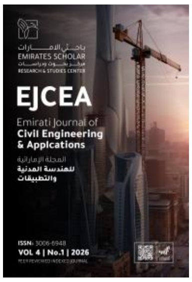

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Enhancing dune sand with biochar: mechanisms, evidence, risks, and a research programme for desert and coastal systems

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ABSTRACT

Biochar amendments are increasingly proposed to "enhance dune sand" by increasing water retention, nutrient availability, microbial colonisation, and vegetation establishment, thereby stabilising mobile sands and improving resilience in arid and coastal landscapes. Yet dune sands are not merely "sandy soils"; they are active geomorphic substrates governed by aeolian transport thresholds, sediment supply, surface moisture, fetch effects, and vegetation-sediment feedbacks. We synthesise evidence spanning soil physics, soil microbiology, dune eco-geomorphology, and governance, and critically evaluate the applicability of biochar for dune systems. Meta-analyses indicate that biochar often increases plant-available water in coarse-textured soils by roughly one-quarter on average, with stronger effects at moderate-to-high application rates and depending on biochar properties and placement. Mechanistic studies show that biochar alters pore networks and can increase the abundance and diversity of microbial communities, with larger pores (>5 μm) and heterogeneous pore architectures linked to the provision of microbial habitats and community shifts. Dune-specific risks include particulate emissions and loss of biochar carbon via wind-driven abrasion and resuspension, with laboratory and field evidence that biochar amendments can substantially increase PM emissions under certain wind regimes. We propose an integrated research programme combining (i) microcosm studies isolating pore-structure and inoculation effects; (ii) mesocosm and wind-tunnel experiments quantifying erosion resistance, threshold shear velocity, and particle loss; (iii) field trials in desert and coastal dunes with coupled hydrological and geomorphic monitoring; and (iv) modelling that links pore-scale processes to dune-scale evolution metrics. We also assess regulatory and standards landscapes, including EU fertilising product rules for pyrolysis/gasification materials, biochar certification thresholds for PAHs/heavy metals, and carbon market durability requirements.

Keywords: *Desert conservation, soil ecology, carbon capture, biochar, carbon, carbon sequestration, agroforestry.*

Introduction:

Dune systems—whether inland desert dunes or coastal foredunes—are dynamic landscapes in which sand transport and deposition are controlled by wind regime, sediment supply, surface moisture, and vegetation. Coastal foredunes in particular arise from coupled biological and physical processes, and their morphology and maximum size can be constrained by vegetation-mediated feedbacks. [9] The governing transport processes are sensitive to beach/dune fetch and rapid spatial-temporal moisture variability, which can shift entrainment thresholds and confound prediction of sediment delivery to dunes. [10] These properties matter for biochar because the amendment may alter (directly or indirectly) surface moisture, particle cohesion, roughness length, and the biological capacity to trap sand as vegetation establishes.

"Dune sand" also has a consistent pedological signature: coarse grains, low fines, low organic matter, low nutrient retention, and weak soil structure. The provided PhD proposal frames this as "ground-zero" soil ecology—barren sand with minimal microbial activity—and hypothesises that date-palm biochar can act primarily as a habitat-creating medium, not merely a nutrient input. This emphasises a critical point for the broader field: in dune sands, the limiting factor is often the absence of persistent habitat and resource scaffolding for microbial networks and plant-microbe symbioses, rather than a simple deficiency of fertiliser nutrients.

Contemporary evidence supports parts of this logic but also warns against overgeneralisation. Meta-analyses and reviews show that biochar effects on soil water and microbial communities are variable and contingent on production and application conditions, suggesting that dune-specific optimisation is essential rather than optional. [11] Moreover, dune systems introduce unique off-site loss pathways: wind abrasion, saltation impacts, and aerosolisation can remove fine biochar fractions and potentially undermine permanence, create air-quality impacts, or relocate contaminants if present. [12]The supplied internal review manuscript in the attachments further broadens the scope: it positions desert interventions within ecological constraints (avoiding simplistic "greening" narratives), and foregrounds microbial and mycorrhizal networks, dust/nutrient dynamics, and the need to integrate social-ecological realities in arid-region land management. That perspective is salient for dune-sand biochar because, in many dune landscapes, "stabilisation" is simultaneously a desired service (reduced dust storms, reduced encroachment) and a potential ecological harm (loss of dune mobility, habitat homogenisation).

Methods

Evidence base from supplied materials and what is unspecified

The uploaded materials include: a PhD proposal (ground-zero dune sand ecology using date-palm biochar), a narrative internal review on desert soil ecology/biochar/mycorrhiza, and several documents listing large sets of DOI links and EndNote codes spanning biochar, salinity resilience, palms/date palms, soil microbiology, and desert agroforestation.

What is **unspecified/missing for full systematic extraction** as requested:

- The full-text PDFs (or equivalent full text) for the majority of the "provided articles" are not included in the attachments; most are supplied as DOI links/codes only, which prevents reliable extraction of detailed methods, sample sizes, statistics, and numerical results beyond abstracts or limited previews.
- A preferred citation style (e.g., Harvard, Vancouver) is not specified. This report uses

- author-year conventions in prose and provides inline source citations for auditability.
- The intended dune context is not specified as coastal, inland desert, or both. The proposal is desert-focused (UAE date-palm systems), whereas the requested target journals include coastal geomorphology outlets, implying a combined framing.

Literature search and synthesis approach

To align with high-tier systematic review expectations, the evidence synthesis framework should follow PRISMA 2020 reporting guidance, including explicit inclusion/exclusion criteria, a transparent search strategy, and structured extraction. [13] For quantitative synthesis, random-effects meta-analysis is generally required given heterogeneity in soils, biochar types, and experimental contexts; however, common estimators such as DerSimonian-Laird can perform poorly in small meta-analyses, so modern variance estimators (e.g., REML with robust confidence intervals) are typically preferred. [14] If conducting meta-analysis in R, the metafor package is widely used and supports mixed-effects meta-regression for moderators such as soil texture class, application rate, pyrolysis temperature, and particle size. [15]

For dune sand specifically, an additional integration step is needed beyond conventional agronomic meta-analysis: synthesis must connect soil and microbial outcomes to geomorphic metrics (e.g., threshold shear velocity, erosion rate, sediment flux) and to eco-geomorphic feedbacks between vegetation and sand transport. [16]

Study synthesis matrix for the core, dune-relevant subset

Because full extraction for every supplied DOI is not feasible from the attachments alone, the table below synthesises the **proposal, along with the most dune-sand-relevant, full-text-accessible primary and high-impact synthesis sources** identified through the searches.

Source	Aims	System / setting	Methods	Key findings relevant to dune sand	Critical limitations for translation to dunes
PhD proposal (“Ground-Zero: Dune Sand Enhancement Potential”)	Test whether date-palm biochar pore structure creates microbial refugia and improves water/nutrient retention and plant performance in barren dune sand	Inland desert dune sand; date-palm production context in United Arab Emirates[17]	Biochar production at 350/450/550 °C; microcosms with inoculation regimes; glasshouse pots; field trial in date-palm plantation; SEM/µCT; eDNA sequencing; enzyme assays; ANOVA/regression/SEM	Mechanistic “habitat creation” hypothesis; explicit bridging of pore metrics to microbial assembly and plant outcomes; multi-scale design	Field trial framed in plantations (not mobile dunes); wind-driven loss pathways and dune geomorphic metrics not yet central; long-term >2 seasons uncertain

Edeh et al. 2020 meta-analysis on soil water properties [18]	Quantify biochar impacts on soil water retention and hydraulic conductivity across soil textures	Global soils (includes coarse-textured)	Meta-analysis of biochar effects on AWC, FC, PWP, Ksat, bulk density	Reports average AWC increase ~28.5%, FC ~20.4%, PWP ~16.7%, and Ksat reduction ~38.7%; strongest improvement in coarse soils; often higher rates (30-70 t/ha)	Aggregates non-dune soils; does not include wind erosion/permanence losses; application rates may be logistically unrealistic for dunes
Ibrahimi et al. 2022 analysis focusing on sandy soils [19]	Identify factors controlling AWC increases in sandy soils amended with biochar	Sandy soils (including desert contexts)	Meta-analytic/quantitative synthesis with moderator variables	Confirms average AWC increase ~28.5% in sandy soils; identifies biochar characteristics and production conditions as moderators	Outcome focus is hydrology; limited linkage to microbial habitat, aeolian erosion, or coastal constraints
Fu et al. 2021 on biochar particle size and rate in sandy desert soil [20]	Determine how particle size and incorporation rate affect hydraulic/physical properties in sandy desert soils	Sandy desert soil (Tengger Desert context)	Controlled experiments varying particle size and dose	Demonstrates particle size and rate meaningfully influence pore distribution and water-related properties in sandy soils	Not a dune-geomorphology study; wind erosion measured indirectly; local soil and climate specificity
Yang et al. 2022 on pore structure and microbial communities [21]	Link biochar-induced pore changes to microbial diversity/abundance	Agricultural soil context	N adsorption + mercury intrusion porosimetry; sequencing	Biochar increases pore volumes in size classes including 5-30 μm; pores >5 μm positively	Soil type not dune sand; microbial mechanisms may differ under hyper-

				relate to microbial diversity/abundance	aridity and sand abrasion
Yang et al. 2024 on biochar pore structure and microbial composition [22]	Test how pore structure affects microbes and plant growth	Agricultural crop soil	Biochars at different pyrolysis temperatures; microbial and plant measures	Reinforces pore-structure relevance; cites suitability of pores ~5-20 µm for microbial habitation and water retention	Crop-specific; the pore size "optimum" may not transfer straightforwardly across climates and sands
Yan et al. 2022 on aeolian sandy soil rhizosphere microbes [23]	Identify microbial mechanisms by which biochar promotes root growth in aeolian sandy soil	Aeolian sandy soil (closer analogue to dunes)	Biochar amendment; rhizosphere bacterial community analysis	Suggests biochar promotes root growth via bacterial community shifts in aeolian sandy soil	Still not a dune-mobility experiment; geomorphic endpoints absent
Ravi et al. 2016 on PM emissions from biochar-amended soils [24]	Test particulate emission tradeoffs from biochar-amended soils	Dryland/aeolian transport relevance	Experiments and mechanistic interpretation	Biochar can increase particulate emissions via resuspension of fine biochar and abrasion by sand grains	Shows a major dune-relevant risk pathway; does not quantify carbon permanence loss directly in dune field conditions
Ravi et al. 2020 on resuspension and transport of biochar particles [25]	Quantify PM10 emission mechanisms across wind regimes	Wind environments	Empirical + theoretical framework	Reports large PM10 increases (order hundreds of %) under some wind conditions and shows models may	Strong relevance to dunes; still requires dune-specific validation under saltation/substrate conditions

				underestimate emissions	
European Biochar Certificate guidance on PAH/heavy metal controls [26]	Define quality classes and contaminant thresholds for biochar applications	EU/Europe governance	Standards document	Provides explicit contaminant thresholds (e.g., Σ16 EPA PAH and Σ8 carcinogenic PAH controls) and links to fertiliser regulation alignment	Not site-specific; compliance does not guarantee ecological suitability for sensitive dunes
EU delegated regulation adding CMC14 pyrolysis/gasification materials [27]	Harmonise pyrolysis/gasification materials as fertiliser component category	EU market	Regulation text	Establishes regulatory pathway by defining eligible inputs and product standards, affecting marketability and conformity assessment	Applies to EU market; not directly applicable to UAE deployment but influences global standard-setting norms

Possible end-to-end experimental workflow

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flowchart LR
  A[Feedstock selection & traceability] --> B[Pyrolysis design: temperature, residence time, oxygen limitation]
  B --> C[Biochar characterisation: proximate/ultimate, H/Corg, ash, pH, EC, BET, pore size, particle size]
  C --> D[Lab microcosms: dune sand + biochar +/- inocula; moisture & salinity regimes]
  D --> E[Mesocosm & wind/rain simulators: erosion thresholds, particle loss, infiltration/evaporation]
  E --> F[Field trials: desert dunes and/or coastal foredunes; vegetation establishment + geomorphic monitoring]
  F --> G[Coupled modelling: soil-water-plant + aeolian transport + sediment budgets]
  G --> H[MRV & governance: permanence, contaminant risk, biodiversity safeguards]
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Expected Results

What the best available quantitative syntheses say about coarse sands Across broad soil datasets, biochar amendments tend to improve soil water retention metrics and reduce saturated hydraulic conductivity, with improvements often most pronounced in coarse-textured soils. Reported mean effects include increases in available water capacity

(AWC) of ~28% and reductions in Ksat of ~39% (aggregated across soil types), with coarse-textured soils showing stronger gains and many included studies using comparatively high application rates. [5]

This general pattern is consistent with mechanistic expectations: adding a porous, carbon-rich solid into a coarse sand matrix can (i) increase total and micro/meso-porosity, (ii) shift pore-size distributions toward pores that retain water against gravity, and (iii) decrease bulk density, thereby increasing plant-available water even when total infiltration remains high. Experimental results in sandy contexts also indicate that the particle size of biochar and the application rate modulate hydraulic outcomes, implying that "biochar" cannot be treated as a single uniform intervention in dune sands. [28]

A dune-specific implication is that "more is not always better." Several studies report intermediate rate optima for some hydrologic outcomes (e.g., water retention/microporosity), and hydrophobicity or poor mixing can reduce or reverse expected gains. [29] For dunes, this interacts with feasibility and risk: high rates amplify logistics and may increase the fraction of loose, wind-transportable biochar unless incorporated and protected.

Biochar as microbial habitat and the dune "charosphere" hypothesis

The proposal's focus on pore-scale habitat creation aligns with broader literature that biochar can create a biologically active zone around and within biochar particles ("charosphere") and that pore architecture is a key microbial determinant. [30] Empirical evidence shows biochar can alter soil pore networks, increasing volumes of pores in size classes above ~5 μm, and that such pore volumes can correlate positively with microbial diversity and abundance (bacteria and fungi), while smaller pores may be associated with more anaerobic or facultatively anaerobic taxa patterns in some soils. [31]

Multiple syntheses indicate that microbial responses are heterogeneous: even where microbial biomass increases on average, some studies observe neutral or negative responses, reinforcing the need for mechanistic, dune-specific parameterisation rather than assuming universal stimulation. [32] For aeolian sandy soils specifically, biochar-mediated shifts in rhizosphere bacterial communities have been implicated as a mechanism for enhanced root growth, providing a closer analogue to dune sands than many agricultural loams. [23]

The pore-size emphasis in the proposal (~5-20 μm pores) is consistent with a broader thread of literature linking mesopore ranges to microbial shelter and water retention, though claims of a universal "optimal" range should be treated cautiously because pore accessibility, connectivity, moisture regime, and nutrient constraints differ strongly between humid agricultural soils and hyper-arid dune sands. [33]

Dune geomorphology and why "soil improvement" metrics are insufficient

Coastal dune evolution is fundamentally governed by interactions among sediment supply, wind regime, and vegetation establishment; the relative influence of vegetation and sand supply has been formalised in eco-geomorphic frameworks and empirical studies. [34] Aeolian transport from beach to dune is highly sensitive to surface moisture and fetch; storm-day observations show moisture contents can span from a few percent to saturation across short distances and times, and open-access work demonstrates that transport over wet beds can deviate from classical threshold formulations developed for dry sand. [35]

A dune-biochar intervention therefore requires outcomes that map onto these process controls. If biochar increases near-surface moisture retention, it may both (i) support plant establishment and (ii) raise entrainment thresholds by increasing moisture and cohesion, potentially reducing sand supply to foredunes in coastal contexts. Because coastal dune resilience is sometimes maintained by a balance between vegetated and bare-sand states, excessive stabilisation can be ecologically undesirable, and some literature warns that anthropogenic stabilisation and succession can cause dune systems to become over-fixed and less resilient. [36]

Carbon sequestration potential and permanence constraints in dune environments

The proposal references biochar as a negative-emissions strategy and situates the work within net-zero commitments. In the climate literature, the sustainable mitigation potential of biochar is reported with a wide range. The IPCC's land report summarises estimates of sustainable potential spanning roughly 0.5-2 $GtCO_2$-eq yr^{-1} (among cited studies), and related process-based analyses estimate that land- and calorie-neutral biochar systems could provide ~0.44-2.62 Gt CO_2 yr^{-1} under specific assumptions about yield improvements and deployment. [37] For dunes, permanence has two additional dimensions beyond biochemical stability: (i) physical retention (avoid wind removal and redistribution) and (ii) compliance with durability frameworks used by carbon markets and regulators, which frequently operationalise stability via elemental ratios such as H/Corg, sometimes in combination with temperature and ageing models. [38]

The dune-specific "permanence threat" is strongly evidenced by particulate emission studies: biochar amendments can increase emissions through direct resuspension of fine biochar particles and through abrasion of larger biochar by saltating sand grains, which is precisely the mechanical regime of mobile dunes. [7] This makes incorporation depth, particle-size engineering, and surface protection (mulch layers, crusts, vegetation) central to both environmental safety and carbon accounting integrity.

Discussion

Knowledge gaps and prioritised research questions for biochar-enhanced dune sand

Microhabitat mechanism to ecosystem function. The key mechanistic unknown is whether pore-scale refugia translate into persistent, functionally meaningful microbial networks under dune-specific stresses (heat, desiccation, salinity, UV exposure, sand abrasion). The proposal directly targets this but will need to explicitly connect pore occupancy (μCT/SEM) to functional traits (enzyme activities, nutrient mineralisation, plant-microbe interactions) and to hydrologic performance under repeated wet-dry cycles. [39] **Dune-appropriate hydrological endpoints.** Conventional soil metrics (field capacity, wilting point) assume vegetated soils with stable horizons. In dunes, the relevant questions include: how does biochar change the duration and spatial pattern of near-surface moisture films, the timing of germination windows, capillary rise where groundwater is shallow, and salt accumulation where evapoconcentration occurs? Coastal dune slacks and coastal groundwater interactions show nutrient and hydrology coupling is complex and spatially variable, indicating that dune hydrology is a legitimate research domain in its own right rather than a mere "soil moisture sensor" add-on. [40]

Eco-geomorphic feedbacks and unintended consequences. For coastal dunes, vegetation establishment changes sand trapping and dune morphology. Biochar that accelerates vegetation could alter dune growth trajectories and sand budgets; conversely, higher moisture may reduce entrainment and decrease sediment delivery to foredunes, potentially changing dune-building rates.

These are competing pathways that must be resolved empirically, ideally with a coupled monitoring and modelling framework. [41]

Wind-driven loss pathways and air-quality trade-offs. There is strong evidence that particulate emissions can increase after biochar application, including under wind speeds below thresholds for background soil erosion, implying that dunes (where winds and saltation are common) may be high-risk settings for biochar dust unless engineered and incorporated. This is a first-order gap because it affects both human health (PM exposure) and carbon permanence. [7]

Contaminant mobilisation and ecological toxicity. Biochar can contain PAHs, heavy metals, and other contaminants; standards require testing and impose thresholds, but dune environments raise special concerns (wind dispersal, coastal water contamination, sensitive habitats). High-quality analytical methods for PAHs in biochar are established, and synthesis research documents large variance in PAH concentrations across biochars, requiring strict feedstock and process QA/QC. [42]

Scale-up and feedstock economics. Desert regions may have constrained biomass supply, and the proposal's focus on abundant date-palm residues is a pragmatic alignment with feedstock constraints. Nonetheless, scale-up must address feedstock traceability, competing residue uses, transport, and the economics of seeding dunes with sufficient biochar at realistic rates. [43]

A concise set of **prioritised research questions** (high → medium priority):

Priority	Research question	Why it is load-bearing for "dune sand enhancement"
High	What fraction of applied biochar carbon is physically retained in dune sands over multi-year timescales under realistic wind/saltation regimes?	Determines whether enhancement is durable and whether carbon claims are credible. [7]
High	Which combinations of particle size, pyrolysis temperature, and placement (incorporated depth) minimise PM emissions while maximising moisture retention?	Directly couples benefit-risk trade-offs in dunes. [44]
High	Does pore-size architecture causally increase microbial diversity/function in hyper-arid dune sand, or are effects dominated by moisture regime and nutrient co-amendments?	Tests the proposal's central mechanism and generalisability. [39]
High	How does biochar-driven vegetation establishment alter dune sediment budgets (trapping vs reduced supply), and what is the "acceptable stabilisation" window for conservation?	Central for coastal dune management and avoids ecological harm from over-stabilisation. [45]
Medium	How do salinity and alkalinity interact with biochar ageing and microbial functions in dune sands (desert vs coastal)?	Determines applicability across dune types; informs selection of inocula and monitoring. [46]
Medium	What MRV pipeline is defensible for dunes (durability model + field verification + dust-loss accounting)?	Necessary for high-integrity deployment and any carbon-credit integration. [47]

Proposed experimental designs and monitoring protocols

The proposal provides a strong backbone for microcosm, pot, and plantation field work in the UAE. To meet the broader dune-sand objective (including coastal geomorphology), the programme should be expanded with **explicit dune transport, erosion, and landscape monitoring modules**.

Laboratory microcosms (mechanism isolation). A factorial design that remains analysable yet mechanistically rich:

- Factors: biochar pyrolysis temperature (3: 350/450/550 °C), biochar rate (4: 0, 1, 2, 4% w/w), inoculation (2: indigenous rhizosphere inoculum vs defined AMF/PGPR consortium), moisture regime (2: constant low moisture vs wet-dry pulses).
- Treatments: 3×4×2×2 = 48; replicates: n=6 per treatment (288 microcosms) to detect moderate effects while allowing for time-point subsampling.
- Timepoints: baseline; 2 wk; 8 wk; 24 wk, with destructive sampling for DNA/enzyme assays and non-destructive moisture tracking.
- Statistics: mixed-effects models (treatment fixed effects; time as repeated measure where applicable), multivariate ordination for community composition, and pre-registered causal models tested via piecewise SEM to link pore metrics → microbial metrics → hydraulic metrics. [48]

Mesocosm / wind-rain simulator experiments (process translation). Because dunes are transport systems, wind tunnel or field wind-simulator work is non-negotiable.

- Treatments: subset of "best" and "worst" performers from microcosms (e.g., 2 pyrolysis temperatures × 3 rates × 2 placements (surface vs incorporated ~10 cm) = 12); n=5 trays per treatment (60).
- Endpoints: threshold friction velocity, sediment loss rate, PM10 emission potential, crust formation, infiltration under rainfall simulation, and biochar particle loss fraction. Evidence indicates biochar particle abrasion/resuspension is a plausible major pathway; thus, PM monitoring should be incorporated as a primary outcome. [49]

Field trials (desert dunes and coastal dunes). A dual-site approach is recommended to disentangle desert vs coastal constraints:

- Inland desert field trial: aligned with the proposal's plantation-adjacent trial (control + low + high rates; randomised blocks).
- Coastal foredune trial: small, replicated plots in a managed dune system, with conservation oversight to avoid unacceptable stabilisation. Coastal dune management literature and guidance emphasise geomorphic processes in flood defence and conservation planning and should shape permitting and intervention intensity. [50]

Monitoring package (minimum defensible set).

Domain	Variable	Method	Frequency	Rationale
Hydrology	Volumetric water content	Multi-depth probes (e.g., 5/15/30 cm)	Continuous (hourly)	Captures persistence of moisture windows,

	profile			critical for establishment in coarse sands. [51]
Salinity	EC of pore water and soil extract	Lysimeters + lab EC	Monthly; event-based after storms/irrigation	Coastal and irrigated desert dunes risk salt accumulation; biochar effects can be bidirectional depending on ash/salts. [52]
Geomorphology	Surface elevation change	UAV photogrammetry / RTK GNSS transects	Quarterly; post-storm	Quantifies dune accretion/erosion and stabilisation effects. [53]
Sediment transport	Sand flux	Sand traps; saltation sensors	Continuous during wind events	Links intervention to transport regime; essential for mechanistic eco-geomorphology. [54]
Air quality / permanence	PM emissions, biochar loss	PM10 sensors + dust sampling + carbon fingerprinting	During wind events; seasonal audits	Addresses wind-driven loss evidence and carbon leakage risk. [7]
Biology	Microbial community	16S/ITS sequencing; functional gene panels	Baseline; 3-4× per year	Tracks whether "ground-zero" communities assemble and persist. [55]
Biology	Mycorrhizal colonisation	Root staining + microscopy; AMF qPCR	Twice per growing season	Literature supports biochar-AMF interactions but context dependence is high. [56]
Vegetation	Cover, plant traits	Quadrats; spectral indices; plant physiology subset	Monthly during season	Dunes are vegetation-sediment systems; cover is a state variable for morphodynamics. [57]
Contaminants	PAHs, metals	Accredited lab assays (Σ16 EPA PAHs, Σ8 carcinogenic PAHs)	Every production batch + annual soil audit	Needed for safety and to align with certification and regulatory thresholds. [58]

Risk assessment and regulatory considerations

Air-quality and occupational risk. The strongest dune-specific environmental risk signal in the literature is wind-driven particulate emission and transport of biochar particles, including under wind speeds below erosion thresholds for the background soil and under regimes where sand-biochar collisions generate new inhalable fractions. [7] Any dune deployment should therefore: (i) avoid fine biochar fractions at the surface, (ii) incorporate biochar below a protective layer where feasible, and (iii) treat particle-loss monitoring as core MRV rather than an optional add-on. [59]

Contaminants and ecological toxicity. Biochar can carry PAHs and metals; synthesis studies show wide PAH concentration ranges, and standards emphasise monitoring of PAH16 and carcinogenic subsets. [60] The European Biochar Certificate guidance documents explicitly discuss Σ16 EPA PAH and additional Σ8 carcinogenic PAH limits and safety rationales, and also ground heavy-metal limits in EU fertilising product rules and national ordinances. [26] For dunes, the key additional issue is **mobility**: contaminants in a mobile substrate can become airborne or enter coastal waters; thus "compliance-level" contaminant testing should be considered necessary but not sufficient.

Eco-geomorphic harm from over-stabilisation. Coastal literature anticipates resilience in systems where vegetation and bare sand coexist in a stable equilibrium, and warns that anthropogenic stabilisation and successional fixation can cause shifts toward less dynamic states. [61] Therefore, coastal dune biochar programmes require conservation governance safeguards: explicit limits on treated area, performance thresholds that include biodiversity and sand-dynamics indicators, and adaptive management triggers.

Regulatory frameworks across jurisdictions.
In the EU, pyrolysis and gasification materials have been incorporated as a component material category (CMC 14) within the fertilising products regulatory framework, specifying eligible inputs, quality constraints, labelling and conformity assessment rules. [62] Voluntary standards (e.g., EBC) position their certification classes as aligned with EU fertiliser regulation and specify contaminant thresholds and testing regimes. [63]

In the UAE context (directly relevant to the supplied proposal), fertilisers and agricultural conditioners are regulated through federal law, requiring approvals and defining testing/analysis and labelling procedures; organic production by-laws include standards for fertilisers/soil conditioners and lists of permitted/prohibited materials. [64] Operationally, this implies that a dune-sand biochar product deployed in the UAE is likely to face both (i) product registration / approval requirements and (ii) site-level environmental oversight if deployed beyond established farms.

Carbon markets and MRV. Biochar is actively used in voluntary carbon markets with methodologies that quantify removals from converting waste biomass into biochar and applying it in soils and non-soil applications. [65] Durability frameworks increasingly offer multi-century crediting options, and modules specify durability modelling and monitoring requirements for biochar storage in soils. [66] For dune applications, MRV must explicitly treat wind-driven loss as a potential permanence leakage, which is not always foregrounded in agricultural protocols.

Conclusions and recommendations

The best available evidence supports the plausibility that biochar can materially improve hydrologic function in coarse sands and can restructure microbial habitat and communities, but dune sands impose additional constraints that must be treated as central: aeolian transport, surface moisture dynamics, sediment budgets, conservation thresholds, and wind-driven particulate loss. [73] The supplied PhD proposal is structurally strong in its mechanistic focus and multi-scale pathway, and is particularly well positioned to generate publishable mechanistic insight by linking pore architecture to microbial assembly in "ground-zero" sands.

To elevate this into a dune-focused high-tier contribution, the work must add: (i) direct measurement of wind erosion resistance and PM/biochar loss pathways; (ii) dune-appropriate hydrologic and geomorphic endpoints; (iii) explicit "avoid over-stabilisation" safeguards in coastal settings; and (iv) a governance/MRV package aligned with fertiliser regulations, contaminant standards, and durability methodologies used in carbon markets.

A meta-analysis on biochar's effects on soil water properties

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