully systematic review. The intent is to preserve the seed manuscript's conceptual integrity while strengthening its evidentiary base with primary studies, meta-analyses, and major assessments from high-impact venues and authoritative bodies. Because proprietary bibliometric databases (e.g., subscription-only Web of Science interfaces) were not programmatically accessible in this environment, the search strategy relied on open-web discovery and full-text sources where accessible (e.g., PubMed/PMC, publisher open-access pages, institutional PDF repositories), combined with backward citation chaining from key syntheses.

Literature search strategy

Searches were conducted using targeted query strings spanning four main concept clusters:

1) Dryland ecology and desertification: "drylands cover global land area IPCC", "desertification definition UNCCD", "pulse-reserve paradigm Noy-Meir", "biological soil crust nitrogen fixation PNAS". [25]2) Dust biogeochemistry and transport: "Saharan dust fertilizes Amazon phosphorus", "Bodélé Depression dust source PNAS", "desert dust microorganisms transport review", "dust iron ocean biogeochemistry Science". [26]3) Biochar in arid/saline/sandy soils: "biochar sandy soils available water capacity meta-analysis", "biochar salinity meta-analysis Geoderma", "biochar stability meta-analysis", "date palm waste biochar pyrolysis". [27]4) Mycorrhiza and stress resilience, including desert systems: "AMF salt stress mechanisms", "arbuscular mycorrhizae drought water relations Auge", "date palm AMF salinity", "AMF communities Southern Arabia date palm". [28]

Inclusion and exclusion criteria

Included sources met at least one of the following:

Primary empirical studies directly measuring outcomes relevant to arid land management (soil moisture retention, salinity metrics such as ECe/ESP, microbial biomass, AMF colonisation, plant growth/yield under drought/salt stress). [29]

Quantitative syntheses (meta-analyses/systematic reviews) providing effect-size estimates or moderators relevant to arid/sandy/saline contexts. [30]

Authoritative assessments and definitions (e.g., IPCC, UNCCD) used to ground scope and terminology. [14]

Classic foundational theory papers directly relevant to dryland dynamics (e.g., pulse–reserve; Birch effect). [31]

Findings and synthesis

Desert systems are pulse-driven, microbially mediated, and externally connected

Dryland functioning is governed by temporal discontinuity: long dry intervals separated by short precipitation pulses that reorganise biological activity. The pulse–reserve paradigm formalises this, conceptualising precipitation events as "resource pulses" that are captured and stored (in soil moisture, biomass, or nutrients) and then deployed during inter-pulse periods. [32] This framework is foundational for designing interventions because it reframes "average rainfall" as a poor predictor of ecological opportunity; instead, pulse size, timing, infiltration pathways, and soil storage capacity become primary determinants of biological success. [33]

At the microbial level, drying–rewetting produces characteristic respiration pulses (the Birch effect), with rapid mineralisation following rewetting of dry soils and subsequent decline to a steady state. [34] Empirical work confirms that desert microbial communities can be particularly sensitive to repeated drying–rewetting cycles relative to other soils, implying that intervention-driven changes in wetting regimes (e.g., irrigation scheduling) can restructure microbial function and greenhouse gas fluxes. [35] In hot desert edaphic systems, microbial communities exhibit distinct temporal dynamics linked to rainfall events, supporting the broader claim that microbial "resurrection" and substrate accessibility shifts are core to desert biogeochemistry rather than niche phenomena. [36]

Biological soil crusts (biocrusts)—complex assemblages of cyanobacteria, lichens, mosses, and associated microbes—often occupy the open interspaces between vascular plants and materially affect infiltration, erosion resistance, and nitrogen cycling. [37] A PNAS study demonstrates that biocrusts can accelerate the nitrogen cycle and influence reactive nitrogen dynamics in drylands, reinforcing that "soil fertility" in deserts is partly a surface community property. [38] This strengthens the seed manuscript's warning that interventions which destabilise soil surfaces (mechanised planting, crust disturbance, overgrazing) can undermine the very microbial infrastructure needed for long-term sustainability.

Dust storms as both a hazard and a nutrient infrastructure

The seed manuscript's emphasis on dust storms as ecologically significant aligns with Earth-system science: mineral dust links arid land processes to marine and terrestrial productivity through nutrient transport, and dust fluxes are sensitive to land cover, hydrology, and climate variability. A classic Science synthesis frames dust-driven iron transport to the oceans as a key component of an "iron cycle" with feedbacks to ocean biogeochemistry and climate, and identifies dried lake systems—such as the Bodélé Depression[39]—as particularly important dust source regions. [40] Complementary work in PNAS characterises the Bodélé Depression as a dominant Saharan dust source and uses this to illustrate how regional geomorphology can act as a tipping element in dust mobilisation. [41]

The often-cited Saharan dust–Amazon linkage is supported by quantitative remote-sensing and deposition analyses: a Geophysical Research Letters study estimates that ~28 Tg of Saharan dust is deposited into the Amazon annually and argues this deposition plays a major role in maintaining phosphorus availability. [42] Independent lines of evidence include NASA satellite-based reporting on Saharan dust phosphorus deposition dynamics and additional peer-reviewed analyses on African dust contributions. [43] The key implication is conceptual as well as quantitative: deserts are not only nutrient-limited receivers but also nutrient exporters that help stabilise other ecosystems' stoichiometry.

Dust also provides a vehicle for microorganism transport. Reviews document the presence and long-range movement of bacteria and fungal spores in association with dust, and AGU literature further details factors controlling microbial loading. [6] For arid land management, this has two practical implications. First, dust suppression policies should avoid simplistic "zero dust" objectives that might disrupt natural nutrient pathways, and should instead focus on preventing anthropogenically amplified dust emissions via land degradation. [14] Second, restoration decisions should anticipate that microbial community assembly may be influenced by atmospheric dispersal, which complicates inoculation strategies and strengthens the case for working with native or locally derived microbial consortia rather than assuming closed-system microbiomes. [44]

Conservation versus afforestation in drylands: why bio-physical accounting matters

The seed manuscript argues that reforesting deserts can be ecologically inappropriate and can create unsustainable irrigation demands or biodiversity loss when non-native species or dense plantations are introduced. Recent climate-focused synthesis reinforces that the net climatic benefit of dryland forestation can be small when albedo changes are included: Rohatyn et al. estimate that while 448 Mha might be "afforestable" within global drylands, the warming effect of reduced albedo offsets much of the carbon benefit, leaving a relatively modest net cooling equivalent over 2020–2100 in their scenario. [13] The study also motivates "smart forestation" (excluding areas predicted to yield net warming) as a partial corrective, but even that framing implies that geographic targeting and biophysical modelling are prerequisites for climate-justified planting. [45]

At a broader scale, the tree-restoration debate in Science illustrates how carbon-centric narratives can misclassify ecosystems and inflate sequestration estimates. Comments on the global tree restoration potential highlight errors related to soil organic carbon and warn that planting trees in non-forest biomes can be ecologically inappropriate. [46] These critiques support the seed manuscript's normative shift: from "greening deserts" as a universal climate intervention to conserving and enhancing desert ecosystems using locally adapted species and soil–water engineering that aligns with dryland dynamics.

Biochar in arid soils: quantified benefits, strong heterogeneity, and design risks

What biochar is, and why arid regions care

Biochar is commonly defined as the carbon-rich solid product formed when biomass (e.g., wood, manure, crop residues) is heated under oxygen-limited conditions and then used for environmental management, including soil improvement and carbon management. [47] In drylands, the appeal is straightforward: biochar can alter soil physical structure (porosity, bulk density), increase cation exchange capacity, and influence water retention—traits that directly target the dominant constraints in sandy, nutrient-poor, and salinity-affected soils. [48]

However, "biochar" is not a single material class. Its properties depend on feedstock (woody biomass versus manure versus crop residues), pyrolysis conditions (temperature, heating rate, residence time), and post-production ageing/weathering in soil. [49] Because deserts experience extreme thermal regimes and repeated wet–dry cycles, ageing processes and functional group evolution may be particularly consequential, yet long-duration desert field trials remain comparatively scarce relative to temperate research emphases—one of the seed manuscript's core knowledge gap claims.

Water retention in sandy soils: strong evidence for potential, but not a guarantee

A dedicated meta-analysis of sandy soils finds that biochar amendments increase available water capacity (AWC) by ~28.5% on average, but also identifies important moderators: no significant AWC effect for very large particle sizes (>5 mm) or when soils already have relatively high SOC (>2%). [8] The same analysis reports larger effects in controlled laboratory conditions than in field trials and in short-term versus long-term experiments, implying that translation to real desert field settings requires careful expectation management and monitoring for persistence. [8] These findings are directly relevant to desert dune or dune-margin agroforestry proposals, because dune sands often represent extreme cases of coarse texture and low SOC where biochar might produce a relatively more detectable shift—provided application logistics and wind erosion are addressed.

Crop productivity: modest mean effects with wide variance and practicality constraints

A widely cited meta-analysis reports a grand mean ~10% increase in crop productivity following biochar application, with outcomes ranging from negative to strongly positive and with larger average responses at very high application rates (e.g., 100 t ha^{-1} in the analysed dataset). [7] The same synthesis warns that most included studies were short-term (1–2 years) and that auxiliary data are often incomplete—limitations that are magnified in arid settings where interannual rainfall variability can dominate yield outcomes. [7] This supports a central design principle for deserts: biochar should be trialled at operationally feasible rates and evaluated over multiple seasons with explicit accounting for rainfall pulses and irrigation regimes, rather than extrapolated from high-dose pot experiments.

Salinity and sodicity: meta-analytic evidence for amelioration, but feedstock is decisive

For salt-affected soils, a 2024 meta-analysis (660 paired observations, 99 articles) finds that biochar significantly reduces ECe (mean ~13.2%) and increases cation exchange capacity (~17.0%) without a consistent effect on soil pH; critically, the most important moderators for salinity response were initial salinity level and biochar feedstock type. [9] This is aligned with the seed manuscript's caution that biochar can sometimes increase

ISSN: 3006-6948 - https://doi.org/10.54878/r0g1jb56

salinity if it carries soluble salts (ash-rich chars, manure-based feedstocks), especially if applied at high rates without leaching or drainage pathways. In desert agroforestry, where irrigation water is often brackish and where drainage infrastructure can be limited, the feedstock–salinity interaction becomes a first-order safety issue rather than a secondary optimisation variable.

Stability and carbon persistence: long residence times, but "stability" is not uniform

Biochar's climate rationale depends on persistence. A long-duration incubation study using ^14C-labelled biochar reports extremely slow decomposition rates and estimates mean residence times on the order of millennia under field conditions, while acknowledging uncertainty in extrapolating laboratory estimates to field environments. [50] Complementary meta-analysis evidence suggests biochar contains a small labile fraction and a dominant recalcitrant pool, with estimated mean residence times of ~108 days (labile, ~3% of pool) and ~556 years (recalcitrant, ~97% of pool), and emphasises that decomposition rates vary with feedstock, pyrolysis temperature, and soil texture/mineralogy. [51] For deserts, this implies two parallel evaluation tracks: (1) carbon permanence for climate accounting, and (2) functional persistence of agronomic benefits (water retention, microbial habitat), which may change as biochar surfaces oxidise and interact with salts and minerals.

Microbial responses: biochar can strengthen microbial biomass, but arid translation requires field evidence

Microbial mediation is central in desert soils, and biochar often increases microbial biomass carbon (SMBC) in field settings but with strong dependency on climate, soil properties, biochar ageing, and co-amendments. [52] A field-focused meta-analysis reports an overall positive impact of biochar on SMBC (~21.31%), identifies stronger effects in lower-fertility soils, and finds that repeated application and shorter "fresh" ageing windows can increase SMBC more than single/aged applications. [52] This matters for desert design because microbial responses can underpin nutrient cycling improvements, but they can also influence greenhouse gas fluxes and salt dynamics—variables that must be monitored rather than assumed beneficial. [53]

Desert-relevant feedstocks: date palm residues and invasive shrubs as realistic candidates

A decisive feasibility constraint is biomass availability. The seed manuscript suggests leveraging local residues (e.g., date palm fronds) or invasive shrubs for biochar production. This aligns with emerging literature on date palm waste valorisation: studies characterise biochar produced from date palm residues, and engineering-focused work demonstrates feasibility of local pyrolysis units for date palm fronds with subsequent physicochemical characterisation. [54] For invasive woody species such as Prosopis juliflora (context-dependent invasive status), biochar applications have been evaluated for improving degraded soil biochemical properties, illustrating a potential "two-problem" strategy: invasive biomass control and amendment production. [55] The key research need is to evaluate these feedstocks not only for general biochar quality but for soluble salt content, ash fraction, and performance under saline irrigation typical of desert agriculture.

Mycorrhiza in arid environments: mechanisms are well supported, deployment is not trivial

Core mechanisms for drought and salinity tolerance

AMF enhancement of plant salt tolerance is supported by extensive mechanistic literature, including improved nutrient acquisition, maintenance of favourable K^+/Na^+ ratios, osmolyte accumulation, modulation of antioxidant pathways, and altered hormonal signaling. [56] For drought, reviews and experimental syntheses emphasise improved plant water status, stomatal regulation, and changes in root system architecture and hydraulic properties, with Augé's synthesis treated as foundational for linking arbuscular mycorrhizae to plant–water relations. [57] Mechanistically, AMF can influence soil aggregation via hyphal networks and glomalin-related soil proteins, improving structure and potentially supporting infiltration and water retention—processes especially valuable in fragile desert soils. [58]

Desert specificity: native AMF communities and host compatibility

The seed manuscript notes that desert AMF diversity and function remain underexplored relative to temperate systems. Evidence supports this as both a knowledge gap and an opportunity: an AMF community study in southern Arabia explicitly targets previously "unknown" AMF communities in date palm plantations and surrounding arid habitats, demonstrating that desert agroecosystems host distinctive AMF assemblages shaped by management and landscape context. [59] Additional desert microbiome work using co-occurrence network analysis shows strong plant-species effects on desert microbiota composition and interaction networks,

reinforcing that inoculation should be host- and site-specific rather than generic. [60]

Date palm as a model desert agroforestry species for AMF-based management

Date palm agroecosystems are central to arid livelihoods and are explicitly highlighted in the seed manuscript as culturally and ecologically embedded systems. A review in Land Degradation & Development reports that while date palm tolerates substantial salinity levels, salt accumulation strongly reduces yield, which emphasises the need for soil–water–salt management rather than relying on crop tolerance alone. [61] Controlled experiments show that AMF inoculation can enhance date palm tolerance to salinity by improving nutrient uptake and antioxidant systems, supporting the plausibility of AMF as part of an adaptation-oriented toolkit. [62] Field-relevant microbial studies further indicate that irrigation water salinity structures date palm-associated bacterial communities, implying that AMF interventions will interact with irrigation chemistry and broader microbiome assembly. [63]

Operational challenges: inoculum viability, stress thresholds, and scaling

Despite credible mechanisms, desert deployment faces practical constraints: AMF colonisation can be inhibited by extreme salinity, poor soil structure, and lack of carbon supply from host plants in degraded sites. [64] This supports the seed manuscript's recommendation to inoculate seedlings at the nursery stage, ensuring symbiosis establishment before outplanting into harsh conditions. It also suggests that AMF application should be paired with microhabitat improvements (mulch, compost, or carefully designed biochar blends) that stabilise moisture pulses and reduce ionic stress near roots.

Biochar–mycorrhiza interactions: why co-application must be designed, not assumed

The seed manuscript proposes "synergistic effects" between biochar and mycorrhiza in deserts, attributing these to biochar's porous refugia and ion sorption moderating stress. The broader literature supports synergy as plausible but conditional. Experimental evidence indicates that biochar produced at high pyrolysis temperatures can reduce nutrient uptake in some contexts, while AMF can alleviate negative biochar effects, implying interaction dependencies on biochar chemistry. [65] Soil-matrix context also matters: mechanistic work emphasises that outcomes depend on soil properties and that strong effects should not be presumed across settings. [66] Importantly, evidence shows AMF can colonise biochar particles in soils, but the processes controlling colonisation remain under characterisation—suggesting that "biochar as microbial habitat" is a testable design assumption rather than an established universal. [67]

A practical synthesis for arid agroforestry is therefore:

Synergy is most likely when biochar improves near-root moisture retention, reduces exchangeable sodium impacts, and provides microsites that protect hyphae during dry periods, while not immobilising key nutrients. [68]

Antagonism is plausible when biochar sorbs nutrients or creates unfavourable chemistry (e.g., excessive alkalinity or soluble salt contribution), reducing plant carbon allocation to symbionts or directly inhibiting hyphal growth. [69]

For desert field implementation, this motivates a co-application methodology: characterise biochar (EC, ash, pH, particle size distribution), match AMF consortia to target plant species and site salinity regime, and run factorial field trials (biochar × AMF × irrigation salinity) with at least multi-season monitoring. [70]

Water and salinity governance as the binding design layer for desert agroforestry

The seed manuscript discusses microcatchments, drip irrigation, and renewable-energy pumping as design principles. The wider irrigation literature reinforces that using poor-quality (saline) water requires integrated crop selection, irrigation technology, and maintenance of soil physical properties to meet leaching requirements. [71] Economic synthesis of salt-induced land degradation estimates substantial global costs from salinity-driven yield loss, reinforcing that salinity is not a niche issue but a systemic constraint on irrigated agriculture. [72] In oasis contexts, empirical and modelling work documents how salinity distribution and water flow interact with irrigation systems in Saharan oases, with groundwater depletion and salinisation as recurrent risks—consistent with the IPCC emphasis on desertification in irrigated lands. [73]

Therefore, in arid agroforestry, biochar and AMF should be framed as supporting technologies that can improve near-root conditions and plant stress resilience, but they cannot substitute for drainage, salinity monitoring, and governance of extraction. In practice, this means that desert agroforestry designs should explicitly specify irrigation water salinity ranges, target soil salinity thresholds by crop, drainage/leaching strategy (including

leaching fraction where relevant), and soil testing frequency. [74]

Comparative tables to structure the evidence

Table: Selected high-value evidence supporting arid-region biochar design (meta-analyses and key primary studies)

Study	Evidence type	System focus	Quantified headline finding	Key moderators / cautions relevant to deserts
Jeffery et al. (2011) [7]	Meta-analysis	Crop productivity across studies	~10% grand mean increase; wide range (negative to positive)	Most studies short-term; strong dependence on soil pH/texture and application rate, with very high rates often showing largest effects [7]
Ibrahimi & Alghamdi (2022) [8]	Meta-analysis	Sandy soils	~28.5% mean increase in available water capacity	No significant effect when biochar particle size >5 mm or SOC >2%; field effects smaller than lab; short-term effects larger than long-term [8]
Wang et al. (2024) [9]	Systematic review & meta-analysis	Salt-affected soils	ECe reduced ~13.2%; CEC increased ~17%; no consistent pH change	Initial salinity level and feedstock most important moderators; highlights heterogeneity and need for thorough characterisation [9]
Kuzyakov et al. (2014) [50]	Long-duration incubation (primary)	Biochar stability	Very slow decomposition; field MRT order of millennia estimated (with uncertainty)	Stability varies by fraction; extrapolation from lab to field is uncertain; deserts may alter ageing pathways [50]
Wang, Xiong & Kuzyakov (2015) [51]	Meta-analysis	Decomposition & priming	Labile ~3% (MRT ~108 days), recalcitrant ~97% (MRT ~556 years); priming effects vary	Biochar can stimulate SOM mineralisation in sandy soils; indicates fertility/texture dependence crucial in arid sands [51]
Kumar et al. (2025)	Field meta-analysis	Soil microbial biomass	Overall SMBC	Effects vary by

ISSN: 3006-6948 - https://doi.org/10.54878/r0g1jb56

[52]		carbon	increase ~21%; repeated application larger	climate/soil/biochar; emphasises need for long-term field experiments and attention to ageing [52]

Table: Mycorrhizal functions most relevant to arid agroforestry and soil restoration

Functional pathway	Mechanistic summary	Representative support
Ion homeostasis under salinity	AMF can support improved K^+/Na^+ balance and nutrient acquisition, reducing physiological salt injury	[75]
Water relations and drought buffering	AM symbiosis influences plant water status and stomatal behaviour, improving tolerance under water limitation	[76]
Soil aggregation and structure	Hyphal networks and glomalin-related soil proteins contribute to aggregate stability, supporting infiltration and reducing erosion susceptibility	[58]
Host specificity and desert assembly	AMF communities differ across habitats and management, implying inoculation must consider local communities and compatibility	[77]
Salt-tolerant crop relevance (date palm)	Empirical work shows AMF can enhance date palm tolerance to salinity via growth and physiological pathways	[78]

Table: Reframing "greening" in deserts—comparative objective functions

Intervention framing	Primary objective	Typical risks if misapplied	Evidence-based corrective
Carbon-centric dryland afforestation	Maximise tree cover and carbon sequestration	Water depletion, biodiversity loss, albedo warming offsets, plantation failure	Include albedo and water accounting; target only locations with net cooling and feasible water; prioritise ecosystem-appropriate restoration [19]
Desert conservation and targeted agroforestry	Improve livelihoods and resilience while maintaining desert ecosystem integrity	Underinvestment, slow vegetation recovery, governance constraints	Use native/adapted species, protect biocrusts, microcatchments, targeted soil amendments, adaptive monitoring [79]

Integrated conceptual framework for desert agroforestry with biochar and AMF

The seed manuscript proposes a conceptual framework in which biochar modifies dune sands and AMF enhance plant establishment, leading to a gradual increase in soil carbon and ecosystem services. The following mermaid flowchart formalises that framework as a design–mechanism–outcome chain with explicit monitoring loops (a key upgrade from narrative proposals).

flowchart TD A[Site assessment: aridity, soil texture, salinity, biocrust condition, water supply] --> B{Intervention suitability\nand constraints} B -->|Water & drainage feasible| C[Water-harvesting + irrigation design\nmicrocatchments, drip, leaching strategy] B -->|Severe constraints| D[Conservation-first restoration\nbiocrust protection, grazing management, assisted natural regeneration] C --> E[Soil amendment package design] E --> E1[Biochar selection\nfeedstock, ash/EC, particle size, pyrolysis temp] E --> E2[Organic co-amendments\ncompost/manure where feasible] E --> E3[Gypsum/mineral amendments\nif sodicity requires] C --> F[Biological package design] F --> F1[Seedling nursery inoculation\nnative AMF consortia] F --> F2[Optional co-inoculation\nrhizobia/PGPR for legumes] E --> G[Planting design] F --> G G --> H[Species & structure\nnative/adapted trees, nurse shrubs, understory] H --> I[Establishment phase\n1–3 years: survival, salinity control, wind erosion control] I --> J[Soil development phase\n3–10+ years: litter inputs, aggregation, microbial network maturation] J --> K[Outcomes] K --> K1[Livelihood outcomes\nfood, fodder, shade, biomass] K --> K2[Ecosystem outcomes\nreduced erosion, improved soil function] K --> K3[Climate outcomes\ncarbon storage, albedo & ET effects] I --> L[Monitoring, reporting, adaptive management] J --> L L --> A

A note on data and figures

No numerical datasets, site measurements, or figures were present in the attached .docx beyond narrative claims and DOI listings; therefore, no original data could be reproduced. Where the seed manuscript provided quantitative statements without sources, this redraft either (i) supplies peer-reviewed support or (ii) reframes them as qualitative claims pending verification.

Implications for practice and policy

Practice implications: "desert agroforestry" as engineered co-existence, not forest substitution

The strongest evidence-based practice implication is that desert agroforestry should be designed as a bounded, water-accounted, soil-surface-protecting system—not as ecosystem substitution by dense plantations. High-level assessment work foregrounds governance, land tenure, and integrated water management as enablers of dryland resilience. [80] Because desertification risk is concentrated in irrigated margins and oases, interventions should prioritise salinity management (monitoring ECe/ESP), drainage/leaching strategies, crop salt tolerance matching, and avoidance of irrigation practices that accelerate salt accumulation. [81]

Within that envelope, biochar can be justified as a targeted physical–chemical tool where coarse texture and low SOC limit infiltration storage and where salt-affected soils dominate productivity constraints, but only when feedstock salt risks are controlled and application rates are operationally feasible. [82] Date palm residues are particularly promising as local feedstocks in many arid regions, with studies demonstrating production and characterisation pathways; however, agronomic benefits under field-scale saline irrigation still require more region-specific trials. [83]

AMF should be treated as a biological infrastructure investment—most plausibly delivered via nursery inoculation to ensure early colonisation—rather than as a generic additive applied to degraded desert soils at planting. Evidence from date palm systems supports the plausibility of AMF-mediated salinity tolerance, but desert host specificity and management effects on AMF communities necessitate local inoculum development and compatibility testing. [84]

Policy implications: regulating the "greening" paradigm through accounting and ecosystem typology

The scientific critique of global tree restoration potential and the dryland forestation albedo-offset findings together imply a policy need: land-based climate mitigation claims in drylands should be restricted unless they include albedo, water, and biome-appropriateness assessments. [85] In practice, this means that carbon market methodologies and national afforestation plans should not treat "tree cover increase" as inherently beneficial in deserts and adjacent non-forest biomes; instead, they must incorporate ecosystem typology (forest vs savanna vs desert), water budgets, and biodiversity safeguards.

At the same time, drylands provide opportunities for nature-based adaptation and livelihood resilience if interventions are designed around local constraints and governance systems—an emphasis consistent with IPCC reporting. [86] In this framing, desert agroforestry programmes are best justified as adaptation investments (food security, dust reduction via soil stability, shade/microclimate, salinity management) with potential co-benefits for carbon storage, rather than as primary climate-offset projects.

Research agenda

The seed manuscript provides a strong list of knowledge gaps; this section refines those gaps into researchable

questions and methodological priorities while maintaining the manuscript's integrative intent.

Long-term, factorial field trials in representative desert soilscapes

A recurring limitation across biochar and AMF evidence is an overreliance on short-term pot studies and controlled experiments, while key meta-analyses explicitly call for long-term field experiments. [87] In deserts, field trials should be designed as factorial experiments capturing interactions among (1) biochar properties (feedstock, ash/EC, particle size), (2) AMF inoculation strategy (native consortia vs commercial inoculum; nursery vs field), and (3) irrigation salinity regimes and leaching/drainage design. Outcomes should include not just yield/survival but mechanistic mediators: soil water retention curves, aggregate stability, microbial network structure, and salinity partitioning across depth profiles. [88]

Native AMF discovery and "inoculum ecology" for arid hosts

AMF community work in southern Arabia demonstrates that desert agroecosystems host distinctive AMF assemblages and provides a template for regional surveys. [59] Priority research should map AMF diversity across key arid host species (trees, nurse shrubs, stabilising grasses) and across management gradients (oasis agriculture, rangeland, restoration sites), then test functional traits under salinity and drought stress through controlled inoculation trials. This would shift AMF deployment from generic inoculants to locally adapted consortia, reducing mismatch risk anticipated by host-specific desert microbiome network patterns. [89]

Biochar feedstock optimisation for arid-region residues

Work on date palm waste biochar and local pyrolysis systems supports feasibility, but research should expand from material characterisation to agroecological performance under realistic irrigation salinity and wind erosion conditions. [83] Key open questions include how soluble salt content varies by residue type and pyrolysis temperature; how biochar ageing changes EC and nutrient retention under repeated wet–dry cycles; and whether biochar incorporation strategies (banding, spot application in planting basins, surface mulching) reduce losses to wind. Meta-analytic evidence on sandy soils suggests particle size is a decisive moderator for water retention benefits, making particle engineering an actionable research pathway. [8]

Integrating biocrust conservation and restoration into agroforestry planning

Given the evidence that biocrusts materially influence nitrogen cycling and soil stability in drylands, agroforestry interventions should not be developed independently of crust conservation/restoration science. [90] Research should evaluate whether common agroforestry establishment practices (mechanised planting, irrigation) degrade crust function and whether hybrid designs can protect crusts while enabling tree establishment (e.g., planting in discrete basins while maintaining crusted interspaces). This aligns with the seed manuscript's warning about destabilising dunes and crusts but formalises it as a testable design question.

Full-system accounting: water, albedo, and carbon permanence

Dryland forestation modelling that integrates albedo and carbon sequestration illustrates that climate mitigation narratives can fail without full biophysical accounting. [13] Desert agroforestry research therefore requires integrated monitoring, reporting, and verification that includes: (i) water consumption and groundwater impacts, (ii) land-surface energy balance changes where tree cover expansion is substantial, and (iii) biochar carbon permanence in the specific thermal and oxidative regime of deserts. Biochar stability studies show long persistence in general but also emphasise uncertainty in extrapolating across environments; deserts may impose distinct oxidation and abrasion dynamics that remain under-studied. [91]

Socio-economic and governance research embedded in field programmes

Assessment work underscores governance and enabling environments as determinants of outcomes in drylands. [86] Therefore, intervention science should embed socio-economic evaluation: feedstock supply chains, labour requirements, farmer acceptability of inoculated seedlings, land-tenure implications, and distributional effects (who benefits from water allocation). This is particularly important where projects are justified under "greening" narratives that may attract external finance but impose local water burdens.

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